Referee #2's comments

I appreciate the authors' reframing of the adaptation results as a macro-regional benchmark exercise rather than as direct policy prescription. The revised abstract, the added caveats in Section 2.5 and Section 4.3, and the more moderate language in the conclusion address the concerns I raised about overclaiming. I also acknowledge the addition of Table D3 with the regional CES calibration parameters, which closes a substantive gap in the original submission. These are meaningful improvements.

What I still find problematic is the empirical grounding of the calibration that the rescoped contribution now relies on. The authors state in their response that "a comparison of our adaptation cost estimates, and empirical estimates would be useful, such a comparison is complex. No empirical data exists for all regions and impacts covered in the AD-MERGE model". The authors themselves acknowledge such a comparison would be useful, yet none is provided. The justification offered — that no empirical data exists for all regions and impacts — does not hold, because the comparison does not need to cover all regions to be informative. Doing it for even one region where the data already exists at the appropriate aggregation would substantially strengthen the paper. In the case of Western Europe it is not complex: Cortes-Arbuez et al. (2025) report total national adaptation investment as a percentage of GDP for EU countries and the UK over 2018–2022, which is the same unit and aggregation level as the model's WEU output, with an overlapping time window with the model's 2020-onwards trajectory. The $\beta_{1,r}$ value for WEU in the new Table D3 is 2000, near the top of the 4-to-4000 range (quite a wide range as well) across the 15 regions, which means the calibration is doing substantial work in precisely the region where direct empirical data exists and was not used. An order-of-magnitude check — whether the model's WEU optimal adaptation expenditure for 2020-2025 is plausibly consistent with the 2018-2022 observed investment, or diverges sharply from the start — requires no new modelling. The same concern applies to Africa and Other Asia. The authors describe the scientific value of the adaptation results as "representing broad interregional differences in exposure, adaptive response, and mitigation-adaptation trade-offs within a unified welfare-consistent IAM framework". For this to hold, the model's output for those broad interregional differences has to align, at least roughly, with the empirical regularities of those same macro-regions. The model predicts the largest adaptation benefits in precisely the regions where UNEP (2025) documents a widening gap between adaptation needs and realised action. As with the Western Europe case, the issue is not one of framing but of the model's own output: if the OA trajectory in AFR and OAS already diverges in the near term from what is empirically observed at the macro-regional level, the model is not representing the interregional differences in adaptive response it claims to represent. It is producing a benchmark whose near-term output is inconsistent with the empirical reality of the very regions whose differences are meant to be its contribution.

The authors further position the present study as "an intermediate but necessary step to strengthen the empirical and structural foundation of the adaptation module before richer institutional and behavioural dimensions are incorporated more explicitly", and as setting the stage for "future coupling with more granular, bottom-up behavioral simulations". I would push back on the word necessary. The richer coupling the authors point to as future work is already underway in the literature, including in Filatova et al. (2025), which the authors themselves cite. That line of work couples IAM-type structures with microdata-driven simulations that match observed empirical regularities. The present paper is therefore not a necessary precondition for that integration. It is one possible route, and the route it chooses — a top-down recalibration without empirical validation of the resulting expenditure trajectories — is precisely the route that the more recent literature is moving beyond.

The authors' own response defers a fuller empirical description of the calibration to a "forthcoming paper on the impacts and adaptation calibration". For a model-description paper whose central contribution now rests on the credibility of the macro-regional benchmark, deferring the empirical foundation to a future publication is not adequate. The abstract states the results highlight "critical trade-offs and synergies between adaptation and mitigation strategies, [...] regional heterogeneity in adaptation needs, residual damages, and mitigation-adaptation interactions". Without minimal empirical anchoring at the macro-regional level, the adaptation component risks misleading rather than informing the analysis of exactly those interactions. In that case it would be more scientifically honest not to include adaptation at all, rather than to include it in a form that can produce misleading conclusions about the mitigation-adaptation interplay that the paper makes central. To summarise what I think still needs to be addressed before recommending acceptance:

(a) A direct comparison of modelled WEU adaptation expenditure (% of GDP) for 2020–2025 against the Cortes-Arbuez et al. (2025) estimates for 2018–2022, with a discussion of whether the model's trajectory is plausibly consistent with observed investment levels. If the comparison reveals a substantial discrepancy, the implications for the interpretation of the adaptation results need to be addressed in the discussion, not just reported.

