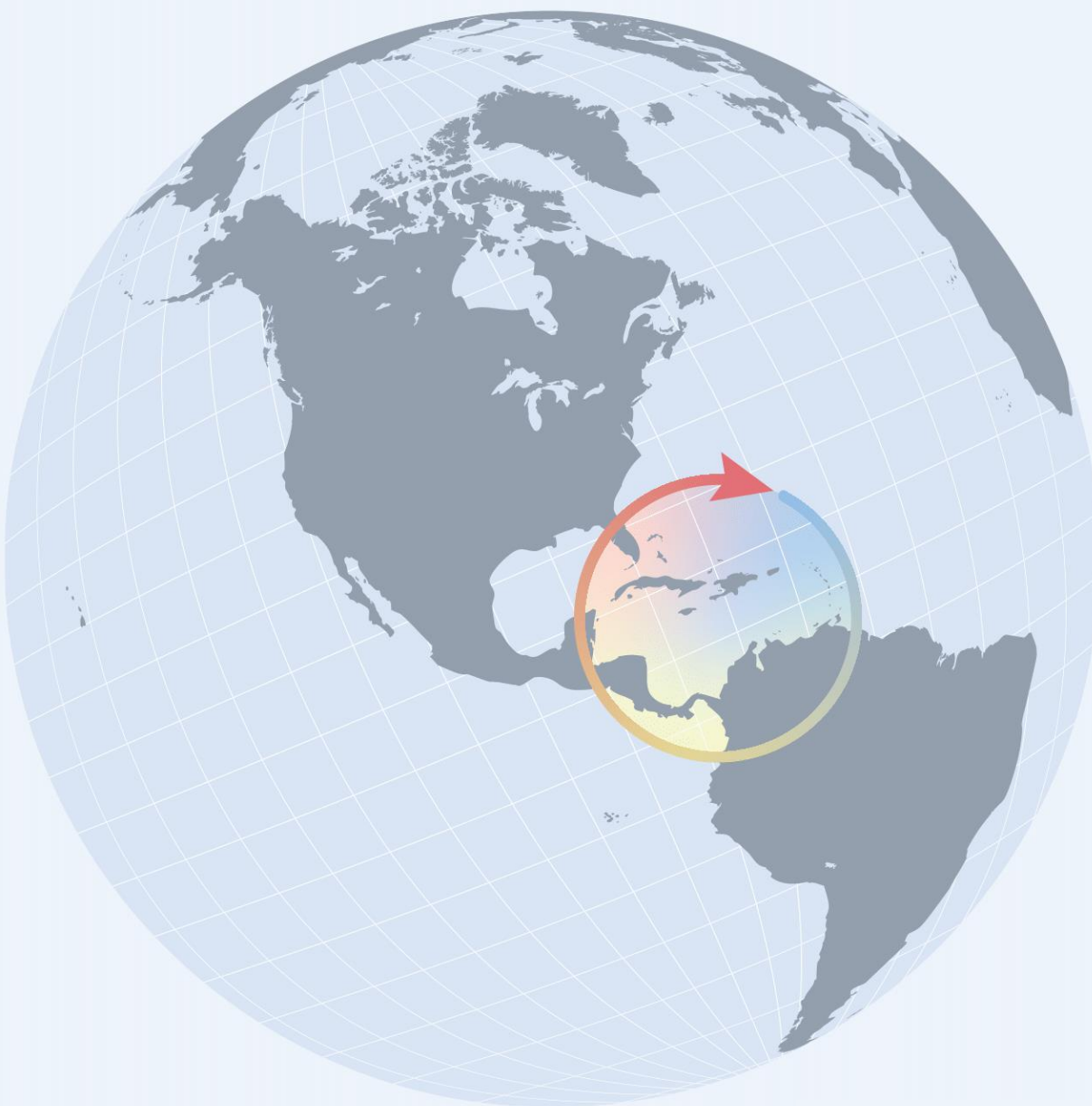


A BACKGROUND PAPER >> MANGROVES FOR COASTAL PROTECTION

# 360° Resilience

A Guide to Prepare the Caribbean  
for a New Generation of Shocks



# Mangroves as a Coastal Protection of local economic activities from hurricanes in the Caribbean

## Authors:

*Juan Jose Miranda*

*Rashmin Gunaskera*

*Luigi Butron*

*Chrissie Pantoja*

*James Daniell*

*Johannes Brand*

This work is a product of the staff of The World Bank and the Global Facility for Disaster Reduction and Recovery (GFDRR) with external contributions. The sole responsibility of this publications lies with the authors. The findings, analysis and conclusions expressed in this document do not necessarily reflect the views of any individual partner organization of The World Bank (including the European Union), its Board of Directors, or the governments they represent, and therefore they are not responsible for any use that may be made of the information contained therein.

Although the World Bank and GFDRR make reasonable efforts to ensure all the information presented in this document is correct, its accuracy and integrity cannot be guaranteed. Use of any data or information from this document is at the user's own risk and under no circumstances shall the World Bank, GFDRR or any of its partners be liable for any loss, damage, liability or expense incurred or suffered which is claimed to result from reliance on the data contained in this document. The boundaries, colors, denomination, and other information shown in any map in this work do not imply any judgment on the part of The World Bank concerning the legal status of any territory or the endorsement or acceptance of such boundaries.

## Contents

1. Introduction .....	3
2. Data and Statistics.....	5
2.1. Night Lights Application .....	5
2.2. Hurricane Damage Frequency .....	9
2.3. Mangroves Forest Data.....	11
3. Empirical Strategy .....	15
3.1. Modeling the Windstorm Model .....	15
3.2. Mangroves for Coastal Protection .....	16
4. Results and Discussion.....	18
4.1. Impact of Hurricanes on Nightlights .....	18
4.2. Mangroves Reduce Hurricane Impact.....	19
5. Conclusion.....	22
6. Annexes.....	23
7. References .....	27

## **Abstract**

In recent decades, hurricane frequency and intensity have increased in the Caribbean basin. From 2000 to 2012, more than 100 hurricanes impacted lives, infrastructure, gross domestic product, and natural environments along the coastal shorelines. Recent academic references mention that the dense root system of mangrove forests might mitigate the impact of hurricanes, which would help stabilize the coastline and prevents erosion from waves and storms. Many tropical mangroves are found on the coasts of Caribbean islands, unfortunately, these wetland ecosystems have been cleared at a rate of one percent per year since the nineties by climatic and anthropogenic events. Given this critical context, this study quantifies the causal effects hurricane windstorms on local economic activity, using as a proxy nightlights in the Caribbean region at the highest spatial resolution data available (1 square kilometer), and then measure the level of mangrove natural protection against the impact of hurricanes, employing different widths of the mangroves belt, which leads to a broader socio-economic and environmental perspective study. The results suggest that major hurricanes show negative effects of approximately two percent in nightlights and even a greater negative impact of sixteen percent in storm surge prone areas. However, the presence of mangroves on the coast minimizes the impact of hurricanes, shows a reduction of nightlights between one and six percent. The paper contributes to the literature of natural coastal protection against natural disasters by providing robust estimates of the causal effects of major hurricanes windstorms in the Caribbean, producing regional evidence that could improve targeting of environmental policies and disaster risk management toward those most impacted islands.

## 1. Introduction

The Caribbean is a region highly susceptible to damages arising from natural disasters, particularly prone to tropical storms and hurricanes formed in the Western North Atlantic Ocean basin, which includes the Caribbean Sea and the Gulf of Mexico areas (Tomblin, 1979). The peak of the hurricane season in the Caribbean runs mostly in the second half of the year, although there have been infrequent storms that formed outside these dates (Johnson, 2015). According to the National Oceanic and Atmospheric Administration (NOAA), an average Atlantic hurricane season produces twelve named storms, including six hurricanes of which three become major hurricanes (category 3, 4, or 5). Between 2017-2019, the region experienced three Category 5 hurricanes.

Caribbean population are subjected to repeated hurricane strikes without respite and a sense of helplessness and hopelessness set in (Gin & Lubin, 1989). Despite general improvements in living standards, poverty rates average 30 percent in the Caribbean region (Bowen, 2007). Since 2010, the countries have shown persistently weak economic growth. Annual gross domestic product (GDP) growth rates average only 0.8 percent compared with 4.7 per cent in other small states (OECD, 2019). Most of Caribbean islands exhibit high levels of growth volatility, creating uncertainty, hindering economic growth, and negatively affecting public finances (Beuermann & Schwartz, 2018).

The repercussions from meteorological damages have long-term consequences at the national and regional levels. According to EM-DAT, has 283 records of disasters in the Caribbean caused by hurricanes between 1950 and 2014 that either made landfall or passed within 69 miles of the Caribbean islands<sup>1</sup>. Of those storms, the database only recorded damages for 148 hurricanes, which caused roughly US\$52 billion (in 2010 constant U.S. dollars) in damages. This is equivalent to an average of 1.6 percent of GDP in damages every year in the islands (IMF, 2016).

In fact, 15 out the top 25 counties worldwide with the most tropical cyclones per square kilometer are Caribbean islands. Hurricanes have caused major damage to hotel facilities and disrupted tourist arrivals, particularly since tourism infrastructure is usually concentrated in coastal areas, which are more exposed to hurricanes and floods. For example, when Hurricane Ivan hit Grenada in 2004, it damaged most hotels, while Hurricane Omar in 2008 essentially wiped out tourism in Nevis by damaging the main hotel on the island. In 2012, Hurricane Sandy caused severe disruptions to hotel operations in The Bahamas.

Recent scientific literature demonstrates that disasters have direct and indirect economic consequences. Direct effects by natural disasters can negatively affect infrastructure, crops, extractable natural resources, and of course mortality and morbidity, in the short term (Noy & DuPont, 2018; Ishizawa, Miranda, & Strobl, 2019). By contrast, indirect effects are associated with emergency costs, business interruption, consequence for economic growth, social and community network, and impacts on security and stability, in the long term (Cavallo & Noy, 2011; Hallegate, 2014). Therefore, the direct impacts can lead to indirect impacts, which refer to changes in economic activity that follow the disaster (Botzen, Deschenes, & Sander, 2019).

---

<sup>1</sup> It must be noted that not all hurricanes and tropical cyclones that pass close to an island in the Caribbean should result in a natural disaster as the threshold for that classification requires at least 100 people affected, or at least 10 people killed, or a state of emergency to be declared.

In specific, the very nature of the storm themselves, however, as well as local community characteristics (e.g. weak infrastructure) means that the economic impact, both direct and indirect, can vary widely across space (Bertinelli & Strobl, 2013). Developing nations are more susceptible to the adverse impacts of disasters than industrialized nations in the short and long term (Rasmussen, 2004; Loayza et al., 2012). For example, the most vulnerable countries are Small Island Developing States (SIDS), such as the Caribbean islands, which experience a growth collapse as a result of climatic events. Mainly, the region's island economies find it difficult to recover immediately after the shock, especially due to the impact on their macroeconomic indicators, including the deterioration of the fiscal and trade balance (Heger et al., 2018).

However, the natural habitats (e.g. coral reefs, seagrasses, and mangroves) have the ability to protect coastal communities against the impacts of waves and storms. Especially, mangroves<sup>2</sup> are a form of natural infrastructure from storm surge and flooding that provides a coastal protection in tropical regions (Blankespoor, Dasgupta, & Lange, 2016). An array of studies has shown that mangrove forests can attenuate wave energy (Brinkman et al., 1997; Mazda et al. 1997; Massel et al., 1999; Quartel et al., 2007; Barbier et al. 2008, Gedan et al. 2011; McIvor et al. 2012; Pinsky et al. 2013). One of the main factors affecting wave height decline is the width of mangrove greenbelt and cross-shore distance (Bao, 2011). Other factors include shore slope, root diameter, shore slope, spectral characteristics of incident waves, and tidal stage upon entering the forest (Alongi, 2008).

