AUTHORS' RESPONSE TO REFEREE #1

Research article:

Bresch, D. N. and Aznar-Siguan, G.: CLIMADA v1.4.1: Towards a globally consistent adaptation options appraisal tool, Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2020-151

Authors:

David N. Bresch (dbresch@ethz.ch), Gabriela Aznar-Siguan (Gabriela.Aznar@meteoswiss.ch)

We thank the anonymous referee for his comments, which have improved the quality of the manuscript.

The original comments from the referee are listed below directly followed by our responses in blue and italic and changes to the manuscript in blue and ***bold*** *(unless where it gets complicated or tiny, where changes are made in the manuscript only).*

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The authors present an amendment and application of their open-source python tool CLIMADA to study the benefit of various adaptation options to climate extremes. Their current application deals with a very specific case of tropical cyclone impacts to small islands in the Caribbean. The amendment of the CLIMADA tool seems very useful and timely as it allows to address the full modeling chain from climate impacts to adaptation within a single tool. The code availability and reproducibility on github is best practice. The paper is well motivated and well written despite several very long and complex sentences. Please see my further comments below:

Major points:

1. As mentioned above, the manuscript contains very long and complex sentences that make it difficult for the reader to follow (just to name a few: page 1, line 19; page 14, line 22-28; page 15, line 10). Throughout the text you find many parentheses providing additional information

that disturb the flow of reading. Consider to split these long sentences and to provide extra information in additional sentences.

We took care of splitting sentences where appropriate (quite some instances, indeed) and did move (longer) remarks in brackets into full sentences to increase readability as suggested. Please find all in the track change version of the revised manuscript rather than listing all changes here.

2. Section 2.2.1: This section is very technical and hard to grasp for the non-expert. While I appreciate the discussion along the lines of the actual methods provided in CLIMADA, the reader might get lost easily. It would be helpful to produce a visualization similar to Fig 1 but less technical that summarizes and describes the different methods and their interrelationship. Maybe even a table might be sufficient.

The UML diagram displayed in Fig 1 helps to locate the main classes and to understand their relation. It extends Fig 1 of the previous paper Aznar-Siguan & Bresch 2019b. We decide therefore to modify this figure instead of inserting a new one.

We have modified Fig 1 to include all the methods and attributes described in Section 2.2.1 and 2.2.2, since many of them were not represented before. These are:

- *In CostBenefit class the methods combine_measures, apply_risk_transfer, plot_cost_benefit and plot_event_view*
- *In Measures class the attributes cost, exp_region_id, hazard_set, hazard_freq_cutoff, exposures_set, imp_fun_map, mdd_impact, paa_impact, risk_transf_cost_factor, risk_transf_attach and risk_transf_cover.*

3. Section 3.1.1: It is understood that this section can only provide a rough introduction to the different adaptation measures. However, I think that one needs to be more rigorous and/or comprehensive in order to highlight that CLIMADA is not just a toy model. My comment about uncertainty assessment below points into the same direction. Here are some points one should elaborate on: 1) the impact intensity reduction by mangroves is considered to be 0.74%. This number is given without reference and should be explained. It appears later in Table 1 and seems to be related to the Turks and Caicos Islands, but this remains very opaque. 2) preparedness is set to avoid damages for events with return periods of up to 7 years. Is there some deeper reasoning

behind that? Can the authors provide a reference? 3) the paragraph about risk transfer throws around many numbers which are not very well motivated. For instance, it remains unclear to me whether the cost of insurance refers to annual costs or the costs over the whole period.

How realistic the adaptation measures are in CLIMADA depends only on the input data and/or models of each specific case. CLIMADA does not provide "default" measures but several ways of parametrizing and comparing them. The parametrizations presented here have been chosen to reproduce the main findings on Anguilla in Caribbean Catastrophe Risk Insurance Facility (2010), where CLIMADA was used together with field data. This analysis uses only openly available data and, as such, can be used as a preliminary study to select which measures could be considered and further modelled with local data. This is stressed in Section 4: "While the idealized case study already provides elements relevant for the development of adaptation strategies and the interplay of prevention, preparedness and risk transfer (c.f. Joyette et al. (2015)), further locally bespoke data would improve the accuracy and representativeness of results, starting from spatially-explicit mapping of specific exposures such as infrastructure and sectoral split."

We add a sentence in Section 3.1.1: "The parametrizations chosen here allow to reproduce the main findings on Anguilla in Caribbean Catastrophe Risk Insurance Facility (2010)". We modify as well the abstract to clarify the scope of this case study as follows: "We apply the open-source Python implementation to a tropical cyclone impact case study in the Caribbean **with openly available data**. This allows to prioritize a small basket of adaptation options, namely green and grey infrastructure options as well as behavioural measures **and risk transfer**, and permits inter-island comparisons. In Anguilla, for example, mangroves avert simulated damages more than 4 times the cost estimated for restoration, while enforcement of building codes shows to be effective in the Turks and Caicos islands **in a moderate climate change scenario**."

Ad 1) Factor 0.74 provides sensible results for Anguilla (based on Caribbean Catastrophe Risk Insurance Facility, 2010) and is used as reference to interpolate linearly the factors of the other islands according to their ratio of mangrove area to island area.

We have rephrased the explanation in Section 3.2:"The mangrove protection is set by linearly interpolating Anguilla's factor proportionally to the island's ratio of mangroves' area to total area."

Ad 2) This criteria is set to show the effect of such a threshold on the computations. It is set to avoid damages of events generating less than 1.5 m USD.

We have rephrased the explanation in Section 3.2: "This measure ideally reduces the effective wind intensity and avoids most of the damages for events with low return periods. We set a wind intensity reduction of 0.5% (see impact function in Figure 2) and a threshold of 7 year events under which no damages are generated. This threshold corresponds to events with exceedance damages lower than 1.5 m USD."

Ad 3) Again, to the illustrative character of the study, the exact definition of the risk transfer "layer" (as it is called in the insurance industry) is inspired by business practice, yet other levels of attachment (instead of 12 years) and cover (instead of up to a return period of 145 years) are equally well possible. The numbers chosen are realistic for a multi-island scheme (such as CCRIF). Please note that the Jupyter notebook (see points 5 and 6 below) does allow to experiment with these settings.

We hence clarified as follows: "Finally, risk transfer is considered, being particularly suitable to manage risks of low frequency, high severity events. We define an insurance layer with attachment point (or deductible**, i.e. the damage amount corresponding to a frequency at which the risk transfer gets triggered on average**) and cover (**the amount of damage covered by risk transfer**) proportional to the island's expected exceedance damages. The attachment is set to the 12 year per event damage (approximately 32 m USD) and the cover **designed such as** to cater for events with up to **a** 145 year return period (**the risk transfer thus covering** approximately 314 m USD **per event**)."

As for costs of measures, all are net present value (NPV) over the whole period, in order to compare also with NPV of averted damage over the whole period. We clarified in the manuscript by adding on page 5 after the explication about risk transfer costs: **"For risk transfer therefore, the cost is calculated by CLIMADA."**.

4. Figure 3 and Figure 4: The reader expects to read off the averted damage (black arrow in Fig. 3) from Fig. 4b. But instead the gap of roughly 300m USD in Fig. 3 corresponds to less than 100m USD in Fig. 4b. Somewhere towards the end of the manuscript it becomes clearer what might have happened: retrofit was neglected. This is rather unsatisfactory, in particular, because

the authors claim that combined measures behave differently than single measures. Thus, the reader is unable to reproduce the numbers from the information provided.

The combination of a subset of measures is represented in Figure 3 to represent the fact that only a selection of the studied measures are eventually implemented due to budget limitations and other constraints (see also point 6 below).

*We add a label with the name of the measures represented in Figure 3 and modify its caption using "**combining** the measures" instead of "**implementing** the measures".*

5. Section 3.1.3: CLIMADA's ability to combine measures is highlighted in the beginning. When reaching Section 3.1.3 the reader is slightly disappointed as no information about the methods behind the combination is provided (e.g., how is double-counting avoided?). Instead, the reader is confronted with many numbers that require further explanation. In order to better understand how the different measures interact and the numbers come about, I would like to see additional supporting figures in the supplement. Those figures should reproduce the combination effect for the various combinations covered in Section 3.1.3. The figures produced in the jupyter notebook (https://github.com/CLIMADAproject/climada_papers/blob/master/202008_climada_adaptation/reproduce_results.ipynb) should suffice.

Thanks for pointing to this issue. Combine measures primarily means that double-counting of the simple kind is avoided. In combining benefits, the combined benefit can never amount to more than the damage itself. As CLIMADA is fully event based, the benefit of each measure is first calculated independently for each event. In a second step, the benefits of say two measures are added for each event and it is ensured that this sum never exceeds the damage without measures (i.e. combined measures can maximally avoid any damage). Combinations of the second kind, i.e. synergies or dis-synergies are not modelled. A synergy would mean two measures lead to higher a benefit than the sum of benefits, as could be the case when combining e.g. an early warning system with an evacuation plan (e.g. in the Bangladesh case study, Wieneke and Bresch, 2016). Dis-synergies lead to a reduction of the combined benefit (see the following illustration).

