Climate risk management in Coastal LDCs and SIDS

Assessment of adaptation potentials with CLIMADA

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1. Climate risks for coastal nations and the need for coastal adaptation

1.1 Coastal Least Developed Countries and Small Island Developing States

Fifty-four nations across the globe are designated as coastal Least Developed Countries (LDCs) or Small Island Developing States (SIDS). All are extremely vulnerable to the impacts and risks of climate change in general, and ocean and coastal-related climate change in particular. Both coastal LDCs ('low-income countries confronting severe structural impediments to sustainable development')[1] and SIDS, a distinct group of island developing countries, are particularly vulnerable to coastal and ocean-based climate change because of the large proportions of people, assets, and infrastructure located in their coastal zones. These countries are already experiencing negative impacts from climate change, including sea level rise (SLR), land erosion, changes in the global water cycle, and increased storm intensity (Thomas et al., 2020). Direct coastal impacts include marine inundation of low-lying areas, coral bleaching, saline intrusion into terrestrial systems, degrading ecosystems, species shifts, habitat loss, and climate-induced diseases. Impacts on people and infrastructure include loss of homes, lives, and livelihoods, human displacement, economic sector disruption, increased water insecurity, and disruption to key infrastructure such as transportation and communication (Ferris et al., 2011; GIVRAPD, 2015; Albert et al., 2016; Pill, 2020; Thomas et al., 2020).

1.2 Climate change related Slow-Onset Processes and Extreme Weather Events

The impacts of climate change include slow-onset processes (SOP)[2] and extreme weather events (EWE), which may both result in losses and damages. EWE are events, such as tropical storms and floods, which occur on short timescales (hours to days). SOP, on the other hand, are slow, gradual changes and refer to 'the risks and impacts associated with

Dominica Fishermen's Cooperative Building at Scotts Head after hurricane Maria; © Owen Day

1 United Nations Department of Economic and Social Affairs, www.un.org/development/desa/dpad/least-developed-country-category.html.
2 In this paper, the term slow-onset processes (SOP) is used instead of slow-onset events (following GIZ & IIASA, forthcoming).

increasing temperatures; desertification; loss of biodiversity; land and forest degradation; glacial retreat and related impacts; ocean acidification; sea level rise; and salinization'.[3] Key hazards of relevance to coastal LDCs and SIDS include:

- SOP, specifically SLR, rising water temperatures, and salinisation;
- EWE such as tropical cyclones and flooding.

These hazards contribute to significant secondary risks and impacts, including physical, socio-economic, and ecological (loss of biodiversity, increased algal blooming, etc.) impacts. Furthermore, in so-called compound events, when EWE and SOP combine (Zscheischler et al., 2018), the total risk can be greater than the sum of the risk arising from individual SOP or EWE.

Most regions in the world experience cascading effects as EWE and SOP interact and compound each other. Interdependencies exist between distinct events and processes and some climate-induced risks are becoming increasingly **compound** (with interactions between multiple hazards and societal drivers) as well as **systemic** (with interdependent hazards across space and time). Furthermore, SOP can trigger additional hazardous impacts, such as coastal erosion, or saltwater intrusion (IPCC, 2019a).

1.3 Climate Risk Management (CRM)

It is vitally important to understand the negative impacts of climate change, the potential to avert, minimise and address such impacts and the losses and damages that may nevertheless occur through climate mitigation and risk management approaches. This is particularly the case for coastal LDCs and SIDS, which have developing economies, limited financial buffers, and a heavy dependence on biological ecosystems that will be severely negatively impacted by climate change. The Intergovernmental Panel on Climate Change (IPCC), through its Fifth Assessment Report (IPCC, 2014) and a special report on managing risk to advance climate change adaptation (IPCC 2012), has provided a framework for risk assessment that considers the climate hazards countries or regions may experience, as well as the exposure and existing or future vulnerabilities that determine the severity of impacts that human and ecosystems experience as a consequence of hazard occurrence (Figure 1).

For coastal LDCs and SIDS, climate hazards that affect coastal areas directly or indirectly combine with the increased exposure of the population and assets in low-lying and/or coastal areas, and can be exacerbated by the existing or potential vulnerabilities of certain groups (IPCC 2019a).

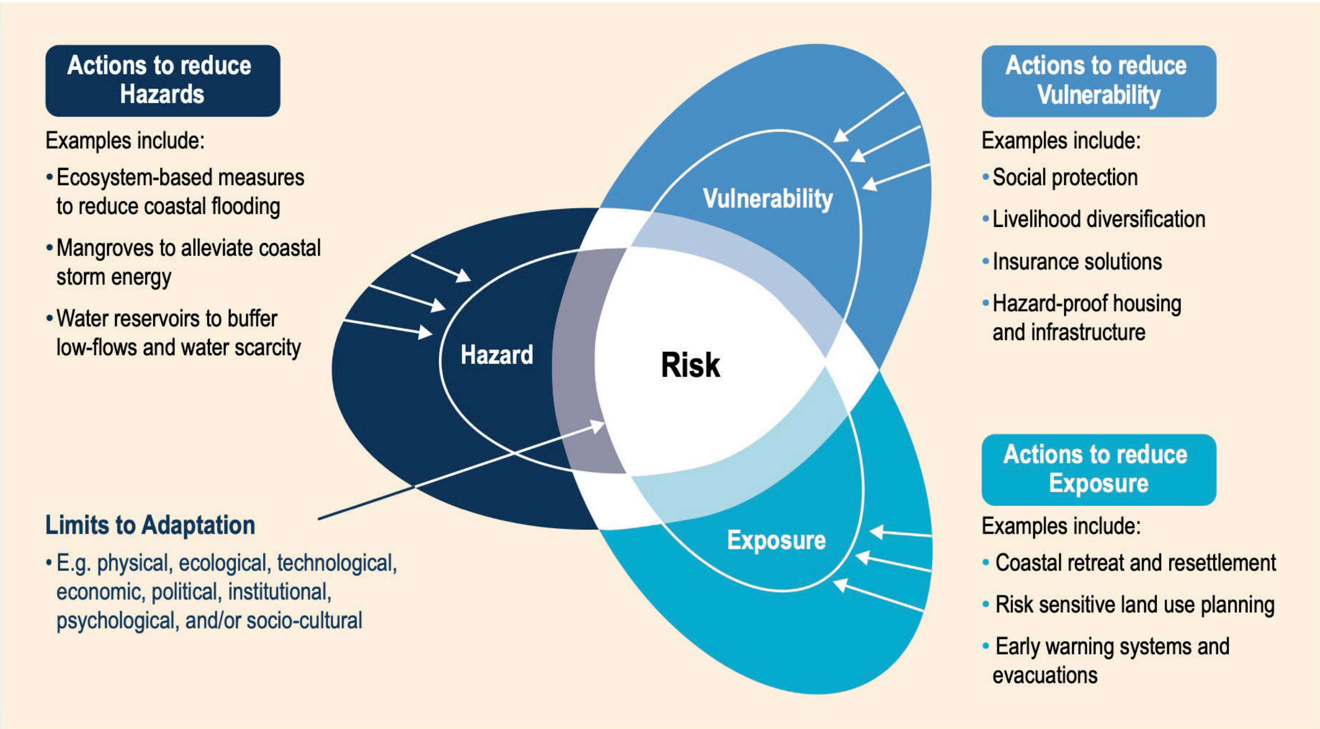


Figure 1: Climate Risk Framework in accordance with IPCC 5th Assessment (IPCC, 2019).

3 United Nations Framework Convention on Climate Change, https://unfccc.int/wim-excom/areas-of-work/slow-onset-events.

Quantification of the hazards, exposure and vulnerability a community faces can inform risk assessments, and adaptation strategies and planning. Generally, coastal adaptation strategies can include 'hard' measures such as sea walls and ecosystem-based adaptation, and 'soft' measures such as improved building codes and coastal early warning systems. These adaptation measures contribute to risk reduction by reducing the impact of identified hazards. Risk transfer methods, such as catastrophic risk insurance, can be used to alleviate the financial risk burden and help communities cope with extreme events that are exacerbated by climate change. Finally, a community may choose to absorb the negative impacts of climate change through risk retention, which – in most cases – is linked to losses and damages. Although risk is reduced and/or transferred, there is still residual negative impact which will have to be absorbed.

In addition to these measures and methods, holistic strategies are being developed to comprehensively manage the risks and potential impacts of natural and climate-induced hazards. The Climate Risk Management (CRM) approach used here, as well as the Comprehensive Risk Management framework, a multi-pronged approach developed by the United Nations Executive Committee of the Warsaw International Mechanism (WIM) for Loss and Damage (Executive Committee of the Warsaw International Mechanism for Loss and Damage 2019), are useful mechanisms for assessing negative climate impacts, and quantifying damages averted through adaptation.

GIZ's Global Programme of Risk Assessment and Management for Adaptation to Climate Change (Loss and Damage) (GP L&D), which is supported by the German Government's Federal Ministry for Economic Cooperation and Development (BMZ), has developed a risk-based, iterative framework to guide the management of climate-related risks, considering biophysical, social, economic, non-economic, and environmental aspects (Figure 2). It considers the entire spectrum of climate-related hazards and risks from short-term EWE to long-term SOP. Each CRM strategy is ideally built on a context-specific climate risk assessment; suitable measures are then chosen accordingly.