(b) Either inclusion of the empirical calibration description within this paper, or, if deferred to the forthcoming paper, citation of that paper as a preprint with a DOI so it is accessible to readers and reviewers.

(c) A direct comparison in the discussion of the modelled OA adaptation trajectory for AFR and OAS in the near term (2020–2030) against the levels of realised adaptation and the adaptation needs documented by UNEP (2023, 2025) for these regions. If the model's near-term OA output already diverges substantially from what is empirically observed, the implications for the interpretation of the "broad interregional differences in adaptive response" the paper claims to represent need to be addressed.

If the authors consider any of these comparisons or the calibration documentation not to be feasible within the scope of the revision, an explicit and substantive explanation of why would itself be informative, both for the interpretation of the current results and for the positioning of the forthcoming calibration paper.

References Cortés Arbués, Ignasi, et al. "Private investments in climate change adaptation are increasing in Europe, although sectoral differences remain." Communications Earth & Environment 6.1 (2025): 470.

Response to Referee #2

We thank the referee for the reassessment of the manuscript and for acknowledging the improvements made in the revised abstract, methodological caveats, conclusion, and supplementary calibration table. We agree that the adaptation component requires clearer empirical anchoring.

We provide this anchoring by comparing the modelled adaptation costs used in our paper with the modelled costs and financial needs in the UNEP (2025) Adaptation Gap Report. The methodology for calculating the modelled costs in both our paper and the UNEP (2025) report involves calculating adaptation costs within each impact category and summing them to obtain the total adaptation cost for each region. Our modelled costs differ from those in the UNEP (2025) in three main ways: 1. We consider all countries, whilst the UNEP (2025) report only considers developing countries, 2. The exact country composition in each region varies when comparing our regions with the regions in UNEP (2025), and 3. Whilst we both consider the impacts on coastal, river flooding, and health, we also consider impacts on labour productivity and tourism, which they do not. Instead, the UNEP (2025) report includes quantitative estimates of adaptation in agriculture, infrastructure, fisheries, the marine environment, biodiversity and ecosystems, industry, and disaster risk reduction. So, even before we present the empirical comparison, we are aware that our modelled costs are likely to differ from those in the UNEP (2025) report due to different impacts and countries included in the analysis. The comparison with the latest Adaptation Gap Report (UNEP, 2025) was chosen because it incorporates their most recent estimates and thus provides a fairer comparison than an older version. Please note that the exact numbers for the modelled costs are estimates based in Figure 4.1 on page 43 of UNEP (2025) as the exact numbers were not provide.

Table 1 compares the modelled adaptation costs for 2035 in our paper with those in UNEP (2025), expressed in billions of US dollars at constant 2023 prices. This shows that for our paper, the ranking of adaptation costs by region is: OEA < MEA < CLA < OAS< Africa, whilst for UNEP (2025)'s modelled costs, this is OEA < MEA < Africa < CLA < OAS. So, the ranking of OEA < MEA < Africa holds in both our estimates of adaptation costs and in the UNEP (2025) modelled costs. The UNEP (2025) adaptation finance needs for each region, except for OAS, are lower than their modelled cost estimates. The ranking of adaptation finance needs is OEA < MEA < CLA < Africa < OAS. So comparing this to our modelled costs, the ranking is the same for OEA < MEA < CLA < Africa. Compared with our modelled adaptation costs and the UNEP (2025) equivalent, for all regions except OAS, the UNEP (2025) adaptation finance needs fall between our adaptation estimates and the UNEP (2025) estimates.

