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THE CURRENT AND FUTURE COSTS OF TROPICAL CYCLONES: A CASE STUDY OF LA REUNION

IDRISS FONTAINE, SABINE GARABEDIAN, HELENE VEREMES

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The current and future costs of tropical cyclones: A case study of La Réunion [*]

Idriss Fontaine[†]
Université de La Réunion

Sabine Garabedian[‡]
Université de La Réunion

Hélène Vérèmes[§]
Université de La Réunion

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[†] Department of Economics (CEMOI), Université de La Réunion; E-mail: idriss-fontaine@univ-reunion.fr

[‡] Department of Economics (CEMOI), Université de La Réunion; E-mail: sabine.garabedian@univ-reunion.fr

[§] Department of Atmospheric Physics (LACy, OSU-Réunion), Université de La Réunion; E-mail: helene.veremes@univ-reunion.fr

Contents

Abstract

In comparison to the current losses, how would the economic losses associated with tropical cyclones on La Réunion vary in a warmer climate? This paper provides a response to this question by following a strategy based on two steps. First, to proxy economic activity at the local level, we employ night light data available at a high level of resolution. Second, because historical tropical cyclone data cover a relatively short period of time and do not define the characteristics of future tropical cyclones, we rely on synthetic tropical cyclones generated under a “current” and “future” (warmer) climate scenario. By combining these two input data, we find that economic losses due to tropical cyclones passing in the vicinity of La Réunion are likely to increase. Specifically, annual expected economic losses are estimated to amount to 0.23% of the economic value under a climate scenario similar to what is currently observed compared to 0.43% under a different scenario based on low action on climate mitigation and air pollutant emission reduction. The return period of losses of 10% of the total economic value decreases from 149 years to 78 years. Sensitivity analyses applied to verify the consistency of our baseline estimation show that our approach neither overestimates nor underestimates the costs associated with tropical cyclones in this French overseas region. Overall, our findings suggest that policy designers should engage in adaptation policies to improve the resistance of goods to cyclonic winds and thus reduce the total losses associated with such meteorological events.

Keywords: Tropical cyclone, costs, nightlight data, La Réunion.
JEL classifications: Q51, Q54, R12

1 Introduction

Tropical cyclones are often viewed as one of the most destructive natural phenomena faced by an economy (Camargo & Hsiang, 2015). For instance, during the 2000-2009 period, the EMDAT database estimates that the total damage due to tropical cyclones amounts to approximately US$ 466 billion. Likewise, the total number of deaths caused by tropical cyclones during this period was estimated at 172,000 people, while approximately 4 million were recorded as homeless in the wake of a tropical cyclone. There is strong evidence indicating that economic losses due to such meteorological events have been steadily increasing for several decades (Cavallo et al., 2010; Grinsted et al., 2019). Perhaps even more concerning is the growing body of evidence in the scientific literature that climate change is likely to alter the frequency, genesis, spatial extent, and characteristics of the most extreme tropical cyclones (Knutson et al., 2010; IPCC, 2019; Knutson et al., 2020). Combined with the fact that future economic and demographic growth would lead to an increase in human and asset exposure (Botzen et al., 2019; Dinan, 2017), this tends to suggest that the future economic losses associated with tropical cyclones are likely to be higher.

Located in the Southwest Indian Ocean (SWIO), a basin that records 11% of global cyclonic activity according to Leroux et al. (2018), the French overseas region of La Réunion is frequently threatened by cyclonic systems. The historical study of Mayer Jouanjean (2011) on the cyclonic events in La Réunion during the 20th century shows that the island has experienced many devastating events. Of course, the quality of the island's infrastructure has been greatly improved since then, but the documentation shows that throughout the 20th century, cyclones have had a significant impact on Reunion society as a whole as in terms of damage. The cyclone of the "year" in 1948 is perceived as the strongest, since, according to the few existing measurements at that time, the wind gusts could have exceeded 300 km/h (Mayer Jouanjean, 2011). Other strong cyclonic events have affected La Réunion such as Jenny in 1962, Denise in 1966, Hyacinthe in 1980, Clotilda in 1987, Firinga in 1989, or Colina in 1993, each time causing significant damage and revealing the local population's vulnerability to these cyclonic events. The improved measurement of the intensity of tropical cyclones shows that in 2002, half of the maximum wind speed generated by tropical cyclone Dina on the territory of La Réunion exceeded 186 km/h, while the last quantile was above 217 km/h. Surprisingly, given the threat of tropical cyclones on La Réunion, there is no comprehensive study providing an assessment of the economic losses caused by such events for this French overseas region. However, such a study could be of interest to political decision-makers to help develop adaptation policies as well as companies or economic agents more broadly. The purpose of this paper is to fill this void.

Assessing the economic losses associated with tropical cyclones is nevertheless a difficult task, as it encounters both conceptual and methodological challenges. Conceptually, the distinction between what the literature calls the direct and indirect costs of tropical cyclones is not always easy to make (see Cavallo et al. (2010) or Kousky (2014) for detailed surveys). In this paper, we will focus on the direct losses: i.e., the immediate physical destruction occurring in the wake of the event. The methodological challenges are threefold. First, historical data on tropical cyclones cover a short period, and high-quality observations are fairly recent. Looking at past events is probably inappropriate, since damaging cyclonic events, and even more so the most extreme events, are still uncommon from a statistical viewpoint. Such an issue is probably more acute when the focus is placed on a particular and relatively small island, as is the case in the present paper. Second, historical observations alone are likely to be uninformative about the characteristics of tropical cyclones in a future and warmer climate. As a matter of fact, the future costs of tropical cyclones as well as the variation in future costs compared to what we call contemporaneous costs is a key indicator when engaging in adaptation policies. Finally, the extent of the economic damage depends on many factors such as the physical characteristics of tropical cyclones themselves as well as the spatial distribution of economic assets over a given territory. Consequently, and even more so in the case of a small island like La Réunion, it is necessary to objectively assess the distribution of economic activity and cyclone hazards at a high resolution spatial level (Bertinelli et al., 2016).

To overcome these methodological issues, we proceed as follows. Instead of relying on historical data, we follow a similar strategy as Hallegatte (2007), Emanuel (2011), or Bertinelli et al. (2016). We use synthetic storms or cyclones generated using large-scale meteorological variables (derived from a global model) as inputs to a high-resolution coupled ocean-atmosphere cyclone system model. Since many characteristics of cyclonic systems are downscaled from a given climate model, this method also allows us to overcome the need for a high spatial resolution as mentioned in the previous paragraph. Thus, by considering two simulations, one for a climate similar to what has been observed for the last 30 years and another for a future anticipated scenario of global warming, this methodology allows us to investigate the extent to which future economic losses due to tropical cyclones will change in comparison to the contemporaneous economic losses. Then, to proxy the economic activity and the spatial distribution of the economic value at a local level, we rely on nightlight brightness observed from satellites. This is part of a new and flourishing body of literature that uses night light data as a proxy for economic activity to study various issues such as the measurement of economic activity in low-income countries (Chen & Nordhaus, 2011; Henderson et al., 2012; Chen & Nordhaus, 2015; Pinkovskiy & Sala-i Martin, 2016), the growth impact of natural disasters (Bertinelli & Strobl, 2013; Elliott et al., 2015) or the recovery period after a disaster (Heger & Neumayer, 2019; Kocornik-Mina et al., 2020; Nguyen & Noy, 2019).[1]

Armed with these two input data, we then compute the wind field profiles of each simulated cyclonic system across La Réunion and then we use the wind damage function of Emanuel (2011) to translate them into economic losses.[2] Our key findings are as follows. First, the average cost per cyclonic system circulating around La Réunion increases by about 89%, implying that localities concentrating more economic activities are likely to suffer greater damage in the future. Second, our risk assessment, which consists of 100,000 simulated years of potential cyclonic events under both climate scenarios while keeping the average number of systems affecting La Réunion identical, shows that the proportion of years without damage decreases in the future. The magnitude of the average annual losses due to tropical cyclones increases from 0.23% to 0.43% of the economic value. Furthermore, for the same level of total losses, the associated return period sharply decreases in a warmer climate. For instance, a total loss of 10% of the economic value is associated with a return period of 149 years in a contemporaneous climate compared to 78 years in a future and anticipated climatic environment. Finally, sensitivity analyses based on changing the parameters that shape the damage function or the frequency of future cyclones indicate that our baseline estimates neither overestimate nor underestimate the losses and the variation of losses due to tropical cyclones in a future warmer climate.