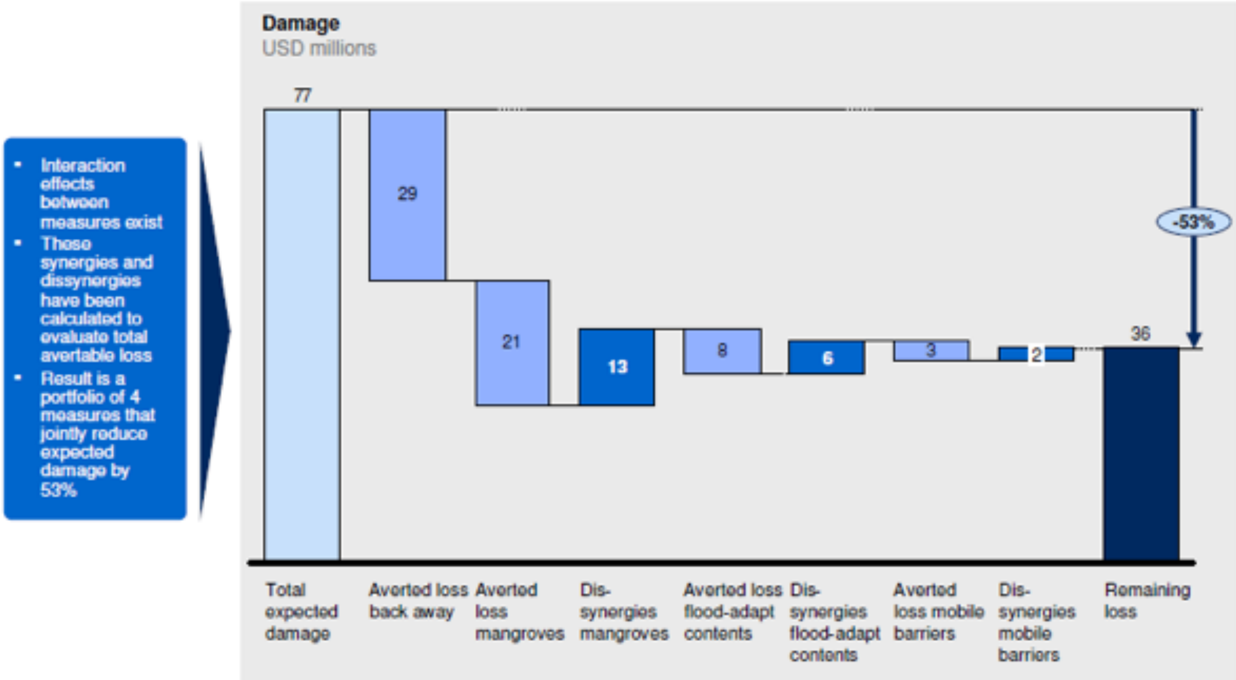

Illustration of dis-synergies (unpublished backup material of the Samoa case study, as summarized in Bresch, D. N. and ECA working group, 2009, https://ethz.ch/content/dam/ethz/special-interest/usys/ied/wcr-dam/documents/Economics_of_Climate_Adaptation_ECA.pdf#page=110). A detailed treatment of this complex interplay of measures is far beyond the scope of the present paper, albeit we did use a – precursor of – CLIMADA for this figure.

Instead of adding a supplement or appendix, we decided to make available the full Jupyter notebook, which allows for a reproduction of the detailed results, an inspection of specific parameters and – if CLIMADA is locally installed, even for an interactive change of parameters and settings. We therefore added the reference to the Jupyter notebook in the references as:

Aznar-Siguan, G. and Bresch, D. N.: CLIMADA - Caribbean case study. Jupyter notebook, 2020. https://github.com/CLIMADA-project/climada_papers/blob/master/202008_climada_adaptation/reproduce_results.ipynb [last retrieved 24 Oct 2020] and added the reference in page 11 as: "**Please find the detailed results in Aznar-Siguan and Bresch, 2020.**"

Please note further that we present a case study and hence numbers are illustrative. Therefore, a lengthy appendix could far less serve the purpose of providing exemplary insights compared to the notebooks – and numbers from the appendix would not be of much use in isolation either.

6. Section 3.2: What is the reasoning behind choosing the three most cost-effective measures plus risk_transfer? In terms of benefit-cost, this seems not to be the optimal choice based on Fig 4b. Similar to major comment 5, I would also like to see additional supporting figures for all the island groups considered in Figure 6 as a supplement. As above, the figures produced in the jupyter notebook should suffice.

We chose a set of three measures merely for illustrative purposes. With the combination of measures being treated in an approximate way, we would like to show how far one can get by using this features, especially to explore the effectiveness of risk transfer. Risk transfer costs are substantially lowered by any (combination of) adaptation measures. We decided not to combine all four measures to mimic the budgetary constraints one might encounter in a real case. It needs to be noted further that in many of the real case studies the authors have been involved in, sets of measures were often built more on a multi-criteria (MCA) rather than a purely CBA approach. But given the purely illustrative purpose of the present case study, we do not venture into this here.

We chose risk transfer to exemplify the risk-reducing benefit of measures translating into considerable reduction in risk transfer costs, a point (very) relevant to the Caribbean Cat Risk Insurance Facility (CCRIF, 2010) and its offering to strengthen societal resilience in the region. But we did abstain from modelling the proper scheme (index based etc.) again for the sake of simplicity of the case study provided. As a side remark, we are currently working on a study applying CLIMADA to the cash-out structure of the European Stability Fund (ESF) in the Caribbean region (as there are European liabilities) …

As for the details about combining measures, the Jupyter notebook does provide the detailed results for all islands and we deem it (as in point 5) more suitable to provide direct access to the notebook (on GitHub, maintained, even versioned) rather than adding lengthy tables in an appendix. We therefore added to the text at the bottom of page 12 as follows: **"Detailed results per island as well as the possibility to further experiment with different parameters/settings can be found in Aznar-Siguan and Bresch, 2020."**

7. Uncertainty assessment: While I understand that uncertainty assessments in this context are very demanding, I still think that the authors need to comment on uncertainties nonetheless. First, in order to strengthen the real-life applicability of CLIMADA, and second, to put the presented numbers into context. The authors cannot extensively discuss benefit-cost ratios with

two decimal digits and rate them by effectiveness (fig 6), while claiming in the same instance that uncertainty assessments would overload this paper. I do not want to see an in-depth assessment (knowing the difficulties) but I expect a discussion of the potential sources and ranges of uncertainties for the different measures and how these could affect the presented benefit-cost ratios. This would tremendously help the reader and user to judge on the findings presented in this manuscript and the possibilities to account for uncertainties using CLIMADA.

We truly appreciate your kind understanding that a comprehensive uncertainty assessment in this context would be very demanding. We are currently exploring non-standard (beyond brute-force Monte-Carlo approaches), but these early stage experiments with CLIMADA do in fact exceed the scope of the present paper.

We agree that it does not make sense to state unnecessary mock precision in benefit/cost ratios. Indeed, in the right part of Figure 6, we aim at illustrating the fact that islands can be grouped and the second digit merely stems from labelling the vertical axis. We had a version with rounded figures, but felt it looked awkward. To clarify, we amended to the legend of Figure 6 as follows: "The three most cost-effective measures are combined with the risk transfer solution and the resulting net present value of the total expected averted damages from 2016 to 2050 (benefit) is categorized into **three equally spaced ranges**, cyan (53% to 61% damages averted), purple (61% to 68%) and gold (68%-76%) **and Benefit/Cost ratio is also shown in three indicative ranges**. The color intensity represents the benefit/cost ratio: the darkest colors result in more cost-effective measures."

As for a discussion of the potential sources and ranges of uncertainties for the different measures and how these could affect the presented benefit-cost ratios, we added the following in the Discussion:

"Main drivers of uncertainty, beyond those in hazard, exposure, and vulnerability (Aznar-Siguan and Bresch, 2019b) for the four adaptation measures, while not quantified, can at least be qualitatively described as follows. As for preparedness, the level and scope for this study have been chosen based on general findings of previous ECA studies (Caribbean Cat Risk Insurance Facility, 2010), where large differences had been found across regions, mainly stemming from barriers to implementation, not least such as lack of agency of non-owner property residents. Notwithstanding, in all cases, preparedness does lower damages and almost always at a Benefit/Cost ratio >1 on a societal level, which does not necessarily

mean it being ‘worth the money’ for the single property owner each time. As for mangroves, differences of applicability to single islands have been mentioned above. Again, as shown in studies (Reguero et al., 2018), such nature-based solutions, while difficult to assess at great precision in terms of exact Benefit/Cost yield ratios far above one if applied at scale. With building codes, it all depends on design - and enforcement. The latter being utterly cultural, any assessment must remain spurious, even past experience might not provide solid a guidance for present and future uptake. On the other hand, implementation is rather straightforward in CLIMADA in terms of the impact function as far as the design component is concerned, hence relative uncertainty can be limited there. Retrofit is implemented the exact same way as building codes and exposed to the same threat of enforcement. Risk transfer in contrast to measures discussed so far, being a purely monetary transaction, does, in its assessment at least, suffer from far less uncertainty. But it inherits all the underlying uncertainty of the probabilistic model as well as of the measures in terms of their risk-reducing capacity. Testing with many (sets of) parameters (Aznar-Siguan and Bresch, 2020), results regarding the effectiveness of risk transfer proved robust.”

Minor points:

1. Abstract: I would find it very useful to mention tropical cyclones as the object of study in the abstract. It remains unclear otherwise against what the discussed adaptation measures for the Caribbean are guarding.

*This point is very valid, thanks for bringing this to our attention. We added to the Abstract as follows: “*We apply the open-source methodology and its Python implementation to a **tropical cyclone impact** case study in the Caribbean, which allows to prioritize a small basket of adaptation options, […]*”*

2. Page 1, line 14: basked -> basket

Corrected

3. Page 3, line 4: the reference “Aznar-Siguan and Bresch 2019“ does not appear in the list of references. Please also correct the multiple occurrences of this reference.

*Thanks. That’s in fact “*Aznar-Siguan and Bresch 2019**b***”, corrected.*

4. Page 3, line 10: The (net present value of) the difference : : : -> The (net present value of the) difference

Corrected

5. Page 5, line 6: the concept of mean damage degree (MDD) is mentioned here and throughout the following pages without being defined properly. As MDD is a central concept of this manuscript, I would strongly suggest to explain it on first use. In addition: What is the difference between MDD and mean damage ratio (see Fig. 2)?

Aznar-Siguan and Bresch 2019b describe this in detail, hence we clarified as follows:

"Even if new impact functions can be easily introduced, the following attributes allow to perform linear transformations to given impact functions: hazard_inten_imp transforms the abscissae (e.g. implementing elevation of homes in the case of flood) while mdd_impact and paa_impact transform, respectively, the Mean Damage Degree **(MDD)** and the Percentage of Affected Assets (**PAA,** e.g. to reflect an improved building code). **Please note that the Mean Damage Ratio (MDR) is defined as the product of MDD and PAA for any given intensity, see Aznar-Siguan and Bresch (2019b) for a detailed description.**"

6. Page 5, line 28: on -> one

Corrected

7. Page 5, line 29 (end of line): as well as -> as

We replaced "as well as" *by* "**and**"*, which makes it more lisible.*

8. Page 7, line 6: 2.2.10 -> 2.2.1 ?

That's strange, as it reads 2.2.1 in the Word file, but got wrongly stated in the pdf generated. We now checked again in the revised pdf and resolved this.

9. Page 9, line 20: the reference to Fig 1 seems not correct.

Indeed it should refer to Figure 3, corrected.

10. Page 9, line 25: the sentence starting with “building code” sounds strange. Are you sure that the 1 m USD mentioned here is correct?

Thanks for pointing this out, we clarified as follows:

“Building_code averts **order of** 1 m USD **of damage more** than mangrove, but its benefit/cost ratio stays bellow 2.”

11. Page 10, line 9: Preparedness : : : -> By construction, preparedness: : : I would add this in order to re-iterate that this threshold was chosen at will earlier.