In the Caribbean region, mangroves are quite widespread along the coast of 13 sovereign states and 17 dependent territories, ranging from Bahamas in the north to Trinidad and Tobago in the south. The low-island mangroves growing in the territory of Bermuda are among the northernmost communities in the world (32°20'N). High population pressure in coastal areas, has however, led to the conversion of many mangrove areas to other uses including urbanization, industrialization, conversion to aquaculture, and increasingly, for tourism; this disturbances occur, respectively, at increasing spatial and temporal scales, and require increasing recovery time (Tuholske et al., 2017; Polidoro et al., 2010; FAO, 2007; Duke, Pinzon, & Prada, 1997; Ellison & Farnsworth, 1996). Overall, the region is losing mangrove forest at 1 percent per year, although the rate is much faster on the Caribbean mainland (1.7 percent per year) than it is on the islands (0.2 percent per year) (Ellison & Farnsworth, 1996). After the Indo-Malay Philippine Archipelago, the Caribbean has the second highest mangrove area loss relative to other global regions, with approximately 24 percent of mangrove area lost over the past quarter-century (FAO, 2007).

A novel notable study suggest that mangroves also can mitigate the impact of hurricanes on local economic activity (e.g. Del Valle, Eriksson, Ishizawa, and Miranda, 2020). They show that within coastal lowlands of Central America, the nightlights, as a proxy of GDP, decrease by up to 24 percent in areas that are unprotected by mangroves; although, the sample is fully mitigated in areas protected by mangrove belts of 1 km or more. Following this line, the contribution of this study is to provide a regional perspective about how mangroves can act as natural barriers to mitigate the negative impact of hurricane windstorm in the Caribbean on a particular set of social and economic outcomes. In a region where more than half of the population lives within 1.5 km of the shoreline, hurricanes might pose serious socioeconomic risks (Waite et al. 2014).

This paper finds robust evidence that hurricanes significantly affect the intensity of nightlights. For locations that were hit by Category three hurricane (wind speed of 203 kph), we estimate a negative impact of 2.9% in nightlights, using the average level of nightlights in 2000. Moreover, the effect of

---

<sup>2</sup> Mangroves are areas of forest and other wooded land with mangrove vegetation (FAO, 2010).

windstorms is more negative in storm surge prone areas, measured as low elevation coastal zones, the negative effect of Category three hurricane winds is associated with a 16.1% decrease in nightlights. Including the mangrove forests as a natural defense, this hurricane category would reduce nightlights between 4.7% and 5.1%, above and below the median (0.25 km of mangrove width). Moreover, when the mangrove is greater than 1.26 km and with an average width of 2.3 km, the reduction in nightlights is equivalent between 1% and 6.5%.

The remainder of the paper proceeds as follows. Section 2 describes thoroughly the night lights data used in this study, the frequency of hurricane damages, and mangroves forest data, in the Caribbean region. A brief description of the hurricane data and our proxy for potential damage from hurricanes is also included in this section. Section 3 explains our empirical estimation approach, and Section 4 turns to the results. Finally, Section 5 concludes the paper.

## **2. Data and Statistics**

To quantify the impact of hurricanes strikes on local economic activity in the Caribbean, we used three main sets of data: (i) night lights data as a proxy for local economic activity, (ii) hurricane windstorm hazard data derived from a wind field model, and (iii) Global Mangroves Database.

### **2.1. Night Lights Application**

The nighttime light (NTL) data from the Defense Meteorological Satellite Program (DSMP) – Operational Linescan System (OLS) are a primary data source for economic activity from local, regional to global scales (Bertinelli & Strobl, 2013; Henderson, Storeygard, & Weil, 2012; Chen & Nordhaus, 2011). Compared to other remote sensing satellite observation, it lends itself particularly well to projects in which a policy with highly localized effects is being evaluated, or to a policy evaluation in countries with poor or non-existent subnational GDP data (Lowe, 2014). Furthermore, because of its global coverage and long temporal span, the DSMP NTL data have also been extensively used in studies such as electricity consumption, socioeconomic activities, light pollution, urban ecosystems, and urban extent mapping (Li, Zhou, Zhao M., & Zhao X., 2020).

Since 1992 to 2013, raw daily night light imageries are processed by scientists at the National Oceanic and Atmospheric Administration (NOAA), who developed a method to remove cloud obscured pixels, as well as sources of transient lights such as the bright half of the local cycle, auroral activity, forest fires, and other events, delivering yearly cloud-free night light composite that essentially capture nocturnal human activity (Elvidge et al., 1997). Records in night light images data are the digital number (DN) values, ranging from 0 (no light) to 63 (maximum light); and the spatial resolution is 30 arc-seconds, with a near-global coverage of 180°W to 180°E in longitude and 65°S to 75° in latitude (Li et al., 2020).

For this study, we use imagery recorded by satellite from 2000 to 2012, covering 29 Caribbean countries and territories: Anguilla; Antigua and Barbuda; Aruba; Bahamas; Barbados; Bermuda; Bonaire, Saint Eustatius and Saba; British Virgin Island; Cayman Islands; Cuba; Curaçao; Dominica; Dominican Republic; Grenada; Guadeloupe; Haiti; Jamaica; Martinique; Montserrat; Puerto Rico; Saint Kitts and Nevis; Saint Lucia; Saint Vincent and the Grenadines; Saint-Barthélemy; Saint-Martin; Sint Maarten; Trinidad and Tobago; Turks and Caicos Islands; and United States Virgin Islands. There are some studies that use yearly frequency night lights data to predict local economic activities and mapping poverty in the Caribbean such as Bertinelli & Strobl (2013) and Andreano, Benedetti, Piersimoni, & Savio (2020). Nevertheless, this paper

is one of the first studies to use and exploit yearly frequency data, provided by NOAA, in order to assess the role of mangroves as natural protection in front of the damaging effects of hurricane strikes on local economic activities in the Caribbean.

Many economists who usually use night lights as a proxy for economic activity, pay a great attention to night light saturation in urban centers (e.g., Doll et al., 2006; Keola et al., 2015). A study of Henderson et al. (2012) tested whether sensor saturation impairs the capacity of night lights to predictive GDP and, through a fixed-effects specification for a panel of 188 countries over 17 years, found that the estimate of the elasticity night lights with a respect to GDP and the  $R^2$  remain unchanged after controlling by the number of pixels that are top-coded. In the same way, this study examines to what extent saturation weakens the suitability of night lights as proxy of local economic activity in the Caribbean.

Table 1 shows the frequency distribution of DNs across pixels for Caribbean islands, along with the information on land areas and GDP per capita at PPP. Most small states have a large size of their land areas or pixels<sup>3</sup> with no artificial lights (i.e., have a DN value of 0) for the entire sample period of 12 years. In islands relatively more exposed to hurricanes strikes such as Haiti a 70 percent of their pixels are unlit; meanwhile Cuba, the Bahamas, and Dominican Republic, more than a quarter of their pixels are unlit. According to Bertinelli & Strobl (2013) and Elliot et al. (2015), who also use night lights data to study the economic impact of tropical storms on local activity, this study assume there is no economic activity in pixels that have a DN value of 0 for the entire sample period, and exclude them in the econometric analysis (about 67% of the total sample).

Additionally, this table provides the number of top-coded pixels (i.e. have a DN value of 63) as well as the mean DN across the sample. It reveals that the percentages of censored pixels are zero or close to zero, suggesting that night light saturation in urban centers might not be a major issue in the Caribbean. By contrast, the average value of DN across the 29 islands do show some variance. The island Sint Maarten/Saint Martin, half Dutch and half French, for instance, have the highest average DN in the region with 53.67 and 46.02, followed by Bermuda with 36.24 and Aruba with 36.08, countries with the highest income level in the Caribbean. In some way, the correlation between night lights and income levels could be proved for these countries. However, night lights might not be a reliable proxy for income levels due to cultural differences in the use of lights and light saturation in large cities (Ghosh et al., 2010). Instead, night lights data work better as a proxy of economic growth (Henderson et al., 2012). For this reason, the empirical strategy (to be further discussed in the next section) centers on the variations in night light intensity across pixels and over years, after controlling by time-invariant and time-specific effects, to isolate the impact of hurricanes on local economic activity.

The mean nightlights by Caribbean country or territory convey different shapes of trends (see Annex 1). In 2000, Haiti, Dominica, Montserrat, and Cuba, presented the lowest DN value in the region, lower than 5, while Saint Martin, Sint Maarten Bermuda, Puerto Rico, showed a value between 38 and 48, being 63 the maximum value of night lights. Surprisingly, five years later, in 2005, the islands with the lowest value of nightlights at the beginning of the period decreased their luminosity by approximately 2 points. In the way, the islands with the highest value of nightlights, by around 8 points. In other words, the low-income islands reduced their value of nightlights in a lower number than the high-income islands. Overall, the mean of nightlights of the 29 countries and islands fell from 7.73 in 2000 to 6.12 in 2015. The impact of hurricanes and tropical storms on their local economies during that period could be a reason of this decline.

---

<sup>3</sup> The number of pixels of a country is fairly proportional to its land areas.



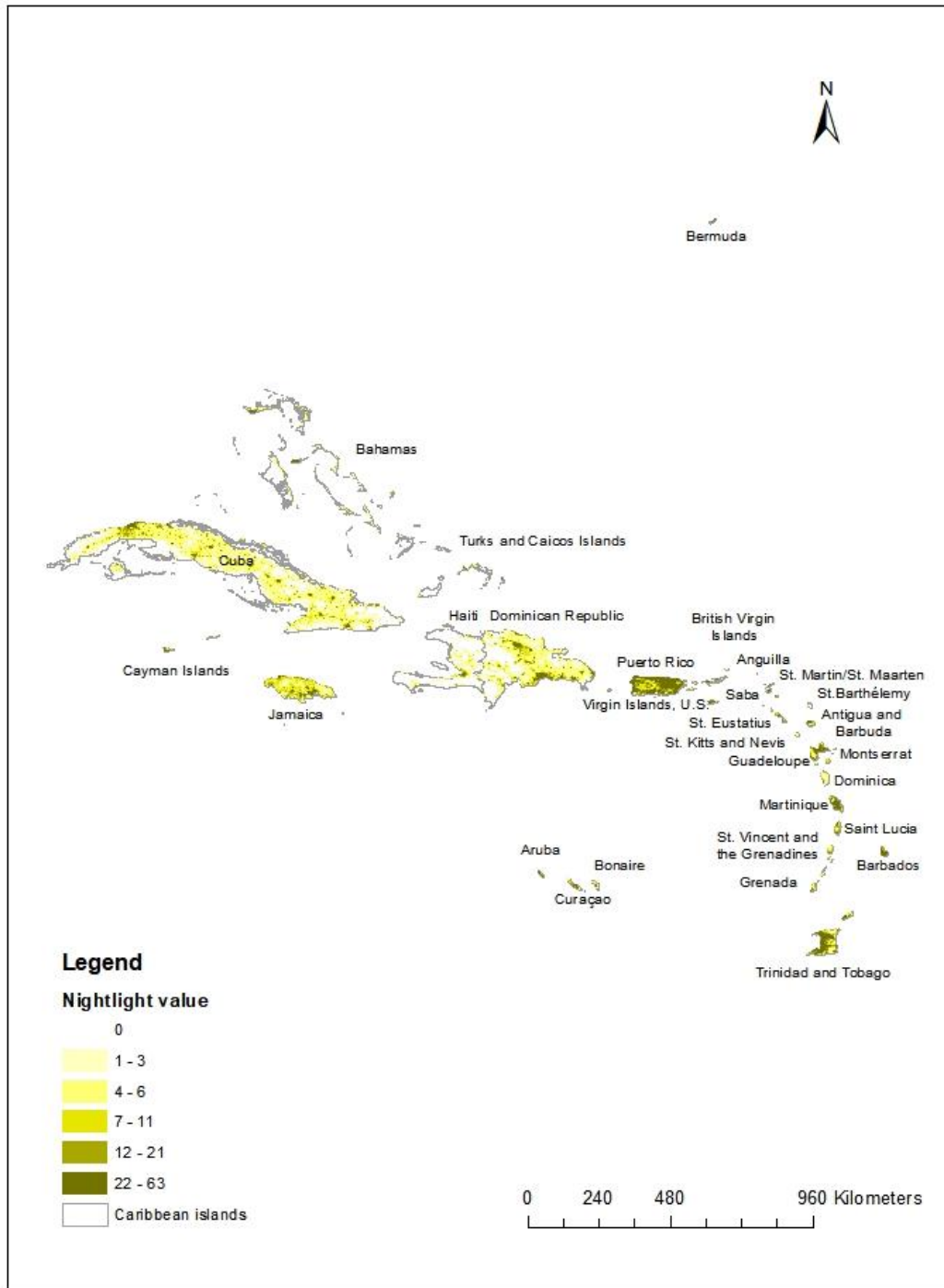
By 2010, the trend was positive for many Caribbean islands. All of them reported an increase from 2 to 16 points of nightlights value, except Aruba which reduced by 1 point. Trinidad and Tobago was the country that exhibited the most improvement in economic growth, from 13.51 to 29.32 of luminosity. Followed by Saint Martin and Martinique, that displayed a rise of around of 11 to 12 points. At the end of the studied period, in 2012, the average of nightlights from all the islands drop in 1 point. Only five countries showed an increase of 1 to 3 points: (i) Aruba, (ii) Bonaire, Saint Eustatius, and Saba, (iii) Cayman Islands, (iv) Curaçao, and (v) Saint Martin; and three islands remained their numbers, for instance, Haiti, Saint Kitts and Nevis, and Saint Lucia. The resilience of natural disasters from those islands might be have improved the last decades. Figure 1 presents the map of nightlights intensity in the Caribbean island during the period of 2000 and 2012.