The structure of the paper is as follows. Section 2 provides some background information on the cyclonic activity in the SWIO and the economy of La Réunion. Section 3 presents the nightlight and tropical cyclone data used in this paper. Section 4 details the methodology and the underlying assumption associated with our baseline strategy. Section 5 presents our main results as well as the sensitivity analyses applied. Finally, section 6 concludes the paper.

2 Background

2.1 Climatology of tropical cyclones around La Réunion

Tropical cyclones are natural atmospheric phenomena. According to Camargo & Hsiang (2015), they are considered as the most destructive natural disaster faced by a socioeconomic system. A tropical cyclone can be defined as a large organized system of winds (driven by

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[1] See the recent survey of Gibson et al. (2020) for more information about how nightlight data has been used by economists in the literature.

[2] Other papers also employ the damage function of Emanuel (2011) for the measurement of economic losses or as a proxy of local destruction to be included in the regressions. Examples include Bertinelli & Strobl (2013), Elliott et al. (2015), Sealy & Strobl (2017), or Mohan et al. (2018).

convective processes) that rotate around a center of low atmospheric pressure (Bobrowsky, 2013).[3] Tropical cyclones are associated with high-speed winds that can be very destructive. In the SWIO basin, tropical systems are considered to be tropical cyclones when they reach a maximum sustained wind speed (at 10 m above the surface) of 118 km/h. If the maximum sustained wind speed exceeds 63 km/h, they are called tropical storms, and tropical depressions when below 63 km/h. In the case of extreme wind speeds, tropical cyclones can cause severe damage along with the total destruction of properties, buildings, crops, or agricultural areas.

The SWIO basin represents 11% of global cyclonic activity (Leroux et al., 2018) with an average of 9.7 tropical systems per year, of which 4.8 generate wind speeds that would characterize them as tropical cyclones[4]. The SWIO islands and countries along the east coast of Africa can suffer significant damage after the passage of cyclonic systems, which can have significant health, economic, and environmental consequences (Jury et al., 1993; Leroux et al., 2018). Although La Réunion has an effective warning system to ensure the safety of the population, it is dependent on the predictability of tropical systems. Nevertheless, due to its complex topography and insularity, Reunion Island is vulnerable to the dangers associated with tropical cyclones (Tulet et al., 2021).

By definition, the National Hurricane Center (NHC) considers a tropical cyclone to have landed (characterized as a “landfall cyclone” in the literature) when the center of the cyclone crosses the coast (NHC, 2019). Given the small size of La Réunion, this definition is inappropriate, because climatological studies on the SWIO conclude that no tropical cyclone has ever landed on Reunion Island (Leroux et al., 2018; Weinkle et al., 2012) for the period covered by their investigations, i.e., from 1970 to 2016. In other words, this situation is unprecedented, as no data can inform us about the passage of a tropical cyclone whose center would have made landfall. Leroux et al. (2018) did not limit themselves to this definition of landfall and differentiated tropical cyclones as falling into two categories: “direct impact” (corresponding to the NHC definition of a “landfall cyclone”) or “threats” (cyclone center passes within 100 km of the coast).[5] Although no tropical cyclone or tropical storm has “directly” impacted La Réunion, there were four threats between 1999 and 2016 (Leroux et al., 2018). These studies focused on the passage of cyclones on or within 100 km of land. However, many examples in the SWIO have shown that a tropical cyclone whose center passed at a

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[3] Depending on the basin where they originate, these systems receive different names (Bobrowsky, 2013). They are called hurricanes in the North Atlantic and northeastern Pacific basins, typhoons in the northwestern Pacific basin, and tropical cyclones in the north Indian basin, the southwestern Pacific, the southeastern and southwestern Indian basins, and the Australian region.

[4] In terms of magnitude, a “tropical cyclone” is equivalent to a “hurricane” or a “typhoon,” terms used to described a given intensity of cyclonic systems in other basins.

[5] Here, the term “direct” impact should be understood from a physical perspective. Consequently, this differs from the notion of direct costs mentioned in the introduction. We nevertheless retain this terminology here, because it is more intuitive to understand the distinction introduced by Leroux et al. (2018).

greater distance could still have impacted territories economically and/or ecologically. Among them, we can mention Gamède in 2007 or Dumile in 2012, which passed the closest to La Réunion, notably within 100 to 150 km. History has also shown that systems that do not reach the tropical cyclone stage can also induce significant damage. For instance, in 2018, at the stage of a strong tropical storm, Berguitta, passed by La Réunion and caused significant economic damage. Throughout this paper, we therefore employ this "extended" definition to identify the cyclonic systems most likely to cause economic damage on La Réunion.

Regarding the evolution of cyclone activity in the future, many climate projections show a decrease in tropical cyclone frequency and an increase in cyclone maximum intensity and associated precipitation (Knutson et al., 2010; Walsh et al., 2016). However, these results vary by cyclone basin. For the SWIO basin, studies predict a decrease in the frequency of cyclones, an increase in their maximum intensity, and a southward shift in the limit of maximum intensity around 22°S (i.e., very close to La Réunion at 21°S) (Cattiaux et al., 2020; Thompson et al., 2021).[6] The simulations of Cattiaux et al. (2020) show that if the temperature increases by 2K, the frequency of tropical cyclones would decrease by 20%, and despite an increase in their maximum intensity, the frequency of the most intense tropical cyclones would remain rather constant. To our knowledge, there are no other studies published in the literature regarding the expected changes in cyclonic activity near La Réunion. Some studies based on other regional or global high-resolution models would be necessary to confirm these results or assess the potential alternative projections (Barthe et al., 2021). It should also be noted that there is no consensus regarding the evolution of cyclonic activity (Walsh et al., 2016; Knutson et al., 2020). Indeed, on a global scale, while the vast majority of studies show a decrease or stagnation in their frequency, some studies show an increase in the frequency of cyclones (Emanuel, 2013). It is therefore difficult to assess whether La Réunion will be impacted by more intense tropical cyclones. We can conclude that changes are expected to the frequency and distribution of tropical cyclones, although there is great uncertainty regarding the amount and the direction of these changes. We must therefore take these many possible evolutions into account in our sensitivity tests.

2.2 Economy of La Réunion

The island of La Réunion is a former French colony. Just after World War II in 1946, La Réunion obtained the status of French department and later became a French overseas territory in 1982. The 1970s correspond to the economic take-off of the island. Between 1974 and 2008, the average annual growth rate was roughly equal to 5% (CEROM, 2004; Parain

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[6] Preliminary results of the BRIO project led by the French meteorological services provide similar results. See also: `https://www.commissionoceanindien.org/portfolio-items/brio/`

& Rivière, 2013). In 2018, the reference year in our study, the annual economic growth was lower (1.8%), and the output per capita of La Réunion was 22,000 EUR. Overall, the strong economic growth since 1970 has been accompanied by an increase in the Human Development Index (HDI), which was estimated at 0.81 by Goujon & Hoarau (2015). However, despite this economic performance, the unemployment rate remains high (24%), while the employment and participation rates are low (46% and 61%). Lastly, the proportion of people living under the poverty line is much higher than in mainland France. In particular, 38.9% of Reunionese are under this threshold versus 14.8% in mainland France (INSEE, 2019).[7]

The Reunionese economy has many specificities, which broadly correspond to those of a small island economy. Specifically, the small size of its territory, which prevents the achievement of economies of scale, its insularity, the large distance separating the island from mainland France, as well as its relative specialization in services and tourism make it particularly vulnerable to shocks of an exogenous nature such as tropical cyclones (Croissant et al., 2019; Hoarau, 2019). The economy of La Réunion is a "tertiary" economy in which the role played by services is largely dominant in the production of wealth. The added value of the service sector represents approximately 80% of the total GDP. By contrast, the industrial and agricultural sectors contribute much less to the total output. Specifically, the output share of the industrial sector amounts to 18%, while the output share of the agricultural sector is around 2%. This distribution of economic activity is non-trivial for our study, because it is known that nocturnal brightness is a better proxy of the service and industrial sectors than the agricultural sector (Elliott et al., 2015; Gibson et al., 2020).

