New damage curves and multi-model analysis suggest lower optimal temperature – **Supplementary Information**

Contents

SI.1. Extra figures for the RCP comparisons

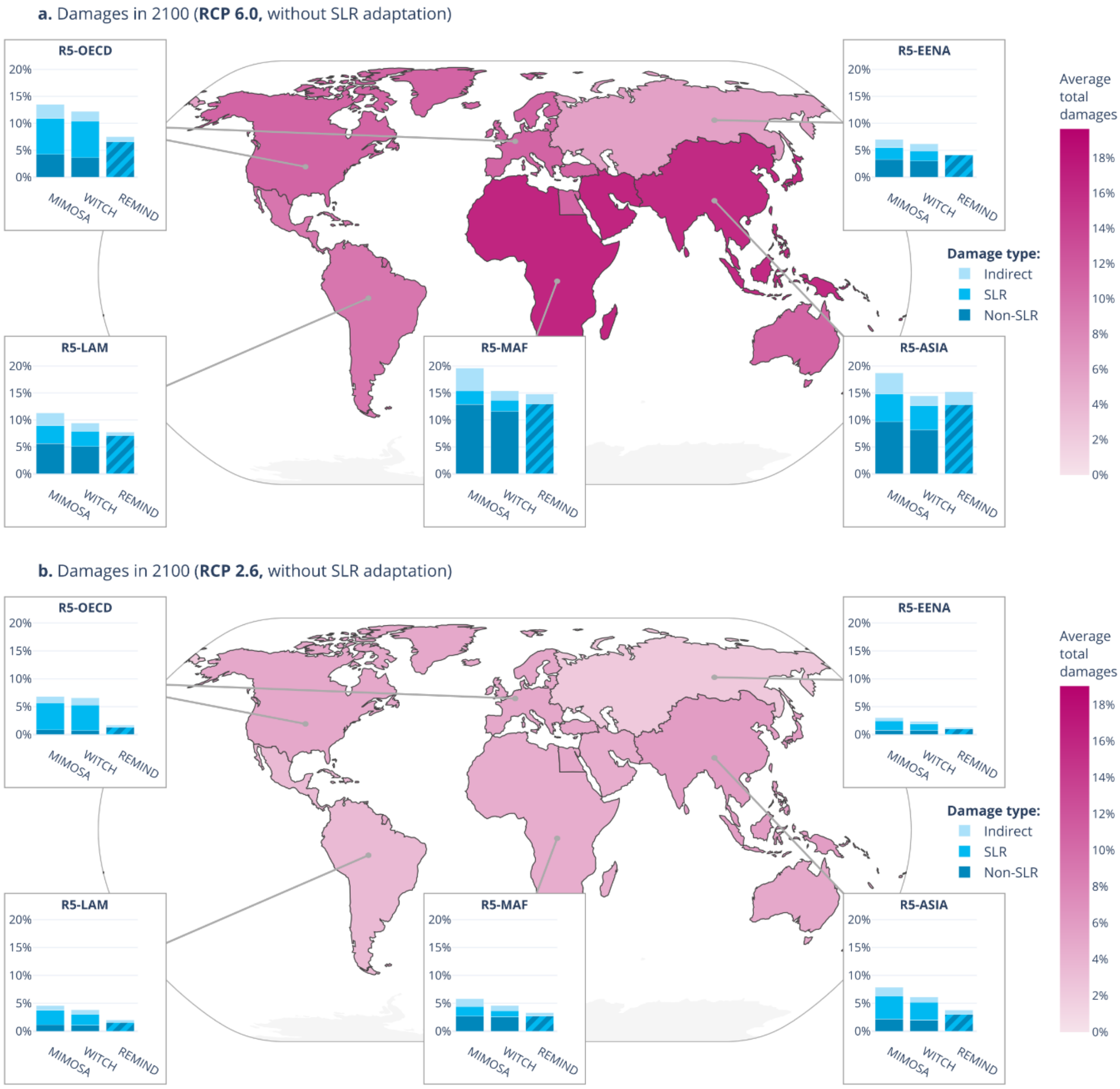


Figure SI.1.1. Regional damage cost decomposition for RCP6.0, without SLR adaptation. The REMIND model doesn't model sea-level rise damages explicitly and uses a combined damage function.