**Table 1. Night lights data for Caribbean countries and territories, 2000-2012 average**

Nº	Country / Area	DN							Avg. DN	Avg. DN (excluding 0)	Area (sq km)	Pop. Density (per sq km, 2018)	GDP per capita, PPP (2019 \$)
		0	(0,3)	(4,6)	(7,11)	(12,21)	(22,63)	63					
1	Anguilla	0%	0%	2%	11%	50%	45%	0%	21.00	21.00	91	169.8	19,890
2	Antigua and Barbuda	11%	15%	13%	27%	27%	30%	0%	17.99	20.22	440	219	22,817
3	Aruba	0%	0%	7%	12%	16%	72%	7%	36.08	36.16	180	588	38,442
4	Bahamas	37%	52%	42%	10%	4%	10%	1%	7.21	11.47	13,880	39	37,266
5	Barbados	0%	0%	0%	9%	36%	61%	4%	30.90	30.90	430	667	16,287
6	Bermuda	0%	0%	1%	3%	11%	89%	0%	36.24	36.24	4,290	1184	59,474.60
7	Bonaire, Saint Eustatius, and Saba	18%	23%	40%	29%	14%	11%	0%	8.93	10.84	328	79.9 (year 2020)	24,266 (year 2016)
8	British Virgin Islands	8%	17%	44%	17%	19%	21%	0%	12.25	13.26	150	199	48,511
9	Cayman Islands	1%	4%	26%	38%	19%	29%	1%	18.88	19.17	260	267	72,481
10	Cuba	44%	57%	43%	12%	3%	2%	0%	3.60	6.38	109,880	109	8,821
11	Curaçao	5%	8%	23%	27%	17%	37%	7%	23.58	24.95	444	361	25,572
12	Dominica	32%	48%	56%	11%	3%	1%	0%	3.47	5.10	750	96	12,659
13	Dominican Republic	33%	41%	42%	18%	7%	6%	0%	6.15	9.18	48,670	220	19,182
14	Grenada	0%	3%	45%	47%	16%	10%	0%	10.07	10.10	340	328	17,956
15	Guadeloupe	1%	4%	24%	26%	28%	31%	1%	17.69	17.88	1,705	245.8 (year 2020)	26,855 (year 2016)
16	Haiti	70%	71%	19%	9%	3%	3%	0%	2.72	9.12	27,750	404	1,801
17	Jamaica	5%	11%	46%	42%	14%	9%	1%	9.59	10.13	10,990	271	10,661
18	Martinique	0%	2%	11%	17%	26%	54%	1%	25.31	25.42	1128	354 (year 2020)	30,056 (year 2016)
19	Montserrat	29%	41%	51%	27%	1%	0%	0%	3.81	5.37	103	52.4 (year 2020)	12,753
20	Puerto Rico	0%	1%	4%	18%	24%	61%	5%	30.69	30.83	8,870	360	34,948
21	Saint Kitts and Nevis	1%	5%	30%	46%	0%	15%	0%	12.58	12.70	260	202	27,449
22	Saint Lucia	1%	6%	31%	39%	0%	16%	0%	12.76	12.94	620	298	16,089
23	Saint Vincent and the Grenadines	14%	23%	47%	32%	10%	7%	0%	7.28	8.44	453	283	12,983
24	Saint-Barthélemy	5%	7%	1%	3%	26%	68%	0%	26.79	28.29	25	9,961 (year 2016)	21,514 (year 2014)
25	Saint-Martin	1%	1%	0%	0%	3%	96%	2%	46.02	46.39	54	672	16,572 (year 2014)
26	Sint Maarten	0%	0%	0%	0%	0%	100%	2%	53.67	53.67	34	1,193	23,366
27	Trinidad and Tobago	8%	11%	25%	25%	19%	33%	3%	19.58	21.27	5,130	271	27,261
28	Turks and Caicos Islands	31%	45%	38%	11%	9%	14%	0%	8.02	11.58	950	40	27,055
29	Virgin Islands, U.S.	1%	2%	11%	15%	17%	63%	1%	32.83	33.11	350	306	35,090 (year 2018)

Source: Authors' calculations based on FAO, World Bank, UN estimates, The French National Institute for Statistics and Economic Studies (INSEE, by its acronym in French), and the Dutch Central Bureau of Statistics (CBS).

**Figure 1. Map of Nightlights Imagery for the Caribbean region**



Source: Author's elaboration based on the Global DMSP-OLS Nighttime Lights Time Series 2000-2012 of NOAA.

## **2.2. Hurricane Damage Frequency**

Hurricanes are the most devastating natural disasters in the Caribbean, their destructive capability is a force that has shaped history and will shape the future of the region. The movement of every tropical cyclic

storm is characterized by extreme winds, storm surges, and exceptional levels of rainfall which may cause flooding (Henderson-Sellers et al., 1998). The official hurricane season in the Greater Caribbean region begins the first of June and lasts through the end of November, with 84 percent of all hurricanes occurring during August and September (Neumann, 1993).

The number and strength of Caribbean storms vary greatly from year to year, which makes it challenging to detect trends in the frequency or intensity of hurricanes over time. In the last twenty years, the islands were facing from low to high-intensity storms. They are classified in four types by the wind speed: (i) tropical depression, a tropical cyclone<sup>4</sup> with maximum sustained winds of 61 kph or less; (ii) tropical storm, winds between 62 kph and 118 kph ; (iii) hurricane, winds between 119 kph and 177 kph, corresponding to a Category 1 and 2; and (iv) major hurricanes, winds between 178 kph and 208 kph for Category 3, between 209 and 251 kph for Category 4, and 252 kph or higher for Category 5. The hurricane category is determined by the Saffir-Simpson Hurricane Wind Scale.

During our sample period of 2000-2012, 146 hurricanes (Categories 1, 2, 3, 4, and 5) and 196 tropical cyclones were reported in the Caribbean region. Figure 2 presents that Cuba, the Bahamas, Haiti, and Dominican Republic were the most affected countries by hurricanes, between category 1 and 5, with more than 40 episodes in the period shown. Surprisingly, the major hurricanes, up to category 3, impacted Cuba and the Bahamas.<sup>5</sup> By contrast, southern areas like the Dutch Caribbean islands of Aruba, Bonaire, and Curaçao are rarely affected because hurricanes tend to travel away from the equator.

In fact, the Dow Jones Island Index ranked Curaçao as the Caribbean island least likely to be hit by hurricanes, followed by Bonaire, Cayman Islands, Barbados, and Aruba, and other Western Caribbean islands are less likely to be affected by hurricanes than Eastern Caribbean spots like the British Virgin Islands and Puerto Rico. Among the least affected islands, during the twelve-year period, are Dominica, Montserrat, and Trinidad and Tobago that showed less than 10 episodes of hurricanes. Furthermore, tropical depressions and storms, in other words, Category 0 of Hurricane Category, occur frequently and anytime in the hurricane season of the Atlantic Ocean. Curiously, the countries most impacted by this natural phenomenon are Dominica and Trinidad and Tobago, which presented fewer impacts by hurricanes, and Guadeloupe. All of these countries, displayed around 13 episodes during 2000-2012, followed by the islands of Barbados and Bonaire, Saint Eustatius, and Saba with 12 episodes.<sup>6</sup>

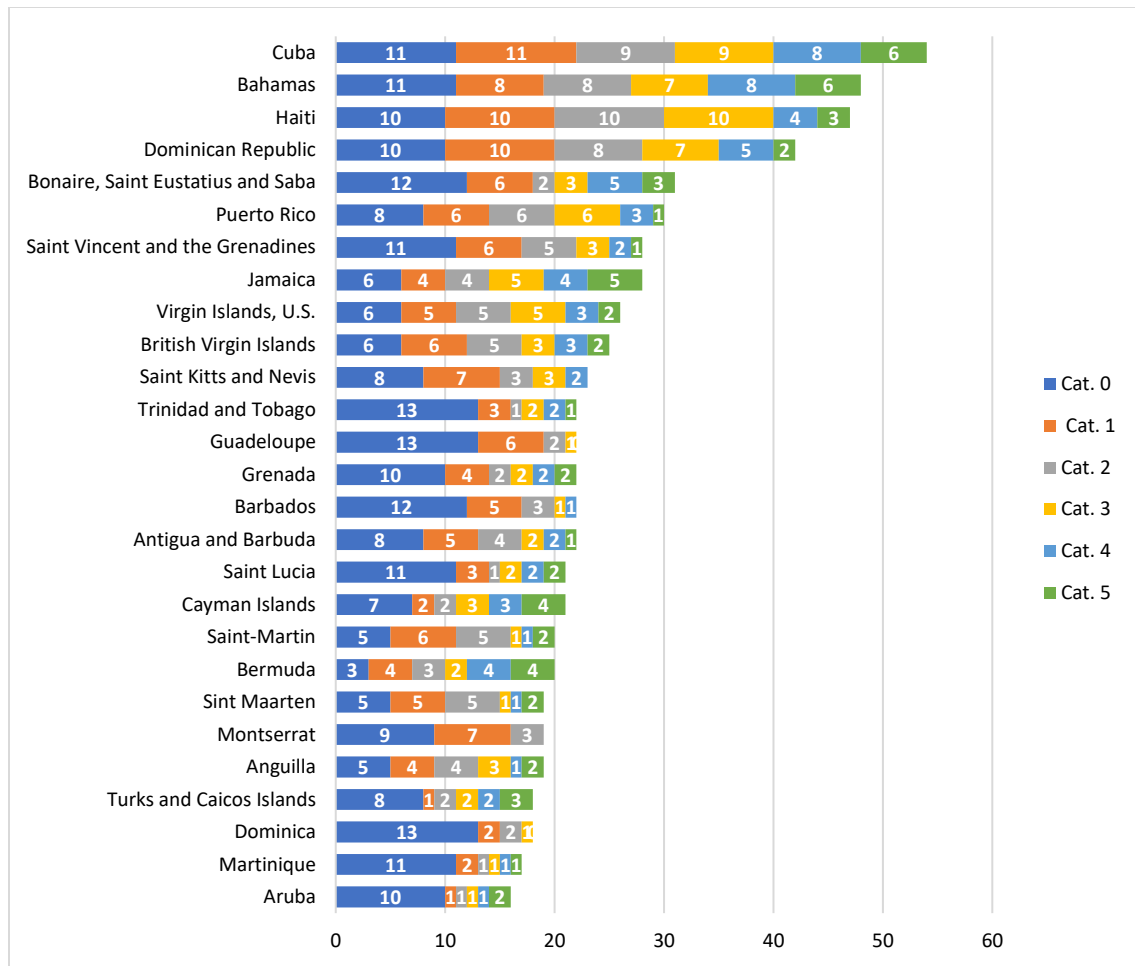
Some islands in the Caribbean are subjected to higher levels of wind speeds more frequently than others. Over time, this has resulted in variations in building vulnerability across the region, as each country adopts or develops its own building codes and construction practices that reflect its historical storm experience and regional building inventory (AIR, 2020). The resulting construction and occupancy mix and height distribution of the building stock is a fundamental determinant of the region's vulnerability. For this reason, many islands in the Caribbean have suffered deep impacts of tropical storms to major hurricanes in the last twenty years.

---

<sup>4</sup> According to NOAA, a tropical cyclone is a rotating, organized system of clouds and thunderstorms that originates over tropical or subtropical waters and has a closed low-level circulation. Tropical cyclones rotate counterclockwise in the Northern Hemisphere.