To minimise losses and damages, CRM combines a smart mix of climate change adaptation and disaster risk reduction measures. To address residual risks, tried-and-tested measures

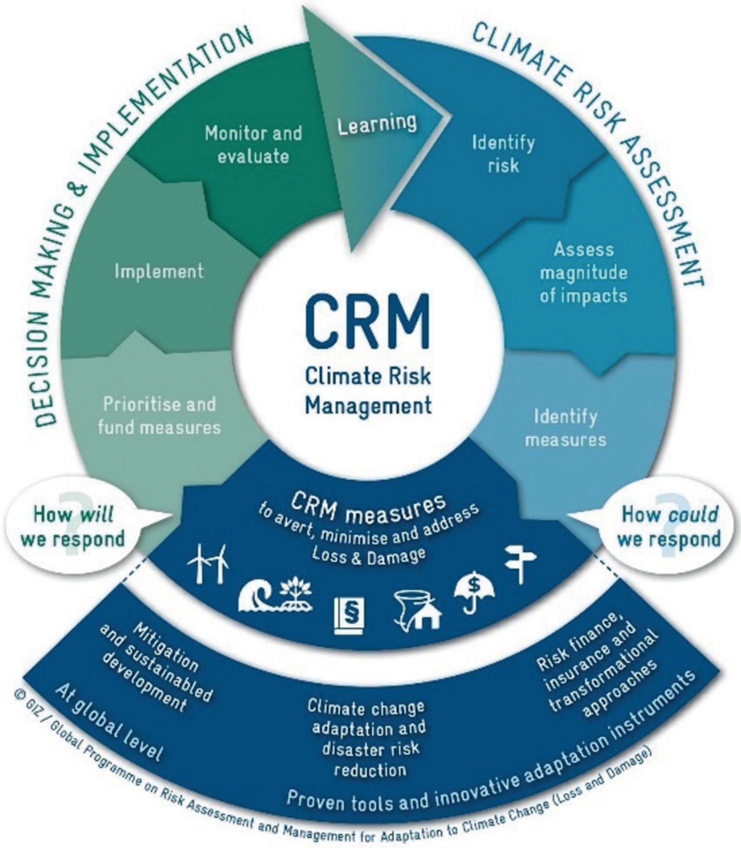


Figure 2: Climate Risk Management Framework developed by GIZ (GIZ, 2021).[1]

are complemented by innovative instruments, such as climate risk insurance and social protection schemes, and transformational approaches, such as livelihood diversification, in a comprehensive, integrated manner. Ultimately, CRM implies that all sectors factor risks into their plans, including considering how risks may affect action across sectors.

Accordingly, there are options available to help coastal LDCs and SIDS adapt to the negative impacts of climate change. These options, which are further described in table 1, address several coastal risks arising from climate change. There is, however, increasing evidence that measures for managing climate risk may face barriers to their implementation and limits in their effectiveness. Such barriers and limitations are context dependent and can be investigated during risk assessments (GIZ, forthcoming). Tools that help practitioners assess the potential suitability of adaptation measures, including through analysis of costs, benefits, and averted damages, are key components in properly implementing such measures and avoiding maladaptation. Such tools are, however, poorly developed and inaccessible, and data are often lacking.

As a result, it has not yet been possible to implement CRM approaches in many regions. Many developing countries have not had their climate risk analysed to the same extent as developed countries. The reasons for this include insufficient information on climate hazards due to a lack of local data, and insufficient knowledge of adaptation measures at spatial scales relevant to coastal developing countries. Furthermore, there are often physical, biological, policy/governance, financial, and economic barriers to implementing adaptation options (see Table 1). Countries are already experiencing the negative impacts of climate change and adaptation approaches are not being applied in a timely manner. Hurricane Dorian, which hit the Bahamas in 2019, is a stark example of those impacts: scientific research indicates that anthropogenic climate change increased the likelihood of

Table 1: Examples of coastal adaptation options, barriers, and limits in SIDS. These options are also relevant and applicable to coastal LDCs. (Source: Thomas et al., 2020 based on IPCC, 2019).

Adaptation option	Risks addressed	Barriers	Limitations
Ecosystem-based approaches: coral reef restoration, mangrove replanting	Coastal erosion, loss of biodiversity, coastal flooding from storm surges	• Competing land uses (e.g., tourism versus mangroves) • Non-climate stressors on ecosystems, reducing effectiveness	• Biophysical limitations relating to ocean acidification, ocean temperature, SLR, and species adaptation are likely to arise during the 21st century • Space and competing land uses • Increases in extreme events (e.g., marine heatwaves) leading to catastrophic events (e.g., mass mangrove die-off)
Strengthened building codes, retrofitting of infrastructure	Damages from tropical storms	• Costs • Governance (including compliance) • Political and public acceptability • Trade-offs with short-term development priorities	• Increases in extreme and unprecedented events
Sea walls, levees/ dykes, groynes	Coastal flooding	• Costs/cost effectiveness • Potential displacement of impacts • Political and public acceptability • Adverse impacts on biodiversity and natural systems	• Prohibitive costs (including maintenance) linked to economic, financial, and social barriers • Technical limits to hard protection are expected to be reached under high emission scenarios beyond 2100
Rainwater harvesting	Freshwater stress	• Predominately at household level	• Does not overcome related freshwater issues (e.g., salinisation of freshwater lens in low-lying atolls)
Ridge-to-reef and whole-island approaches	Multiple impacts and interconnected stressors	• Complexity • Public and political acceptance • Requires high level of commitment • Trade-offs will be exposed	• Less likely to face limits than isolated adaptation options due to holistic approach (e.g., changes in agricultural practices can reduce impacts of run-off on reef systems)

Hurricane Dorian's extreme rainfall by up to 18 % (Reed, et al. 2021). The costs of Hurricane Dorian's impact on the Bahamas are estimated at US$717M in losses, US$2.5B in damages, 67 fatalities, 30,000 people impacted, with evidence of displacement and forced migration (Deopersad, et al. 2020).

The case of the Caribbean

The case study in this report focuses on the effect of climate change on EWE, specifically tropical cyclones, and the subsequent economic impact on SIDS. Global incidences of disasters related to natural hazards have increased since 1980, with the majority of such disasters being weather-related, particularly floods and storms (Moody's Investors Service, 2016). The study region of the Caribbean is extensively exposed to natural disasters – six Caribbean islands are in the top 10 most disaster-prone countries in the world, and all Caribbean countries are in the top 50 (Moody's Investors Service, 2016) (see the Box on Caribbean Climate Risk Profile). Tropical cyclones are a key coastal and ocean climate change risk relevant to LDCs and SIDS. With projected increases in tropical cyclone intensity and precipitation as a result of climate change (IPCC 2019), it is crucial to understand the impact of EWEs on at-risk coastal developing economies such as Caribbean SIDS, as well as to chart a potential path to resilience through analysis of adaptation potential.

Saint Louise du Sud, Haiti © GIZ / Britta Radike

Caribbean Climate Risk Profile

The Caribbean region has more than 700 islands, islets, reefs, and cays, and a population of 43.5 million people (Fuller, Kurnoth and Modello 2020). The climate is tropical maritime; it is warm and humid with temperatures ranging from 25°C in the winter to 32°C in the summer. The annual wet season, which coincides with the hurricane season, runs between May/June and November/December, with the dry season making up the other half of the year. Heat stress is much higher during the wet season, especially during dry spells. The Caribbean region is extensively exposed to natural disasters, specifically tropical cyclones, hurricanes, and floods. Six Caribbean islands are in the top 10 most disaster-prone countries in the world, and all Caribbean countries are in the top 50 (Moody's Investors Service, 2016). Since 1950, 511 disasters worldwide have hit small states – that is, developing economies with populations of fewer than 1.5 million people. Of these, 324 occurred in the Caribbean, killing 250,000 people and affecting more than 24 million through injury and loss of homes and livelihoods (International Monetary Fund, 2018).

Key climate hazards in the Caribbean

Caribbean Small Island Developing States are susceptible to the negative impacts of climate change due to their size, location, and reliance on sectors vulnerable to changing climate patterns (see Table 2 for further information on current impacts and projected risks). Warming is projected to be greater over land areas, particularly affecting the northwest Caribbean territories (Cuba, the Dominican Republic, Haiti, and Jamaica) (IPCC, 2018). It is predicted that Dominica, Saint Vincent, the Grenadines, and Saint Kitts and Nevis will experience increasing numbers of hot days each year, with 25–65 % of days annually being hot by 2060. Cold weather events are anticipated to disappear by 2060 (USAID 2018). Precipitation is projected to change throughout the region, including a 15–20 % decrease in Saint Lucia, and a decrease of up to 29 % in Guyana. Overall, the frequency of categories 4 (wind speeds of 209–251/km/hr) and 5 (wind speeds of › 251 km/hr) hurricanes is expected to increase by 25–30 % (USAID 2018).

Table 2: Current climate impacts and projected risks for ecosystems and selected sectors in the Caribbean
Source: IPCC, 2019; Thomas et al., 2020.

	Current Climate change impact	Projected Risk at 1.5°C warming	Projected Risk at 2°C warming
Ecosystem			
Coral	Negative	• Very high	• Very high
Coastal wetlands	Negative	• High	• High
Mangrove	Negative	• Moderate	• Moderate
Human systems			
Fisheries	Negative	• High	• Very high
Tourism	Negative	• Moderate	• Moderate

The 11 northern Caribbean SIDS within this study (Anguilla, Antigua and Barbuda, the Bahamas, Dominica, Dominican Republic, Haiti, Jamaica, Montserrat, Puerto Rico, Turks and Caicos Islands, British Virgin Islands) (Figure 3) vary in size, population, and economic development. They are characterised by different levels of exposure and vulnerability to tropical cyclones, predominantly due to their geographical location and economic situation.

A quantitative analysis was performed on the regional-to-country level to assess economic damages and climate risk from tropical cyclones and predominantly adaptation potential in the Caribbean region. A probabilistic modelling approach using the CLIMADA modelling tool was applied to quantify the risk from tropical cyclones, and the damages averted through a range of adaptation options (the model is described in further detail in Chapter 2). Present-day risk from tropical cyclone damage, was determined at the country-level, without considering potential adaptation. The impacts of climate change in the near-term (2030) and at the end of the 21st century (2100) were assessed for two scenarios of climate change: 1) a scenario in line with the Paris Agreement, pursuing efforts to limit global warming to 1.5°C by 2100, relative to pre-industrial temperatures; and 2) a scenario based on current government policies to reduce emissions, leading to projected global warming of 3°C by 2100, relative to pre-industrial temperatures[4]. These warming projections are in line with representative concentration pathways scenarios RCP2.6 and RCP6.0, respectively (IPCC 2019).

In this case study, a mixed portfolio of distinct adaptation measures was assessed, including both hard measures, involving flood protection structures and building retrofitting, and soft measures, specifically risk transfer. Within the hard measures, grey infrastructure (levees, dykes, and seawalls) as well as ecosystem-based adaptation (particularly coral reefs and mangrove preservation) were applied. A benefit/cost analysis was performed for each measure. An effective CRM portfolio contains not only a mix of adaptation options, but also an assessment of the co-benefits and feedback effects of the options and governance aspects. Although the CLIMADA modelling tool has the ability to analyse the potential co-benefits and feedback effects of adaptation measures, this was out of the scope of the current study. Instead, this study offers insight into coastal risk in the Caribbean, shows trends in annual expected damages due to climate change, and illustrates a range of potential adaptation options and their effectiveness at reducing economic damages. This approach is a first step towards more detailed analyses at the island level to produce more accurate estimates of projected economic damages. Nevertheless, the results shown here reflect accurate trends in the performance of various adaptation options and portfolios for multiple climate change scenarios.