3 Data and methodology

3.1 Nightlight data

One prerequisite for our study is to objectively proxy economic activity at a local level. To do so, we follow an approach first used by Sutton & Costanza (2002) and further developed by Chen & Nordhaus (2011), Henderson et al. (2012), Chen & Nordhaus (2015), Bertinelli et al. (2016), Yerema et al. (2020) or Gibson (2021) (among others) by relying on the nightlight brightness observed from satellites. As stressed by Gibson et al. (2020), nightlight data are growing in popularity among economists, especially in contexts where other data sources are non-existent or presumed to be of poor quality. The appropriateness of nightlight data as a proxy for economic activity has been discussed in many studies, and in general, a strong

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[7] According to the French National Institute of Statistics and Economic Studies, the poverty line per consumer unit was 1063 EUR per month in France for the same year.

positive relationship between the logarithm of GDP and the logarithm of the radiance value of nightlights is found (Chen & Nordhaus, 2011; Henderson et al., 2012; Bertinelli & Strobl, 2013; Li et al., 2013; Doll et al., 2006). Against this background, it should be observed that nightlight data is not appropriate for capturing all types of economic activity. This is especially the case for rural activities, which are often characterized by large unlit or low-lit areas (Gibson et al., 2020). *A priori*, such issues are not an important concern for our study, since the GDP of La Réunion relies more on the tertiary sector than on agriculture. Finally, in the context of La Réunion, we are not aware of other data capturing the spatial distribution of economic activity, thus indicating that nightlights are a relevant departure point.

In contrast to many economic papers such as (Bertinelli & Strobl, 2013; Elliott et al., 2015; Bertinelli et al., 2016) (among others), we use nighttime satellite images taken from the Day/Night Band (DNB) sensors of the Visible Infrared Imaging Radiometer Suite (VIIRS) on board the Suomi-National Polar-orbiting Partnership (S-NPP) instead of nightlight data from the Defense Meteorological Satellite Program (DMSP). This choice is motivated by the shortcomings of DMSP data, especially the existence of blurred images, geo-location errors, and sensor saturation (Gibson et al., 2020). Furthermore, DMSP data are only available until 2013, and the original spatial resolution of the images is less than that of VIIRS.

For our study, the VIIRS input data correspond to the 2018 daily nighttime data, also known as the "black marble" data, produced following the methodology of Román et al. (2018).[8] We aggregate daily data to annual data by employing a simple arithmetic average. The final resolution of cells of nocturnal brightness is 0.004° (approximately 500 meters of horizontal resolution), implying that the entire territory of La Réunion is represented by approximately 10,000 pixels. Figure 1 shows the spatial distribution of nighttime brightness in La Réunion for our reference year, namely 2018. In the figure, unlit areas are depicted in black, while the most lit areas change from gray to white depending on the radiance value. Figure 1 shows that the most lit cells are located in areas near the coast and especially in cities with a concentration of economic activity. This is especially true for the capital city of La Réunion, namely Saint-Denis, but also for industrial areas around the seaport. In contrast to the other parts of the island, the eastern part shows more unlit pixels, especially in areas near the volcano. Given the nature of our input data, we implicitly assume, like Elliott et al. (2015), that unlit areas do not capture any economic activity. Table 1 reports the summary statistics associated with the average night light intensity in 2018. Approximately 80% of the cells have a radiance value less than the average nightlight intensity of 21.75. This feature is confirmed by a positive skewness. The standard deviation of the distribution of nightlight intensity is twice the mean and amounts to 56.62. The total nightlight brightness in 2018 is

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[8] The "black marble" products are freely available on `adsweb.modaps.eosdis.nasa.gov`

roughly 273,084.

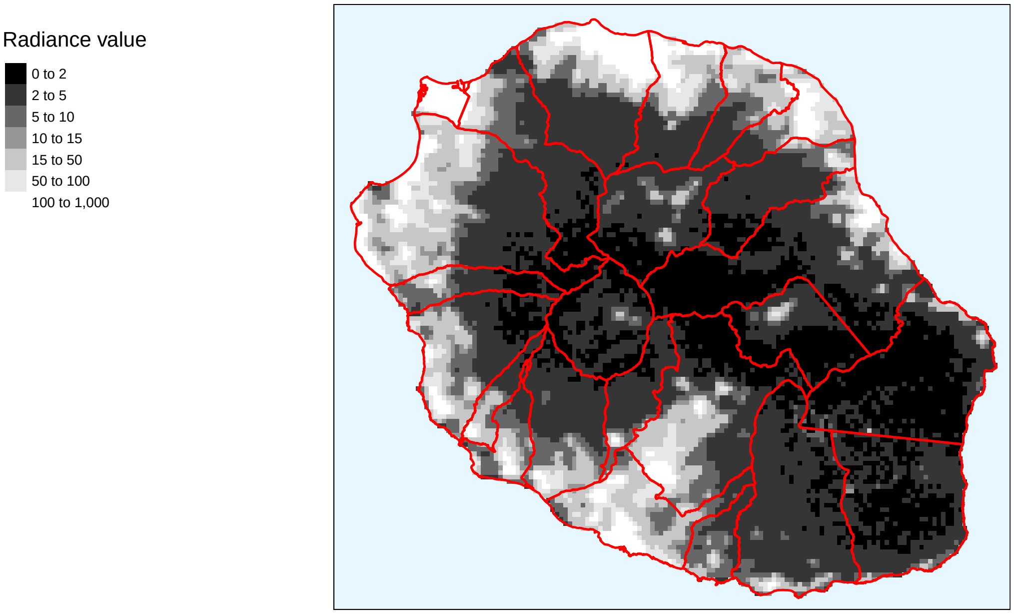

Figure 1: Mean value of daily nightlight intensity per pixel for La Réunion in 2008.
Sources: Black marble night light data (Román et al., 2018) and authors' own calculations.

3.2 Tropical cyclone data

When studying the economic costs and risks associated with tropical cyclones in La Réunion, relying on historical and observed events is likely to be problematic for at least two reasons. The first issue relates to the availability of historical data in the best track archive (Knapp et al., 2010). Indeed, when they exist, historical data are of short duration, and high-quality observations are only recent, since records began with the era of satellite observation. As stressed by Emanuel et al. (2008), in the southern hemisphere, which interests us here, good observations of cyclonic systems were achieved since the 1970s, namely when satellite coverage encompassed most of the earth's surface. In addition, even if historical data were of sufficient duration, their use for risk analysis is challenging, because the occurrence of extreme events is very uncommon from a statistical point of view, especially at an island level as in the case of La Réunion. The second shortcoming relating to the use of historical tropical cyclone data is that they are likely to be uninformative about what future cyclonic systems will be. In addition to the amount of historical costs, policymakers as well as economic agents are likely to be interested in the future characteristics associated with tropical cyclones.

Anticipating the future characteristics of tropical cyclones is, however, a challenging task,

	Nightlight intensity
Min.	0.00
Percentile 1%	1.01
Percentile 5%	1.47
Percentile 10%	1.65
Percentile 25%	2.05
Percentile 50%	3.11
Percentile 75%	12.38
Percentile 90%	55.81
Percentile 95%	106.03
Percentile 99%	315.90
Max.	975.09
Mean	21.75
Standard deviation	56.62
$\frac{\text{Standard deviation}}{\text{Mean}}$	2.60
Skewness	5.62
Total night light brightness	273084.20

Table 1: Summary statistics of the average nightlight intensity in La Réunion in 2018.
Sources: Black marble nightlight products of Román et al. (2018) and authors' own calculations
Notes: Nightlight intensity is measured in nWatts cm^{-}2 sr^{-}1

especially in a context of anthropogenic global warming that is likely to modify the genesis, path, and maximum intensity of cyclonic systems (Knutson et al., 2010; IPCC, 2019; Knutson et al., 2020). To achieve this challenging task, several techniques have been employed. One approach, adopted by Thompson et al. (2021), consists of studying how a climatologically representative tropical cyclone could be damaging if a similar one were to occur in the future. For the specific case of cyclone Bejisa that affected La Réunion in 2014, the result suggests that future "Bejisa-like" cyclones will be about 6.5% more intense.[9] The latitude at which this type of cyclone would reach its maximum lifetime intensity would be 2° further poleward, but no substantial change was detected in the north-south trajectory, meaning that Reunion Island would still be impacted. However, Thompson et al. (2021) acknowledge that it is necessary to reproduce this kind of projection for various cyclones, especially to evaluate cyclonic risks. In our study, we rely on another technique first pioneered in Emanuel (2006) and thereafter used by Hallegatte (2007), Emanuel et al. (2008), Emanuel (2011), or Bertinelli et al. (2016). This alternative approach consists of building synthetic cyclonic systems generated by large-scale meteorological variables derived from climate models as well