<sup>5</sup> Annex 2 shows the tendency of the damage index by Hurricanes Category 3 by Caribbean country and territory.

<sup>6</sup> For further detail, see Annex 3.



Source: Author's calculations.

For all those hurricanes, it is used a windstorm hazard model<sup>7</sup> to simulate the maximum sustained wind speeds (MSWS), which is a proxy for potential damage from hurricanes (PDH), experienced by the affected areas at a resolution of 1 sq km. In other words, it is capable of producing a fully exogenous measure of hurricane intensity and its potential destructive power at a fine-grained geographical level. The resulting wind speed data are then merged with night lights data.

Recent studies have focused on improving modeling natural hazard in order to more explicit address the impact of adverse natural events on socioeconomic indicators. For example, Hsiang & Jina (2014) and Strobl (2012) evaluate the hurricane windstorm hazard data using global hurricane models to generate gridded data set with different levels of resolution. One of the main innovations in this paper is to use fully probabilistic hurricane windstorm model developed by Strobl (2012) which has been validated and calibrated for the Caribbean region to generate hazard information with the temporal and spatial resolution needed for this study. The windstorm hazard data are used to calculate the damage indexes which are used as input in both the macro and micro models. As a result, the paper substantially improves the understanding of how hurricane windstorm hazards could affect socioeconomic outcomes.

### 2.3. Mangroves Forest Data

<sup>7</sup> We thank Eric Strobl for sharing the model results.

Mangroves are commonly found along sheltered coastlines in the tropics and subtropics where they fulfil important socio-economic and environmental functions. These include the provision of a large variety of wood and non-wood forest products; coastal protection against the effect of wind, waves, and water currents; conservation for biological diversity, including the protection of coral reefs, sea-grass beds, and a number of endangered animals (FAO, 2007). Especially, the coastal mangroves, together with coral reefs and seagrass beds, act as a natural barrier from high wave energy and strong coastal currents typical of the Caribbean environment (Menéndez, Losada, Torres-Ortega, Narayan, & Beck, 2020).

Caribbean mangroves have sustained human activity since pre-Columbian times (Sanoja, 1992). Nevertheless, the climate forcing factors (e.g. extreme winds caused by tropical storms) and the anthropogenic ones (e.g. deforestation and urbanization) impact severely to mangroves of the region. In fact, impacts of climate change on mangroves expected to result from anthropogenically-driven increases in atmospheric carbon dioxide (CO<sub>2</sub>) concentration and regional sea level (Ellison & Farnsworth, 1996). Unfortunately, the demands on mangrove forests are more intensive and pervasive and include conversion of mangroves to other uses such as agriculture production and the urbanization of their uplands. In that way, the lack of concern for this ecosystem has led to the loss of mangroves and the change in the conditions that regulate their functioning as well as the overexploitation of dependent fisheries and other forest products (Lugo, 2002).

Although the literature on mangrove forests is extensive and numerous case studies describe their extent and losses over time, global, comprehensive information on the status and trends in the extent of mangroves has been lacking. The first attempt to estimate total mangrove area worldwide was undertaken as a part of the FAO and United Nations Environment Programme (UNEP) *Tropical Forest Resources Assessment* in 1980. In that study, the world mangrove total was estimated at 15.6 million hectares, while more recent estimates range from 12 to 20 million hectares (FAO, 2007).

For this study, we used two of the mangroves distribution sources: (i) the mangroves data from the World Atlas of Mangroves, the first collection of harmonized maps, 1960 to 1996, published in 1997 by Spalding, Blasco & Field, they estimated a total of 18.1 million hectares in 112 countries and territories (including small island nations); and (ii) the first global map of mangrove forests that utilized remotely sensed data produced by Giri, et al. in 2010. This work used over 1000 Landsat scenes acquired over the period 1997-2000, with supervised and unsupervised digital image classification to construct a 30 m<sup>2</sup> resolution map of the global mangrove distribution, estimating a total mangrove extent of 13.7 million hectares in 118 countries and territories in the tropical and subtropical regions of the world.

Regarding Spalding et al. (1997), we find mangrove forests in 880,173 hectares in 29 Caribbean countries and territories selected for this study. Cuba and the Bahamas were the countries with the most extensive areas of mangroves, with approximately 556,900 and 211,400 hectares, respectively. By contrast, we located in Giri et al. (2010) a mangrove extension of 616,440 hectares in the 26 Caribbean countries and territories studied (excluding Dominica, Montserrat, and Sint Maarten). Unlike Spalding et al. (1997), they estimated 440,641 ha for Cuba and 82,408 hectares for the Bahamas, both the countries with a higher number of mangroves areas as is shown in table 2.

**Table 2 Mangrove areas in the Caribbean region (in hectares)**

Country/Territory	Spalding et al. (1997)	Giri et al. (2010)	Country/Territory	Spalding et al. (1997)	Giri et al. (2010)
Anguilla	90	5	Haiti	13,400	15,496
Antigua and Barbuda	1,316	973	Jamaica	10,600	9,817
Aruba	420	79	Martinique	1,587	1,197
Bahamas	211,400	82,408	Montserrat	31	-
Barbados	30	40	Puerto Rico	9,200	8,831
Bermuda	10	9	Saint Kitts and Nevis	43	57
Bonaire, Sint Eustatius, and Saba	-	252	Saint Lucia	125	158
British Virgin Islands	435	82	Saint Vincent and the Grenadines	154	46
Cayman Islands	7,100	8,063	Saint-Barthélemy	-	3
Cuba	556,900	440,641	Saint-Martin	-	17
Curaçao	-	81	Sint Maarten	-	-
Dominica	156	-	Trinidad and Tobago	5,400	7,419
Dominican Republic	32,500	19,180	Turks and Caicos Islands	23,600	17,921
Grenada <sup>8</sup>	536	229	Virgin Islands, U.S.	106	199
Guadeloupe	3,983	3,229	The Netherlands Antilles (leeward group) <sup>9</sup>	1,051	-

Source: Authors' calculations based on estimates by Spalding et al. (1997) and Giri et al. (2010).

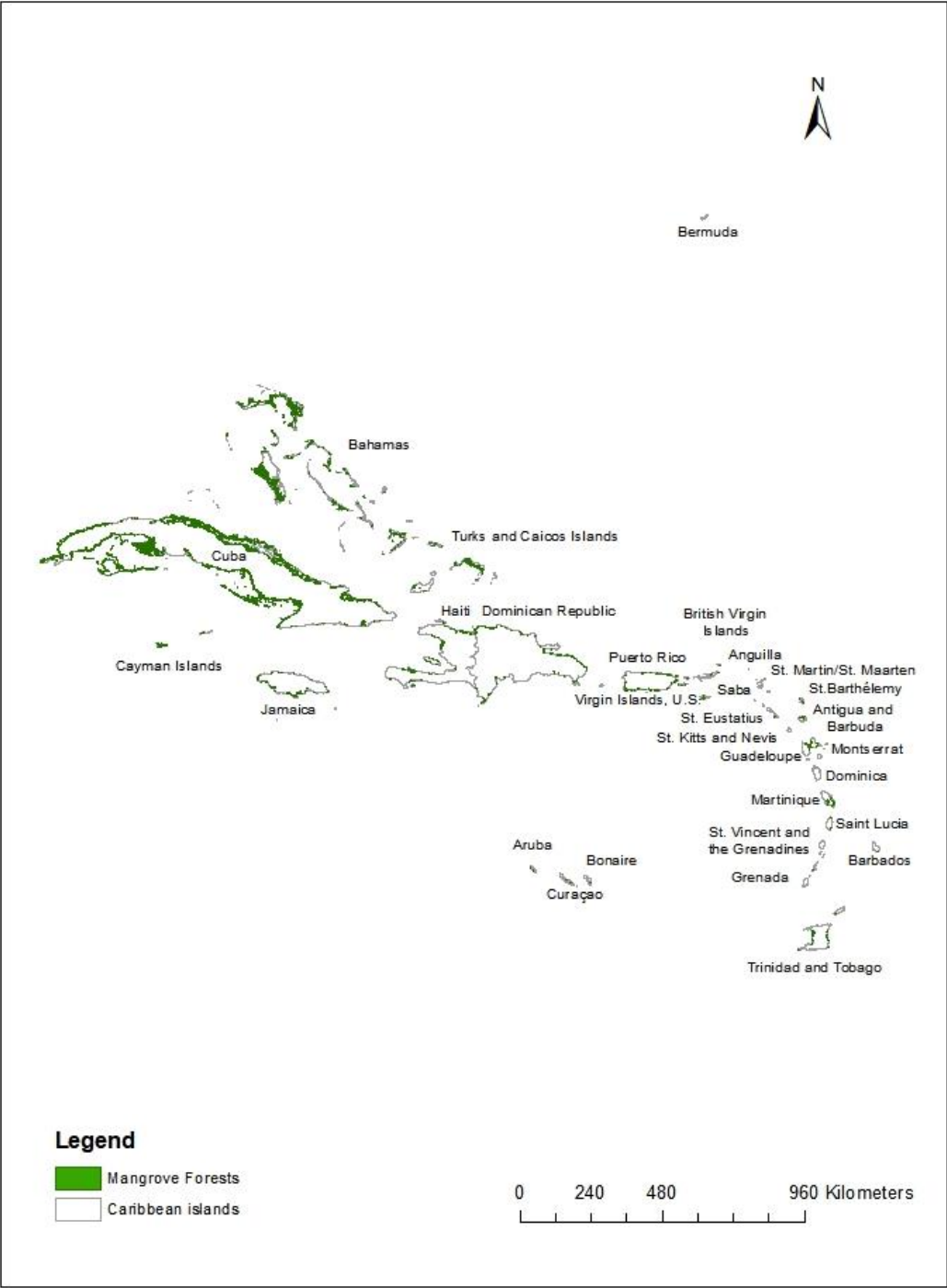
The services provided by mangroves are threatened by anthropogenic processes including deforestation and sea-level rise (Schuerch, 2018). Historically, Caribbean mangroves were reclaimed for urbanization, industrialization, and increasingly, for tourism. Overall, the region is losing mangrove forest at 1% per year, although the rate is much faster on the Caribbean mainland ( $\approx 1.7\%$  per year) than it is on the islands ( $\approx 0.2\%$  per year), according to Ellison and Farnsworth (1996). However, since the turn of the millennium global mangroves deforestation rates have slowed, with annual loss rates of 0.2% to 0.7% (Hamilton & Casey, 2016; Friess, 2019).

Despite the lack of a robust post-2000 mangrove change database, concern over mangrove deforestation is well clarified in recent literature, with numerous studies of mangrove change at the global, national, and local scales (e.g. Satapathy et al., 2017; Hamilton, 2013). Moreover, mangrove forests have been shown to contain economic value to ecosystem services and carbon sequestration per hectare of any forest type globally (Barbier & Cox, 2004; Barbier, 2006; Bouillion et al., 2008; Donato et al., 2011), including substantial carbon stored below ground in mangrove soil (Donato et al., 2011; Murdiyarso et al., 2015). Therefore, mangrove deforestation probably releases more  $CO_2$  per hectare than deforestation of any other forest type. Indeed, work is under way in placing economic value on the carbon stored in mangrove forests (Siikamäki et al., 2012), adding substantially to the potential economic value of preserved mangroves. Figure 3 presents the map of mangroves in the Caribbean region, using the distribution of Giri et al. (2010).

<sup>8</sup> Including St. Martin and St. Barthélemy.

<sup>9</sup> Formed by Bonaire and Curaçao. The Netherlands Antilles dissolved on October 10<sup>th</sup>, 2010. Curaçao and Sint Maarten (the Dutch two-fifths of the island of Saint Martin) became autonomous territories of the Kingdom of the Netherlands. Bonaire, Saba, and Sint Eustatius now fall under the direct administration of the Netherlands.

Figure 3. Map of Caribbean Mangroves



Source: Author’s elaboration based on Geographic System Information of Giri et al. (2010).



### 3. Empirical Strategy

To estimate whether mangroves can reduce hurricane damage, we divide Caribbean region into  $1 \text{ km}^2$  grid cells and construct a cell-year panel for the 2000 to 2012. The panel combines measures of economic activity, potential hurricane damage, and mangrove protection.