Good point, adjusted as “**By construction**, *preparedness* averts …”

12. Figure 5: The figure is difficult to understand in its current state. 1) I would likely replace the black bars by thicker/colored bars and refer to them as boxes instead of bars, 2) Reducing alpha for the 40y return period in order to highlight different y scales makes blue the predominant color and confuses the reader. Why don’t the authors simply use a vertical line between the 10y and 40y case to highlight the difference between the two bars?

Ad 1) The plot shows bars (as a bar chart) and colored boxes. The black bars represent the total exceedance damage for events with the corresponding return period. The colored boxes represent the amount of damage that can be averted by the corresponding measure. The last ones are “boxes” or “blocks” in the sense that their height and not their y-value is the averted damage.

Ad 2) Agree

We remove alpha and add the suggested line in Figure 5. Further, we clarified the figure caption as follows: “Averted impact of each measure in 2050 for different return periods, without taking into account climate change nor economic growth (a) and with the moderate risk increase (b). The **thin** black bars show the expected exceedance damage at each return period and each coloured block indicates the amount averted by the corresponding measure. **The capacity of measures to absorb damage exceeds expected damage for high frequency (7 year) events and risk transfer is more than sufficient in a)**. Note …”

13. Page 11, line 18/19: The mangrove protection discussion is too succinct. Where do the 1.5% and 3% values come from? Why do the Turks and Caicos Islands define the reference? A how is this related to what the reader already knows from section 3.1.1? See also major comment 3.

See our response to point 3 above, where we take this in account, too.

14. Page 11, line 20: I would transfer the last sentence before the table to the table

This formatting suggestion is well taken, we took care of.

AUTHORS' RESPONSE TO REFEREE #2

Research article:

Bresch, D. N. and Aznar-Siguan, G.: CLIMADA v1.4.1: Towards a globally consistent adaptation options appraisal tool, Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2020-151

Authors:

David N. Bresch (dbresch@ethz.ch), Gabriela Aznar-Siguan (Gabriela.Aznar@meteoswiss.ch)

We thank the anonymous referee for his comments, which have improved the quality of the manuscript.

The original comments from the referee are listed below *directly followed by our responses in blue and italic and changes to the manuscript in blue and* ***bold*** *(unless where it gets complicated or tiny, where changes are made in the manuscript only).*

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18 September 2020

The authors intend to introduce a methodology that integrate climate modelled risk, impacts (loss and damage), and adaptation options assessment (cost/benefit analysis). In addition, they provide a case study in Antilles to demonstrate an example to use the tool. The intentions are valuable and the platform seems useful to scientists and decision makers at local levels. However, the authors fail to present their intentions and execution well enough for readers to comprehend the value of this study. Here are my comments to this paper:

1.The paper is difficult to read because of a lot of grammar issues. It is perhaps better to proofread the entire text in the next revision.

We carefully re-checked the paper and adopted a more lisible style throughout – in line also with the other reviewer's remark about occasionally long sentences (sic). With the many changes to the text, we do not list all of them here, but provide both a clean revised version of the paper as well as a version with track changes.

2.Section 1 (Introduction): This section is mixed with problem statement and literature review, which make this section confusing. Unfortunately, both (problem statement and theoretical background) are not presented clearly. What's the problem now? What's the scientific gap now? What does this study aim to achieve? These questions can help readers to get to know the reasons behind this study. In addition, a lot of reviewed literature are citing the authors' previous work and stating the content of the reviewed papers. It lacks of discussion of the problems of current practices from reviewing literature.

The introduction of the paper is structured along the following 'fil rouge': Climate change is a fact, yet greenhouse gas mitigation does not happen at the required scale, hence the need for adaptation and demand for risk assessment and adaptation options appraisal. Adaptation is (utterly) local, but best informed by globally consistent approaches.

In line with point 1, we broke many sentences in two, reformulated as appropriate and better highlighted the 'fil rouge' also by breaking the introduction into sections. Again, as for point 1, given the many changes, we do not list all of them here, but provide both a clean revised version of the paper as well as a version with track changes.

The gap consists in the mere fact that globally consistent approaches to adaptation options appraisal are rare to non-existent – and none are readily available as an open-source and -access software tool.

Hence the need to set globally consistent approaches forth, underpinned by versatile platforms, ready for practical application. In this sense, the introduction states the clear demand and does not focus on an in-depth discussion of current practices, as this is not the aim of the present paper. We deemed it useful to cite key contributions to support our argumentation, but do not aim at a review of the full body of literature, which would warrant a study of its own.

The aim of the paper is to present the open-source and -access CLIMADA platform which implements the Economics of Climate Adaptation (ECA) framework, as described in the last paragraph of the introduction. Hence we deem it useful to provide the basics about ECA, which leads to citing a couple of previous studies.

We carefully reviewed and removed select references as suggested. As we strived to keep the paper to the point, we provide a brief description of ECA in the introduction, too, such that we can focus in CLIMADA in the methods section of the paper.

Having thus laid out the structure of the paper, we deem it useful to end the introduction with a sentence to stress the enabling nature of this work. Again, we set this apart by introducing a break to separate from the signposting in the sentence before. Still, we deem it helpful to stress the enabling function of this work already at the end of the introduction, not only to conclude the paper with, namely:

"This extended version of the CLIMADA platform has been designed to enable risk assessment and options appraisal in a modular form and occasionally bespoke fashion […] yet with high reusability of common functionalities to foster usage in interdisciplinary studies […] and international collaboration."

3.Section 2 (Framework Concept and Design): This section provides a lot of technical details of CLIMADA. It is useful to add some important perspectives. For example, can CLIMADA be used in every climate impacts? The paper uses Hurricane as an example risk, but can other impacts (e.g., agriculture, health, etc.) be used in the platform? Is there a constrain in this tool? Such as data availability? In addition, why a moderate scenario is selected? Since the authors are exploring a hazard/disaster impact, why not use the worst case scenario (RCP 8.5)?

While the present application focuses for purely illustrative purposes on hurricane risk in the Caribbean, the CLIMADA platform can *not only, but* is *actually used for most extreme weather events in a globally consistent manner. To clarify this point, we therefore added to the manuscript:* "**Please note that CLIMADA does provide global coverage of major hazards beyond tropical cyclones (TC), yet we focus in TC in the present paper for illustrative purposes.**"

As of today, CLIMADA provides global coverage of all major climate-related extreme-weather hazards at high resolution, namely (i) tropical cyclones and storm surge at 10 and 1km, (ii) river flood at 4km, (iii) drought at 50km, (iv) wildfire at 1km and (v) European winter storms at 4km. Tropical cyclones (Geiger at al., 2019;) are based on IBTrACS (Knapp et al., 2010; updated monthly since)., river flood (Sauer et al., submitted) and drought (Eberenz et al., in preparation) on isimip (isimip.org), European winter storms on Copernicus WISC (Welker et al., submitted) *and wildfires on MODIS (https://modis.gsfc.nasa.gov, implementation experimental still). For all mentioned hazards, a historic, a probabilistic and several future climate (RCP-based) hazard sets exist, enabling assessment of risks today and under diverse climate scenario futures. CLIMADA does also provide a globally consistent exposure dataset at 1km resolution, based on population and satellite-measured night-light intensity (Eberenz et al., 2020a). To implement bespoke vulnerability, impact functions have been calibrated for global regions for tropical cyclones (Eberenz et al., 2020b, in review), flood (Sauer et al., submitted) and European winter storms (Welker et al., submitted). With hazard, exposure and vulnerability datasets being provided, CLIMADA is currently the only ready to use open-source and access (no strings attached, even free for commercial use, GNU GPL license) globally consistent impact modeling platform.*

Sure there are constraints, but given the versatility of the general concept as well as the openness of the platform itself, it is merely available extreme weather hazard data that limits its use. While the paper focuses on a regional application, the platform has been used an many scales, from global (e.g. Gettelman et al. 2017) to truly local (c.f. Wieneke and Bresch, 2016).

As for the scenario, again, we chose this for illustrative purposes, any other combination of RCP and year, can, based on Knutson et al. 2015, readily be explored. See also last para of the answer to the next point.

One can play with the RCP selection (and other parameters/settings) in the Jupyter notebook as provided - we will add this as a reference to the paper, instead of a static appendix (https://github.com/CLIMADAproject/climada_papers/blob/master/202008_climada_adaptation/reproduce_results.ipynb).

As we intend to use the case study in many conversations, not all are best initiated with the worst case to start with – hence we would like to trigger questions exactly such as yours (why not RCP8.5) rather than impose this. In this sense, too, your comment is highly appreciated.

4.Section 3 (Case Study): It is perhaps helpful if the authors can provide some background information of current response measures of Antilles in facing Hurricane hazards. In addition, one key challenge of climate modeling in island nation is the resolution and hurricane projection. Did you conduct downscaling? How did you project hurricanes in 2050?

With the case study being illustrative, it was by no means within the scope of the present paper to study the local situation in terms of actually implemented response measures. But we welcome the comment in the spirit of the many Economics of Climate Adaptation (ECA) studies we conducted so far in most world regions, with teams on the ground and deeply rooted in a transdisciplinary approach both in shaping and scoping of the studies. Given limited resources, efforts were directed at contributing facts suitable for local decision making and technical reports, rather than bringing these studies into the peer-reviewed body of literature. This was also due to the fact that at that time, the first author was fully employed in a private sector company with global presence and local attention. Other priorities kept him from publishing in other forms than technical reports (see https://wcr.ethz.ch/research/casestudies.html for a collection) and policy briefs, such as e.g. to the G20 (World Bank Group, 2017).

No downscaling was employed in the study, as the probabilistic tropical cyclone track set was modified according to on Knutson et al. 2015. The wind fields, calculated based on Holland (2008) can be calculated at any spatial resolution, down to 1 km is reasonable. Again, as we present an illustrative case for the full options appraisal methodology, any (sub)model can be further refined, the tropical cyclone wind field e.g. by adding a surface roughness component to it, the exposure layer by specifying sector-specific exposure etc.

For the climate projection 2050, we applied the Atlantic basin factors as published by Knutson et al. 2015 to the probabilistic tropical cyclone track set, i.e. we modified the single event frequency and wind field intensity accordingly. Specifically, we multiplied the wind intensity of storms with category greater than 1 by a factor of 1.045, interpolating these values between the time stamps, and left the event frequency unchanged, all as provided by Knutson et al. 2015 table 3 (we just consider changing frequencies and intensities when the significance level of the hypothesis test is lower than 0.05). Again, we would like tom stress the fact the case study is provided as an illustrative example, by no means pre-empting other methods to generate hazard datasets, such as e.g. obtaining tracks from GCMs (as done in Gettelman et al. 2017) or hybrid methods, such as using synthetic tracks (Geiger et al. 2018), both papers employing CLIMADA for all impact calculations.