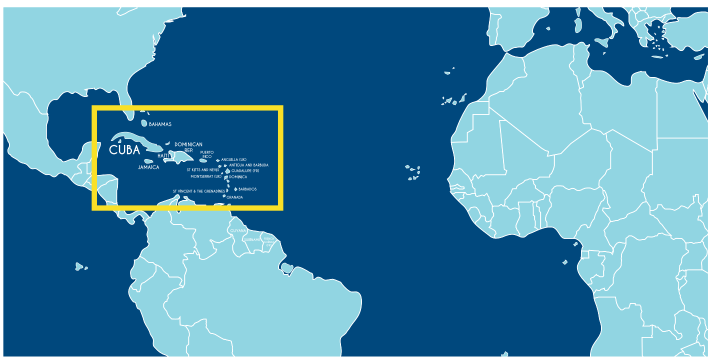


Figure 3: Map of the Caribbean. Several nations in the region are Small Island Developing States (SIDS), and currently already experience negative impacts from climate change. Climate Change impacts are projected to be some of the largest for SIDS.

(Source: depositphotos)

4 Warming projected by 2100 based on current policies is estimated to be between 2.7°C and 3.1°C: The Climate Action Tracker, https://climateactiontracker.org/global/temperatures/

2. CLIMADA methodology

2.1. Introduction

CLIMADA (an acronym for **CLIM**ate **ADA**ptation) is an open-source natural catastrophe model that can be used to calculate climate risk and appraise the averted damages (benefits) of adaptation measures (Aznar-Siguan & Bresch, 2019; Bresch & Aznar-Siguan, 2021). It provides a framework for users to combine exposure, hazard, and vulnerability data from different sources (in line with the IPCC risk framework, see Figures 1 and 4) and to include adaptation measures, climate scenarios, and development scenarios. Users can obtain information about the current and future impact of EWE and on how effectively adaptation measures can reduce risk. The model is written in the programming language Python. As well as allowing users to customise inputs, the model also incorporates a variety of input data from different open-access sources.

2.2. Case study

Input data for the risk assessment

For the purposes of this risk assessment, input data (hazard, exposure, and vulnerability) for the CLIMADA model were obtained from open-access sources such as 'IBTracs' (International Best Track Archive for Climate Stewardship) (see Appendix A.1 for more information).

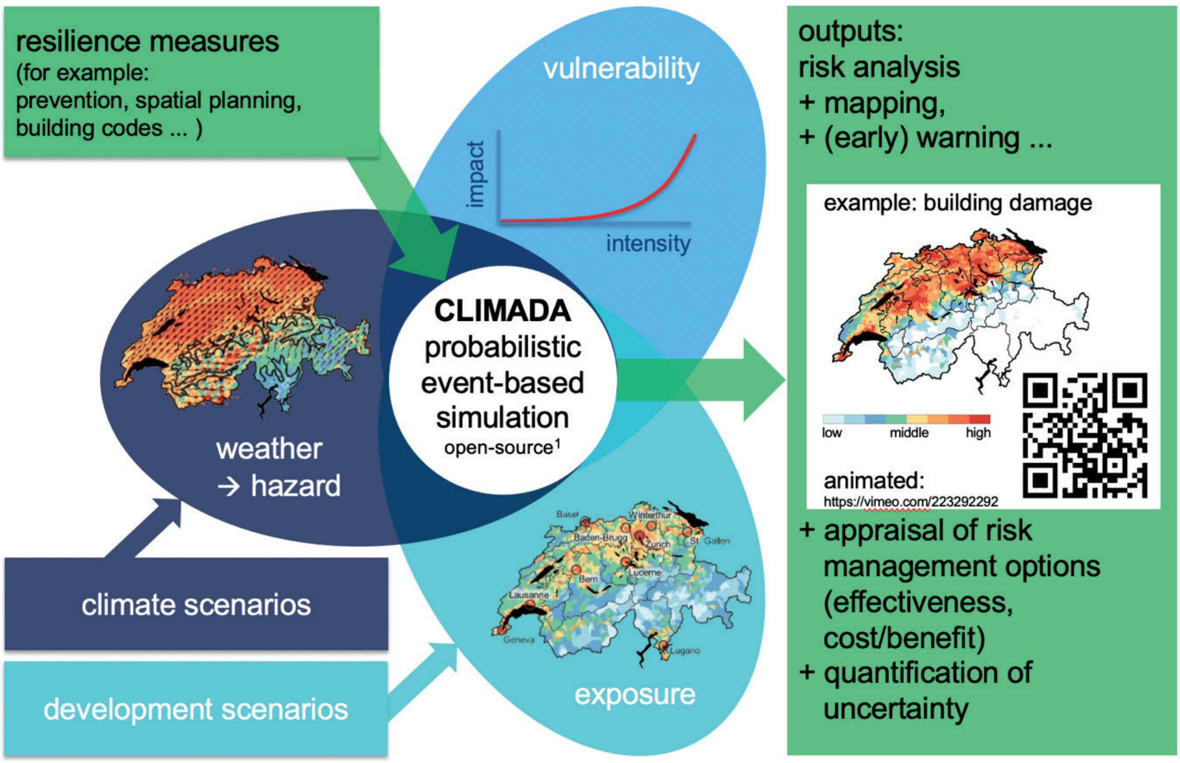


Figure 4: Visualisation of the CLIMADA framework (see https://wcr.ethz.ch/research/climada.html).

5 https://github.com/CLIMADA-project/climada_python.

Selected adaptation measures

Five representative adaptation measures from the examples listed in Table 1 were chosen to illustrate the adaptation appraisal process within CLIMADA:

- **Retrofitting and strengthening of building codes:** the benefits of storm proofing all houses to withstand events occurring with a frequency of one-in-100 years was calculated. The costs of this adaptation measure include initial installation costs, as well as recurring costs for reinstallation once the roof lifespan has been achieved (assumed at 30 years).

- **Seawalls and levee:** seawalls and levees reduce the impact of both wind and storm surges but unlike universal retrofitting of houses they can only be built in designated areas. The CLIMADA model was used to calculate the benefits of building seawalls and levees to withstand a 1-in-100-year storm.

- **Nature-based adaptation measures: mangroves and coral reefs**: the effectiveness and limits of two nature-based measures for coastal protection were assessed in the near-term (2030) and at the end of the 21st century under different degrees of global warming. Both coral reefs and mangroves can reduce coastal flooding by attenuating the power of waves (Badola and Hussain, 2005; Reguero et al., 2021). Mangroves also reduce hurricane wind speeds through their tree canopies (Del Valle et al., 2020).

The work done in this study does not attempt to model ecosystem restoration due to wide variations in restoration methods and their effectiveness. Rather, the work here considers the preservation of mangroves and corals as a coastal protection measure. In the present study, ecosystem coverage was altered over time to account for climate change, depending on the ecosystem measure.

Mangrove coverage remained the same in the two climate change scenarios assessed because of their ability to keep pace with moderate climate change. A significant reduction in future coral reef coverage was considered: Figure 5 shows the estimated losses in coral reef coverage for both climate scenarios. Restricting global warming to 1.5°C reduces coral loss to 70–90 % of recent historical coverage. While no projections of coral coverage are available for a climate change scenario of 3°C ('Current Policies' in Figure 5), it

Mangroves have been shown to be minimally to moderately affected by climate change, and may even be able to adapt to increasing temperatures and SLR, depending on local conditions (IPCC 2019). Coral reefs, however, are significantly threatened by climate change, with increased temperatures and ocean acidification leading to extensive coral die-off (IPCC 2019). More than 50 % of coral reefs have already been lost as a result of climate change and coastal pollution. This trend is projected to continue for future scenarios of global warming.

Because of the immense value these ecosystems provide, as well as their significant losses due to several factors including climate change, efforts have begun to restore and replant mangroves and coral reefs. Several international organisations, including the United Nations Environment Programme, have spearheaded guides to mangrove and coral reef restoration (see, for example, (UNEP 2020) and (UNEP-Nairobi Convention/USAID/WIOMSA 2020)). In many projects of German development cooperation, mangrove restoration plays a major role and through the initiative 'Save our mangroves now!' the Federal Ministry for Economic Cooperation and Development (BMZ) together with the Worldwide Fund for Nature (WWF) and the International Union for Conservation of Nature (IUCN) joined forces to protect and conserve mangrove ecosystems globally.[6]

Mangrove at the coast; © Pixabay

6 Mangroves (mangrovealliance.org)

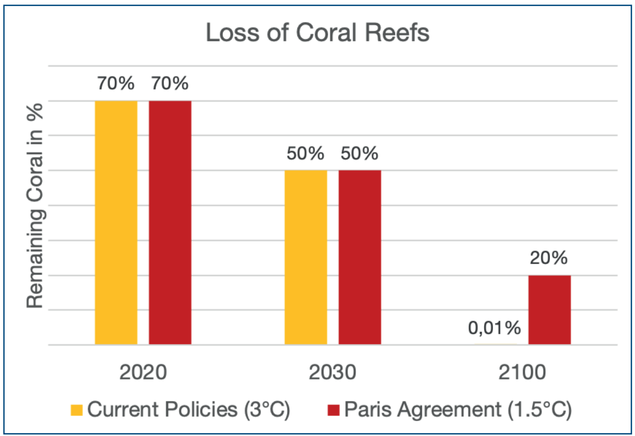


Figure 5: Expected loss of coral reefs due to global warming.