Table 1: A comparison of annual modelled costs in our paper and UNEP (2025) for 2035 with the finance needs in the UNEP (2025) paper

Region	Our modelled adaptation costs for RCP 4.5 for 2035	UNEP (2025) modelled adaptation costs for 2035	UNEP (2025) adaptation finance needs
OEA (Other Eurasia)	3	7*	5
MEA (Middle East for us and Middle East and North Africa for UNEP, 2025)	12	35*	23
CLA (Other Central and Latin America)	16	50*	34
OAS (Other Asian States)	41	180*	253
Africa (Sub-Saharan Africa for UNEP, 2025)	48	38*	51

Note: We include the North African countries in "Africa" but the UNEP (2025) report includes them in their Middle East and North Africa region. We combine the South Asia and East Asia and the Pacific into our Other Asian States region. *These are estimates based on Figure 4.1 on page 43 of UNEP (2025).

However, Table 1 shows that our modelled adaptation costs differ from those in the UNEP (2025) report. This is mainly because of differences in impact categories and regional composition. Whilst one might expect the UNEP (2025) report to have lower adaptation costs because it considers only developing countries, Table 1 shows that, for all regions except Africa, this does not hold. Whilst the UNEP (2025) does not show the modelled adaptation costs by impact category for each region, it does provide a sector breakdown of its finance needs in Figure 4.3 on page 46 of this report. From this, we can see that the sectoral composition of financial adaptation needs differs by region. Agriculture, infrastructure, forests, ecosystems and biodiversity are key areas of financial need. Whilst these are modelled in the UNEP (2025) report, we do not consider them in our paper. We include tourism and labour productivity instead of these impacts, but the sectoral composition of adaptation finance needs shows that the aggregate tourism and energy adaptation needs are lower than the aggregate finance needs for agriculture, infrastructure, forests, ecosystems, and biodiversity. This comparison sheds light on why our modelled adaptation costs are lower than the UNEP (2025) modelled adaptation costs and the UNEP (2025) adaptation finance needs.

The adaptation finance needs for OAS in UNEP (2025) are larger than the report's own modelled adaptation costs and our modelled adaptation costs. To understand this difference, we examine the sectoral composition of adaptation finance needs in South Asia and East Asia and the Pacific, which are aggregated to align with our OAS region. The majority of adaptation finance needs in South Asia are water supply, infrastructure, disaster risk reduction and agriculture. Of these categories, the UNEP (2025) modelled adaptation costs include infrastructure, agriculture, and disaster risk reduction, whilst we do not include any of these impact categories; thus, our estimate is an underestimate. The majority of adaptation finance needs in East Asia and the Pacific come from the forestry, ecosystems, and biodiversity sector (UNEP, 2025). The UNEP (2025) report includes adaptation costs for protected areas, fisheries and marine whilst we do not include any of these impacts. This explains why our modelled costs for OAS, in particular, are much lower than the UNEP (2025) modelled costs and their adaptation finance needs.

Based on the above, we can see that when we rank regions by their modelled adaptation costs, our rankings are similar to the UNEP (2025) modelled costs for three regions and the UNEP (2025) adaptation finance costs for four regions. The exception in both cases is OAS, as our estimate for adaptation in this region is lower than in the UNEP (2025) Adaptation Gap Report but we are able to explain why this occurs. Based on the comparison with the UNEP (2025) report, we can say that the ranking of interregional differences in adaptation costs and finance needs is similar in our study and in the UNEP (2025) report. However, our estimates are closer to the adaptation finance needs than the modelled costs in the UNEP (2025) report. We hope this analysis has answered the referee's request for an empirical comparison of our modelled adaptation costs and the adaptation finance needs in the UNEP (2025) report.