References as used in this reply (which are not referenced in the paper itself):

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CLIMADA v1.4.1: Towards a globally consistent adaptation options appraisal tool

David N. Bresch[1,2], Gabriela Aznar-Siguan[2]

[1]Institute for Environmental Decisions, ETH Zurich, Zurich, Switzerland
[2]Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland

Correspondence to: David N. Bresch (dbresch@ethz.ch)

Abstract.

Climate change is a fact and adaptation to a changing environment therefore a necessity. Adaptation is ultimately local, yet similar challenges pose themselves to decision-makers all across the globe and on all levels. The Economics of Climate Adaptation (ECA) methodology established an economic framework to fully integrate risk and reward perspectives of different stakeholders, underpinned by the CLIMADA impact modelling platform. We present an extension of the latter to appraise adaption options in a consistent fashion in order to provide decision-makers from the local to the global level with the necessary facts to identify the most effective instruments to meet the adaptation challenge. We apply the open-source ~~methodology and its~~ Python implementation to a tropical cyclone impact case study in the Caribbean with openly available data.~~,~~ This~~which~~ allows to prioritize a small basket~~d~~ of adaptation options, namely green and grey infrastructure options as well as behavioural measures and risk transfer, and permits inter-island comparisons. In Anguilla, for example, mangroves avert simulated damages more than 4 times the cost estimated for restoration, while enforcement of building codes shows to be effective in the Turks and Caicos islands in a moderate climate change scenario. For all islands, cost-effective measures reduce the cost of risk transfer, which covers damage of high impact events that cannot be cost-effectively prevented by other measures. This extended version of the CLIMADA platform has been designed to enable risk assessment and options appraisal in a modular form and occasionally bespoke fashion yet with high reusability of common functionalities to foster usage of the platform in interdisciplinary studies and international collaboration.

1 Introduction

Climate change is one of the defining challenges of mankind in the present century. Even if we would stop global greenhouse gas emissions today, we are bound to a significant level of warming and concomitant change (IPCC, 2014). Adaptation to a changing environment therefore is a key priority today and will remain so in future. This challenge will be~~,~~ shaped not only by changes in climate, but also societal stressors ~~is and will remain a key priority today and in future~~. Adaptation is ultimately local, yet similar challenges pose themselves to decision-makers all across the globe and on all levels – from multinational organizations (Berkhout, 2012), sovereign and sub-sovereign states, cities, companies, and down to the local community

(Webler et al., 2016). They all benefit from consistent methodologies providing the facts to identify the most effective instruments to meet the adaptation challenge. But one need to be aware of ~~despite~~ constraints such as insufficient local resources, capacities and the role of authority. Such a globally consistent~~n~~ approach to adaptation needs to combine impact (Burton et al., 2002; Füssel and Klein, 2006) with vulnerability (Fünfgeld and Mcevoy, 2011; Preston et al., 2011) assessments to strengthen societal resilience. This best happens through co-generation of adaptation knowledge (Muccione et al., 2019) and proper ~~,~~ dissemination of information (Moser, 2014, 2017). The combined assessment of impacts and options appraisal does further ~~and~~ enable~~ing~~ more sustainable access to funding (Adger, 2006; Eakin and Lemos, 2006; Smit and Wandel, 2006; Yohe and Tol, 2002).

In this spirit, the Economics of Climate Adaptation (ECA) methodology established an economic framework to fully integrate risk and reward perspectives of different stakeholders (~~Bresch, 2016;~~ Bresch and ECA working group, 2009~~; Bresch and Schraft, 2011~~; Souvignet et al., 2016) to foster climate-resilient development (Watkiss and Hunt, 2016). ECA can be applied on different levels and granularity, combining elements of top-down and bottom-up approaches (e.g. Dessai et al., 2005), both used in the policy process (Kates and Wilbanks, 2003; Mc Kenzie Hedger et al., 2006). ECA hence~~, as it~~ provides ~~the~~ a fact base to build an adaptation strategy that is robust against a wide range of plausible climate and societal change futures (Lempert and Schlesinger, 2000; Wilby and Dessai, 2010).

ECA starts with a comprehensive cost benefit analysis (CBA), where benefit does not need to be expressed in monetary units, but equally well e.g. in lives saved, as illustrated by many case studies (Bresch and ECA working group, 2009; Wieneke and Bresch, 2016). Such CBA forms the basis for a wider Multi-Criteria Analysis (MCA, e.g. Haque~~, (~~2016~~)~~) to integrate aspects such as specific risk appetite and further locally determined context (Brown et al., 2011; Dessai and Hulme, 2004; Preston and Stafford-Smith, 2009; Truong et al., 2016) and criteria (e.g. in NAPAs, UNFCCC, 2011). This further allows to integrate ~~as well as~~ additional perspectives (Radhakrishnan et al., 2017), including – also indigenous (Kelman et al., 2012) – knowledge with respect to feasibility. ~~This will allow~~Such an approach provides the information to (re-)prioritize measures to constitute an adaptation roadmap as a basis for adaptation funding discussions on all levels, from local to global, including e.g. the Green Climate Fund (GFC). The ECA method is underpinned by the CLIMADA platform (Aznar-Siguan and Bresch, 2019b) which does allow for globally consistent (c.f. Ward et al.~~, (~~2020~~)~~) yet high-resolution modelling of socioeconomic impacts of weather extremes following a fully probabilistic event-based approach. Impacts are assessed today, as well as in future, subject to the increase ~~due to~~driven by economic development, and the further incremental increase of risk due to climate change.

Building on the risk assessment already implemented (Aznar-Siguan and Bresch, 2019b), the present paper describes the concept of options appraisal based on an~~y~~ estimati~~ng~~on of the expected change in socioeconomic impact over time. This allows the risk reduction benefit to be compared to the implementation cost of options, covered in Section 2, where the object-oriented design of the Python implementation is also documented. Section 3 provides an exemplary case study application and Section 4 concludes with discussion and outlook.

This extended version of the CLIMADA platform has been designed to enable risk assessment and options appraisal in a modular form and occasionally bespoke fashion (Hinkel and Bisaro, 2016) yet with high reusability of common functionalities to foster usage in interdisciplinary studies (Souvignet et al., 2016) and international collaboration.

2 Framework Concept and Design

2.1 Concept

Framing the climate adaptation challenge in terms of risk allows to treat adaptation measures as ways to reduce natural hazard risk both today and in future. Starting from a calibrated impact model to assess current risk (as e.g. in Aznar-Siguan and Bresch 2019b), the drivers of risk are first modified to implement the effect of changes in hazard (e.g. climate-driven) and exposure (development-driven) over time, likely in a scenario fashion (c.f. Serrao-Neumann and Low Choy (2018)). Please note that CLIMADA does provide global coverage of major hazards beyond tropical cyclones (TC), yet we focus in TC in the present paper for illustrative purposes. Changes in vulnerability could easily be taken into account, too, but pertinent information does usually not exist. Adaptation measures are implemented through modification of the impact function (e.g. better building codes leading to lower building damages), possibly also exposure or hazard, or a combination thereof. Risk metrics both for today as well as for future years ~~can~~ are thus ~~be~~ calculated with and without any such measure. The (net present value of~~)~~ the) difference of the risk metrics computed with and without the implementation of the measure constitutes the measure's benefit. Together with estimates of implementation (capital expenditures, CAPEX) and maintenance (operations expenditures, OPEX) costs (or payment streams thereof, c.f. Samuelson (1937)), a cost-benefit ratio~~s~~ ~~can be~~ is then calculated for each single adaptation measure. Please note that risk metrics need not be monetary, hence discounting or more general questions of time preference (Frederick et al., 2002) of the benefits might not be directly applicable (e.g. for ~~risk metrics~~ number of people displaced or lives lost as a risk metric) and costs could also be specified in non-monetary units. Please note further that climate scenarios and development pathways are usually employed to assess future risk, hence such cost-benefit considerations are contingent on the scenarios and pathways chosen for analysis. But as it will be shown, very much in the spirit of Wilby and Dessai (2010), (baskets of) adaptation measures can thus be tested for robustness (Dittrich et al., 2016) under different combinations of scenarios and pathways (as well as other key parameters, such as time-dependent discount rates).

2.2 Implementation

The software architecture defined in Aznar-Siguan and Bresch (2019b) has been extended to include the classes which handle adaptation measures (*Measure* and *MeasureSet*), discount rates (*DiscRates*) and the cost/benefit analysis (*CostBenefit*), as shown in Figure 1~~Figure 1~~. Note that other evaluation approaches, such as real options (Hino and Hall, 2017) or multi-criteria analysis (Haque, 2016), could be implemented in a similar fashion, in close correspondence to the cost/benefit as shown here.