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[9] Thompson et al. (2021) consider a scenario described by the IPCC Representative Concentration Pathways (RCP) 8.5 emissions and a 1.1–4.2° warming of ocean surfaces by 2100.

as a high-resolution coupled ocean-atmosphere cyclonic system model. Synthetic systems are randomly launched in space and are assumed to develop according to the chosen climate conditions. Some of them develop until reaching the level of tropical cyclones, while others do not. By downscaling the characteristics of tropical cyclones, this technique allows us to quantify the influence of climate on the tropical cyclone activity. Furthermore, in addition to the appropriateness of the simulation of cyclonic systems by the coupled ocean-atmosphere cyclonic system models, this technique also benefits from the robust estimates of large-scale climate conditions from the climate model (Emanuel, 2011).[10] For our study, the use of synthetic cyclonic systems is motivated by two main reasons. First, it allows us to circumvent the problem that accompanies the use of historical data, especially their shortness and the inherent lack of extreme events. Second, as the technique can be employed for different climate scenarios, rather than making a simulation based on contemporaneous conditions, the method can also be implemented for future meteorological conditions under a given scenario of global warming. Consequently, this technique allows us to compute the economic costs of "contemporaneous" tropical cyclone as well as those associated with "future" tropical cyclones generated by a warmer climate.

Our study is based on two sets of 2,000 synthetic tropical cyclones produced for past and future conditions.[11] Synthetic tropical cyclones are included in the dataset when they have maximum 1-min average wind speeds of 21 m/s when passing within a radius of 150 km around La Réunion.[12] This distance of 150 km was chosen empirically and departs from the definition of a landfalling system, as it aims to capture the idea that cyclonic systems whose center is located at this distance can potentially cause damage on La Réunion. The historical data used for simulating the synthetic cyclones are taken from the best tracks of the Joint Typhoon Warning Center.[13] By filtering the data regarding the criteria of the synthetic cyclonic system simulation, the centers of 12 systems passed within 150 km of La Réunion. Even if none of them formally landed, they have at least threatened the island.

The simulations for the contemporaneous conditions are based on atmospheric and ocean

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[10] Emanuel et al. (2008) assessed the ability of this method to reproduce historical cyclone climatology in the North Atlantic basin and found that it works well.

[11] More specifically, synthetic tropical cyclones are generated using thermodynamic and kinematic statistics (Emanuel et al., 2006) based on recent historical climate data (or outputs from future scenario-based simulations) within a coupled ocean-atmosphere tropical storm model (Emanuel et al., 2008). Synthetic tropical cyclones are produced in three steps: genesis, tracks, and intensity. Track points are initiated randomly (in space and time) by seeding warm core vortices with maximum wind speeds reaching only 12 m.s-1. The tracks are calculated according to a beta-and-advection model (Holland, 1983) applied to the seed vortices, and the intensity is predicted using the CHIPS model (Emanuel et al., 2004). Seeds are considered to form tropical cyclones only when the vortex develops winds of at least a pre-defined threshold. A more detailed description of this technique can be found in Emanuel (2006) and (Emanuel et al., 2006, 2008)).

[12] The exact coordinates of the center are 21.114533°S/ 55.532062°E.

[13] `https://www.metoc.navy.mil/jtwc/jtwc.html?best-tracks`, last access on 6 March 2022

conditions provided by the ERA5 reanalysis from 1980 to 2019. This reanalysis consists of reprocessing all the past observed data archived by ECMWF (European Centre for Medium-Range Weather Forecasts; including some observation data that had not been retrieved when the operational model was initially run) with a consistent (and upgraded) system. ERA5 combines vast amounts of historical observations into hourly global estimates of a large number of atmospheric, land, and oceanic climate variables using advanced modeling and data assimilation systems.[14] The ERA5 dataset covering 1979 to the present day is publicly available. The horizontal resolution is 31 km (versus 80 km for ERA-Interim), and the atmosphere is resolved using 137 levels (from the surface up to an altitude of 80 km). Future conditions are calculated by CNRM-CM6-1, which is a coupled atmosphere-ocean global climate model (Voldoire et al., 2019) developed by the CNRM/CERFACS modeling group for the CMIP Phase 6 (CMIP6) (Eyring et al., 2016). The Couple Model Intercomparison Project (CMIP) aims to better understand past, current, and future climate change in a multi-model context (Eyring et al., 2016). The CMIP provides standardized outputs from different models to facilitate model intercomparisons.[15] The native horizontal resolution is 250 km for the atmosphere and 100 km for the ocean. Thus, the future conditions are the outputs of the CNRM-CM6-1 model simulations calculated for the SSP-based (shared socioeconomic pathway; O'Neill et al. (2016)) scenario named ssp370 for the 2015-2100 period. The ssp370 scenario projects low action targeting climate mitigation and air pollutant emission reduction. This scenario represents the medium to high end of the range of future forcing pathways (O'Neill et al., 2016). Consequently, the use of both historical and future track datasets will allow us to study the evolution of losses due to tropical cyclones on La Réunion.

4 Methodology

The wind field of each synthetic TC is predicted using the CHIPS model (Emanuel et al., 2004, 2008). For each synthetic TC, CHIPS calculates the storm intensity and the radius of the maximum wind along the track according to the potential intensity, wind shear, and thermal stratification of the ocean given by the re-analysis and the climate model data. This a deterministic, coupled atmosphere-ocean, axisymmetric hurricane model. It

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[14] Compared to the former reanalysis (Dee et al., 2011), ERA5 shows a higher horizontal and temporal resolution and a better representation of tropical cyclones.

[15] CNRM-CM6-1 consists of several existing models that are independently designed and coupled through the OASIS-MCT software developed at CERFACS (Craig et al., 2017; Voldoire et al., 2017). The atmosphere is simulated with the ARPEGE-Climat v6.3 global climate model (Roehrig et al., 2020) and the ocean with the NEMO ocean model v3.6 (Madec et al., 2017). The surface fluxes are simulated with the numerical platform SURFEX (Masson et al., 2013) v8.0, and the sea ice is represented by Gelato (Hunke and Dukowicz, 1997) v6.0. More details on the physical parameterizations can be found in Voldoire et al. (2017).

should nevertheless be noted that the CHIPS model does not take into account topographic and baroclinic effects. CHIPS is computed into the potential radius coordinates (i.e., two dimensions; radius and height), which means that the resolution is high/low inside/outside of the eyewall. To accurately represent the increase and decay of wind speed as a function of distance from the center of the tropical cyclone, the parametric wind model of Emanuel & Rotunno (2011) is used in the CHIPS model. Emanuel & Rotunno (2011) improved Emanuel et al. (2004)'s model for the outer part of the tropical cyclone eyewall by assuming a constant Richardson number in the storm outflow. Details regarding the wind field calculation can be found in Emanuel et al. (2004), Emanuel et al. (2006), and Emanuel & Rotunno (2011). Once wind fields are estimated at the local level, the main challenge is to convert them into economic losses. In doing so, as the total dissipation of the power of a cyclonic system (integrated over the lifetime of the event) increases as the cube of the maximum wind speed, a natural first practice was to simply use the cubic value of the maximum wind speed as a proxy for destruction (Emanuel, 2005). Furthermore, given that for wind speeds of "low" intensity there are unlikely to cause significant damage, it was common to fix the damage to 0 when wind speed is below a certain threshold (Strobl, 2011, 2012). However, as noted by Hallegatte (2007), one drawback of these indexes is that economic damage can infinitely increase with the wind speed, even though the total amount of economic losses is limited by the total economic value located at the surface of a given locality. To take into account this issue, we follow the same strategy as Emanuel (2011) and compute the following index of potential destruction f_{ci} that estimates the share of economic losses in a given cell c for event i:

$$f_{ci} = \frac{v_{ci}^3}{1 + v_{ct}^3} \tag{1}$$

with

$$v_{ci} = \frac{MAX\left(W_{ci} - \bar{W}, 0\right)}{W^* - \bar{W}}. \tag{2}$$

Where $\bar{W}$ is the minimum wind speed value above which economic damage is observed and W^* corresponds to the threshold at which half of the economic value of a given cell c is lost. This index of potential destruction captures three important features. First, the parameter $\bar{W}$ captures the fact that positive values of economic damage only occur when the maximum wind speed is above a certain threshold. Second, economic damage increases with the cubic power of maximum wind speed. Lastly, for high wind levels, the index imposes that the fraction of total economic loss cannot exceed one. The choice of the two parameters in equation (2) is thus non-trivial, as they shape the form of our damage function. In the context of La Réunion, we nevertheless acknowledge that we lack strong empirical evidence to choose the values of these two parameters. Indeed, insurance claim data are not publicly available, and in recent years, there have been no "intense" cyclonic systems, so that post-cyclone satellite observations are uninformative. Consequently, we follow Elliott et al. (2015) and set $\bar{W} = 93$ km/h and $W^* = 270$ km/h. The value of 93 km/h makes sense in the context of La Réunion, because it corresponds to the category of "strong tropical storm". Regarding W^*, we check the robustness of our results by varying it by ±40 (see the robustness subsection below). Figure 2 displays our baseline index of potential economic lost. According to the constructed index, a maximum wind speed of 200 km/h is associated with an economic loss of about 16%, while for a wind speed of 300 km/h, the corresponding loss amounts to 58%, which illustrates the non-linearity of economic damage in terms of wind speed exposure. Overall, it should be observed that the shape of the damage function of Figure 2 is consistent with the theoretical damage functions derived from the civil engineering literature, as those developed by Unanwa et al. (2000) or Vickery et al. (2006).

As noted by Emanuel (2011), this proxy of the share of economic losses is "highly idealized" in the sense that it only considers the maximum value of wind speed as an indicator of the hazards associated with tropical cyclones. We acknowledge that given the combination of the low pressure center and wind-induced sea waves, other hazards such as heavy rainfall, landslides, or storm surges are also likely to generate economic damage. However, as observed by Jordan & Clayson (2008) or Haiyan et al. (2008), economic losses but also the magnitude of other hazards are correlated with the wind speed strength generated by cyclonic systems. A comprehensive study of the impact of the four main hazards associated with tropical cyclones, namely wind speed, heavy rainfall, landslides, and storm surge on economic losses, would require a specific damage function for each hazard. In contrast to wind speed, the modeling of inundation-induced or landslides induced by tropical cyclone rainfall is more difficult. In the special case of La Réunion, we are not aware of any studies that establish a relationship between the parameter of rainfall associated with flooding and economic losses. Finally, it should be mentioned that studies that collect post-cyclone insurance data observe that the vast majority of insurance claim payments are due to wind speed rather than rainfall, landslides, or storm surges (CCR, 2020). This evidence combined with the lack of data to model economic damage related to other hazards leads us to use wind speed as the main indicator to determine the magnitude of tropical cyclones.

Against this background, our damage function is used to translate wind speed into economic damage for both the "current" and "future" climate with the same spatial distribution of economic activity on La Réunion, namely that computed from the daily nightlight data of 2018. In other words, we employ the same damage function and the same distribution of economic activity for cyclonic systems generated under contemporaneous and future climate conditions. This entails two implicit assumptions. First, we assume that the sensitivity of

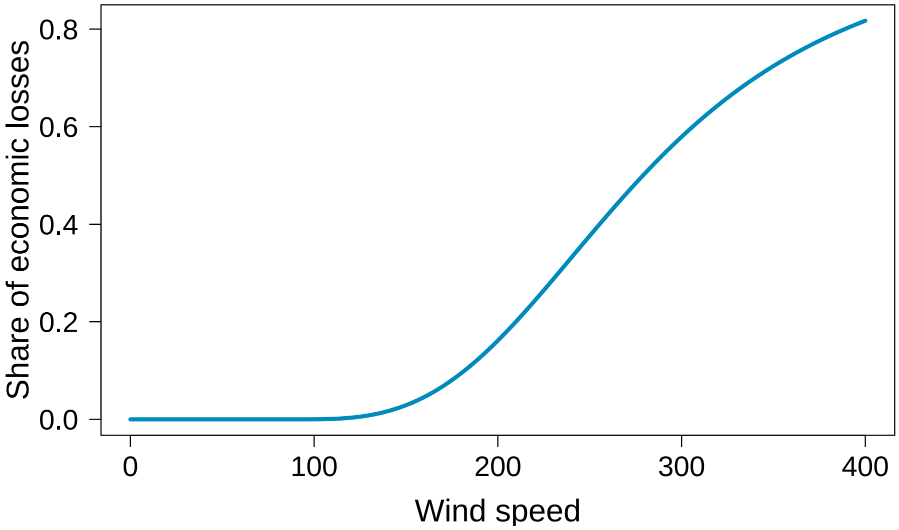

Figure 2: Index of the share of economic losses due to maximum wind speed.
Sources: Authors' own calculations.
Notes: Wind speed is expressed in km/h.

economic assets to wind speed does not change over time, which implies that adaptation policies are not implemented. Given this assumption, our estimation of the economic losses associated with tropical cyclones could be seen as an upper bound, since adaptation policies are likely to reduce the costs of such meteorological events. Second, we do not forecast the potential economic activity of La Réunion in, for instance, 2100. Current knowledge points toward strong demographic and economic growth in La Réunion but with a large amount of uncertainty about the precise estimates of these variables in the future. We acknowledge that such features are likely to change the spatial distribution of economic activity on the island, even if a significant part of the island's surface is protected for environmental reasons. Given this assumption, our estimation of economic losses could be seen as a lower bound, since the anticipated evolution of economic growth is likely to increase the economic value of the island.

5 Results

In this section, we present the results of our analyses in three steps. We first consider the two sets of 2,000 cyclonic systems to provide a detailed analysis of their cost and the spatial distribution of economic losses on the island. Then, we proceed to a simulation to provide annual statistics about the contemporaneous and future expected economic losses. Third, based on these annual simulations, we apply a battery of robustness checks.

5.1 A look at simulated costs

For each of the 4,000 synthetic cyclonic systems and according to the generated wind field, we first compute whether they cause observable economic losses at the island level. In doing so, we combine equation (1) with the spatial distribution of the economic value of Figure 1. We derive the total economic losses F_i at the island level for cyclonic event i by applying the following formula:

$$F_i = \sum_{c=1}^{C} \frac{nl_c}{NL} \times f_{ci} \tag{3}$$

where C is the total number of cells characterizing La Réunion in terms of nightlight, nl_c is the average brightness value of cell c in 2018, and $NL = \sum_{c=1}^{C} nl_c$ is the total "brightness" value observed in La Réunion in 2018. Table 2 reports the summary statistics of total losses at the island level generated by tropical cyclones under "curent" and "future" climates.

Among the 2,000 contemporaneous cyclonic systems circulating within a 150 km radius around La Réunion, 48.88% generated no damage. The percentage of damaging tropical cyclones fell by 12.27% under the future climate scenario, with 42.88% of events generating no damage. Significant economic losses, meaning that they exceed 2% of the total economic value, appear between the 80th and 90th percentiles of the loss distribution for the anticipated weather of the 2070-2100 period, while they appear later, between the 90th and 95th percentiles, for weather similar to the 1984-2014 period. The proportion of damaging events exceeding 5% of the total economic value is also higher under the future climate scenario (7% versus 4%, not shown in Table 2). The most severe tropical cyclones belonging to our sets of synthetic events under the current climate generate a loss of 40.26% of the economic value versus 67.75% under the future climate scenario. The average value of F_i under current climate conditions is 0.76%. Under future climate conditions, the mean value of total economic losses due to tropical cyclone winds sharply increases by almost 90% and amounts to 1.43%. These simple descriptive statistics show that the destructiveness power of future tropical cyclones will exceed that of current tropical cyclones.

To illustrate the spatial distribution of economic losses in La Réunion, Figure 3 plots two maps for each given climate. In these two maps, rather than reporting each element of the sum in equation (3), we multiply each by the total GDP value in 2018. Consequently, the scale of these maps can be interpreted in terms of "output losses".[16] At the island level, the average total losses associated with the two sets of tropical cyclones amount to 136 and 258 million euros, respectively. The spatial distribution of Figure 3 indicates that the most lit pixels are more likely to suffer from high economic damage. In particular, the average

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[16] Rather than using GDP to obtain a monetary value of economic losses, a credible alternative would be to use total property values. However, such data does not exist in a consistent manner for La Réunion.