First, to assess the impact of hurricanes in economic activity, we estimate the impact of a damage function on our dataset of nightlights which is our proxy for economic activity. Specifically, we follow Del Valle et al. (2019) and consider the following two-way fixed effect specification:

$$NL_{it} = \alpha + \beta f_{it} + \pi_t + \mu_i + \varepsilon_{it}$$

Where  $NL_{it}$  is nightlight intensity (in logarithms) of cell  $i$  in year  $t$ ,  $f_{it}$  is the damage index,<sup>10</sup>  $\pi_t$  are year fixed effects,  $\mu_i$  are cell fixed effects, and  $\varepsilon_{it}$  is the error term. The inclusion of cell fixed effects aims to capture the fact that certain areas in the Caribbean may have been exposed to more frequent and greater incidence of hurricanes, leading to reallocation of segments of the population, and thus economic activity, or to the implementation of disaster prevention actions. Issues related to time-varying common shocks and time comparability of nightlights are addressed by including year fixed effects. The estimation method is based on Correia (2015), which account for linear models with many levels of fixed effects (as in our case).

Second, to measure the level of protection we use two datasets with different calculations of mangrove width and test for potential non-linear relationship. Our interest is to study the effectiveness of this potential mitigation property as the level of mangrove protection (width) increases.

#### 3.1. Modeling the Windstorm Model

We use the wind speed data to obtain a damage index using the transformation and parameters proposed by Emanuel (2011) in the following expression:

$$f_{it} = \frac{\left[ \frac{\max(V_{it} - V_T, 0)}{V_H - V_T} \right]^3}{1 + \left[ \frac{\max(V_{it} - V_T, 0)}{V_H - V_T} \right]^3}$$

Where  $V_{it}$  represents the wind speed in cell  $i$  at year  $t$ ,  $V_T$  is the threshold below which damage is unlikely to occur, which is set at 50 knots or roughly equal to 92.6 km/h, and  $V_H$  is the wind speed at which half of all structures are expected to be destroyed set as 150 knots or roughly equivalent to 277.8 km/h.

**Storm surge-prone area.** As we mentioned at the beginning of this section, the  $f_{it}$  represents the damage index that provides an informative measure of wind damages from excess of rainfall and storm surge. Nonetheless, because storm surge is often considered one of the most harmful aspects of hurricanes, we further investigate whether coastal lowlands are disproportionately affected by hurricanes. Specifically, we create a coastal lowland indicator variable identifying continuous areas along the coast that are less

---

<sup>10</sup> For this exercise we used the f damage index with  $V_H = 203 \text{ kph}$ . However, the impact was estimated with  $V_H = 278 \text{ kph}$  as well with similar results.

than 10 m above sea level.<sup>11</sup> This storm surge-prone area is composed of 432,068 cells (18.70% of all cells). For each of these cells, we additionally calculate the shortest path (Euclidean distance) from the centroid of the cell to the coast. The average distance to the coast is 23.44 km.

### **3.2. Mangroves for Coastal Protection**

Data on the distribution of mangroves come from two sources, as it was described in section 2.3, Spalding et al. (1997) and Giri et al. (2010). We used the first mangrove distribution to identify areas that have historically supported mangrove habitats, and the second dataset to precisely measure the presence of mangrove at the beginning of our sample period (2000-2012).

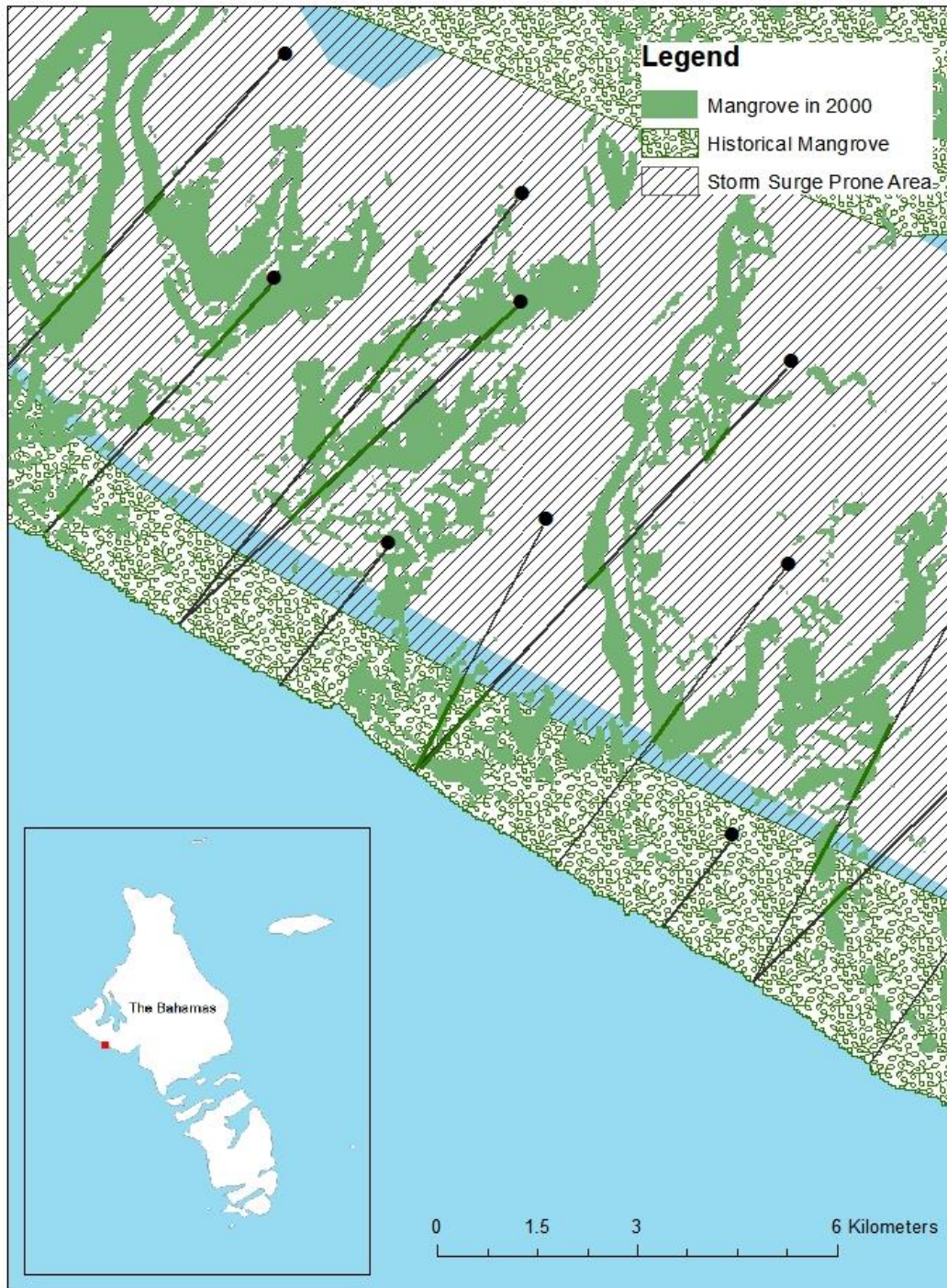
Mangroves protection benefits not necessarily can be derived by its location in areas that are naturally more protected. For example, areas that are on a continental shelf, with a rugged coastal topography with elevations rising up to 200 m, between the shoreline and the continental slope (Jackson, 1997). Hence, we begin by excluding from the analysis areas that have not historically supported mangrove habitats. In specific, for every cell in the storm surge-prone area, we exclude cells that have no mangrove as defined by Spalding et al. (1997) in their shortest path to the coast. We find there are 20,504 cells (4.74% of cells in storm surge-prone areas) with mangrove on their path to the coast.

Then, for each of the remaining cells, we calculate the mangrove width in two steps. First, we identify the line segments along the shortest path to the coast that overlap mangrove forests as defined by Giri et al. (2010). Second, we sum the line segments to measure cumulative mangrove width on the shortest path to the coast. Figure 4 provides a visual representation of the mangrove width calculation in the coast. We find that in our sample the average mangrove width is 0.25 km, with a minimum of 0 km and a maximum of 20.67 km.

---

<sup>11</sup> Nordhaus (2016) considers areas with elevation less than 8 m as vulnerable to storm surge. We use less stringent definition because Shuttle Radar Topography Mission elevation estimates below 10 m are not considered reliable (McGranahan, Balk, & Anderson, 2007).

**Figure 4. Distribution of mangrove in the North Caribbean Coast Autonomous Region, The Bahamas.**  
Dots represent centroids of cells; lines show the shortest path to the coast. The green line segments represent mangrove on the path to the coast.



Source: Author's elaboration based on Geographic System Information of Giri et al. (2010), Spalding et al. (1997), and the National Oceanic and Atmospheric Administration (NOAA).

## 4. Results and Discussion

In this section, we first evaluate the impact of hurricanes on economic activity and assess the mitigating role of mangroves against hurricanes in the Caribbean region. For this, we used the hurricane windstorm model and the night light dataset and quantifies the causal effects of the hurricane windstorm model on local economic activities, categorizing three hurricane damage indexes, which provides a higher level of detail. In a second step, we include mangrove data, and its characteristics to evaluate its potential mitigation effect of the impact of hurricanes on economic activity. Main descriptive statistics for the variables in the sample used in this section can be found in Annex 4.

### 4.1. Impact of Hurricanes on Nightlights

We initially explore the impact of hurricanes in nightlights using data for 29 countries and territories of the Caribbean region, which comprises more than 2 million observations due to the grid-cell measurement for the period 2000-2012.<sup>12</sup>

According to the econometric results, there is a negative, and statistically significant, association between nightlights and the hurricane damage index. Table 3 provides estimates for equation (2) using three specifications (columns 1 to 3) to include a potential lagged effect of hurricanes on nightlights and to discriminate the effect in low elevation coastal zones. Particularly, the size for the estimate for  $\beta$ , which measures the impact of hurricanes in nightlights, shows that nightlight in cells that experience category three hurricane winds ( $f = 0.2$ , wind speed of 203 kph) decrease by 0.35 units ( $\approx -1.75 * 0.2$ ).<sup>13</sup> Given that the average level of nightlights in 2000 was 12.1,<sup>14</sup> we took the inverse to multiply by the number of reduced units, thus the effect is equivalent to a 2.9% decrease in economic activity.

The negative association between nightlights and the hurricane damage index seems to be short-lived. In column (2) it is possible to evidence that, consistent with previous literature (Elliott et al., 2015; Del Valle et al. 2018), there is a short-lived effect of hurricanes in local economic activity. To evaluate this, we included a lagged term for the hurricane damage index and found that, while the contemporaneous coefficient remains negative and statistically significant, the lagged coefficient is positive and statistically significant. This may be related to the implementation of rehabilitation and reconstruction stages following a disaster shock.

The effect of windstorms is more negative in storm surge prone areas, measured as low elevation coastal zones. Column (3) provide estimated to assess if the impact of hurricane is dissimilar in coastal lowland zones. For this, we included dummy variables to identify these areas and create interaction terms with the  $f$  damage index. The estimated coefficient estimated for non-storm prone areas positive and statistically significant, while the coefficient for storm-prone areas in negative and statistically significant as well. This suggest that hurricanes have considerably greater effects in low-elevation coastal zones. Specifically, using the average level of nightlights in 2000 as the analysis for Column 1, we found that the

---

<sup>12</sup> For the regression analysis, we excluded Cuba as it seems to be driven a positive association between nightlights and the damage index perhaps due to its limited data density but large coverage. For further detail, see Annex 5.

<sup>13</sup> Recall that our specification is a log-linear regression model. Therefore, to find the coefficient that is multiplied by the damage index ( $f$ ), the following calculation is performed:  $[\exp (-0.0177)-1] * 100$ .

<sup>14</sup> Records in night light images data are the digital number (DN) values, ranging from 0 (no light) to 63 (maximum light).

negative effect of category three hurricane winds is associated with a 16.1% decrease in local economic activity.<sup>15</sup>

**Table 3. Impact of hurricanes on nightlights**

	(1) Ln (nightlights)	(2) Ln (nightlights)	(3) Ln (nightlights)
$f$	-0.0177** (0.00715)	-0.0244*** (0.00733)	
$f(t - 1)$		0.0991*** (0.00731)	
$f$ in non – storm surge prone areas			0.0211** (0.00831)
$f$ in storm surge prone areas			-0.103*** (0.0117)

Note: Dependent variable: nightlights. Estimates from OLS regression, cell and year fixed effects included but not reported. \*\*\*p<0.01, \*\*p<0.05, \*p<0.1. Robust standard errors in parentheses. The number of observations is 1,159,340 for column (1) and (3); and 1,070,160 for column (2). The average nightlights in the year 2000 is 12.1.