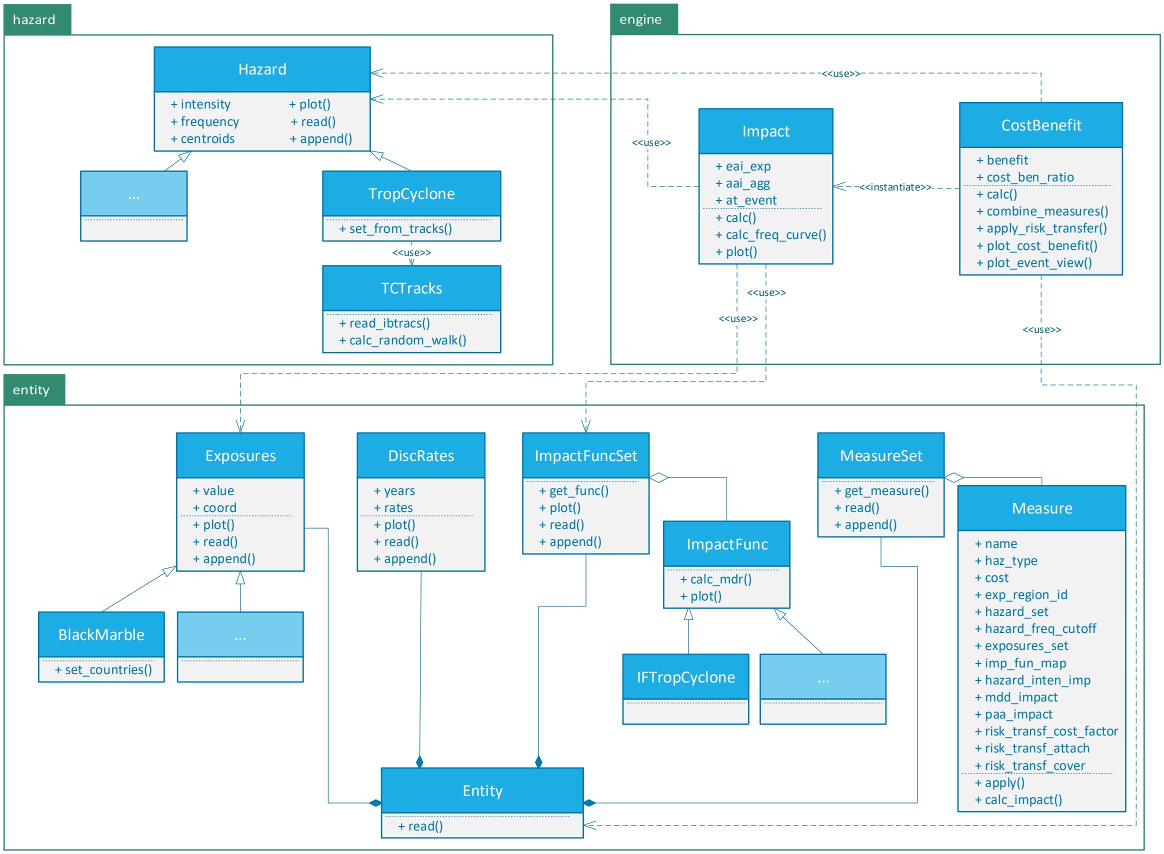

Figure 1: Simplified architecture of CLIMADA including classes for adaptation measures, discount rates and cost-benefit considerations. An extension of Aznar-Siguan and Bresch (2019b).

2.2.1 Adaptation Measures

An adaptation measure in CLIMADA is a parametrization of a risk-reducing measure which modifies either the impact function, the exposure or the hazard, or a combination of any of them, or even the resulting impact. A measure is defined in the *Measure* class and is uniquely identified by its name and the hazard type it is acting on. Its parametrization is implemented via attributes. *exp_region_id* sets the physical boundaries of the measure, where exposures and hazards outside the defined regions are not modified by the measure; *hazard_set* and *hazard_freq_cutoff* change a given *Hazard* instance. The first replaces the hazard by a new *Hazard* instance which allows for the flexibility to introduce any desired protection distribution, spatially and in frequency of occurrence (e.g. a flood hazard event set built with higher flood protection in place). *hazard_freq_cutoff* defines a frequency cut-off which sets impacts at higher frequency to zero and can thus be used to model a seawall, for example, which avoids all impacts with a frequency higher than *hazard_freq_cutoff* within its protected region defined by *exp_region_id*. The exposures are modified through the parameters *exposures_set* and *imp_fun_map*. *exposures_set* replaces the *Exposure* instance and *imp_fun_map* changes the selected impact functions assigned to each exposure for others. *exposures_set* provides more freedom to define changes on the exposure, such as changes in the assets distribution through modified spatial planning. Implementing a building code for a specific construction type could be modelled with a new impact function and relating it to the former one through the *imp_fun_map* attribute.

Even if new impact functions can be easily introduced, the following attributes allow to perform linear transformations to given impact functions: *hazard_inten_imp* transforms the abscissae (e.g. implementing elevation of homes in the case of flood) while *mdd_impact* and *paa_impact* transform, respectively, the Mean Damage Degree (MDD) and the Percentage of Affected Assets (PAA, e.g. to reflect an improved building code). Please note that the Mean Damage Ratio (MDR) is defined as the product of MDD and PAA for any given intensity, see Aznar-Siguan and Bresch (2019b) for a detailed description.

Finally, a classical risk transfer option can be defined setting a deductible (or attachment point) and a cover. Deductible and cover are considered for the resulting damage of each event. Damages greater than the *deductible* up to *cover* are carried by the insurer, hence lowering the damage burden for the insured. As the insurer incurs transaction and capital costs, the total cost of insurance is approximated by application of the multiplicative *risk_transf_cost_factor (>1, usually order of 1.5 to 2)* to the raw expected damage which is calculated for the insured layer (for details, see the case study below as well as e.g. Surminski et al. (2020)). For risk transfer therefore, the cost is calculated by CLIMADA.

For measures other than risk transfer, their cost is provided by the user through the *cost* attribute. This should provide the Net Present Value (NPV) of the initial investment (capital expenditure, CAPEX) as well as the maintenance costs during the whole time range of implementation considered (operating expenditures, OPEX). The set of measures that are going to be compared in the cost-benefit analysis are gathered in the container *MeasureSet* as represented in Figure 1~~Figure 1~~.

2.2.2 Cost and Benefit

The *CostBenefit* class in Figure 1~~Figure 1~~ computes the costs and benefits of implementing a set of adaptation measures through its *calc* method. There, the socioeconomic variables are provided by the *Entity* class, where the exposure to the hazard (*Exposures* instance), a set of impact functions representing the exposures vulnerability (*ImpactFuncSet* instance), a set of measures (*MeasureSet* instance) and the (if applicable time- and even measure-dependent) discount rates (*DiscRates* instance) to be applied over the time period of interest are gathered. The natural hazard is provided by a *Hazard* instance or a derivate class. Within the *calc* method the probabilities of impact resulting from the implementation of each measure are computed through the *Impact* class as explained in Aznar-Siguan and Bresch (2019b) and compared to the risk when no measure is applied. The benefit of the measure is its averted impact in terms of a configurable "risk function". As a default, the average annual averted impact is used, but any risk function, such as any quantile or the averted impact for events with a specific return period (e.g. one in a hundred years) can be considered.

Scenarios of both future hazard as well as exposure at the end of the time period considered can be provided as well as follows: A second *Hazard* captures the changes of intensities and probability of occurrence and a second *Entity* contains the changed exposures, measures and eventually new impact functions (to account for change in building quality, for example). The probabilities of impact for each measure are computed at the beginning and at the end of the time range, and stored, respectively in the attributes *imp_meas_present* and *imp_meas_future*. The benefit is then computed as the NPV of the average annual averted impact (or the configured risk function) using the discount rates of *DiscRates*. The values discounted in the years between the beginning and the end of the period are estimated by interpolation through the parameter *imp_time_depen*. This allows to set a linear (as by default) or either a concave (large increase at the beginning) or convex (increase mainly towards the end) change of risk over time.

The resulting benefits per measure are stored in the attribute *benefit*, while the cost/benefit ratio is stored per measure in the *cost_ben_ratio* attribute. These values are used by the method *plot_cost_benefit* where the benefit of each measure is represented against the corresponding benefit/cost ratio in an adaptation cost curve. *plot_event_view* provides a further understanding of the efficiency of the measures by showing the quantity of averted impact in events of selected return periods at the end of the time range considered (see case study below for illustrations). If some of the measures are to be implemented simultaneously, the method *combine_measures* can be used to obtain an approximation of the combined averted impact. There, the benefits of the measures are aggregated at event level, avoiding double counting, and the risk function is applied afterwards. Furthermore, the *apply_risk_transfer* method allows to implement risk transfer on top of selected measures (after combination, if applied, to properly account for risk reduction and diversification effects).

3 Case study: Adaptation to hurricanes in the Antilles

Building on the risk assessment case study documented in Aznar-Siguan and Bresch (2019b), we consider here the small Caribbean islands hit by hurricane Irma. The consequences of the 2017 Atlantic Hurricane season underscore the importance of investing in disaster risk reduction for resilience, enhancing disaster preparedness for effective response and the imperative of "Building Back Better" during recovery, rehabilitation and reconstruction (ECLAC, 2018).

CLIMADA has been used to quantify adaptation options before, see Bresch (2016), Bresch and ECA working group (2009), Bresch and Schraft (2011) and Souvignet et al. (2016). These assessments were performed following the Economics of Climate Adaptation (ECA) methodology within consortia where data provided by dedicated surveys and local experts fed the models. Please note that these studies were well embedded in local stakeholder consultation and co-design processes, especially regarding both the scope as well as the set of adaptation measures considered. The analysis documented here aims at showing the versatility that CLIMADA offers to compare adaptation measures of different nature under different scenarios, but does not provide a fully comprehensive adaptation assessment in the sense of a full ECA (Souvignet et al., 2016). In order to keep the case study lean and illustrative, only openly available national indicators are used and uncertainties not explored in detail, even though CLIMADA is designed to do so. We first describe the approach for Anguilla in 3.1 and apply it later on all the targeted islands in 3.2.

3.1 Adaptation in Anguilla

The analysis of Aznar-Siguan and Bresch (2019b) concludes that the current Average Annual Impact (AAI) of hurricanes in Anguilla is 18±4 million current US dollars. The impacts were assessed in terms of physical damage on infrastructure whose value is proportional to its contribution to the national produced goods and services. Using these modelled assets, the generated tropical cyclone events (historical and synthetic) and the impact function of the previous work, we define several adaptation measures as explained in 2.2.1 ~~2.2.1~~, and quantify their cost and benefit in terms of physical protection following 2.2.2. The time frame considered for this study ranges from 2016 (hereafter referred to as ’current’ time, establishing a risk baseline) until 2050.

3.1.1 Adaptation measures definition

We consider measures of different nature, such as green and grey infrastructure options (Denjean et al., 2017) as well as behavioural measures. The parametrizations chosen here allow to reproduce the main findings on Anguilla in ~~(~~Caribbean Catastrophe Risk Insurance Facility~~,~~ (2010). Ecosystem-based measures such as mangroves can provide substantial protection to properties, even relatively far away from them, against both storm surges and cyclonic wind (Das and Crépin, 2013; Reguero et al., 2018). The need on reforestation of mangroves in the Caribbean started in the 1980s, when large-scale conversion of mangroves for aquaculture and tourism infrastructure took place. Even if Anguilla has maintained its mangrove area relatively constant to 90 hectares (Food and Agriculture Organization of the United Nations, 2007), these can be further damaged by storms. We define an investment of 100’000 USD per hectare for restoration of Anguilla’s mangroves (Lewis, 2001) and an annual maintenance cost of 200 USD per hectare that leads to a reduction of the impact function intensity of 0.74% on the coast and twice as much inland. The resulting impact functions (*mangrove_coast* and *mangrove_inland* respectively) are represented in Figure 2~~Figure 2~~.