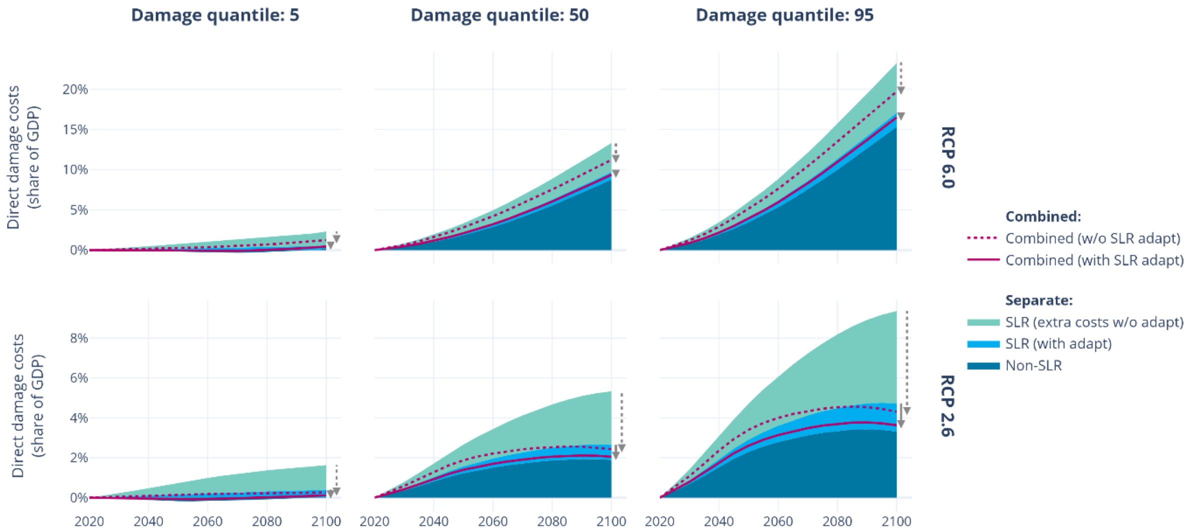


Figure SI.1.2. Comparison of the direct costs when modelling sea-level rise and non-sea-level rise separately (blue/green) versus combined in one damage function (pink lines). All these values are calculated with the same model (MIMOSA) and same scenario settings. The arrows indicate the differences between total separate and total combined, for the scenario with (solid arrow) and without (dotted arrow) SLR adaptation.