	Contemporaneous	Future	Δ in %
% of TC with 0 damage	48.88	42.88	-12.27
Percentile 50%	0.00	0.00	–
Percentile 60%	0.00	0.01	–
Percentile 70%	0.03	0.10	–
Percentile 75%	0.08	0.24	–
Percentile 80%	0.19	0.55	–
Percentile 90%	1.15	2.76	–
Percentile 95%	3.76	7.66	–
Percentile 99%	17.44	31.76	–
Percentile 100%	40.26	67.75	–
Mean	0.76	1.43	89.56
Standard deviation	3.20	5.33	–
$\frac{\text{Standard deviation}}{\text{Mean}}$	4.21	3.73	–

Table 2: Summary statistics of tropical cyclone losses generated by 2,000 contemporaneous and 2,000 future cyclonic systems.

Sources: Black marble nightlight products of Román et al. (2018) and authors' own calculations

Notes: Economic damage is expressed as the percentage of total brightness of La Réunion.

economic losses in excess of 100,000 euros per pixel are more frequent in Saint-Denis and around the industrial area next to the seaport. Furthermore, the average economic losses per pixel are higher for the synthetic cyclones simulated under the future climate scenario. In line with our strategy, the unlit areas like those located in the southeast of the island show less economic damage.

5.2 Annual probabilities

The analysis of subsection 5.1, though interesting as an initial point of departure, lacks an economic interpretation, since the economic losses are expressed per cyclonic event without considering the average number of cyclones per year. Consequently, to provide annual statistics about the risk associated with tropical cyclones in La Réunion, we run the following simulations. We produce a hypothetical year of tropical cyclone events with a random sampling of the number of cyclonic systems associated with a given year following a Poisson distribution. In doing so, we fix the parameter of the Poisson distribution λ to 0.30, which corresponds to the average number of cyclonic systems circulating within 150 km of La Réunion per year during the 1980-2019 period (see also subsection 2.1).[17] We then randomly select the previously chosen number of events associated with that year from among the corresponding set of cyclonic systems circulating around La Réunion. For each of the selected cyclonic systems,

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[17] In a Poisson distribution, the parameter λ shapes the mean and standard deviation of the distribution.

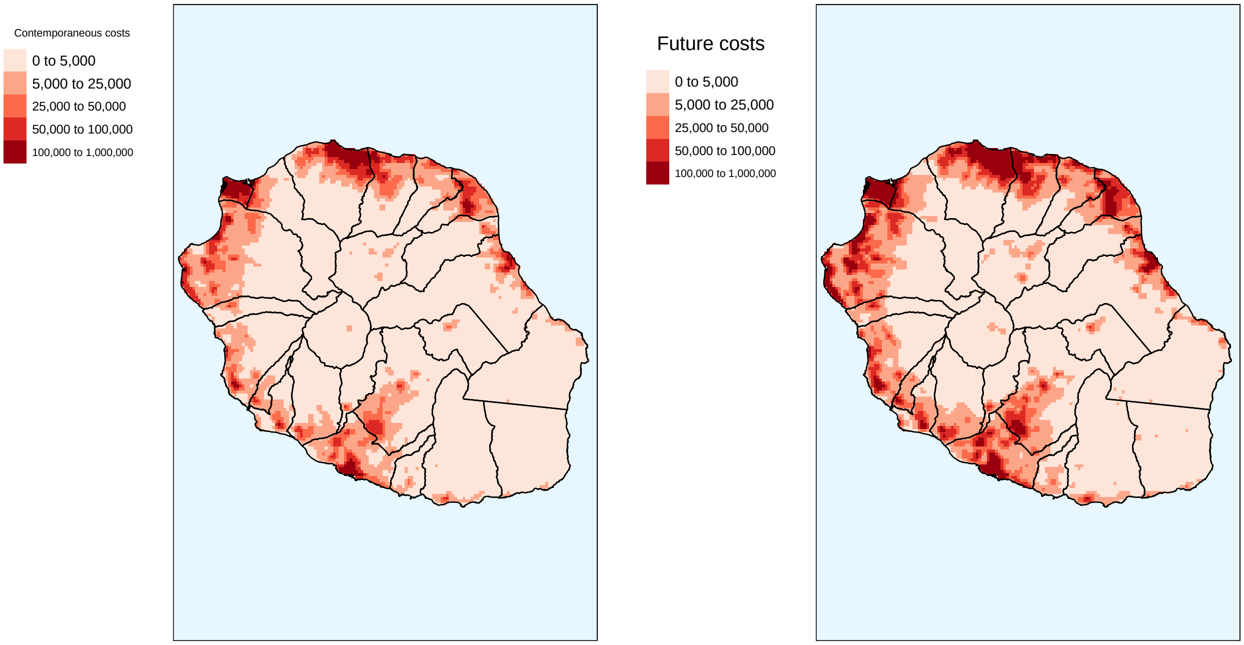

Figure 3: Contemporaneous and future average costs per pixel.
Sources: Black marble nightlight data (Román et al., 2018), synthetic tropical cyclones (Emanuel, 2011), and authors' own calculations.

we compute the total economic losses as in equation (3).After the selection, the chosen event is replaced in the pool of selectable events. We repeat the experiment 100,000 times, leaving us with potentially 100,000 years of tropical cyclone occurrences under both climate scenarios. We then consider that for each climate, the annual probability of drawing a hypothetical year is identical. In Table 3, we report the summary statistics of the annual losses obtained by simulating 100,000 hypothetical years under current and future climate scenarios. Given the first row of this table, the annual probabilities of experiencing a damaging tropical cyclone are 0.142 and 0.158, respectively. These annual probabilities translate into return periods of 7 and 6 years, respectively. In other words, under the current climate (resp. future climate), La Réunion should expect a damaging tropical cyclone to occur once every 7 years (resp. once every 6 years). In addition to the occurrence of a damaging tropical cyclone, the magnitude of the incurring losses is also of interest. In this respect, the bottom of Table 3 reports the expected annual average losses. Thus, for a climate similar to what was observed during the 1984-2014 period, the average annual losses are 0.23%, while for an anticipated future climate,

	Contemporaneous	Future	Δ in %
% years with 0 cost	85.80	84.20	-1.86
Percentile 80%	0.00	0.00	–
Percentile 90%	0.01	0.04	–
Percentile 95%	0.34	0.86	–
Percentile 99%	6.90	12.55	–
Percentile 100%	43.01	67.89	–
Mean	0.23	0.43	86.96
Standard deviation	1.82	3.05	–
$\frac{\text{Standard deviation}}{\text{Mean}}$	7.91	7.09	–
Return period of damage >0	7.00	6.00	–

Table 3: Summary statistics of the annual costs generated with 100,000 years of simulation of contemporaneous and future climates.

Sources: Black marble nightlight products of Román et al. (2018) and authors' own calculations

Notes: Economic damage is expressed as the percentage of total brightness of La Réunion.

this statistic increases to 0.43%. Overall, the variation in expected annual losses between the two climates amounts to approximately 87%, indicating that the risk associated with tropical cyclone wind speeds will be much higher in the future.

The two panels of Figure 4 complement our description of the expected annual average losses. The left panel reports in the y-axis the total annual losses, while the x-axis reports the corresponding return periods. The right panel has the same y-axis, although the x-axis corresponds to the associated probability loss. The figure of this panel thus describes the probability that a given level of loss will be exceeded. When looking at the left panel of Figure 4, several comments are in order. First, the curve describing the future climate is always higher than the one describing the contemporaneous climate. This suggests that the return periods of events would be shorter under a warmer climate. In other words, for the same amount of total cost, the associated return period is always higher for a climate similar to the current one. As an example, a total cost of 10% is associated with a return period of 149 years for weather similar to the current climate. For the anticipated climate scenario, the return period associated with such an event decreases by 71 years and amounts to 78 years.[18] Second, a closer look at the two curves suggests that for the same return period, the associated total cost due to tropical cyclones is substantially higher under the future climate scenario. For instance, a 100-year return period event causes a total loss of economic value of about 7% under current climatology compared to 12.5% for the future climate. The gap in terms of total loss sharply increases before stabilizing at around 15 percentage points for

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[18] The corresponding return period of an event generating a loss equivalent to the expected average annual loss is 13 years under the current climate and 12 years under the future climate.