Source: Authors' calculations.

## 4.2. Mangroves Reduce Hurricane Impact

Mangrove forests, an essential component of a significant part of Caribbean coastlands, may act as natural defenses against hurricanes. For example, in a study in the Gulf Coast of South Florida, Zhang et al. (2012) found that storm surge is reduced by 50 cm per km of mangrove width. Del Valle et al. (2019) found a similar result studying how mangrove forest mitigates the impact of hurricanes in economic activity in Central America. Therefore, given that, initial findings can be interpreted as hurricanes having an adverse effect on local economic activity, we explore the potential benefit of mangrove forest in mitigating this effect in the Caribbean region.

To measure the level of protection we use two datasets with different calculations of mangrove width and test for potential non-linear relationships. Our interest is to study the effectiveness of this potential mitigation property as the level of mangrove protection (width) increases. The calculation of mangrove width in the two databases used for the econometric results are described in Section 2.3.

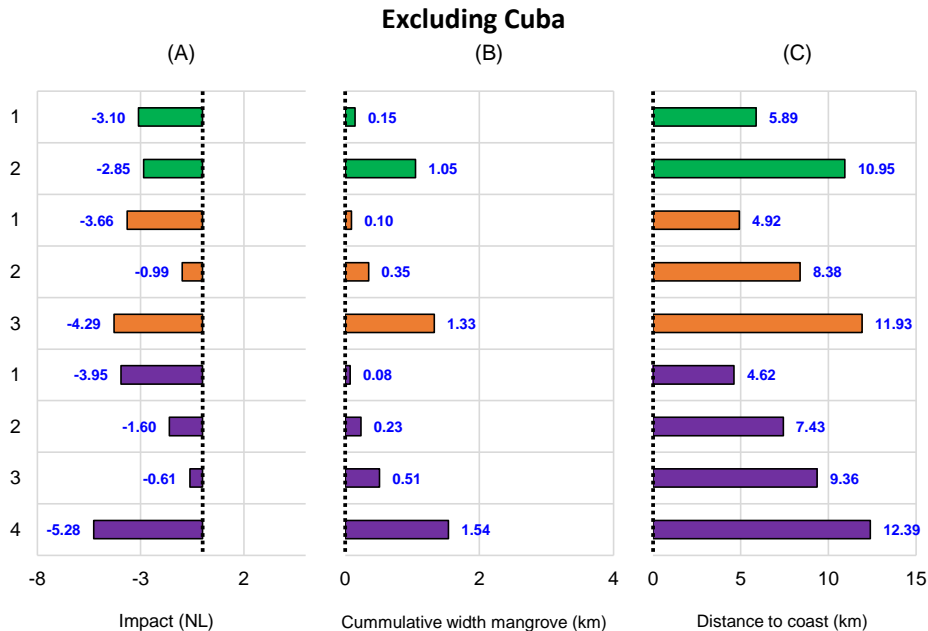
Our results indicate that mangrove forests act as natural defense and mitigate the impact of hurricanes in local economic activity. To obtain the results, we estimate three models, as in Del Valle et al (2019), where we discretize mangrove width into various bins that correspond to its q-quantiles in Low Elevation Coastal Zones (LECZ). The first model uses q=2, and we create a dummy variable for each bin and interact these variables with the  $f$  damage index. We then take the resulting variables and include them in Equation 1 in place of the  $f$  damage index. We proceed to repeat this approach for the second model using q=3; and the third model, q=4.

<sup>15</sup> The calculation was as follows:  $[[[\exp(-0.0103)-1] * 100] * (0.2)] * [1/12.1]$ .

Figure 5 plots the results in 3 panels (A, B and C) for 3 different models, excluding Cuba in the sample. Panel (A) show point estimates for each of the model regarding the impact of hurricanes on nightlights for each bin of model. Panel (B) plots the distribution of mangrove width for each bin, and panel (C) plots distance to the coast for each model and bin. For example, top two rows, colored with green bars, plot the impact of hurricanes on nightlights for each bin of model 1 ( $q=2$ ), where the bins correspond to cells with above and below median mangrove width on their path to the coast ( $\approx 0.25$  km). It is possible to see that below median areas hurricanes can significantly reduce nightlights. The estimated coefficient of -3.10 indicates a category three hurricane winds ( $f = 0.2$ , wind speed of 203 kph) would reduce nightlights by 0.62 units ( $\approx -3.10 * 0.2$ ) equivalent to a 5.1% reduction, using the inverse of the average level of nightlights in 2000.<sup>16</sup> In contrast, the effect above the median is smaller and would imply a reduction of 4.7% in nightlights.<sup>17</sup>

From the third to the fifth row, colored with orange bars, correspond to model 2, we used  $q=3$  that is the third tercile (mangrove width greater than 1 km and average width of 2 km), and from the sixth to ninth row, colored with purple bars, correspond to model 3, we used  $q=4$  that is the fourth quartile (mangrove width greater than 1.26 km and average width of 2.3 km), respectively. Most models, although not in every case, show a decreasing pattern of hurricane damage as we move through the corresponding bins. For example, using model 3, the impact is reduced until the third bin where the reduction in nightlights is equivalent to 1%,<sup>18</sup> instead of decrease by 6.5% in the first bin.<sup>19</sup> A similar result can be found in the case for panel (C), where, on average, a longer mangrove width also implies a longer distance to the coast.

**Figure 5. Impact of hurricanes on nightlights by mangrove width – Low Elevation Coastal Zone (LECZ) database**



<sup>16</sup> The calculation was as follows:  $[\approx -3.10 * 0.2] * [1/12.1]$

<sup>17</sup> Following the same procedure to find the percentage, using the coefficient -2.85.

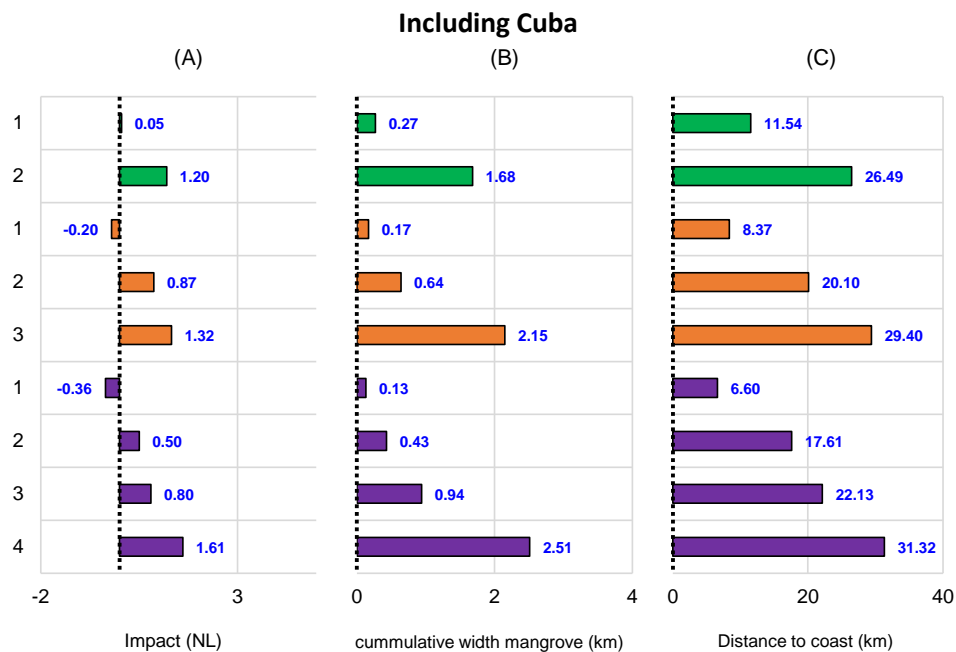
<sup>18</sup> Following the same procedure to find the percentage, using the coefficient -0.61.

<sup>19</sup> Following the same procedure to find the percentage, using the coefficient -3.95.

Note: In models one to three, from panel (A) we discretize the mangrove width variable into various bins that correspond to its q-quantiles and estimate the impact of hurricanes on economic activity for each bin. Model one uses q=2 and is colored in green. Model two uses q=3 and is colored in orange. Model three uses q=4 and is colored in purple. Panel (B) plots the distribution of mangrove width for each bin, and Panel (C) plots the distribution of distance to the coast for each bin. Regression coefficients are shown in panel (A) and the average value for panels (B) and (C).

By contrast, Figure 6 plots the results in 3 panels (A, B and C) for 3 different models, including Cuba in the sample. Unfortunately, we can see only in the first quantile of the Model 2 and Model 3 in panel A that the mangroves width might mitigate the impact of hurricanes on nightlights. In the Model 2, the estimated coefficient of -0.20 indicates a category three hurricane winds ( $f = 0.2$ , wind speed of 203 kph) would reduce nightlights by 0.04 units ( $\approx -0.20 * 0.2$ ) equivalent to a 0.33% reduction, using the inverse of the average level of nightlights in 2000.<sup>20</sup> In the Model 3, the effect of hurricanes in the presence of mangroves is greater and would imply a reduction of 0.60% in nightlights.<sup>21</sup> As in previous case, the panel B and C outlines that cells greater than 1 km and 2.3 km of mangrove width reduce the hurricane damages during the sample period.

**Figure 6. Impact of hurricanes on nightlights by mangrove width – Low Elevation Coastal Zone (LECZ) database**



Note: In models one to three, from panel (A) we discretize the mangrove width variable into various bins that correspond to its q-quantiles and estimate the impact of hurricanes on economic activity for each bin. Model one uses q=2 and is colored in green. Model two uses q=3 and is colored in orange. Model three uses q=4 and is colored in purple. Panel (B) plots the distribution of mangrove width for each bin, and Panel (C) plots the distribution of distance to the coast for each bin. Regression coefficients are shown in panel (A) and the average value for panels (B) and (C).

Source: Authors' calculations.

In general, the results show the potential value of mangroves as natural defenses against hurricanes in the Caribbean region, which reflects the importance of their conservation and restoration. Also, these findings is consistent with other estimates of mangrove protection, which indicate that 2 to 7 km of

<sup>20</sup> The calculation was as follows:  $[\approx -0.20 * 0.2] * [1/12.1]$

<sup>21</sup> Following the same procedure to find the percentage, using the coefficient -0.36.

mangrove width would be needed to fully attenuate storm surge for the hurricanes that make up the bulk of our sample, in particular, for Category 3. Specifically, we show that we find similar results using a wide range of alternative assumptions for the construction of the hurricane damage function, the calculation of mangroves width, and the model specification.

## 5. Conclusion

In this study, we show that wide mangrove belts in the Caribbean have the potential to mitigate the disruption to economic activity generated by hurricanes. We measure local economic activity using remote sensing data on nightlights, potential hurricane destruction using a damage index derived from a wind field model calibrated for the Caribbean, and mangrove protection by calculating the cumulate width of mangrove along the closest path to the coast. Using these data, we estimate the impact of hurricanes on economic activity under the assumption that hurricane strikes are exogenous conditional on cell and year fixed effects. We then explore using a binning estimator whether there is a negative and plausibly nonlinear relationship between mangroves and hurricanes damages.

In particular, hurricanes have negative short-run effects on economic activity, with losses likely to be concentrated in coastal lowlands at risk for both wind and storm surge. Within the coastal lowlands, we further show that the impact of hurricanes declines with mangrove width and specifically, that the effect of hurricanes in our sample is mitigated by 0.25 km or more of mangrove width. We additionally conduct various robustness checks and rule out that these findings are driven by the physical characteristics of the location of the mangrove habitat or by the distance to the coast.