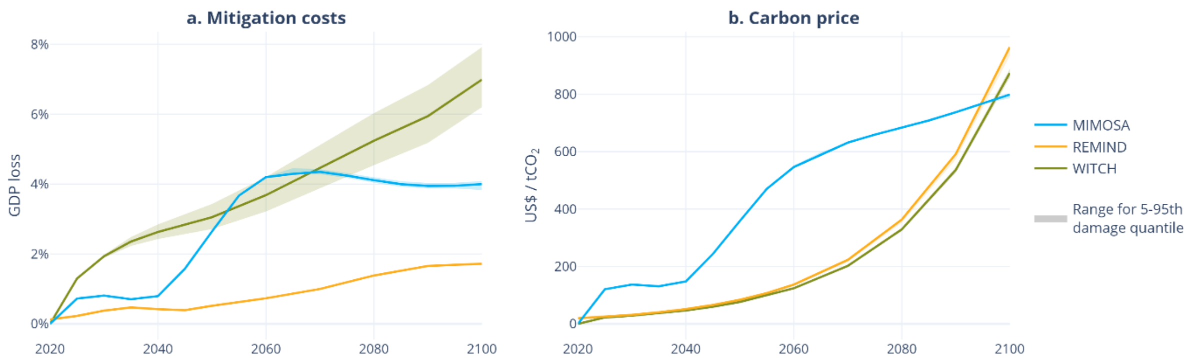
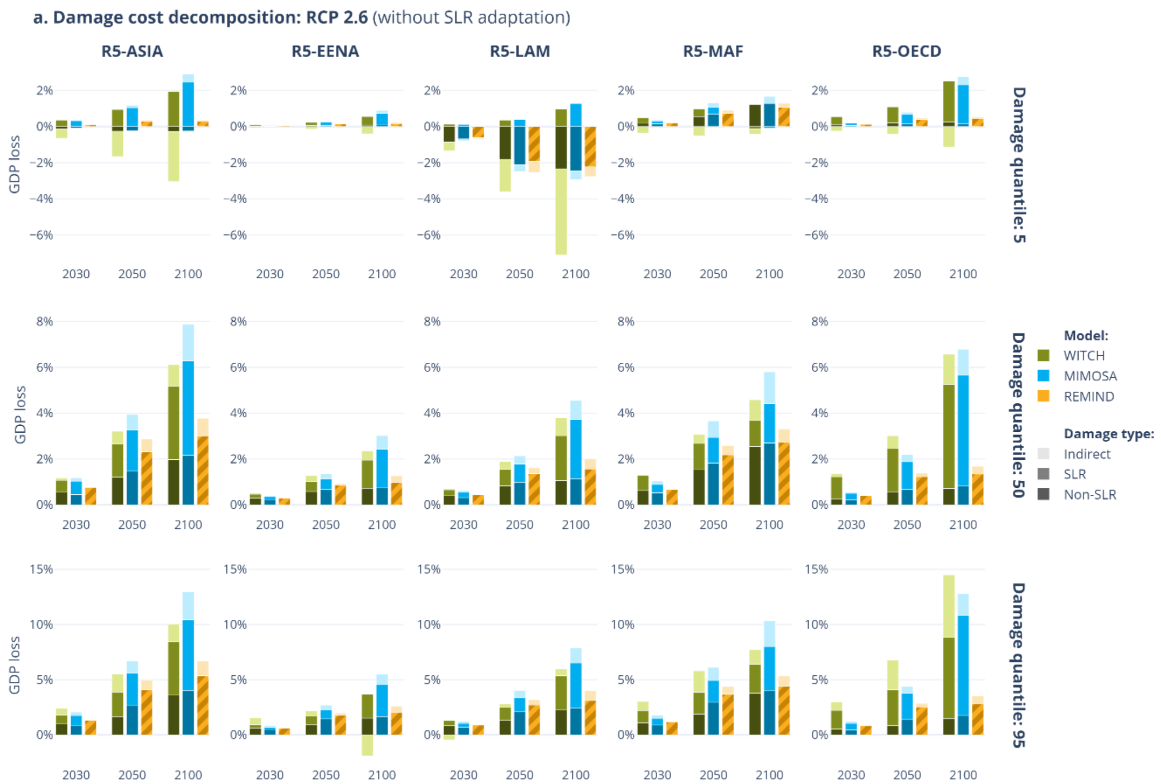