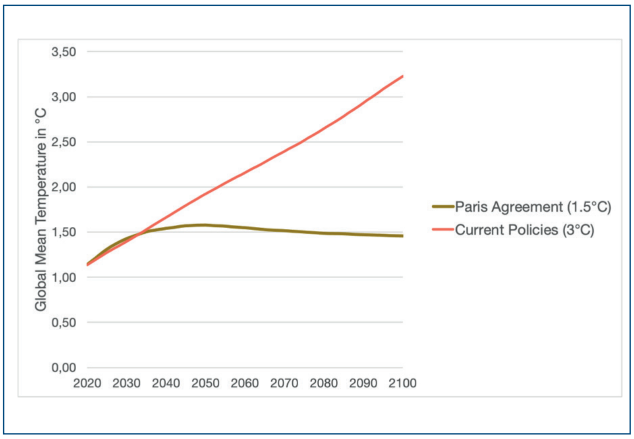


Figure 6: Global mean temperature for the two different climate change scenarios (changes relative to pre-industrial levels). (Source: NGFS scenarios, Climate Impact Explorer, Climate Analytics 2021, http://climate-impact-explorer.climateanalytics.org/)

is estimated that at 2°C of global warming, at least 99 % of coral will be lost (IPCC, 2019). It can therefore be implied that at 3°C of global warming, almost all coral reefs will be lost by the end of the 21st century.

- **Risk transfer:** the final adaptation measure assessed was risk transfer, which is applied to complement strategies and address economic losses that remain after applying all available adaptation measures. Risk transfer, which for the purposes of this study was an insurance policy, is defined by setting a deductible and a level of cover. Damages greater than the deductible up to the level of cover are then insured. Risk insurance has been applied in the Caribbean to limit the financial impacts of high-intensity, low-probability events such as disasters related to natural hazards.[7]

Modelling steps

1. The CLIMADA model was used to calculate climate risk for the two different time horizons (2030 and 2100) and climate change scenarios (1.5°C and 3°C of global warming at the end of the century) without any additional adaptation. Until 2030 both scenarios are projected to cause the same amount of global warming (1.4°C). After 2030, the trajectories start to diverge and the gap increases over time, with the current policies scenario reaching global mean temperatures above 3°C and the Paris Agreement scenario limiting global warming below 1.5°C. These trajectories are illustrated in Figure 6.

2. The annual expected damages (AED)[8] in 2020, 2030, and 2100 and the aggregated damages for 2020–2030 and 2020–2100 were calculated for each scenario. AED are the total damages in each grid cell (1km x 1km) summed over all events weighted by frequency. Aggregated damages are the damages summed over 11 (2020–2030) or 81 (2020–2100) years.

3. Benefit/cost ratios for each measure were then calculated. The costs of each measure, in US dollars, were extracted from external sources (Simpson et al., 2010; Bayraktarov et al., 2016; Reguero et al., 2020) and were estimated based on regional studies or global assessments (see Appendix). Benefits were calculated as the averted damages resulting from the hazard reduction factor of each adaptation measure or, in the case of risk transfer, the covered losses.

4. The reduction in damages through adaptation measures was calculated for each scenario. Results are presented as both the reduction in AED and in terms of reducing the damages associated with low-probability, high-impact events (e.g., 1-in-100-years events) to highlight the benefits of adaptation to these circumstances. Benefit/cost ratios greater than 1 indicate that for each dollar spent, more than 1 dollar could be saved.

7 The Caribbean Catastrophic Risk Insurance Facility (CCRIF) is an example of an insurance instrument to provide funds in the aftermath of natural disasters such as hurricanes, earthquakes and excess rainfall events
8 AED (Annual Expected Damage) and AAI (Average Annual Impact) are used synonymously in this framework.

3. Coastal adaptation to tropical cyclones in the Caribbean SIDS

3.1. Changing hazards and exposure

For this risk assessment, a time-independent damage function and an exemplary constant 2 % economic growth rate were used for assessing exposure. For all 11 locations of interest, the intensity of the hazards increases at differing magnitudes under the two climate change scenarios modelled.

An increase in intensity has the biggest effect on high-intensity, low-probability events. A return period is the average time between two events of the same magnitude. The damage frequency exceedance curve generated through this approach (Figure 7) shows that for low-intensity, high-probability events a small increase in intensity would not cause a large increase in risk; however, small increases in intensity for high-intensity, low-probability events increase the risk significantly.

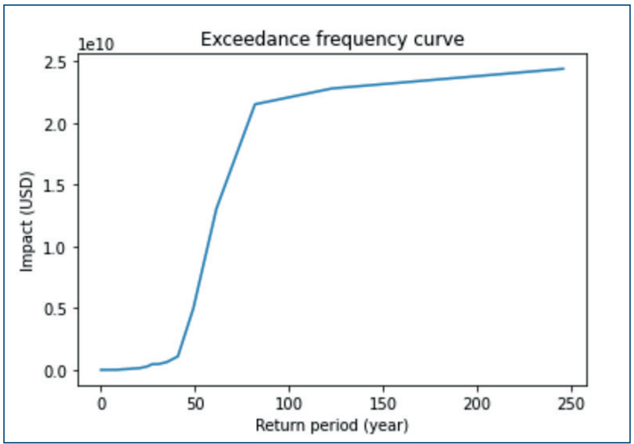


Figure 7: Damage frequency curve for Haiti.

3.2 Changing risk

AED is defined as 'the expense that would occur in any given year if monetary damages from all hazard probabilities and magnitudes were spread out equally over time'.[9] This does not mean that every year will experience the same damages – in some years damages may be higher, while for others they may be lower. However, overall, AED is the monetary impact that can be expected over time.

Table 3 shows the increase in AED for the 11 Caribbean SIDS considered in this study. The column labelled present-day risk shows the calculated AED in 2020 divided by GDP in 2014. With strong mitigation efforts (limiting warming to a maximum of 1.5°C by 2100), results indicate that risk can be reduced by two-thirds, with the median increase in AED being 19 % in comparison to 94 % for the 3°C scenario.

The projected risk is highest in the 3°C scenario for islands in the northern Caribbean, with the Dominican Republic, for example, facing a projected 150 % increase in AED by the end of the century, if no additional adaptation is implemented. The minimum expected increase in AED under the same scenario is 53 % (for Dominica).

9 Definition of Annual Expected Damages, ARCGIS Storymaps: https://storymaps.arcgis.com/stories/7878c89c592e4a78b45f03b4b696ccac

Table 3 Percentage increase in annual expected damages (AED) resulting from tropical cyclones in the absence of adaptation measures. n.a. = no GDP values available in the World Bank Database

Country	Present-day risk 2020 AED divided by 2014 GDP (World Bank)	Increase in AED (annual expected damage) by		
		2030 due to current climate change (1.4°C)	2100 due to reduced climate change (1.5°C of global warming)	2100 due to high climate change (3°C of global warming)
Anguilla	n.a.	3.6	18.91	93.51
Antigua and Barbuda	1.197	4.1	21.66	111.76
The Bahamas	0.117	3.8	20.18	100.69
Dominica	0.269	2.0	10.64	52.71
Dominican Republic	0.094	5.4	28.75	149.14
Haiti	0.166	2.8	15.20	75.34
Jamaica	0.455	3.5	30.52	96.52
Montserrat	n.a.	3.2	16.81	83.30
Puerto Rico	0.019	2.9	15.66	78.54
Turks and Caicos Islands	3.348	2.7	14.20	70.31
British Virgin Islands	n.a.	3.7	19.95	99.53
Median	n.a.	3.5	18.9	93.5

3.3 Potential of adaptation

To assess the potential of adaptation measures to reduce tropical cyclone risk, the effects of the selected adaptation options described in Chapter 2 were analysed for two countries, Antigua and Barbuda, and Dominica.

The short- and long-term (11 and 81 years, respectively) adaptation cost curves for Antigua and Barbuda as shown in Figure 9 are based on the benefit/cost ratio (y-axis) and the averted damages (x-axis) for each adaptation measure assessed. It is important to note that the results displayed represent one possible case scenario only; the spatial distribution of the adaptation measures was randomly selected because the exact locations of potential seawalls, levees, and surviving corals is not known.

Benefit/cost ratio of measures

Protection measures that have a benefit/cost ratio greater than 1 indicate that the reduction in damages provided by these measures exceeds their costs over time frame considered. Mangroves, coral reefs and retrofitting of houses are measures whose benefits exceed their costs. Retrofitting of houses (indicated by the light blue shading in Figure 9) has the second-highest benefit/cost ratio in the short term and the third-highest benefit/cost ratio in the long term. In the short term, the benefit/cost ratio is not clearly above the required threshold of 1 but in the long-term, higher-risk scenario, retrofitting would reduce the total risk by more than two-thirds, with a benefit/cost ratio near to 5. Levees and seawalls are both expensive interventions which are also locally very limited because of construction constraints. Thus, neither is cost-efficient in this analysis.

Mangroves and coral reefs are included in the adaptation portfolio to illustrate the potential that they are able to provide. Initial costs cover preservation, however no recurring costs are considered, as mangroves and coral reefs are not replanted or reforested over time. As a result, the potential of these measures to contribute to risk reduction is reduced over time due to reduced coverage from climate change-induced loss.

AED from hurricanes for Antigua and Barbuda and Dominica

Antigua and Barbuda, located in the north-eastern Caribbean, comprises the highly populous island of Antigua to the south, and the less populated island of Barbuda to the north. Infrastructure is concentrated on Antigua, with the nation's capital, St. John's, located in the northern area of the island. Antigua and Barbuda are surrounded by a large coral reef, which serves as protection from storm surges. The islands also have a sizeable number of mangrove forests protecting them from both storm surges and wind (Kramer et al., 2016). Dominica is a mountainous island located in the middle of the eastern Caribbean island chain, at the southern tip of the Leeward Island group. In contrast to Antigua and Barbuda, Dominica has very few corals or mangroves (Kramer et al., 2016a).

During the 2018 hurricane season, Antigua and Barbuda and Dominica were badly affected by hurricanes Irma and Maria, respectively.

The spatial patterns for present-day AED for Antigua and Barbuda (Figure 8, left panel) and for Dominica (Figure 8, right panel) show the distinct contributions of vulnerability and exposure in driving overall damage risks: Antigua experienced higher overall damages than Barbuda because it has a larger population and greater exposure. Furthermore, higher AED were seen in the more densely populated areas in the north of Antigua, compared to the southern and eastern portions of the island. In Dominica, AED were higher in coastal areas in the northwest and southwest of the island. The largest AED for Dominica were experienced in the southwestern area of the island, where the capital, Roseau, is located.