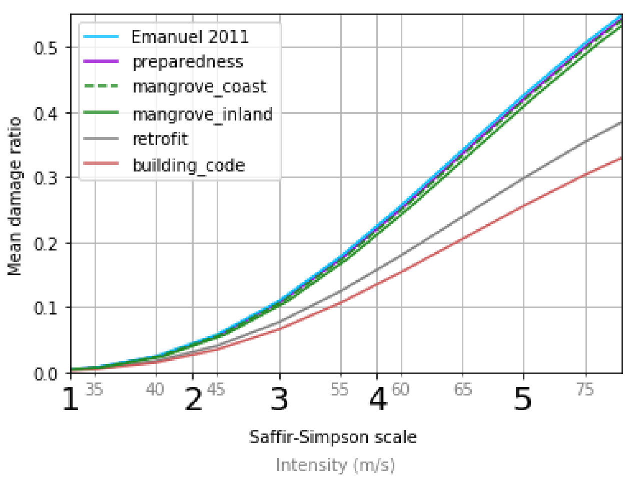

Figure 2: Impact functions used in the definition of adaptation options. *Emanuel 2011* refers to the impact function used in the risk assessment, following (Emanuel, 2011), and the Saffir-Simpson hurricane wind scale is shown as reference (Schott et al., 2019).

***Preparedness* is the impact function obtained once the behavioural measure named preparedness is implemented. Mangroves reforestations generate the impact functions *mangrove_coast* on a distance of up to 500 meters from the coast and *mangrove_inland* in the rest of the island. *Retrofit* and *building_code* show an impact reduction of 30% and 40% respectively at every wind intensity with respect to *Emanuel 2011*. See Aznar-Siguan and Bresch (2019b) for details about mean damage ratio (MDR).**

As grey options we consider retrofitting and the implementation of building codes. Retrofitting existing housing not only reduces damages due to natural disasters, but can also lead to a reduction in insurance costs (Surminski et al., 2020), potentially increases the market value of a building, and may have co-benefits such as energy saving. Here we only consider the benefit caused just by physical protection, which we set to an idealized 30% of damage reduction at every wind intensity (see Figure 2~~Figure 2~~). Retrofitting can cost anywhere between 1% and 20% of the value of the property (Ou-Yang et al., 2013; Triveno and Hausler, 2017) and can be efficiently subsidized by governments. For illustration purposes, we set a total cost of 10% of the retrofitted assets. The retrofit is performed progressively, having 10% of the assets value retrofitted in 2016 and achieving 90% in 2050.

Implementing building codes has similar benefits as retrofitting, but only in newly constructed buildings. Its success lies in its enforcement and subsequent inspection, especially in residential housing (Prevatt et al., 2010). To assess its benefits and costs, we consider an annual rate of urbanization in Anguilla of 0.9% (Central Intelligence Agency, 2019) and 40% reduction in the impact function (see Figure 2~~Figure 2~~). To approximate the costs from the government to train construction workers and hire inspectors, as well as the owners expenses, the cost is set to 5% of the annual newly built houses.

Preparing houses by protecting windows, roofs and clearing the exteriors helps to reduce damage. Such action can be explained and promoted through labels (Attems et al., 2020) leaflets or e.g. at the bottom of bills such as the electricity invoice. We name this measure *preparedness*, and approximate its cost per inhabitant as (i) the cost of communication of 1 USD plus (ii) an annual 0.2 USD maintenance, and (iii) 100 USD as bulk expense for protection material. This measure ideally ~~is set to avoid all damages for events with return periods of up to 7 years and to~~ reduces the effective ~~vulnerability by modification of the curve along the~~ wind intensity and avoids most of the damages for events with low return periods. We set a wind intensity reduction of 0.5% (see impact function in Figure 2~~Figure 2~~) and a threshold of 7 year events under which no damages are generated. This threshold corresponds to events with exceedance damages lower than 1.5 m USD.~~ axis by 0.5% for events with higher return period (see impact function in Figure 2).~~

Finally, risk transfer is considered, being particularly suitable to manage risks of low frequency, high severity events. We define an insurance layer with attachment point (or deductible, i.e. the damage amount corresponding to a frequency at which the risk transfer gets triggered on average) and cover (the amount of damage covered by risk transfer) proportional to the island's expected exceedance damages. The attachment is set to the 12 year per event~~s~~ damage~~s~~ (approximately 32 m USD) and the cover designed such as to cater for events with up to a 145 year return period (the risk transfer thus covering approximately 314 m USD per event). It comes at a cost of 1 m USD plus 2% of the cover amount (a simple proxy for transaction and capital costs) plus 1.5 times *(the risk_transf_cost_factor*) the expected damage in the insurance layer (more to illustrate the implementation in principle than to model a specific case).

3.1.2 Cost and benefit of adaptation measures under changing risk

Risk to tropical cyclones during the 35 years of implementation of the measures will change because of economic development (increased exposure and modified impact functions) and climate change (changing hazard). In order to assess the uncertainty of the future, CLIMADA compares different plausible future scenarios. We consider here a moderate scenario, where the economic growth follows the trend of the previous years, a 2% annual increase, and the change in tropical cyclones follows a climate change stabilization scenario, the Representative Concentration Pathway (RCP) 4.5. We implement the consequent changes in intensity and frequency of tropical cyclones at 2050 following Knutson et al. (2015). Under this scenario the AAI is increased by 23 m USD, leading to a mean AAI of 41 m USD in 2050. Considering a linear change of risk during the 35 years and a discount rate of 2%, the Net Present Value (NPV) of the total expected damages is 723 m USD, 57% higher than without increase of risk due to economic development and (moderate) climate change, as illustrated in Figure 3~~Figure 3~~. Almost one fourth of the damage increase in the moderate scenario is attributable to climate change, while the main increase is due to economic development. These changes in risk over time have a substantial impact on the cost-benefit analysis of the adaptation measures.

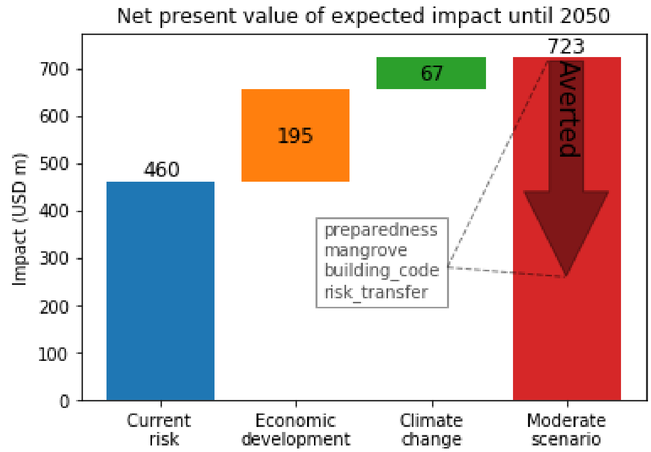

Figure 3: Net Present Values (NPVs) of the expected tropical cyclone damages (average annual impact, AAI) in Anguilla by 2050. *Current risk* represents the NPV of the expected impacts from 2016 until 2050 if neither assets nor climate changes. *Moderate scenario* shows the NPV of expected impacts with moderate economic development and climate change following RCP 4.5. Separate contribution to the total expected impact are shown in columns *Economic development* and *Climate change* respectively. The arrow *Averted* shows the quantity of impact that can be averted ~~implementing~~ combining the measures *preparedness, mangrove, building_code* and *risk_transfer*, as explained below (Figure~~.~~ 4).

Figure 4~~Figure 4~~ represents the NPV of the expected impact ("Total risk" tag) without changing risk (a) and with the moderate risk increase scenario (b). These amounts are compared to the total averted impact of each measure in the x-axis. Whilst with current risk the implementation of all measures could eventually lead to avert almost all of the expected impact, this is not possible by 2050 any more, given the increase in risk both driven by economic growth and climate change (Figure~~.~~ 3~~1.~~), despite the concomitant increase in averted impact of each measure. Nevertheless, the cost-effectiveness of all measures increases in the moderate scenario (and would even more so in a high change scenario). *Preparedness* and *mangrove* increase their benefit/cost ratio to values well above 1, 11.7 and 4.5 respectively, while the grey solutions effectiveness increase more moderately. *Retrofit* remains the measure averting most of the damage after *risk_transfer* but is still not cost-effective, reaching a benefit/cost ratio of 0.88. *Building_code* averts ~~more than~~order of 1 m USD of damage more than *mangrove* but its benefit/cost ratio stays bellow 2. The *risk_transfer* option is not cost-efficient in the narrow sense, due to transaction and capital costs, but likely remains attractive to a risk averse agent nevertheless (e.g. Jullien et al., 1999).

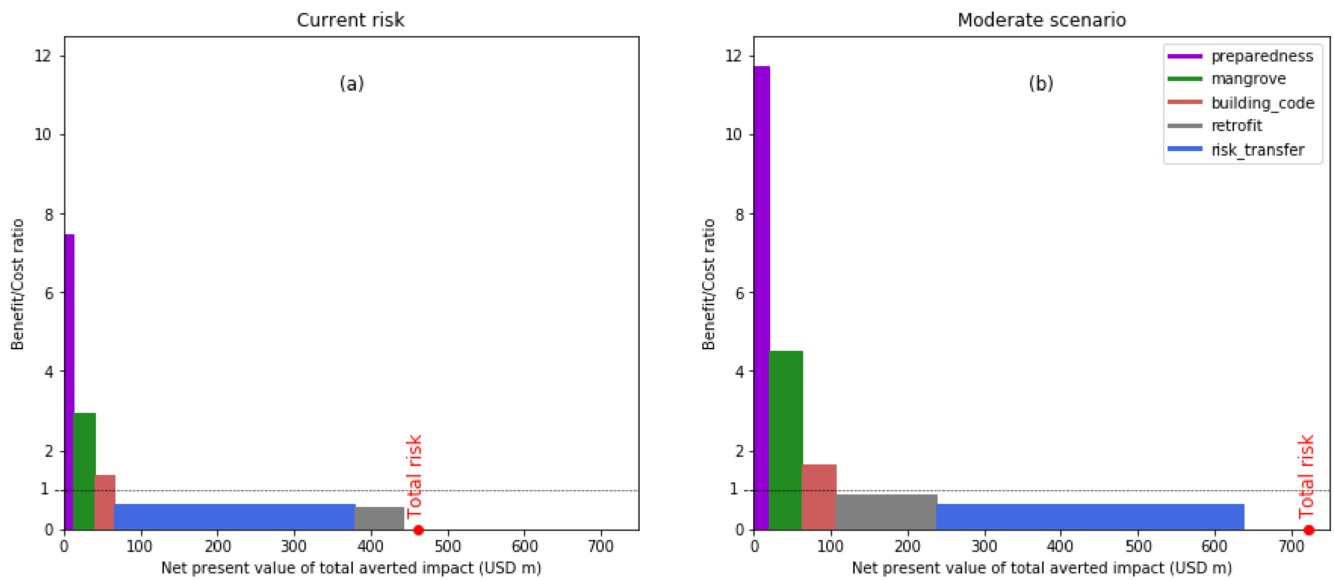

Figure 4: Net present value (NPV) of each measures total benefit and benefit/cost ratio without a changing future (a) and with a scenario of moderate change (b). "Total risk" indicates the NPV of the total damage expected if no measure is implemented (as in Fig 3. Above).