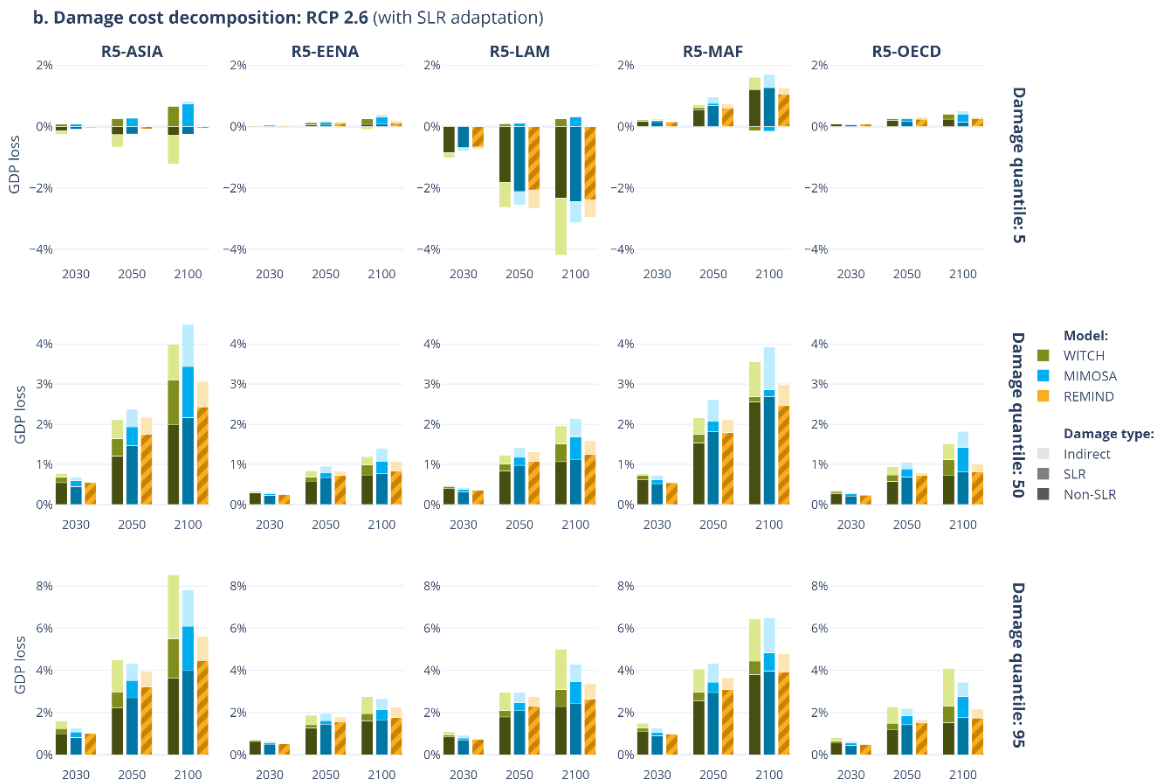
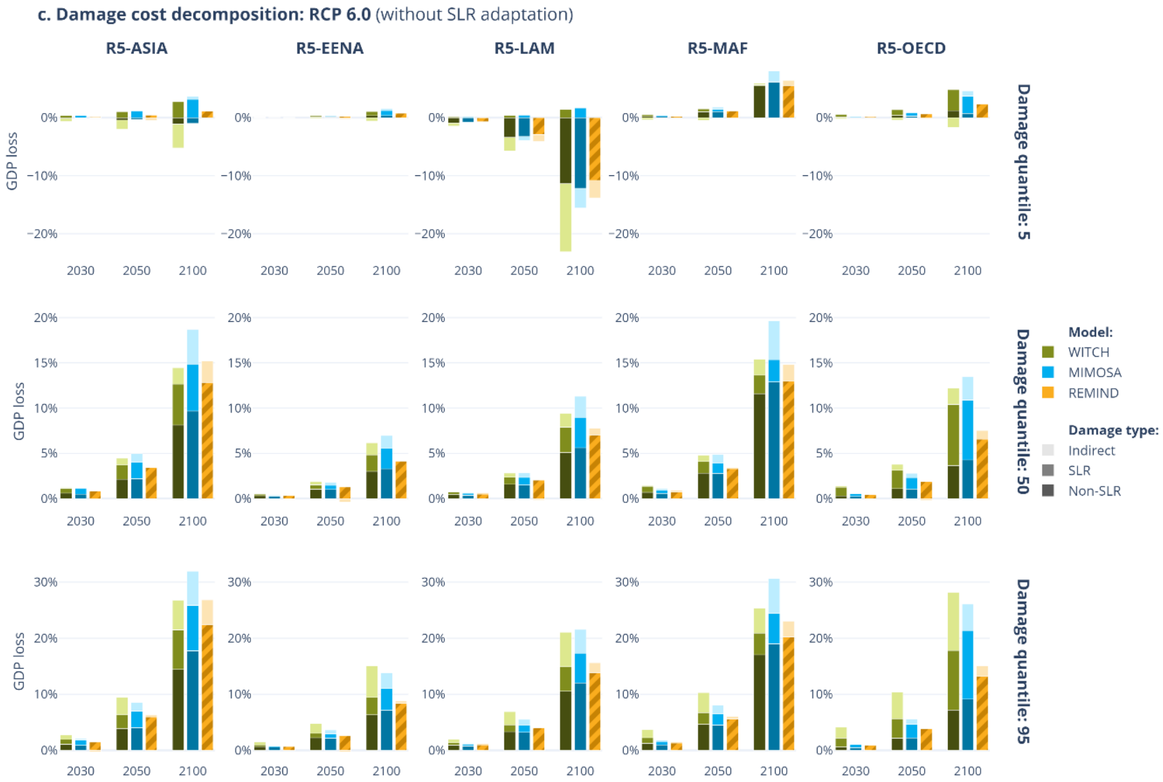