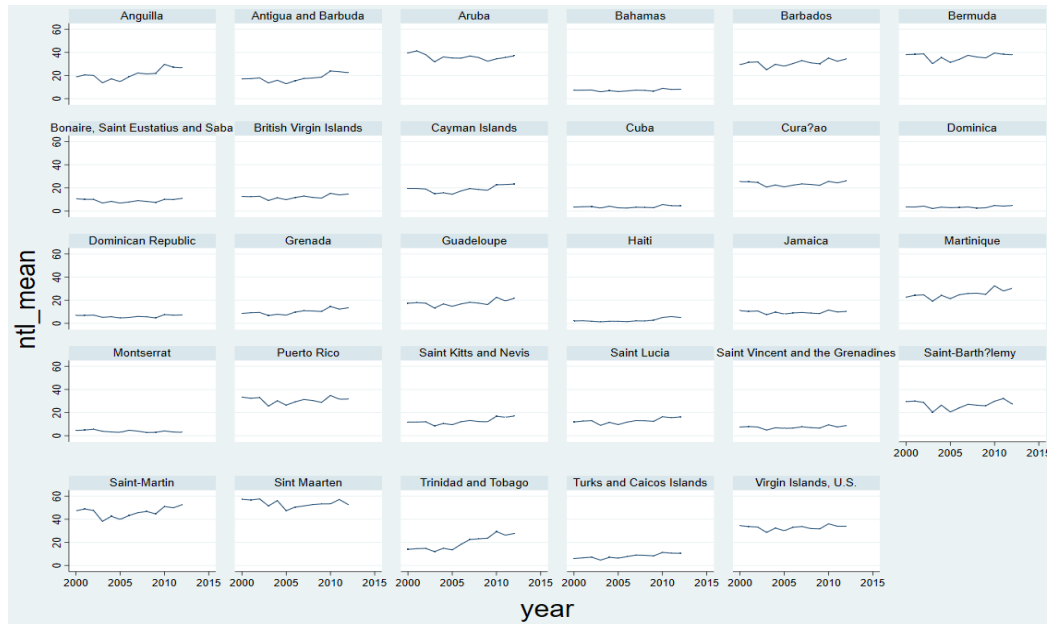
Our results contribute with policy makers from the Caribbean region to highlight the importance of mangrove conservation and restoration, especially in the coastal lowlands in order to protect local economic activity against the tropical cyclones and hurricanes. It is important to mention that the benefit of protection is carried out by the wide of mangrove belts, which can be effective in reducing the flooding impacts of storm surges occurring during major storms. This observation implies that large-scale efforts will be required to achieve the benefits of the mangrove protection.

Finally, there are two important points to comment. First, our estimates are likely to underestimate the protective value of mangroves in the long run because mangrove protection may entail benefits on outcomes, such as lives save, health, and human capital accumulation, which are not well captured by nightlights. Second, while the climate change and the result of intensification of storm may increase the value of conservation for protection purposes, areas designated for conservation or restoration must be carefully chosen given the threat of sea-level rise. Consequently, an important avenue for future research is the identification of areas that should be prioritized for conservation and restoration and that have the potential to be mangrove habitats.



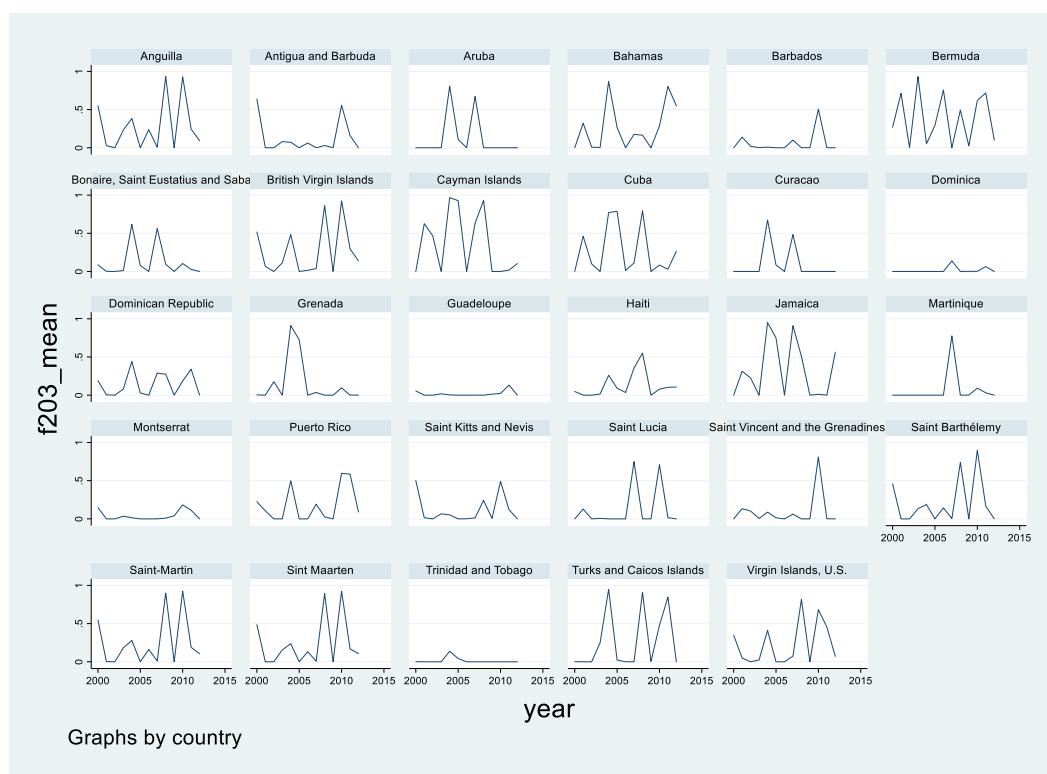
## 6. Annexes

**Annex 1. Mean nightlights by Caribbean country and territory**



Source: Authors' calculations.

**Annex 2. Mean f (203kph) damage index by Caribbean country and territory**



Source: Authors' calculations.

### Annex 3. Number of hurricanes in the Caribbean between 2000 and 2012

Country / Area	Hurricane category (Saffir-Simpson Scale)						
	Cat. 0	Cat. 1	Cat. 2	Cat. 3	Cat. 4	Cat. 5	Total
Anguilla	5	4	4	3	1	2	19
Antigua and Barbuda	8	5	4	2	2	1	22
Aruba	10	1	1	1	1	2	16
Bahamas	11	8	8	7	8	6	48
Barbados	12	5	3	1	1	0	22
Bermuda	3	4	3	2	4	4	20
Bonaire, Saint Eustatius and Saba	12	6	2	3	5	3	31
British Virgin Islands	6	6	5	3	3	2	25
Cayman Islands	7	2	2	3	3	4	21
Cuba	11	11	9	9	8	6	54
Curaçao	0	0	0	0	0	0	0
Dominica	13	2	2	1	0	0	18
Dominican Republic	10	10	8	7	5	2	42
Grenada	10	4	2	2	2	2	22
Guadeloupe	13	6	2	1	0	0	22
Haiti	10	10	10	10	4	3	47
Jamaica	6	4	4	5	4	5	28
Martinique	11	2	1	1	1	1	17
Montserrat	9	7	3	0	0	0	19
Puerto Rico	8	6	6	6	3	1	30
Saint Kitts and Nevis	8	7	3	3	2	0	23

Saint Lucia	11	3	1	2	2	2	21
Saint Vincent and the Grenadines	11	6	5	3	2	1	28
Saint-Barthélemy	0	0	0	0	0	0	0
Saint-Martin	5	6	5	1	1	2	20
Sint Maarten	5	5	5	1	1	2	19
Trinidad and Tobago	13	3	1	2	2	1	22
Turks and Caicos Islands	8	1	2	2	2	3	18
Virgin Islands, U.S.	6	5	5	5	3	2	26

Source: Authors' calculations.

#### Annex 4. Descriptive statistics

Variable	Description	Mean	Std. dev.	Min.	Max.
Luminosity Index (nightlight)	Intensity of nightlights, on scale that ranges zero (no light) to 63 (maximum light)	7.66	12.72	0.00	63.00
f index (203)	Emanuel f index (2012) with Vhalf = 203 Km/h	0.21	0.31	0.00	0.97
Low elevation	Low Elevation Coastal Zone Indicator	0.19	0.39	0.00	1.00
Old mangrove	Areas that have historically supported mangrove habitats	0.03	0.16	0.00	1.00
Mangrove width	Sum of line segments where is located mangrove areas on the shortest path to the coast	0.25	0.74	0.00	20.67
Distance to coast	Distance from the centroid of the cell of nightlights to the coast	23.45	16.90	0.01	82.10

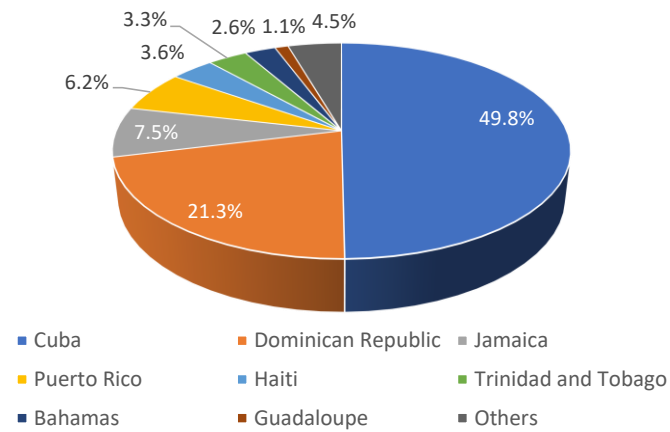
Note: Number of observations in raw data are equal to 2,310,113.

Source: Authors' calculations.

#### Annex 5. Relative observations per country (% of total number of observations)

The initial number of observations is equivalent to 2,310,113 and includes 29 countries and territories. It is important to note, however, that, due in principle to a greater territorial extension, some countries

present a greater concentration of observations. This is the case of Cuba, which comprises 49.8% of the observations, followed by the Dominican Republic with 21.3%, Jamaica with 7.5%, Puerto Rico with 6.2% and Haiti with 3.6%, among others.



Source: Authors' calculations

## 7. References

AIR (2020). The AIR Tropical Cyclone Model for the Caribbean.

Alongi, D. (2008). Mangrove Forests: Resilience, Protection from Tsunamis and Responses to Global Climate Change". *Estuarine, Coastal and Shelf Science* 76, pp. 1-13.

Andreano, M.S., Benedetti, R., Piersimoni, F. & Savio, G. (2020). Mapping Poverty of Latin American and Caribbean Countries from Heaven Through Night-Light Satellite Images. *Social Indicators Research*. <https://doi.org/10.1007/s11205-020-02267-1>

Bao, T.Q. (2011). Effect of mangrove forest structures on wave attenuation in coastal Vietnam. *Oceanologia* 53, pp. 807-818.

Barbier, E.B. (2006) Mangrove dependency and the livelihoods of coastal communities in Thailand. Environment and livelihoods in tropical coastal zones: managing agriculture-fishery-aquaculture conflicts (ed. By Hoanh, C.T., Tuong, T.P., Gowing, J.W., Hardy, B.), Comprehensive assessment of water management in agriculture series. Oxford University Press, London.

Barbier, E.B. & Cox, M. (2004). An economic analysis of shrimp farm expansion and mangrove conversion in Thailand. *Land Economics*, 80, pp. 389-407.

Barbier, E.B., E.W. Koch, B.R. Silliman, S. Hackaer, E. Wolanski, J. Primavera, E.F. Granek, S. Polasky, S. Aswani, L. A. Cramer, D.M. Stoms, C.J. Kennedy, D. Bael, C.V. Kappel, G.M.E. & Perillo, D. J. Reed. (2008). Coastal Ecosystem-Based Management with Nonlinear Ecological Functions and Values. *Science* 319, pp. 321.

Bertinelli, L. & Strobl, E. (2013). Quantifying the local economic growth impact of hurricane strikes: An analysis from outer space for the Caribbean. *Journal of Applied Meteorology and Climatology*, 52(8), pp. 1688–1697.

Blankespoor, B., Dasgupta, S., & Lange, G.M. (2016). Mangroves as Protection from Storm Surges in a Changing Climate. Policy Research Working Paper; No. 7596. World Bank, Washington, DC. © World Bank.

Botzen, W. J. W., Deschenes, O., & Sanders, M. (2019). The Economic Impacts of Natural Disasters: A Review of Models and Empirical Studies, *Review of Environmental Economics and Policy*, Volume 13, Issue 2, pp. 167–188, <https://doi.org/10.1093/reep/rez004>

Bouillon, S., Borges, A.V., Casteñeda-Moya, E., Diele, K., Dittmar, T., Duke, N.C., Kristensen, E., Lee, S.Y., Marchand, C., Middelburg, J.J., Rivera-Monroy, V.H., Smith, T.J., & Twilley, R.R. (2008). Mangrove production and carbon sinks: a revision of global budget estimates. *Global Biogeochemical Cycles*, 22, GB2013.