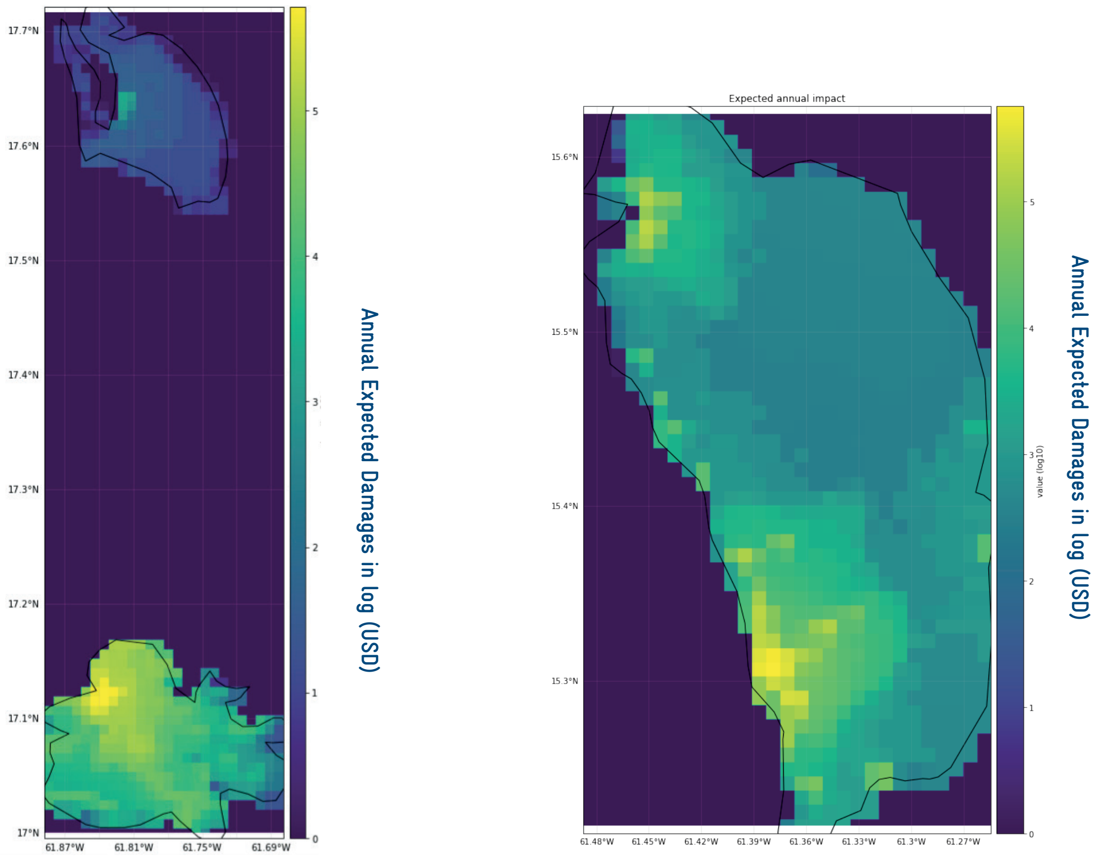


Figure 8: Annual Expected Damages in 2020: Antigua and Barbuda (left), and Dominica (right).

Mangroves have the highest benefit/cost ratio of all measures in both the short- and long-term scenarios (see Figure 9). In the high-risk scenario (3°C warming by 2100) the benefit/cost ratio increases from 3.5 to above 20. This indicates that for every dollar spent, up to 25 dollars of damages could be averted. However, the capacity of mangroves is limited by geographical restrictions (indicated by the narrow width of the mangrove box in Figure 9) and thus only a small proportion (less than USD 10 million) of the total risk can be averted with mangroves. Corals have a low benefit/cost ratio in the short term but the second-highest benefit/cost ratio in the long term. Any corals remaining in 2030 would avert only a small fraction of the damages, and corals are predicted to be almost completely lost by 2100.

The assessment shows that preservation of mangroves and corals can provide cost-efficient coastal protection measures. Further investigation, including restoration, is required to assess the full cost/benefits of these measures. Nature-based solutions have additional co-benefits, such as for the tourism or fishing industries, which have not been included in the study, and therefore may have even higher benefit/cost ratios.

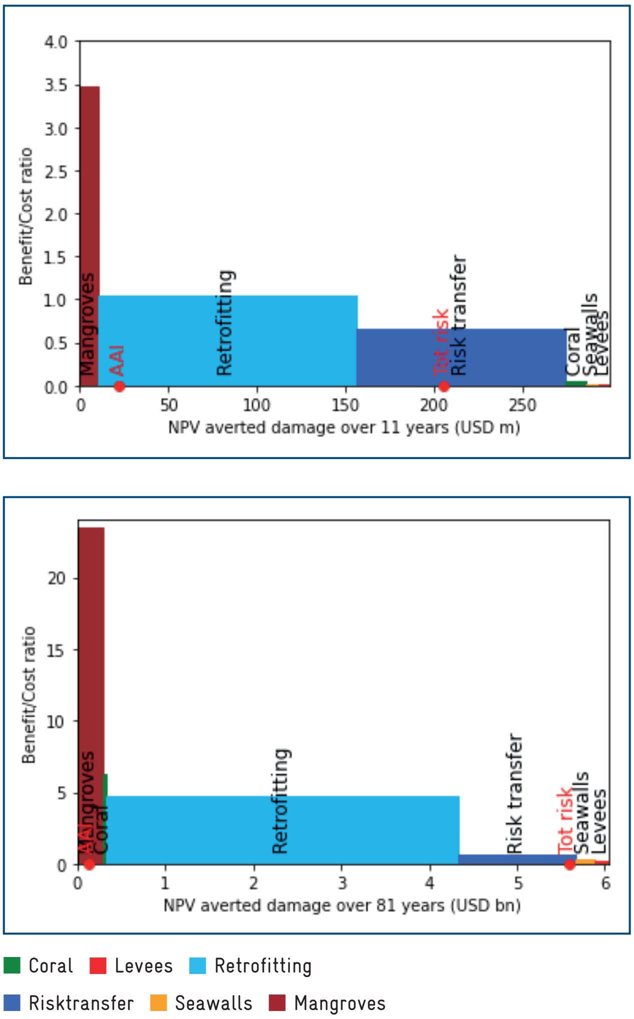


Figure 9: Adaptation cost curves for Antigua and Barbuda in (upper) 2030 (1.4°C global warming) and (lower) 2100 (3°C global warming). Net present value (NPV) of averted damages is presented in USD million (upper) or billion (lower). Two red dots are provided: one for the annual expected impact ("AAI") and one for the total aggregated risk over the whole period ("Tot risk").

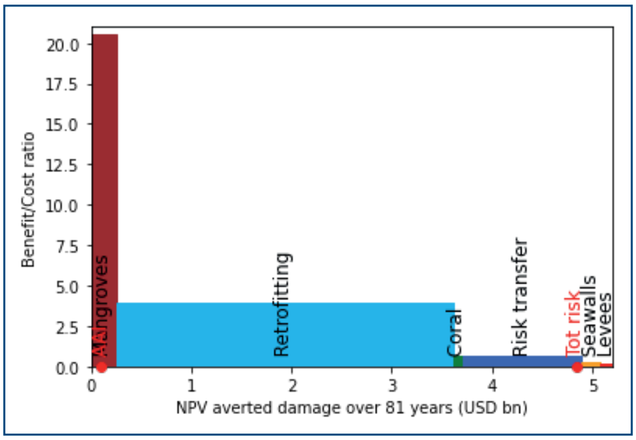
Example of a seawall in Kiribati, South Pacific; © GIZ / Michael Siebert

Impact of climate change on adaptation effectiveness: The case of coral reefs

In this study, coral reefs have been shown to have a potentially high benefit/cost ratio (well above 1) in the future; however, a small amount of damages can be averted because coral reefs are shrinking as a result of climate change. The biophysical limits of coral reefs are reached at temperatures above 1.5°C. As such, the services of this ecosystem (of which coastal protection is one) continue to be viable only up to a 1.5°C warmer world.

If global warming could be limited to 1.5°C, the coral remaining in 2100 (20 % of historical coverage) could offer a positive adaptation benefit and contribute to reducing risk (see Figure 10). The benefit/cost ratio in such a scenario is 1.2 and the remaining corals could avert 4 % of total risk. At 3°C global warming in 2100, while the predicted benefit/cost ratio increases to 4.8, the remaining coral would avert only 0.5 % of the risk. The benefit/cost ratio is thus higher for a 3°C scenario, because the costs per km are assumed to be equal for both scenarios, but the benefits are much higher for the 3°C scenario which predicts more intensive storms and thus higher damages.

However, regardless of the greater benefit/cost ratio, corals are unable to survive at higher temperatures and therefore would not contribute to coastal adaptation anymore under high global warming.



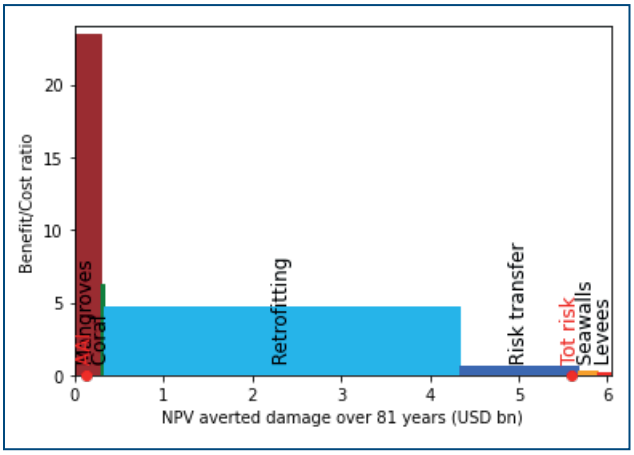


Figure 10: Adaptation cost curves for Antigua and Barbuda in 2100 at (upper) 1.5°C and (lower) 3°C global warming.

Assuming full implementation of available adaptation options, the model outputs show that adaptation measures can effectively reduce risks of tropical cyclones that occur once in every 10 and once in every 25 years (Figure 11). For a 1-in-100-years scenario at each time point, risk transfer could be applied to reduce the risk and close the adaptation gap. However, for the 1-in-100-years scenario in 2100, only half of the damages associated with a high-impact cyclone can be averted, even with risk transfer, and the adaptation gap is significant.