Figure SI.1.3. Mitigation costs and associated carbon prices per model for the RCP 2.6 scenario. The range indicates the ranges for the different damage quantiles. This only results in a range for the WITCH model since in this model the mitigation costs have a stronger dependence on the GDP path: since the different damage levels affect GDP differently, the resulting mitigation costs will also vary.


a. Damage cost decomposition: RCP 2.6 (without SLR adaptation)
R5-ASIA
R5-EENA
R5-LAM
R5-MAF
R5-OECD
GDP loss
Damage quantile: 5
Damage quantile: 50
Damage quantile: 95
2030
2050
2100
Model:
WITCH
MIMOSA
REMIND
Damage type:
Indirect
SLR
Non-SLR


b. Damage cost decomposition: RCP 2.6 (with SLR adaptation)
R5-ASIA
R5-EENA
R5-LAM
R5-MAF
R5-OECD
GDP loss
Damage quantile: 5
Damage quantile: 50
Damage quantile: 95
2030
2050
2100
Model:
WITCH
MIMOSA
REMIND
Damage type:
Indirect
SLR
Non-SLR



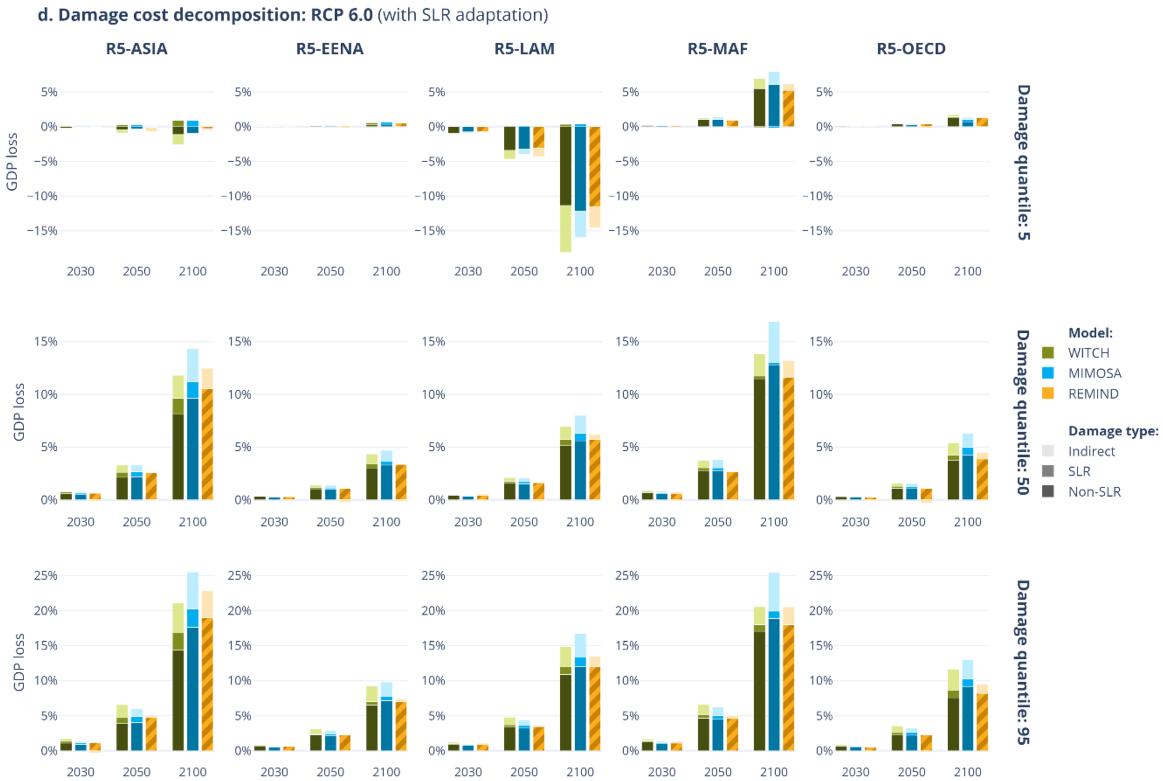


Figure SI.1.4. Regional damages for RCP 2.6 (a, b) and RCP 6.0 (c, d) both with SLR adaptation (b, d) and without SLR adaptation (a, c).