How the measures perform is further represented in Figure 5~~Figure 5~~. The expected exceedance damages for events of return periods 7, 10 and 40 are shown together with the amount of damage that every measure averts, both considering the current risk (a) and the moderate change scenario (b). By construction, *p~~P~~reparedness* averts all the damages for events with return periods lower and equal than 7 years but its protection is minimal for less frequent events. This is not the case of *building_code*, which improves its performance with increasing return period events, the same way as *retrofit* does. The later just averts more damage than *building_code* because it is implemented more extensively. For events with 10 years return period the current risk scenario does not reach the attachment point of the *risk_transfer* (set at 12 years), while the increase in risk under the moderate scenario triggers risk transfer already more often than every 10 years in future. However, even by using *risk_transfer* solutions together with all the other measures, 40-year events cannot be fully covered any more under the moderate change scenario by 2050.

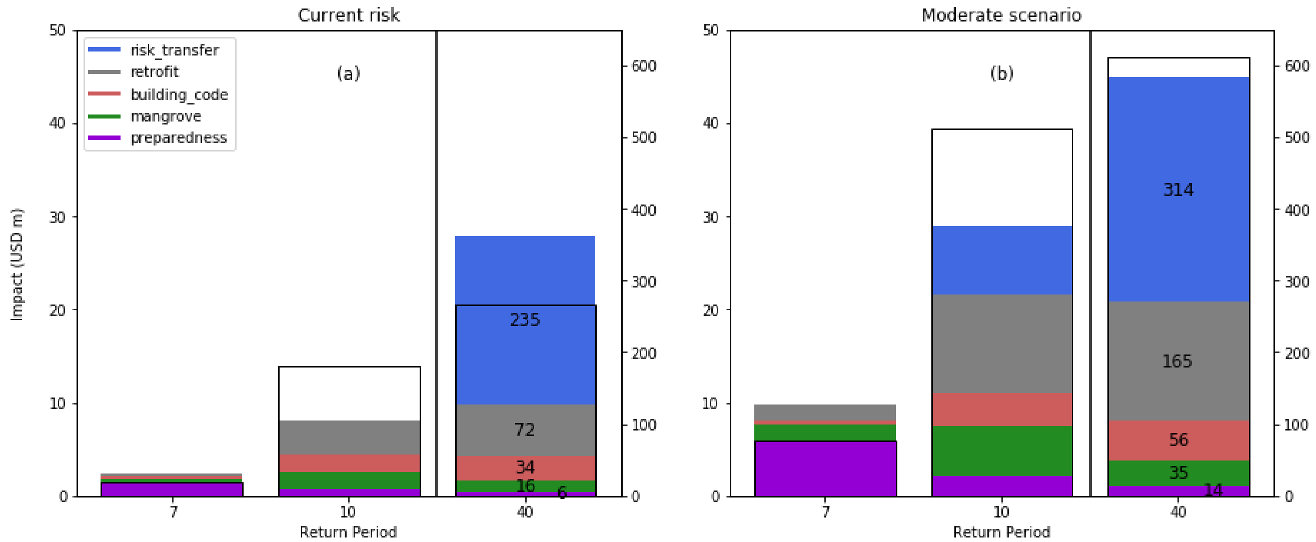

Figure 5: Averted impact of each measure in 2050 for different return periods, without taking into account climate change nor economic growth (a) and with the moderate risk increase (b). The thin black bars show the expected exceedance damage at each return period and each coloured block indicates the amount averted by the corresponding measure. The capacity of measures to absorb damage exceeds expected damage for high frequency (7 year) events and risk transfer is more than sufficient in a). Note the different vertical scale (on the right) for 40 years return period. Shown are non-discounted values.

3.1.3 Combining measures

Figure 4~~Figure 4~~ represents the averted damages of each measure independently. Combining the three most cost-effective measures for Anguilla (*preparedness*, *mangrove* and *building_code*) in the moderate risk scenario only averts a total damage of 104 m USD, just slightly lower than their added benefits (as combining in CLIMADA avoids double-counting). Applying *risk_transfer* on top will further increase the averted damage to 469 m USD, 65% of all the expected damages (see averted damage in Figure 3~~Figure 3~~). Even if *risk_transfer* alone was already averting 399 m USD, the difference of combining insurance with other adaptation solutions leads to a substantial reduction in cost for insurance. Implemented alone, *risk_transfer* costs 605 m USD, compared to 554 m USD when combined with *preparedness*, *mangrove* and *building_code*, leading to an improved insurance benefit/cost ratio of 0.79 instead of 0.66. Please find the detailed results in the in Aznar-Siguan and Bresch, 2020.

3.2 Antilles heterogeneity

To illustrate the capability to consistently assess a basket of adaption options for different territories with common challenges, the same adaptation measures definition of 3.1.1 can be applied for the neighbouring islands using the indicators of Table 1~~Table 1~~. The mangrove protection is ~~artificially~~ set by linearly interpolating ~~from~~ Anguilla's factor proportionally to the island's ratio~~the relation~~ of mangroves' area to ~~the islands~~ total area. A maximum of 1.5% and 3% reduction in intensity is fixed on the coast and inland respectively. The first parameter in brackets is the reduction on the coast and the second for inland.

Island group	Economic growth	Urban growth	Population growth	Mangroves area (ha)	Total area (ha)	Mangrove Protection (%)
Anguilla	2.00	0.90	1.92	90	9,100	(0.74, 1.48)
Antigua And Barbuda	2.70	0.55	1.20	700	44,000	(1.19, 2.34)
British Virgin Islands	2.00	2.42	2.20	570	15,300	(1.50, 3.00)
Saba And St. Eustatius	2.00	1.00	1.00	0	3,400	(0, 0)
St Barthelemy	2.30	1.00	1.00	2	2,500	(0.06, 0.12)
St Kitts And Nevis	3.00	0.92	0.70	70	26,100	(0.20, 0.40)
St Maarten	2.10	1.56	1.39	0	3,700	(0, 0)
St Martin	2.30	1.00	1.00	25	5,300	(0.35, 0.71)
Turks And Caicos Islands	3.00	1.77	2.09	23,600	61,600	(1.50, 3.00)
US Virgin Islands	2.00	0.10	0.00	150	34,600	(0.33, 0.65)

Table 1: Economic and environmental indicators used in the cost and benefit analysis of adaptation measures per island group. Mangrove protection refers to the percentage of intensity reduced on the cost and in the inland, respectively. The mangrove area (in hectares, ha) is extracted from Food and Agriculture Organization of the United Nations (2007) and the indicators from Central Intelligence Agency (2019).

With this simple setting the different situations of the islands become apparent. Taking the three most cost-effective measures for each island group and combining them together with the *risk_transfer* option, between 53% and 76% of the total accumulated damages can be averted with a benefit/cost ratio ranging from 0.74 to 0.92. The islands which can avert more than 68% of the damages (represented in gold in Figure 6~~Figure 6~~) manage to do it in different ways. The British Virgin Islands appear to see the most cost-effective measures. By preserving their 570 hectares of mangroves, together with implementing *preparedness, building_code* and *risk_transfer*, they avert 75% of the total expected damages with a benefit/cost ratio of 0.92. Restoring all the mangroves of the Turks and Caicos Islands appears to be far too expensive, with a benefit/cost ratio of 0.09. The grey options *building_code* and *retrofit* are the ones which, together with *preparedness* and *risk_transfer* manage to reduce 70% of the damages with a befit/cost ratio of 0.80 there. Also Saba and St. Eustatius and Sint Maarten need grey solutions, since they have no mangroves to restore, and achieve to avert 73% and 76% of the expected damages with a benefit/cost ratio of 0.74 and 0.79 respectively. The amount of mangroves in Anguilla is enough to make it avert 65% of the damages when combined with *preparedness, building_code* and *risk_transfer* (purple category in Figure 6~~Figure 6~~). This is not the case of the United States Virgin Islands, Saint Martin, St Kitts and Nevis and St. Barthelemy, where the same measures lead to a lower reduction of the damage, between 53% and 61% (cyan category in Figure 6~~Figure 6~~). Finally, Antigua and Barbuda manage to avert a similar quantity of expected damage as the later islands with the same measures but has an increased benefit/cost ratio of 0.84. Detailed results per island as well as the possibility to further experiment with different parameters/settings can be found in Aznar-Siguan and Bresch, 2020.