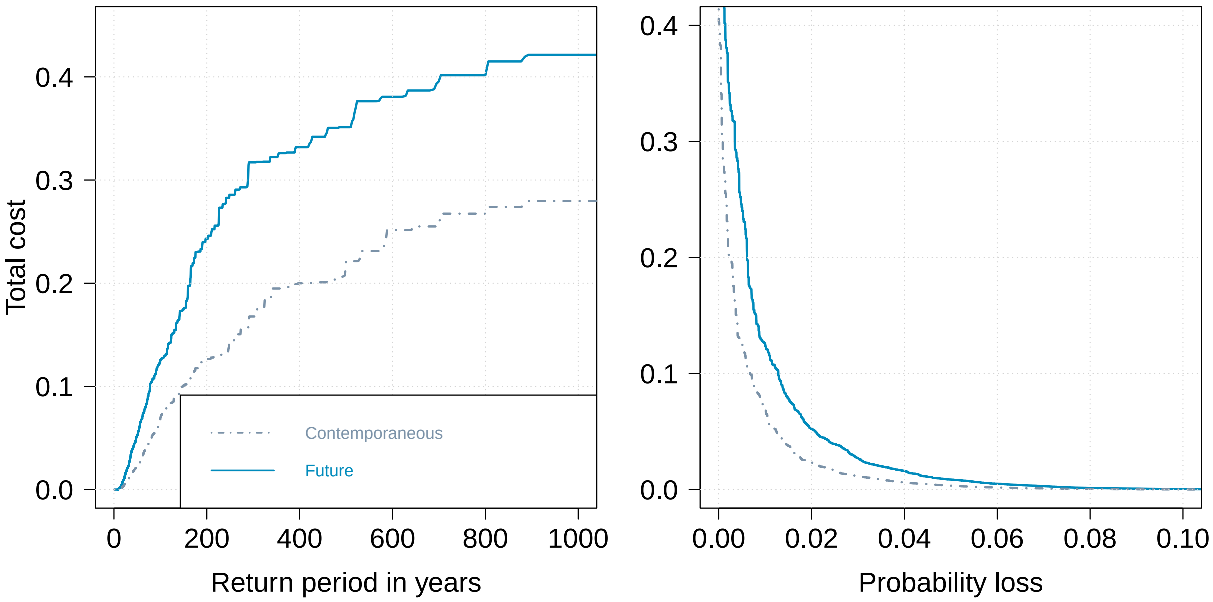

Figure 4: Return period and exceedance probability curves for current and future climates. *Sources*: Black marble nightlight data (Román et al., 2018), synthetic tropical cyclones (Emanuel, 2011), and authors' own calculations.

return periods higher than 400 years. The second panel of Figure 4, which illustrates the annual exceedance probability loss curve, reinforces the main message of our analysis. As the curve representing the future climate is higher than that representing the current one, for a given level of loss, the associated probability is higher in the former case. For instance, the probability of observing economic losses in excess of 10% is 1% in a current climate compared to 2% in a warmer climate.

5.3 Sensitivity analysis

Overall, our estimation of the costs due to tropical cyclones reveals that they are likely to increase in a future warmer climate. As this result could be sensitive to different modeling choices, we check here for its sensitivity along two dimensions. We first apply the same simulation of subsection 5.2, although we change the parameter value shaping the average number of cyclones per year in the future climate scenario. Second, we modify the two parameter values of the damage function of equation (2). The following subsection details these alternative exercises and presents the associated results.

	Contemporaneous	Future	Sce. Future 1	Sce. Future 2	Sce. Future 3
% years with 0 cost	85.80	84.20	89.13	94.43	79.58
Percentile 80%	0.00	0.00	0.00	0.00	0.00
Percentile 90%	0.01	0.04	0.00	0.00	0.18
Percentile 95%	0.34	0.86	0.22	0.00	1.82
Percentile 99%	6.90	12.55	8.00	2.71	15.48
Percentile 100%	43.01	67.89	89.01	67.75	78.97
Mean	0.23	0.43	0.29	0.15	0.58
Standard deviation	1.82	3.05	2.55	1.87	3.55
$\frac{\text{Standard deviation}}{\text{Mean}}$	7.91	7.09	8.79	12.47	6.12
Return period damage >0	7.00	6.00	9.00	17.00	4.00

Table 4: Summary statistics of the annual cost using 100,000 years of simulation of contemporaneous and future climates – Alternative values for λ.

Sources: Black marble nightlight products of Román et al. (2018) and authors' own calculations

Notes: Economic damage is expressed as the percentage of total brightness of La Réunion. In the simulation "Sce. future 1,', λ is set to 0.20. In the simulation "Sce. future 2," λ is set to 0.10. In the simulation "Sce. future 3," λ is set to 0.50.

Changing λ In the simulations of the previous subsection, based on historical data, we used a value of 0.30 for λ, namely the average number of cyclonic systems (as defined when simulating the synthetic tropical cyclones) circulating around La Réunion per year under both climate scenarios. In doing so, we assume that the average occurrence of cyclones does not change with the expected global warming. Some evidence suggests that global warming is likely to decrease the average number of cyclones, while the magnitude of the most intense systems is likely to increase (IPCC, 2019; Cattiaux et al., 2020; Knutson et al., 2020). By contrast, for the SWIO, other evidence indicates that anthropogenic warming could modify the genesis and path of cyclonic systems so that previously less exposed areas could be more exposed in the future (Cattiaux et al., 2020). For the special case of La Réunion, such path modifications could lead to a higher exposure in a warmer climate. Given these uncertainties, we decided to keep the same average number of cyclones under both climate scenarios in our baseline estimates. In this sensitivity analysis, we relax this baseline assumption by considering three other scenarios for the future climate. In the first one, we follow the conclusions drawn by Cattiaux et al. (2020) or Knutson et al. (2020) and consider that the likelihood of having a cyclonic system close to La Réunion decreases. We take into account this possibility by fixing $\lambda = 0.2$. The second scenario is in line with the first one, but we set λ to a lower value, namely 0.1. Finally, in the third scenario, we rather follow suggestive evidence, which indicates that La Réunion will be more exposed given the future genesis of cyclones as well as their future path. We consider this possibility by setting $\lambda = 0.4$. These three scenarios are respectively labeled "Sce. Future 1," "Sce. Future 2," and "Sce. Future 3." Table 4 reports their summary statistics along with our baseline estimates, while Figure 5 displays the return period associated with each scenario.

As expected, in the first two scenarios, the proportion of years experiencing no damage increases, while it decreases when the average number of cyclones close to La Réunion is higher. The return periods of positive economic damage due to tropical cyclones is modified accordingly and respectively amounts to 9, 17, and 4 years. Regarding the expected annual costs of tropical cyclones, we witness that in scenario "Sce. Future 1," it is still higher, being around 25% above what is observed for weather similar to the current period. The third scenario that anticipates the poorest outcome in terms of exposure for La Réunion is characterized by an increase in the expected average annual cost in comparison to the contemporaneous scenario as well as the future baseline scenario. More specifically, the expected annual cost of 0.58% corresponds to an increase of 150% (resp. 35%) in comparison to the baseline contemporaneous (resp. future) scenario. Overall, the return period curves of Figure 5 are consistent with these results. They further show that the total economic costs associated with a return period of 100 years are highest for scenario "Sce. Future 3" and

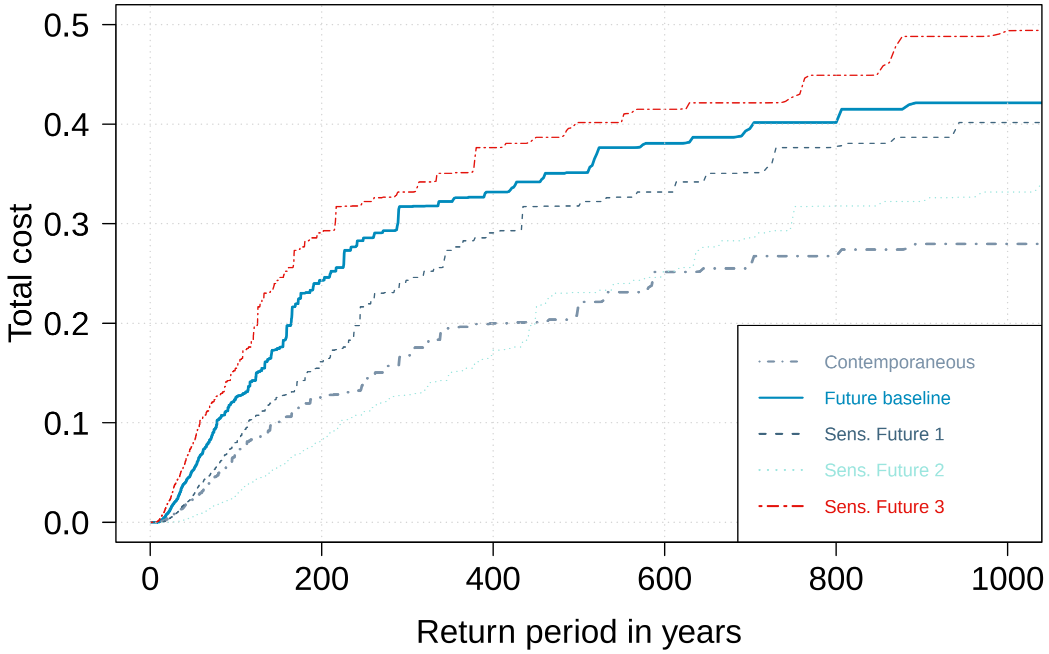

Figure 5: Return period for different calibrations of the average number of cyclonic systems per year.