The referee requested that we compare our estimates with the "levels of realised adaptation" from the UNEP (2023, 2025) reports. These reports contain data on international public adaptation finance flows, which the reports compare with modelled costs or financial needs to estimate the adaptation gap. It is assumed that by "levels of realised adaptation" the referee is referring to the average international finance flows for 2022 and 2023 in the UNEP (2025) Adaptation Gap Report. As UNEP (2025) does, we can compare our modelled 2035 costs with these international finance flows to determine the adaptation finance gap, using the modelled costs as the reference. Table 2 shows this comparison. Again, we can see that for all regions except Africa, the adaptation gap is larger when we compare the international public adaptation finance flows with the UNEP (2025) modelled costs, as these costs are greater than ours, as shown above. Africa is the exception, because our modelled costs were higher than those in UNEP (2025) but lower than the adaptation finance needs for Africa. This may be because we include both North African and Sub-Saharan African countries in our Africa region whilst the UNEP (2025) report only includes Sub-Saharan countries.

Table 2: The adaptation finance gaps with our modelled adaptation costs and the UNEP (2025) modelled adaptation costs as the reference in US$ billions (constant 2023 prices)

Region	Adaptation Gap – Our estimates	Adaptation Gap – UNEP (2025) estimates
OEA (Other Eurasia)	2	6
MEA (Middle East for us and Middle East and North Africa for UNEP, 2025)	10	33
CLA (Other Central and Latin America)	13	47
OAS (Other Asian States)	27	166
Africa (Sub-Saharan Africa for UNEP, 2025)	47	37

Whilst a comparison with the UNEP (2025) modelled costs was useful because of the similarities in the methodology and the impacts considered, a comparison between extreme weather event adaptation is very different to the adaptation costs we consider in our paper. We only consider impacts and adaptation to coastal flooding (this refers to sea level rise not the extreme weather impacts of coastal flooding), river flooding (this does not include extreme weather events), health (we include impacts of heat and cold but not under extreme heatwaves or cold fronts), tourism, energy demand and labour productivity. As such, we do not consider the impacts and adaptation of extreme weather events in our model. We have already established that whilst comparing model costs that have some similarities in the types of adaptation they include is possible, the differences in what impacts are included dilute the comparison. But since the overall methodology for including adaptation is the same, such a comparison is useful. However, comparing our modelled adaptation costs (which do not include adaptation to extreme weather events) with data on adaptation expenditure for extreme weather events (wildfires, extreme heatwaves, droughts, extreme flooding, and other extreme weather events) may confuse the reader and be unhelpful.

From a theoretical perspective, climate change alters future temperatures, affecting tourism, energy demand, labour productivity, and health. When we model these, we focus on the relationship between average temperature change and these impact categories – we do not examine the impact of extreme temperatures on these impacts. Climate change also affects sea level rise and river flooding, but these factors do not account for the impact of extreme rainfall. This approach, which mainly considers average-temperature impacts, is common in the Integrated Assessment Modelling literature (Diaz & Moore, 2017; Howard & Sterner, 2017; Huber et al., 2017; Roson & Sartori, 2016; Tol, 1995; Tol, 2002a; Tol, 2002b). Waidelich et al. (2024) argue that including measures beyond average temperature, such as changes in temperature and extreme rainfall, is important too. However, when we look at which IAMs include extreme weather events, we find that few studies do so (e.g., Narita et al., 2009 (tropical cyclones in the FUND IAM); Narita et al., 2010 (extratropical cyclones in the FUND IAM); Hsiang et al., 2017 (tropical and extratropical cyclones in the SEAGLAS IAM)). Other studies have worked at calibrating damage functions for extreme weather events, but they do not include them in an IAM (Nordhaus, 2006; Mendelsohn et al., 2012; Krichene et al., 2023). This is a gap in the literature which we intend to address in the future (it is the topic of Kirsten Everett's PhD). A fair and useful comparison would be to compare modelled adaptation costs for extreme weather events with the adaptation expenditure reported in the Cortés Arbués et al. (2025) paper. This would be useful because a good proxy for modelled adaptation costs for extreme weather events would be data on actual adaptation expenditure for such events. This would be a like-for-like comparison and would add value to a paper.