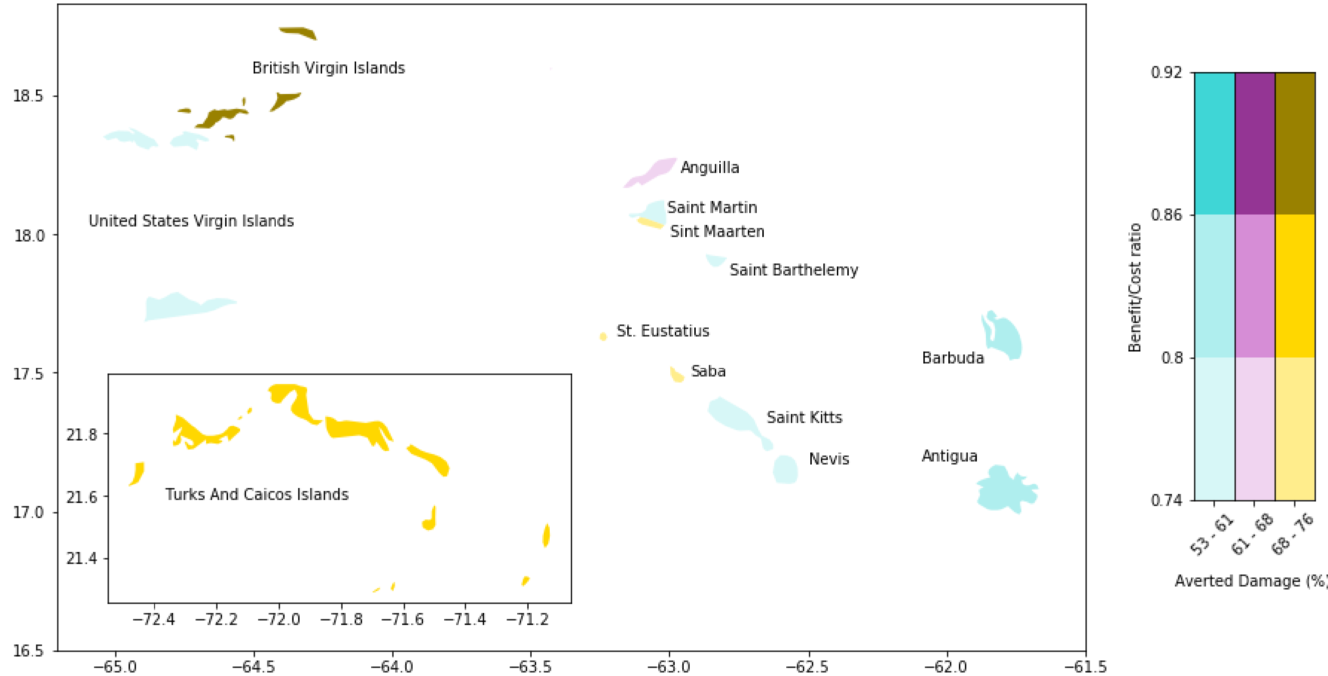

Figure 6: Cost and benefit relations in Antilles selected islands. The three most cost-effective measures are combined with the risk transfer solution and the resulting net present value of the total expected averted damages from 2016 to 2050 (benefit) is categorized into three equally spaced ranges, cyan (53% to 61% damages averted), purple (61% to 68%) and gold (68%-76%) and Benefit/Cost ratio is also shown in three indicative ranges. The color intensity represents the benefit/cost ratio: the darkest colors result in more cost-effective measures.

4 Discussion and Outlook

In this paper we presented the concept of probabilistic options appraisal by extension of the impact modelling platform CLIMADA (Aznar-Siguan and Bresch, 2019b). In addition to the application to a specific and bespoke local situation, the platform allows for an intercomparison of adaptation measures across different contexts. CLIMADA underpins the wider Economics of Climate Adaptation (ECA) approach (Souvignet et al., 2016) and offers ready to use global hazard and exposure models able to provide first approximations at local level and consistent regional comparisons. Additionally, high resolution hazard models as well as specific exposure and impact functions can be implemented in CLIMADA to perform detailed analysis on targeted locations and adaptation measures, which might have been selected based on the findings of a first less granular analysis. Since CLIMADA integrates an end-to-end view on risk, from the risk drivers such as socio-economic development and climate change scenarios up to the resulting metrics for decision-support, it lends itself to comprehensive sensitivity analyses and allows to identify areas for effective model improvement.

Building on previous work (Aznar-Siguan and Bresch, 2019b) we demonstrate CLIMADA's capabilities to analyse a basket of adaptation options for a set of Caribbean islands hit by hurricane Irma in 2017 by use of openly available indicators. Whilst an accurate analysis is out of the scope of this paper, the results illustrate the dependence of cost-effective solutions on social and environmental conditions in a limited area and scope of study. While CLIMADA would lend itself to a detailed assessment of uncertainties in all elements of the analysis, we abstained from doing so in order to keep the case study illustrative and the figures more easily readable. Main drivers of uncertainty, beyond those in hazard, exposure, and vulnerability (Aznar-Siguan and Bresch, 2019b) for the four adaptation measures, while not quantified, can at least be qualitatively described as follows. As for preparedness, the level and scope for this study have been chosen based on general findings of previous ECA studies ~~(~~(Caribbean Catastrophe Risk Insurance Facility, 2010)~~Caribbean Cat Risk Insurance Facility, 2010)~~, where large differences had been found across regions, mainly stemming from barriers to implementation, not least such as lack of agency of non-owner property residents. Notwithstanding, in all cases, preparedness does lower damages and almost always at a Benefit/Cost ratio >1 on a societal level, which does not necessarily mean it being ‘worth the money’ for the single property owner each time. As for mangroves, differences of applicability to single islands have been mentioned above. Again, as shown in studies (Reguero et al., 2018), such nature-based solutions, while difficult to assess at great precision in terms of exact Benefit/Cost, yield ratios far above one if applied at scale. With building codes, it all depends on design - and enforcement. The latter being utterly cultural, any assessment must remain spurious, even past experience might not provide solid a guidance for present and future uptake. On the other hand, implementation is rather straightforward in CLIMADA in terms of the impact function as far as the design component is concerned, hence relative uncertainty can be limited there. Retrofit is implemented the exact same way as building codes and exposed to the same threat of enforcement. Risk transfer in contrast to measures discussed so far, being a purely monetary transaction, shows, in its assessment at least, less uncertainty. But it inherits all the underlying uncertainty of the probabilistic model as well as of the measures in terms of their risk-reducing capacity. Testing with many (sets of) parameters (Aznar-Siguan and Bresch, 2020), results regarding the effectiveness of risk transfer proved robust and, most importantly, the relative order of measures in terms of cost-effectiveness in general is very robust, too.

We show that combining measures of different nature, such as mangrove restoration, preparedness, building codes enforcement and retrofitting, can increase the amount of averted damage in a cost-effective way. In Anguilla restoring mangroves averts simulated expected damage of more than 40 m USD over the next 35 years in a moderate climate change scenario. This~~, which~~ represents 6% of the scenario’s expected damage and more than 4 times the cost estimated for restoration (confirming the finding of a study by the Caribbean Catastrophe Risk Insurance Facility (2010) as well as e.g. Reguero et al. (2018)). Furthermore, combining mangroves restoration together with building codes enforcement and preparedness increases the averted damage to 14% of the expected damage by 2050 with a cost of approximately one third of the overall benefit. On the other hand, in the Turks and Caicos islands enforcement of building codes results in a more cost-effective measure than mangrove restoration, with a cost- ¾ of the benefit. The reason ~~is that~~being, even if both measures avert an expected damage of approximately 220 m USD (11% of the islands expected damage), the restoration of mangroves needs to be implemented just in targeted areas to avert more damage than the invested capital. In these islands the combination of ~~the~~ grey measures, namely building codes enforcement and retrofitting, with preparedness education averts 35% of the simulated expected damages in a moderate climate change scenario by 2050 with a high - but effective - cost of 97% of the benefit. In order to avert a significant fraction (more than 50%) of the expected damage over the next 35 years, risk transfer shows to be the most effective complement in all cases studied. Combining insurance – be it indemnity-based or parametric (Caribbean Catastrophe Risk Insurance Facility, 2015) – with other cost-efficient measures reduces its cost (by 50 m USD in the case of Anguilla and 250 m USD in the Turks and Caicos islands) and covers damage of high impact events which cannot be cost-effectively ~~prevented~~ averted by other measures.

While the idealized case study already provides elements relevant for the development of adaptation strategies and the interplay of prevention, preparedness and risk transfer (c.f. Joyette et al. (2015)), further locally bespoke data would improve the accuracy and representativeness of results, starting from spatially-explicit mapping of specific exposures such as infrastructure and sectoral split. The concept could handle both indirect impacts (business interruption etc.) as well as series of consecutive events, but we did not venture into these forays for lack of data to validate the model with.~~,~~ S~~s~~imilar for other related hazards, where one could expand to torrential rain and separate wind from surge action for tropical cyclones, which would pose a major challenge as there is no separately reported damage and indirect methods would introduce further uncertainties (Strobl, 2012). Methodologically, as mentioned in the introduction, Cost Benefit Analysis (CBA) and Multi-Criteria Analysis (MCA) are not mutually exclusive, and a comprehensive analysis builds on both used in conjunction with each other. While ECA studies in cities in other regions such as in El Salvador or Bangladesh (Wieneke and Bresch, 2016) did consider asset damage and impacts on people affected and lives lost in their pertinent metrics, some earlier studies also compared health impacts of reduced reservoir outflow (measured in disability adjusted life years as in Finkel (2019)) with hydropower production (measured in MWh and electricity costs) in Tanzania (Bresch and ECA working group, 2009). In order to keep ~~it~~ the case study exemplary and simple, we did not introduce metrics other than direct damage. ~~in the present case study, with~~ This bears the advantage to easily compare very different adaptation options and their damage aversion potential by reducing all to a common monetary form. ~~,~~ B~~b~~ut we do see eminent potential to develop both the platform and its applications in the direction towards MCA, with determination of relative weights of the multiple criteria remaining a challenge. So far, ECA analyses in general and the underlying CLIMADA platform in particular do not account for a range of critical factors such as the role of institutions, access to and ownership of resources, agency and leadership (Preston and Stafford-Smith, 2009), to name a few. While this will remain a major challenge for long, we do see potential for further development of both the ECA methodology as well as the CLIMADA platform to better serve adaptive management approaches, as they can be used to support the measurement of successful implementation and hence evaluation of proposed adaptation options and therefore provide a framework for lessons learned to inform future actions in an iterative fashion to make better informed, and often incremental, decisions in the face of uncertainty (Wilby and Dessai, 2010). Such a dynamic simulation platform mitigates shortcomings of static adaptation databases (Mitchell et al., 2016) and lends itself as a basis for web-based adaptation support tools (Glaas et al., 2017) and might hence foster better-informed exchange between the disaster risk management and the climate adaptation (expert) community (Klima and Jerolleman, 2017) not least by informing climate adaptation narratives (Krauß and Bremer, 2020).

5 Code availability and data availability

CLIMADA is openly available in GitHub (https://github.com/CLIMADA-project/climada_python, Bresch and Aznar-Siguan (2019a)) under the GNU GPL license (GNU Operating System, 2007). The documentation is hosted in Read the Docs (https://climada-python.readthedocs.io/en/stable/, Aznar-Siguan and Bresch (2019a)) and includes a link to the interactive tutorial of CLIMADA. v1.4.1 was used for this publication, which is permanently available at the ETH Data Archive: http://doi.org/10.5905/ethz-1007-252 (Bresch et al., 2020). The script reproducing the main results of the paper and all the figures is available under https://github.com/CLIMADA-project/climada_papers (Bresch and Aznar-Siguan, 2019b) and the detailed results for the single islands specifically in https://github.com/CLIMADA-project/climada_papers/blob/master/202008_climada_adaptation/reproduce_results.ipynb (Aznar-Siguan and Bresch, 2020).

6 Author contribution

David N. Bresch conceptualized CLIMADA and oversaw its implementation in Python, based on the previous MATLAB implementation by himself. Gabriela Aznar Siguan designed and executed the Python implementation of the software and did most of the exemplary case study work.

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