Bowen, B.A. (2007). The challenges of poverty and social welfare in the Caribbean. *International Journal of Social Welfare*, vol. 16, no.2, pp. 150-158.

Brinkman, R.M., Massel, S.R., Ridd, P.V., & Furukawa, K. (1997). Surface wave attenuation in mangrove forests. *Proceedings of 13th Australasian Coastal and Ocean Engineering Conference* 2, pp. 941-949.

Cavallo, E. & Noy, I. (2011). Natural Disasters and the Economy — A Survey, *International Review of Environmental and Resource Economics*, Vol. 5, No. 1, pp. 63-102. <http://dx.doi.org/10.1561/101.00000039>

Chen, X., & Nordhaus, W.D. (2011). Using luminosity data as a proxy for economic statistics. *Proc. Natl. Acad. Sci. USA*, 108, PP. 8589–8594.

Coffman, M. & Noy, I. (2010). A Hurricane Hits Hawaii: A Tale of Vulnerability to Natural Disasters." *CESifo Forum* 11(2), pp. 67–72.

Del Valle, A., Elliott, R. J., Strobl, E., & Tong, M. (2018). The short-term economic impact of tropical cyclones: Satellite evidence from Guangdong province. *Economics of Disasters and Climate Change*, pp. 1–11.

Del Valle, A., Eriksson, M., Ishizawa, O.A., & Miranda, J.J. (2020). Mangroves protect coastal economic from hurricanes. *Proceeding of the National Academy of Science*, 117 (1), pp. 265-270. DOI: 10.1073/pnas.1911617116

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M. & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, 4, 293-297.

Duke, N.C., Pinzon, Z.S., & Prada M.C.T. (1997). Large-scale damage to mangrove forests following two large oil spills in Panama. *Biotropica* 29, pp. 2–14. <https://doi.org/10.1371/journal.pone.0010095>

Eckstein, D., Künzel, V., Schäfer, L., & Wings, M. (2019). Global Climate Risk Index 2020.

Elvidge, C., Baugh, K., Kihn, E., Kroehl, H., Davis, E., & Davis, C. (1997). Relation between satellite observed visible-near infrared emissions, population, economic activity, and electric power consumption. *International Journal of Remote Sensing*, 18(6), pp. 1373-1379.

Elliott, R. J., Strobl, E., & Sun, P. (2015). The local impact of typhoons on economic activity in China: A view from outer space. *Journal of Urban Economics*, 88, pp. 50–66.

Ellison, A., & Farnsworth, E. (1996). Anthropogenic Disturbance of Caribbean Mangrove Ecosystems: Past Impacts, Present Trends, and Future Predictions. *Biotropica*, 28(4), 549-565. doi:10.2307/2389096

Emanuel, K. (2011). Global warming effects on us hurricane damage. *Weather, Climate, and Society*, 3:261–268.

FAO. (2007). The world's mangroves 1980–2005. A thematic study prepared in the framework of the Global Forest Resources Assessment 2005. FAO Forestry Paper No. 153. Rome, Italy. (Available at <http://www.fao.org/docrep/010/a1427e/a1427e00.htm>).

FAO. (2010). Global Forest Resources Assessment. Main Report. <http://www.fao.org/3/a-i1757e.pdf>

Friess, D. A. et al. (2019). The State of the World's Mangrove Forests: Past, Present, and Future. *Annual Review of Environment and Resources* 44, pp. 89–115.

- Gedan, K.B., Kirwan, M.L, Wolanski, E., Barbier, E.B., & Silliman, B.R. (2011). The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climatic Change*. 106, pp. 7-29.
- Ghosh, T., Powell, R., Elvidge, C., Baugh, K., Sutton, P., & Anderson, S. (2010). Shedding Light on the Global Distribution of Economic Activity. *The Open Geography Journal*, 3, 148-161.
- Gin, R. & Lubin, B. (1989). *Psychological Aspects of Disaster*. New York: Wiley.
- Giri, C., Ochieng, E., Tieszen, L., Zhu, Z., Singh, A., Loveland, T., Masek, J, & Duke, N. (2010). Status and distribution of mangrove forest of the world using earth observation satellite data. *Global Ecology and Biogeography*. 20. 154-159. <https://doi.org/10.1111/j.1466-8238.2010.00584.x>
- Hallegate, S. (2008). An adaptive regional input–output model and its application to the assessment of the economic cost of Katrina. *Risk Anal.* 28, pp. 779–799.
- Hallegate, S. (2014). *Natural Disasters and Climate Change: An Economic Perspective*. Springer.
- Hamilton, S. E. (2013). Assessing the role of commercial aquaculture in displacing mangrove forest. *Bulletin of Marine Science*, 89, 585-601.
- Hamilton, S. E. & Casey, D. (2016) Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21). *Glob. Ecol. Biogeogr.* 25, pp. 729–738.
- Heger, M., Julca, A. & O. Paddison. (2008). Analysing the Impact of Natural Hazards in Small Economies: The Caribbean Case. UNU/WIDER Research Paper 2008/25.
- Henderson-Sellers, A., Zhang, H., Berz, G., Emanuel, K., Gray, W., Landsea, C., Holland, G., Lighthill, J., Shieh, S.L., Webster, P., and McGuffie, K. (1998). Tropical cyclones and global climate change: A post-IPCC assessment. *Bulletin of the American Meteorological Society*, 79, 19-38. [https://doi.org/10.1175/1520-0477\(1998\)079<0019:TCAGCC>2.0.CO;2](https://doi.org/10.1175/1520-0477(1998)079<0019:TCAGCC>2.0.CO;2)
- Henderson, J. V., Storeygard, A. & Weil, D. (2012). Measuring Growth from Outer Space, *American Economic Review*, 102(2), pp.994-1028.
- IMF (2016). *Gone with the Wind: Estimating Hurricane and Climate Change Costs in the Caribbean*.
- IMF (2017). *Unleashing Growth and Strengthening Resilience in the Caribbean*.
- Ishizawa, O.A., Miranda, J.J. & Strobl, E. (2019). The Impact of Hurricane Strikes on Short-Term Local Economic Activity: Evidence from Nightlight Images in the Dominican Republic. *Int J Disaster Risk Sci* 10, 362–370. <https://doi.org/10.1007/s13753-019-00226-0>
- Jackson, J. A. (ed.), 1997. *Glossary of Geology*. Alexandria, VI: American Geological Institute. 769 p.
- Johnson, S. (2015). The History and Science of Hurricanes in the Greater Caribbean. *Oxford Research Encyclopedia of Latin American History*. <https://doi.org/10.1093/acrefore/9780199366439.013.57>
- Kocornik-Mina, A., McDermott, T.K., Michaels, G. & Rauch, F. (2015). *Flooded Cities*. CEP Discussion Paper, Centre for Economic Policy, London.

Li, X., Zhou, Y., Zhao, M., & Zhao, X. (2020). A harmonized global nighttime light dataset 1992-2018. *Scientific Data*, June 4, 7 (1): 168. 32499523.

Lowe, M. (2014). Night Lights and ArcGIS: A Brief Guide. [Online; accessed Nov-2015]

Lugo, A. (2002). Conserving Latin American and Caribbean mangroves: issues and challenges. *Madera y Bosques*, vol.8, nº 1, 2002, pp. 5-25.

Massel S.R., Furukawa, K. Brinkman R.M. 1999. "Surface wave propagation in mangrove forests". *Fluid Dyn. Res* 24: 219-249.

McGranahan, G., Balk, D., Anderson, B. (2007). The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ. Urbanization* 19, PP. 17–37.

Menéndez, P., Losada, I.J., Torres-Ortega, Narayan, S., & Beck, M. (2020). The Global Flood Protection Benefits of Mangroves. *Sci Rep* 10, 4404. <https://doi.org/10.1038/s41598-020-61136-6>

Murdiyarso, D., Purbopuspito, J., Kauffman, J.B., Warren, M.W., Sasmito, S.D., Donato, D.C., Manuri, S., Krisnawati, H., Taberima, S. & Kurnianto, S. (2015). The potential of Indonesian mangrove forests for global climate change mitigation. *Nature Climate Change*, 5, pp. 1089-1092.

Neumann, C.J. (1993). Global Guide to Tropical Cyclone Forecasting – Chapter 1. WMO Technical Document No. 560, Report No. TCP-31. World Meteorological Organization; Geneva, Switzerland.

Nordhaus, W.D. (2016). The Economics of Hurricanes in the United States (NBER Working Paper No. 12813) (National Bureau of Economic Research, Cambridge, MA, 2006).

Noy, I. & DuPont, W. (2018), The Long-Term Consequences of Disasters: What Do We Know, and What We Still Don't. *International Review of Environmental and Resource Economics*: Vol. 12: No. 4, pp 325-354. <http://dx.doi.org/10.1561/101.00000104>

OECD et al. (2019), *Latin American Economic Outlook 2019: Development in Transition*, OECD Publishing, Paris, <https://doi.org/10.1787/g2g9ff18-en>.

Pinsky, M. L., Guannel, G. & Arkema, K.K. (2013). Quantifying wave attenuation to inform coastal habitat conservation, *Ecosphere*, 4(8), art95.

Polidoro BA, Carpenter KE, Collins L, Duke NC, Ellison AM, Ellison JC, et al. (2010) The Loss of Species: Mangrove Extinction Risk and Geographic Areas of Global Concern. *PLoS ONE* 5(4): e10095. <https://doi.org/10.1371/journal.pone.0010095>

Quartel, S., Kroon, A., Augustinus, P.G.E.F., Van Santen, P., & Tri, N.H. (2007). Wave attenuation in coastal mangroves in the Red River Delta, Vietnam. *Journal of Asian Earth Sciences* 29, pp. 576-584.

Rasmussen, T. N. (2004). Macroeconomic Implications of Natural Disasters in the Caribbean. IMF Working Paper WP/04/224.

Sanoja, M. (1992). Wetland ecosystems and the management of cultural heritage. Pages 66-73 In: A.E. Lugo and B. Bayle, eds. *Wetlands management in the Caribbean and the role of forestry and wetlands in the economy*. USDA Forest Service. Southern Forest Experiment Station. New Orleans, LA.



Satapathy, D.R., Krupadam, R.J., Kumar, L.P., & Wate, S.R. (2007). The application of satellite data for the quantification of mangrove loss and coastal management in the Godavari estuary, east coast of India. *Environmental Monitoring and Assessment*, 134, pp.453-469.

Schuerch, M. et al. (2018). Future response of global coastal wetlands to sea-level rise. *Nature* 561, pp. 231–234.

Siikamäki, J., Sanchirico, J.N., & Jardine, S.L. (2012). Global economic potential for reducing carbon dioxide emissions from mangrove loss. *Proceedings of the National Academy of Sciences USA*, 109, pp. 14369-14374.

Spalding, M.D., Blasco, F. & Field, C.D., eds. (1997). World mangrove atlas. Okinawa, Japan, International Society for Mangrove Ecosystems (ISME).

Strobl, E. (2012). The economic growth impact of natural disasters in developing countries: Evidence from hurricane strikes in the Central American and Caribbean regions. *J. Dev. Econ.* 97 (1), pp. 130–141.

Tomblin, J. (1979). Natural Disasters in the Caribbean: A Review of Hazards and Vulnerability" in Caribbean Disaster Preparedness Seminar, Saint Lucia. (Washington, D.C.: OFDA/USAID, 1979).

Tuholske, C., Tane, Z., López-Carr, D., Roberts, D. & Cassels, S. (2017). Thirty years of land use/cover change in the Caribbean: Assessing the relationship between urbanization and mangrove loss in Roatán, Honduras. *Applied Geography*, Volume 88, Pages 84-93. <https://doi.org/10.1016/j.apgeog.2017.08.018>.

Waite, R., et al. (2014). Coastal Capital: Ecosystem Valuation for Decision Making in the Caribbean. Washington, DC: World Resources Institute. Accessible at: <https://www.wri.org/our-work/project/coastal-capital-economic-valuation-coastal-ecosystems-caribbean>

Zhang, K., Liu, H., Li, Y., Xu, H., Shen, J., Rhome, J., & Smith III, T. J. (2012). The role of mangroves in attenuating storm surges. *Estuarine, Coastal and Shelf Science*, 102, pp. 11–23