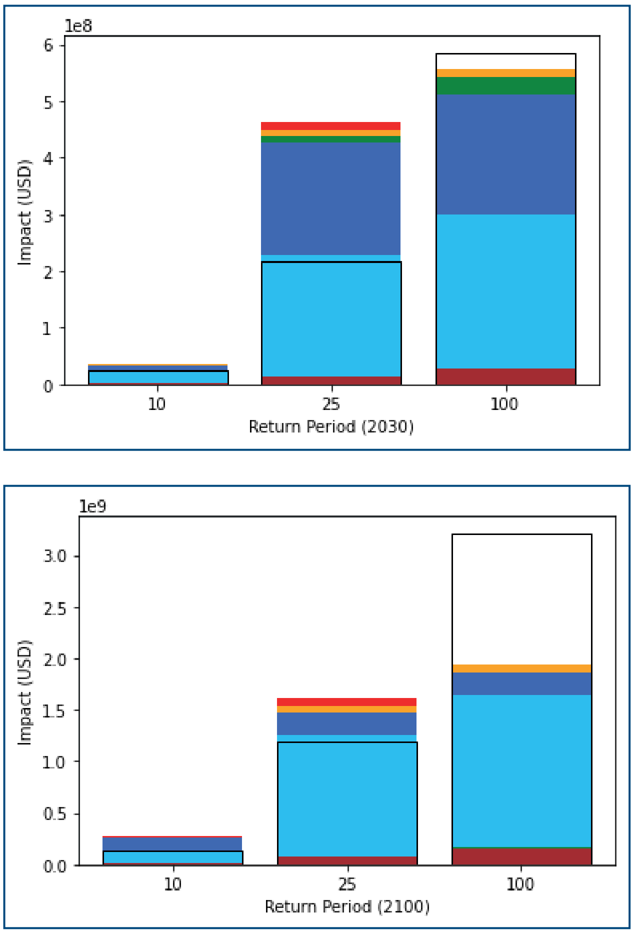


Figure 11: Impact of adaptation measures on the adaptation gap resulting from tropical cyclones affecting Antigua and Barbuda once in 10, 25 and 100 years in (upper) 2030 (1.4°C global warming) and (lower) 2100 (3°C global warming). The y-axis shows the impact of events with return periods of 10, 25, or 100 years. The boxes with black outlines show the risk, while the coloured boxes show the avertable damages. The white space indicates the adaptation gap, the economic losses that remain after applying all available adaptation measures.

The adaptation cost curve for Dominica (Figure 12) shows that not all of the risk can be averted with the adaptation measures assessed in either the short- or long-term scenarios. Nature-based solutions were not considered for this calculation because of their minimal coverage in Dominica. Retrofitting can again mitigate a large amount of risk but the benefit/cost ratio is less than 1 in the 2030 scenario. In the long-term scenario, retrofitting is the only measure with a benefit/cost ratio greater than 1 and can mitigate more than half of the risk. However, other adaptation measures (risk transfer, seawalls, and levees) are neither cost-efficient nor sufficient to close the adaptation gap.

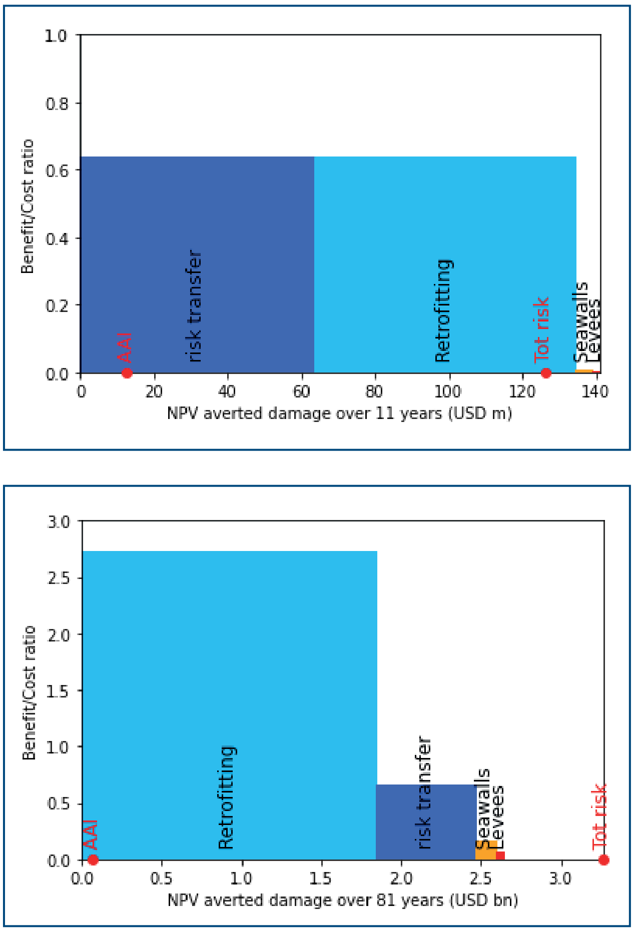
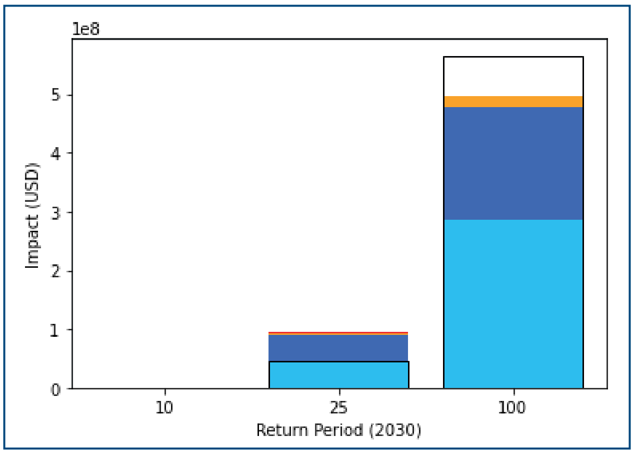


Figure 12: Adaptation cost curves for Dominica in (upper) 2030 (1.4°C global warming) and (lower) 2100 (3°C global warming). Net present value (NPV) of averted damages is presented in USD million (upper) or billion (lower).



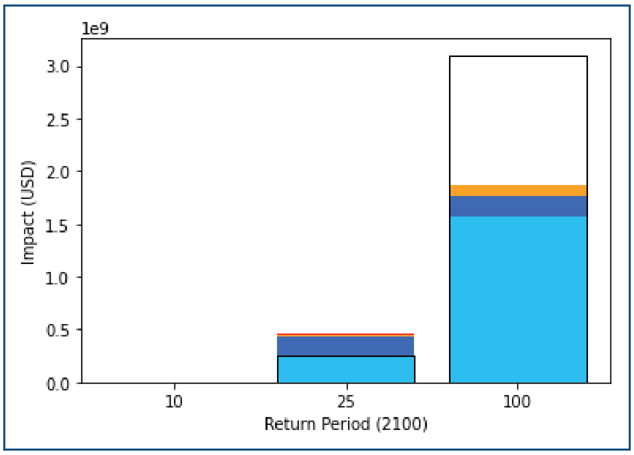


Figure 13: Impact of adaptation measures on the adaptation gap resulting from tropical cyclones affecting Dominica once in 10, 25 and 100 years in (upper) 2030 (1.4°C global warming) and (lower) 2100 (3°C global warming). Expected damages for 10-yr return period are valued at 400.000 USD, which is not visible at the current scale. Expected damages for high-probability events, such as 10-yr events, are comparatively small (see damage curve in Figure 7).

In Dominica, retrofitting seem to have the performance to mitigate all of the risk of a 1-in-10-years event and a 1-in-25-years event and 50 % of the expected damages of a 1-in-100-years event in both 2030 and 2100 (Figure 13). However, the adaptation gap increases for the 3°C warming scenario and one-third of the damages cannot be averted with the assessed measures. Furthermore, the size of the 1-in-100-years event increases by one magnitude while the exposed asset values increase by 5 times. This highlights again the severe danger posed by climate-induced changes affecting extreme events, as well as the role of development in exposure to climate hazards.

Impacts of Hurricane Irma, 2017 © Ellie Fuller

4. Outlook

Responsibility for dealing with the impacts of climate change must be more strongly embedded at the governance and policy levels, and integrated into planning. There is a crucial need for stronger links between international agendas and local policies, while at the same time taking account of the individual nature of situations on the ground. Local empowerment and inclusive approaches to decision-making are fundamental when dealing with climate change-induced risks and developing effective management solutions. The role of available, context-specific, and timely scientific knowledge as the basis for political negotiations and decision-making, and the integration of (political) decisions into local policies, should be emphasised as they constitute a crucial part of the assessment of climate risks and the identification, selection, and combination of suitable adaption measures.

The effectiveness of adaptation options is strongly determined by the level of climate change: as the analysis outlines, even under modelled assumptions of full and functional implementation of measures, for this region and based on the available information residual risks remain for the majority of assessed locations and options. Ecosystem services such as coastal protection can be cost-effective measures, but are increasingly constrained due to their biophysical limits and loss from climate change. While risk transfer provides an important contribution to support affected regions on coping with damages, they do not avert the damages as such, which can lead to very long recovery times, affecting economic growth on the long term. Overall, it can be emphasised that the combination of measures seems to offer flexibility and potential to more effectively avert, minimise, and address losses and damages from climate change.

4.1 Next steps: how to use the results for decision-making

The CLIMADA modelling and analysis tool provides information for Comprehensive and Climate Risk Management and has been successfully applied to climate risk and adaptation analysis across many regions, including for tropical cyclones in Vietnam (InsuResilience Solutions Fund 2021), flooding in San Salvador, El Salvador (InsuResilience Solutions Fund 2019), and economic analysis of ecosystem services of the Mesoamerican Reef (Willis Towers Watson & MAR Fund, 2019). The present case study shows that the CLIMADA tool can be used to not only quantify potential damages from EWE, specifically tropical cyclones, but also to assess the potential benefits and limitations of individual adaptation measures. Such results can be used to support informed decision-making.

The CLIMADA tool is highly dependent on the quality and quantity of data provided, as well as parameter choices. As such, the tool can help to understand trends and uncertainties, however results with absolute numbers should be treated with caution. The tool has a limited set of hazards available, and analysis of multi-hazards and compound events is not feasible at this time (see "*Further Modelling in CLIMADA*" box below). Finally, the tool has predominantly been developed and applied to assess economic loss and damage; however, losses and damages extends into the non-economic sphere and includes impacts on life, health, mobility, territory, and cultural heritage. Assessment of non-economic losses and damages is equally critical in understanding the full impacts of climate change to develop appropriate, inclusive and effective adaptation measures.