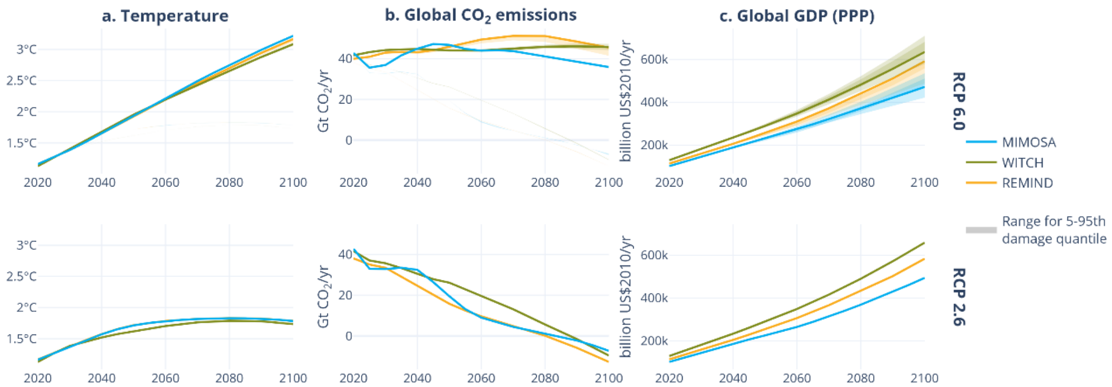


Figure SI.1.5. Temperature, emission paths and GDP per RCP for each model.

SI.2. Extra figures: cost-benefit analysis

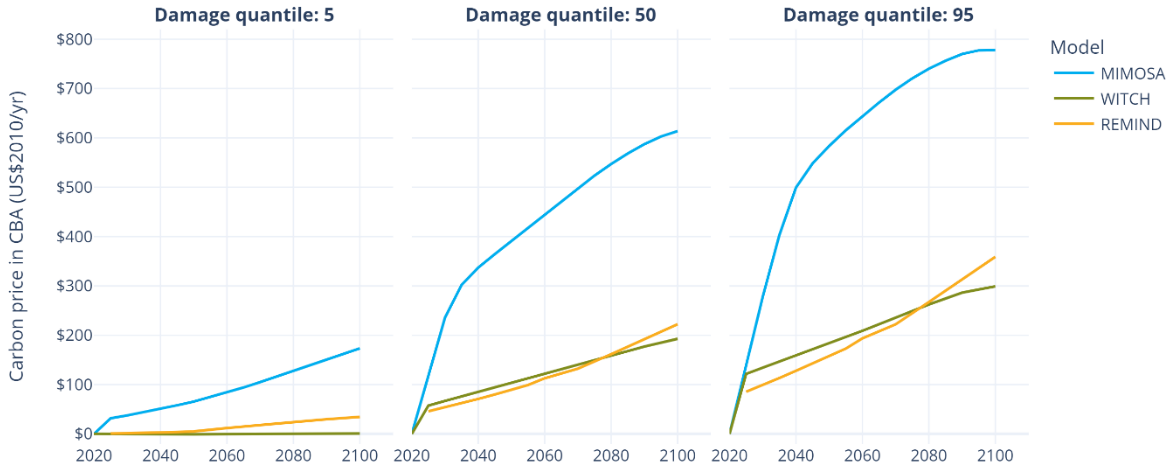


Figure SI.2.1. Carbon prices for the CBA pathways for each model and the three damage function levels (assuming medium discounting).

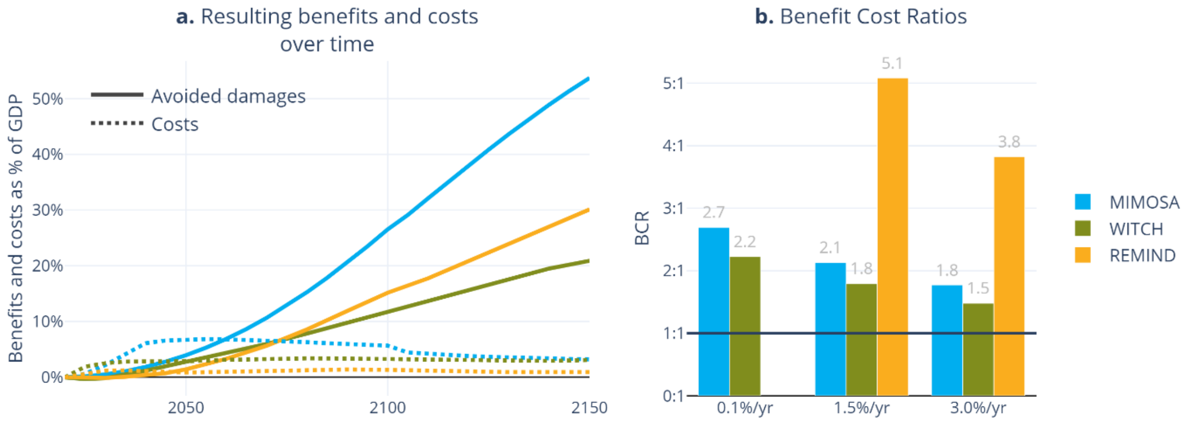


Figure SI.2.2. Benefits, costs and benefit cost ratios for the 95th damage percentile. Left: policy costs (dotted lines) and avoided damages (benefits, solid lines) over time for the scenario with medium discounting. Right: Benefit-Cost Ratio (BCR): total discounted avoided damages divided by the total discounted mitigation costs.