Sources: Black marble nightlight data (Román et al., 2018), synthetic tropical cyclones (Emanuel, 2011), and authors' own calculations.

Notes: In the scenario labeled "Rob Future 1," the parameter λ is set to 0.375. In the scenario labeled "Rob Future 2," the parameter λ is set to 0.175.

lowest for scenario "Sce. Future 2," which is our baseline scenario situated in the middle of these estimates. However, for a return period of about 300 years, even scenario "Sce. Future 2" is associated with a higher total cost compared to our baseline contemporaneous scenario. This suggests that the possibility, though weak, of having extreme events is likely to be greater than what we can be observed under the current climate scenario. Finally, total costs of 10% of the economic value have a return period of 115, 223, and 58 years in scenarios "Sce. Future 1," "Sce. Future 2," and "Sce. Future 3," respectively. In the baseline future climate, the corresponding return period amounts to 30 years.

To conclude, this sensitivity analysis shows that our baseline assumption about the future exposure of La Réunion does not overestimate the expected future costs. However, this analysis suggests that having an average cost less than what is found for the current climate relies on an "unrealistic" and unlikely scenario based on a very low average occurrence of cyclonic systems circulating close to La Réunion in the near future.

Changing $\bar{W}$ and $\bar{W}^*$ In the baseline estimate, we translate wind exposure at the cell level to damages by using the damage function f_{ci} of equation (1) and (2). This damage function implies a non-linear relationship between wind speed and economic damage. In this damage function, two parameters, namely $\bar{W}$ and W^*, are crucial, as they shape the damage function curve. In the baseline estimate, $\bar{W}$ is set to 93 km/h and W^* to 270 km/h. We reconsider this choice here by changing the parameters one by one while keeping the second one to the baseline choice. Consequently, we rerun the baseline scenario four times by respectively fixing $\bar{W} = 130$ km/h, $\bar{W} = 50$ km/h, $W^* = 320$ km/h, and $W^* = 240$ km/h. To save space, we report here only the summary statistics similar to those provided in Table 3; for each scenario, refer to Tables 5 to 8 of Appendix A.

Overall, the changes made to the parameters have the expected effect on the amount of economic losses. In particular, changing $\bar{W}$ has an incidence on the proportion of years experiencing no damage. Under the current climate condition, when $\bar{W} = 130$, the number of years with no damage is 95 compared to 85.80 in the baseline estimate. Accordingly, this share decreases when $\bar{W}$ is set to a low value (see Table 6). In contrast to $\bar{W}$, changing W^* has almost no incidence on the proportion of years with no damage, so that the return periods of having a year with losses due to a tropical cyclone are the same as the baseline scenario. However, changing W^*, namely the threshold for which half of the economic value is lost, impacts the magnitude of economic damage. As in Table 8, the expected economic losses are the highest when W^* is low. In this scenario, for climate conditions similar to what was observed during the 1984-2014 period, the expected economic losses are 0.41% compared to 0.23% in our baseline estimates. Finally, another interesting feature of these four scenarios is based on the fact that future economic losses always increase. Again, our baseline estimation of the variation of economic losses falls within the range obtained with the sensitivity study.

6 Conclusion

Using wind fields generated by synthetic tropical cyclones under current and future (warmer) climate scenarios, we propose an estimation to determine the economic losses associated with tropical cyclones in La Réunion. We find that compared to the expected current losses, the future economic losses due to cyclonic systems are likely to increase by about 90%, even if the spatial extent and amount of economic activity are assumed unchanged. Sensitivity analyses applied to check for the robustness of our baseline estimation show that we neither overestimate nor underestimate the magnitude of the economic losses associated with tropical cyclones. Consequently, our paper suggests that policy designers should probably engage in adaptation policies to reduce the disastrous nature of these meteorological events.

Our paper should be seen as a first step in understanding the economic damage caused by tropical cyclones in La Réunion. In addition to the monetary losses, tropical cyclones are also associated with considerable non-tangible damage linked to the degradation of the environment or the loss of human life. Furthermore, our strategy only allows us to investigate the amount of direct losses without considering the potential indirect losses that could induce an interruption of economic activity. This issue, which could be analyzed through the lens of a computable general equilibrium model, is on our agenda for future research, although it lies beyond the scope of the present paper.

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Appendices

A Changing the parameters of the damage function

	Contemporaneous	Future	Δ in %
% years with 0 cost	94.57	92.78	-1.89
75%	0.00	0.00	–
80%	0.00	0.00	–
90%	0.00	0.00	–
95%	0.00	0.01 –	
99%	2.23	6.72	–
100%	37.77	71.09	–
Mean	0.11	0.27	145.45
Standard deviation	1.35	2.61	–
$\frac{\text{Standard deviation}}{\text{Mean}}$	12.27	9.67	–
Return period damage >0	5.00	4.00	–

Table 5: Robustness – Summary statistics of the annual cost generated with 100,000 years of simulation of contemporaneous and future climates – $\bar{W} = 130$.

Sources: Black marble nightlight products of Román et al. (2018) and authors' own calculations

Notes: Economic damage is expressed as the percentage of total brightness of La Réunion.

	Contemporaneous	Future	Δ in %
% years with 0 cost	64.49	63.65	-1.30
60%	0.00	0.00	–
70%	0.00	0.00	–
75%	0.00	0.00	–
80%	0.02	0.05	–
90%	0.85	1.31	–
95%	2.70	4.12	–
99%	12.96	18.51	–
100%	50.56	68.78	–
Mean	0.54	0.82	51.85
Standard deviation	2.55	3.74	–
$\frac{\text{Standard deviation}}{\text{Mean}}$	4.72	4.56	–
Return period of damage >0	5.00	4.00	–

Table 6: Robustness – Summary statistics of annual cost generated with 100,000 years of simulation of contemporaneous and future climates – $\bar{W} = 50$.

Sources: Black marble nightlight products of Román et al. (2018) and authors' own calculations

Notes: Economic damage is expressed as the percentage of total brightness of La Réunion.

	Contemporaneous	Future	Δ in %
% years with 0 cost	85.80	84.23	-1.83
75%	0.00	0.00	–
80%	0.00	0.00	–
90%	0.00	0.02	–
95%	0.19	0.48	–
99%	3.99	7.52	–
100%	28.61	54.11	–
Mean	0.14	0.27	92.86
Standard deviation	1.15	2.06	–
$\frac{\text{Standard deviation}}{\text{Mean}}$	8.21	7.63	–
Return period of damage >0	5.00	4.00	–

Table 7: Robustness – Summary statistics of annual cost generated with 100,000 years of simulation of contemporaneous and future climates – $W^* = 320$.

Sources: Black marble nightlight products of Román et al. (2018) and authors' own calculations

Notes: Economic damage is expressed as the percentage of total brightness of La Réunion.

	Contemporaneous	Future	Δ in %
% years with 0 cost	85.80	84.23	-1.83
75%	0.00	0.00	–
80%	0.00	0.00	–
90%	0.02	0.08	–
95%	0.68	1.76	–
99%	13.15	22.34	–
100%	65.00	87.07	–
Mean	0.41	0.73	78.05
Standard deviation	3.00	4.63	–
$\frac{\text{Standard deviation}}{\text{Mean}}$	7.32	6.34	–
Return period of damage >0	5.00	4.00	–

Table 8: Robustness – Summary statistics of annual cost generated with 100,000 years of simulation of contemporaneous and future climates – $W^* = 240$.

Sources: Black marble nightlight products of Román et al. (2018) and authors' own calculations

Notes: Economic damage is expressed as the percentage of total brightness of La Réunion.

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