CLIMADA can help decision-makers to answer the following questions:

- **What are the climate risks today and in the future?**

CLIMADA can be used to quantify the current risk posed by individual hazards, as well as the risk they might pose in the future. Understanding the risk from climate hazards, as well as changes in the development of risk and the associated exposure, allows decision-makers to investigate the evolution of climate risk over time. The results of the present case study project an increased risk from tropical cyclones by 2100 under a warming scenario of 3°C associated with current emissions trajectories. There is a noticeably reduced risk if climate action can limit global warming to below 1.5°C above pre-industrial levels by 2100.

- **What are the expected climate-induced economic losses arising from these risks?**

Over the last 50 years, weather, climate and water hazards have accounted for 75 % of all reported economic losses, half of all disasters, and 45 % of all reported deaths, with 91 % of those deaths occurring in developing countries.[10] In the Caribbean, tropical cyclones – projected to intensify in severity with climate change – have been shown to cause losses of up to 90 % in GDP (for example, Commonwealth of Dominica, 2015). This case study suggests that the expected accumulated damages from tropical cyclones could increase by up to 5 % in 2030 and 150 % in 2100 relative to 2020, due to increased cyclone intensity as a result of climate change. It highlights the benefit of limiting global warming to 1.5°C by 2100: meeting the Paris Agreement would reduce the increase in risk by 80 % in 2100 in comparison with a 3°C warming scenario.

- **What are potential adaptation measures to deal with the risk, and how effective are these measures in terms of damage reduction?**

Countries and communities develop adaptation solutions to respond to the negative impacts of climate change that are already occurring, as well as to prepare for future impacts. Adaptation solutions take many shapes and forms, and there is no one-size-fits-all or single approach that can address all negative impacts of climate change. Instead, a suite of adaptation solutions that work in concert with each other and mitigation measures are envisioned to reduce the negative impacts of climate change.

In the case study reported here, the adaptation options considered included grey infrastructure such as seawalls and levees, nature-based solutions (a key adaptation option of interest to developing countries because of the potentially high benefit/cost ratios), improved infrastructure through retrofitting of houses, and risk transfer through insurance. CLIMADA helps in evaluating adaptation measures of interest to decision-makers by providing a quantitative assessment of averted economic damages. While exact numbers in CLIMADA should be treated with caution, the tool helps to understand trends in damages and adaptation potential. In the case of the Caribbean, it demonstrated that a mix of adaptation measures have the potential to avert damages from tropical cyclones for some islands and in some scenarios. However, for other islands, the adaptation gap – the economic damages that remain after applying all available adaptation measures – may still be incurred.

- **What are the expected benefits and costs?**

Because of the spatially explicit nature of the modelling tool, decision-makers can determine which regions are at particular risk. The provision of a benefit/cost analysis for the investigated measures allows decision-makers to determine which adaptation measures might be prioritized. CLIMADA also helps illustrate the change in benefits over time. In the case of nature-based measures in this study, the reductions to damages are high relative to other measures; however, the negative impact of climate change subsequently reduces the measures' effectiveness. Reduced effectiveness or even a misleading perception of the potential of measures can lead to increased vulnerability and increased potential impact from hazards; thus, the approach applied here could be developed further to prevent maladaptation and support well-informed risk communication in the future.

10 World Meteorological Organization, "Weather-related disasters increase over past years, causing more dam-age but fewer deaths". https://public.wmo.int/en/media/press-release/weather-related-disasters-increase-over-past-50-years-causing-more-damage-fewer

4.2 Further applications of CLIMADA

As described previously, SOP such as SLR, increasing mean temperatures, and salinisation could have significant physical, socio-economic, and ecological impacts globally, affecting coastal developing economies in particular. In this study, increasing temperature was addressed implicitly, through modelling its effect on tropical cyclones and on the potential of nature-based adaptation measures, specifically coral reefs. This impact of climate change can also be analysed explicitly using estimates of increased air and/or sea temperatures derived from spatial distribution maps or discrete location points. Similarly, SLR can be analysed explicitly and estimates of SLR for different global warming trajectories are available at discrete locations globally via the Climate Analytics SLR tool (http://localslr.climateanalytics.org/). Such estimates can be linked to appropriate damage functions (Hummel et al., 2021) to develop projections of economic damages due to SOP and evaluate the effect of adaptation options.

Further modelling with CLIMADA

CLIMADA can currently be used for modelling the effects of tropical cyclones (wind fields only), European winter storms, droughts, wildfires, landslides, earthquakes and volcanoes, and river floods.

Users can add their own hazards sets; for example, spatial data on temperature changes or SLR. They can also modify the existing asset values from LitPop or load their own exposure layer, such as population data. The damage functions can be modified or loaded from other sources; for example, the impact of heat stress on the working population (Dasgupta et al., 2021).

The CLIMADA development team is currently working on adding more hazards, including storm surge and rainfall, and also multi-hazard/compound events.

The latest updates can be found at https://github.com/CLIMADA-project.

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Appendix

The appendix contains background information on the modelling procedure and the modelling inputs.

A.1 Input Data

For the hazards, we use the historical storm track set from IBTracs as a basis to generate a probabilistic set forced with the climate change factors. Those climate change factors are extracted (from Knutson et al., 2020) and then interpolated to the case study. The future hazard is thus different from the historical track set in two ways – first, synthetic storm tracks are created by performing a random walk,[11] thus creating new potential storm tracks, and second, an increase in intensity due to global warming is assumed.

For the damage functions, the regional damage function from Eberenz et al., 2021 is used. Fig. 15 shows the non-linear increase in damage with increasing intensity (blue line is the mean damage degree). While small intensities cause zero damages, high intensities can cause destruction of up to 90 %. Following this trend, a small increase in medium intensity storms can thus lead to a big increase in damages.

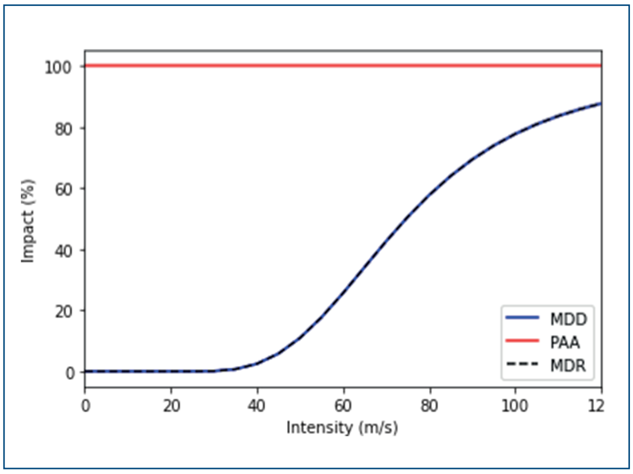

Figure 15: Damage function from Eberenz et al., 2021

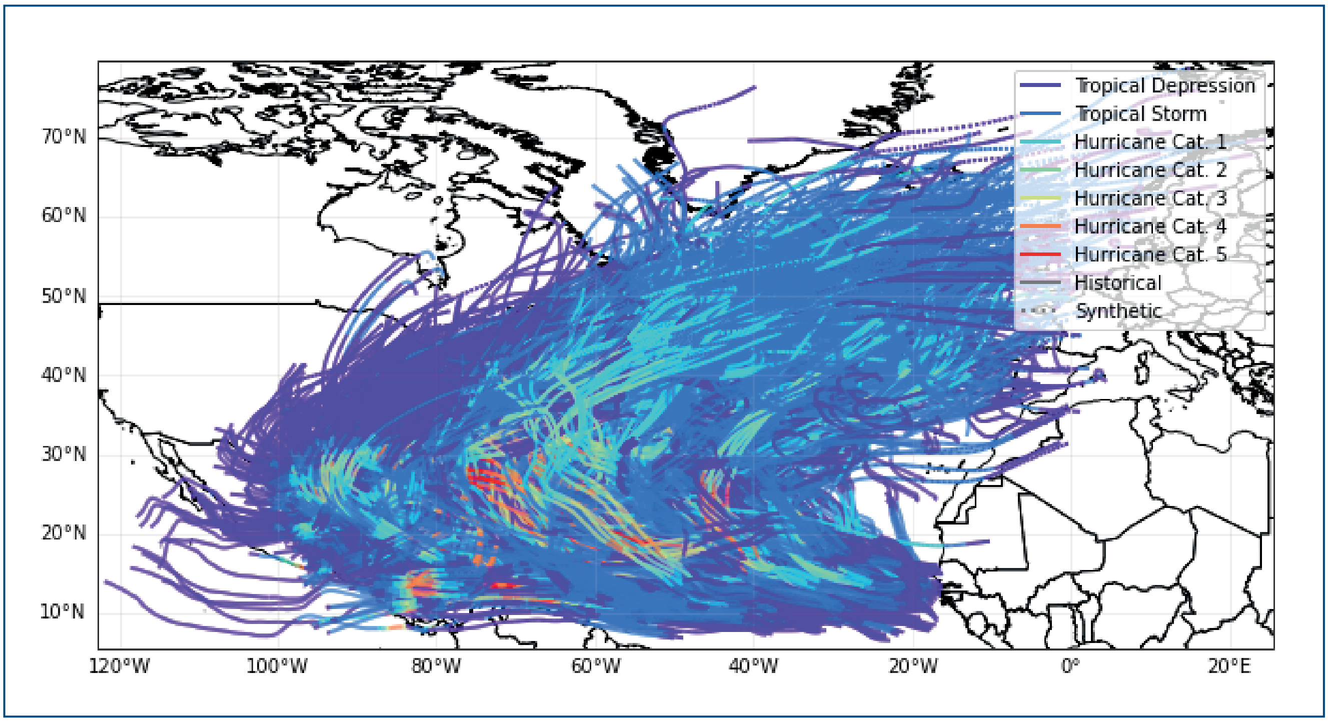

Figure 14: Historical and synthetic storm track in the North Atlantic basin

11 a directed random walk is used to generate synthetic tracks from the historical ones and start at slightly per-turbed initial locations and wind speeds

