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

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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).

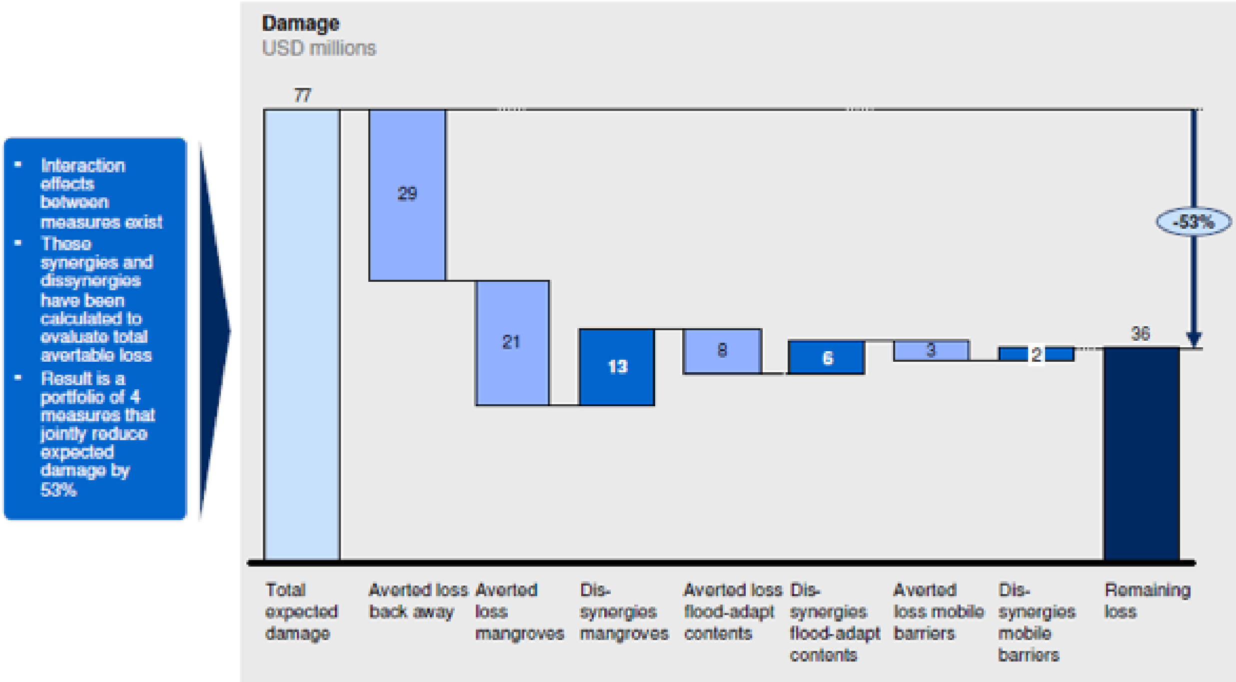

Illustration of dis-synergies (unpublished backup material of the Samoa case study, as summarized in Bresch, D. N. and ECA working group, 2009, https://ethz.ch/content/dam/ethz/special-interest/usys/ied/wcr-dam/documents/Economics_of_Climate_Adaptation_ECA.pdf#page=110). A detailed treatment of this 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.