However, we do not include adaptation to extreme weather events in our paper; therefore, comparing our modelled adaptation costs with data on adaptation expenditures for extreme weather events is not helpful. This is because it is not a like-for-like comparison. We think that including such a comparison in our paper would confuse the reader, as they would know we do not include extreme weather events and would be confused about why we are comparing our results to adaptation to extreme weather events. From a theoretical perspective, we would not expect the modelled costs of adaptation excluding extreme weather events to be the same as those for adaptation only to extreme weather events. Thus, if we were to compare modelled adaptation costs excluding extreme weather events with actual expenditure data only on adapting to extreme weather events, we would not expect them to match. So, if we carried out this comparison and found that the results do not match, the conclusion is that we are not comparing like-for-like data, and thus we cannot use this comparison to decide whether our model is well calibrated. Based on this, we strongly disagree with the referee's suggestion to compare our modelled adaptation costs with the European data on expenditures for adaptation to extreme weather events (wildfires, extreme heatwaves, droughts, extreme flooding, and other extreme weather events) from Cortés Arbués et al. (2025).

We agree with the referee that we should publish the impact and calibration paper and cite it in this article. We have published this paper as a Working Paper and have cited it in the revised manuscript.

We have also revised the manuscript wording to avoid implying that AD-MERGE predicts realized adaptation implementation. The optimal adaptation scenarios are now consistently described as an idealized benchmark of cost-effective adaptation under unconstrained implementation. We replaced terms such as "adaptive response" with "cost-effective adaptation requirements," "optimal adaptation benchmark," or "idealized adaptation expenditure," where appropriate. We also removed the statement that this modeling step is a necessary precondition for future coupling with behavioral or microdata-driven adaptation models. Instead, we now describe the approach as a tractable top-down route for representing adaptation within a welfare-consistent IAM framework, complementary to more granular bottom-up approaches.

The following text has been added to Appendix D of the manuscript:

"Our estimates of the modelled adaptation costs for 2035 have been compared to the UNEP (2025) Adaptation Gap Report's modelled adaptation costs in 2035 and the adaptation finance needs. Both this article and UNEP (2025) estimate adaptation costs for each impact category and then sum them to obtain adaptation costs for each region. We both include costs of adaptation to coastal flooding, river flooding, labour productivity and health impacts. Whilst we use the same model for river flooding impacts, we use different models for coastal flooding and different data for health and labour productivity impacts. We also consider the adaptation costs to tourism and energy demand impacts, whilst UNEP (2025) includes in agriculture, infrastructure, fisheries, the marine environment, biodiversity and ecosystems, industry, and disaster risk reduction. The UNEP (2025) report also focuses solely on developing countries, and the composition of our MEA and Africa regions differs from theirs. Because of these differences, comparing exact values is less helpful than comparing regional rankings of adaptation costs from lowest to highest. Our ranking of regional modelled adaptation costs in 2035 is OEA < MEA < CLA < OAS < Africa, whilst the ranking of modelled adaptation costs for 2035 in UNEP (2025) is OEA < MEA < Africa < CLA < OAS. Nevertheless, UNEP (2025)'s ranking of adaptation finance needs is OEA < MEA < CLA < Africa < OAS. From this, we can see that our ranking of adaptation modelled costs is similar to the modelled costs of UNEP (2025) but more closely matches the UNEP (2025) ranking of adaptation finance needs. The exception is the ranking of OAS, but this is driven by the lack of agriculture, infrastructure, forestry and ecosystem impacts and adaptation in our model. Based on this validation exercise, we can trust that the ranking of interregional differences in our paper broadly aligns with UNEP (2025)."

"Here, we present only the key functional forms and concentrate on the empirical calibration procedure; for detailed information on this calibration, please see de Bruin et al. (2026)."