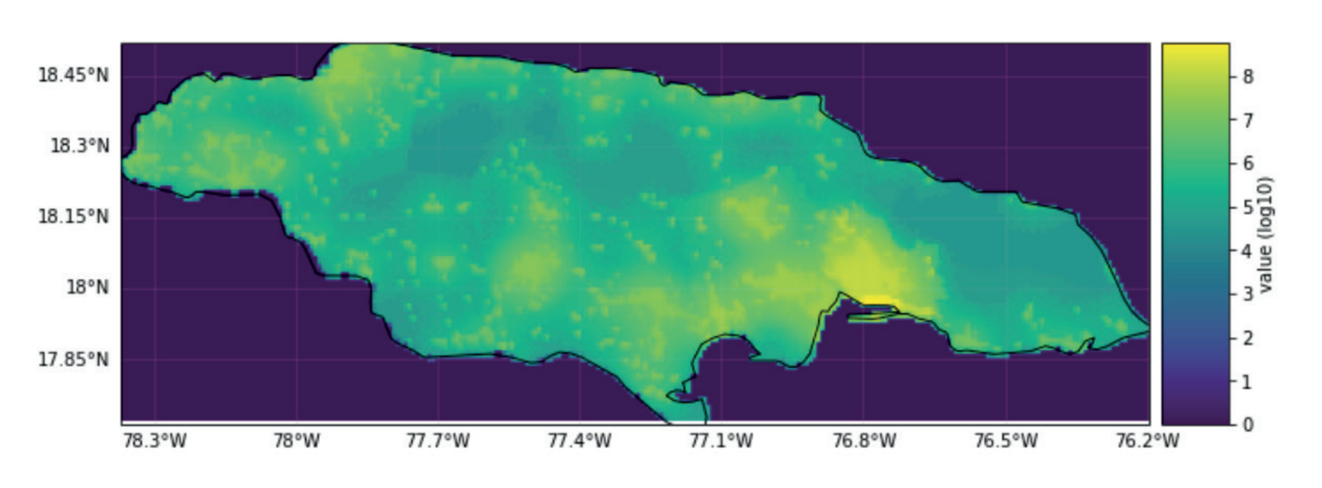

Figure 16: Exposure data from LitPop for Jamaica

For exposure, the "LitPoP" dataset (Eberenz et al., 2020) which contains estimates of physical asset values based on nightlight intensity from satellite and population count data is used (see Figure 16). The nightlight intensity data is extracted from the Blackmarble dataset (2016) and the population data (GDW) from NASA. Financial data is either extracted from the World Bank (produced capital, 2014) or non-financial wealth (Credit Suisse, 2014). The dataset can be downloaded under https://climada-python.readthedocs.io/en/stable/tutorial/climada_entity_LitPop.html.
In this study the focus is laid on climate change impacts, thus a simplified assumption for the socio-economic development is used (2 % of asset value growth per year).

Henceforth, the damages account for both wind- and storm surge-induced damages though only the wind fields are explicitly modelled.[12]

A.2 Adaptation Measures, Costs and Benefits

Table 4: Costs in US$ and benefits in % of hazard reduction/ frequency cut-off

Measures	Costs	Benefits
Retrofitting	10 % of asset values with a lifecycle of 30 years	Protects against events with probabilities lower than 1-in-100 years
Mangroves (Bayraktarov et al., 2016)[13]	800,000USD/km	Protects against events with probabilities lower than 1 in 25 years Reduces wind by 25 %
Corals (Reguero et al., 2021)	4 Mio USD/km	Reduces surge by 100 %
Sea walls (Simpson et al., 2010)	17 Mio USD/km	Protects against events with probabilities lower than 1-in ' -100 years
Levees (Simpson et al., 2010)	4,9 Mio USD/km	Protects against events with probabilities lower than 1-in-50 years
Risk Transfer/Insurance (Bresch & Aznar-Siguan, 2021)	Cost = Deductible = 12 year damage	Benefit are all damages up to the cover = 50 year damage

12 While the damage functions is calibrated with both wind- and surge-induced damages, the hazard model calcu-lates only changes in the wind fields
13 The paper (Bayraktarov et al., 2016) highlights that the actual costs are most likely much higher (two to four times). We use that upper bound of the costs for this study.

A 3: Randomisation

The surviving corals are chosen by a random number generator as it is not known in which locations corals have a higher surviving rate. Therefore, each model run produces different results because the selection of the location plays an important role in calculating potential protection benefits. If the corals are in the proximity of a developed coastline, they will have higher protection benefits on the built environment than if they are in front of a mangrove forest.

For the 1.5°C scenario, the benefit/cost ratio lies between 0.6 and 2.1 with a median of 1.2.
For the 3°C scenario, the benefit/cost ratio lies between 1.5 and 8.2 with a median of 4.5. The higher uncertainty arises because there is only 1% of corals left at 3°C, so the selection has a large effect on the results while for 1.5°C 20% of the coral remains and thus, the location-specific effects is reduced.

A 4: Figures

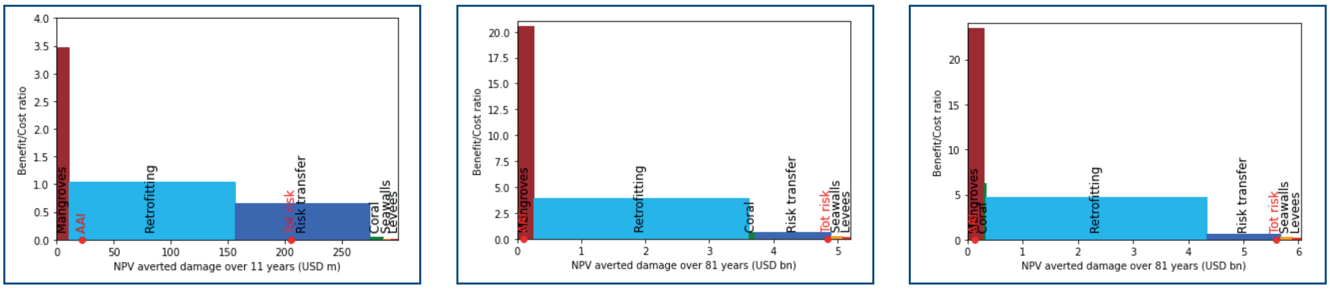

Figure 17: Adaptation cost curve Antigua and Barbuda – 2030 (1.4°C) – 2100 (1.5°C) and 2100 (3°C)

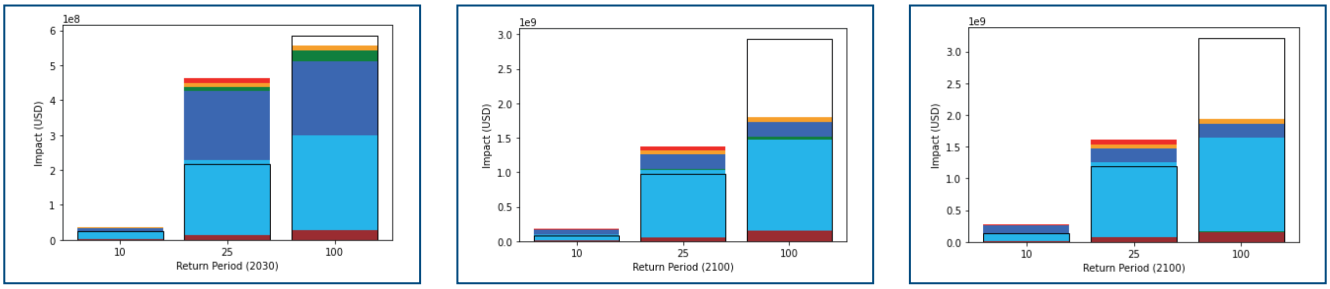

Figure 18: Extreme Events: Antigua and Barbuda – 2030 (1.4°C) – 2100 (1.5°C) and 2100 (3°C)

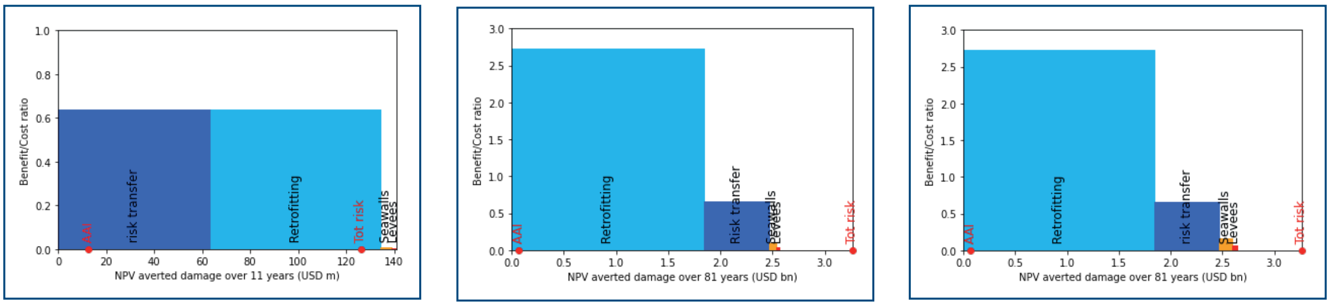

Figure 19: Adaptation cost curve Dominica – 2030 (1.4°C) – 2100 (1.5°C) and 2100 (3°C)

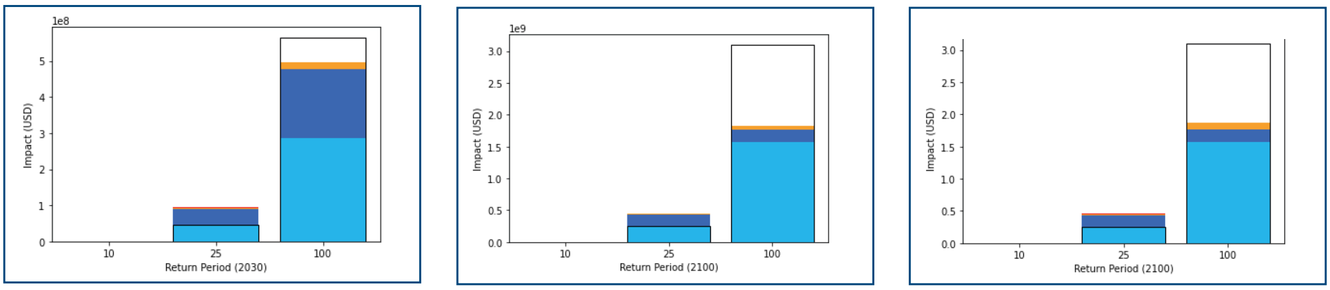

Figure 20: Extreme Events: Dominica – 2030 (1.4°C) – 2100 (1.5°C) and 2100 (3°C)

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