SI.3. COACCH damage functions

SI.3.1. Creation of the damage functions

All the impacts within each scenario combination (Figure SI.3.2.) have been specified for a "low - high" range determined by the variability in output from the climate and the impact models used. The role of market adjustments in determining economic impacts has been also analysed testing result robustness to two assumptions on investment mobility that proved to be very relevant in determining the economic consequences: "high" and "low". The former assumes almost perfect mobility and easier interregional spreading of potential losses on capital stock, the latter assumes capital losses remain within the impacted regions.

The geographical detail of the CGE model is higher than that of the IAMs used. In particular, damages in the EU are specified for 138 single regions. Macroeconomic loss data have been thus aggregated to match the resolution of the WITCH, REMIND and MIMOSA IAMs.

Different functional forms and regression methods to interpolate the data have been tested.[1] Eventually, the better fit was provided by: a linear specification and OLS regression for SLR with adaptation; a quantile regression method and linear or quadratic specification depending on the region[2] for SLR without adaptation; a quantile regression and a quadratic specification for the temperature related damages.

The functional forms used are reported below:

Sea level rise damages with adaptation: $a \cdot (b_1 \cdot SLR)$

Sea-level rise damages without adaptation: $a \cdot (b_1 \cdot SLR)$ or $a \cdot (b_1 \cdot SLR + b_2 \cdot SLR^2)$

Temperature-related damages: $a \cdot (b_1 \cdot \Delta T + b_2 \cdot \Delta T^2)$

The full list of coefficients that have been estimated are reported in Parrado et al. (2021a) and available at: https://zenodo.org/record/5546264#.YlWeBehBw2w

The original data set used for the estimation procedure is reported in Parrado et al. (2021b) and available at: https://zenodo.org/record/5546248#.YlWcXOhBw2w

Additional references

Parrado R., Bosello, F., Van der Wijst, K-I, Standardi G. (2021a), "Reduced-form Climate Change Damage Functions", database, available at: https://zenodo.org/record/5546264#.YlWeBehBw2w

Parrado R., Bosello, F., Standardi G. (2021b), "Macroeconomic assessment of Climate Change Impacts", database available at: https://zenodo.org/record/5546248#.YlWcXOhBw2w

[1] Full results are available upon request.

[2] The regions with a linear especification are: INDIA, JAPAN, NAF, RSAS, SEAS, SSA, WEU (appearing in the MIMOSA model) EUR, IND, JON, SSA (appearing in the REMIND model) Europe, India, jpn_kor, sasia, seasia, ssa (appearing in the WITCH model).

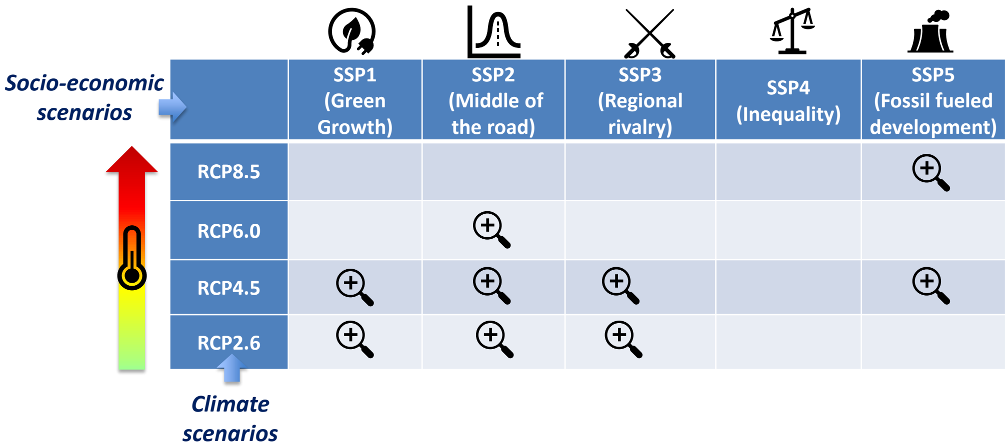
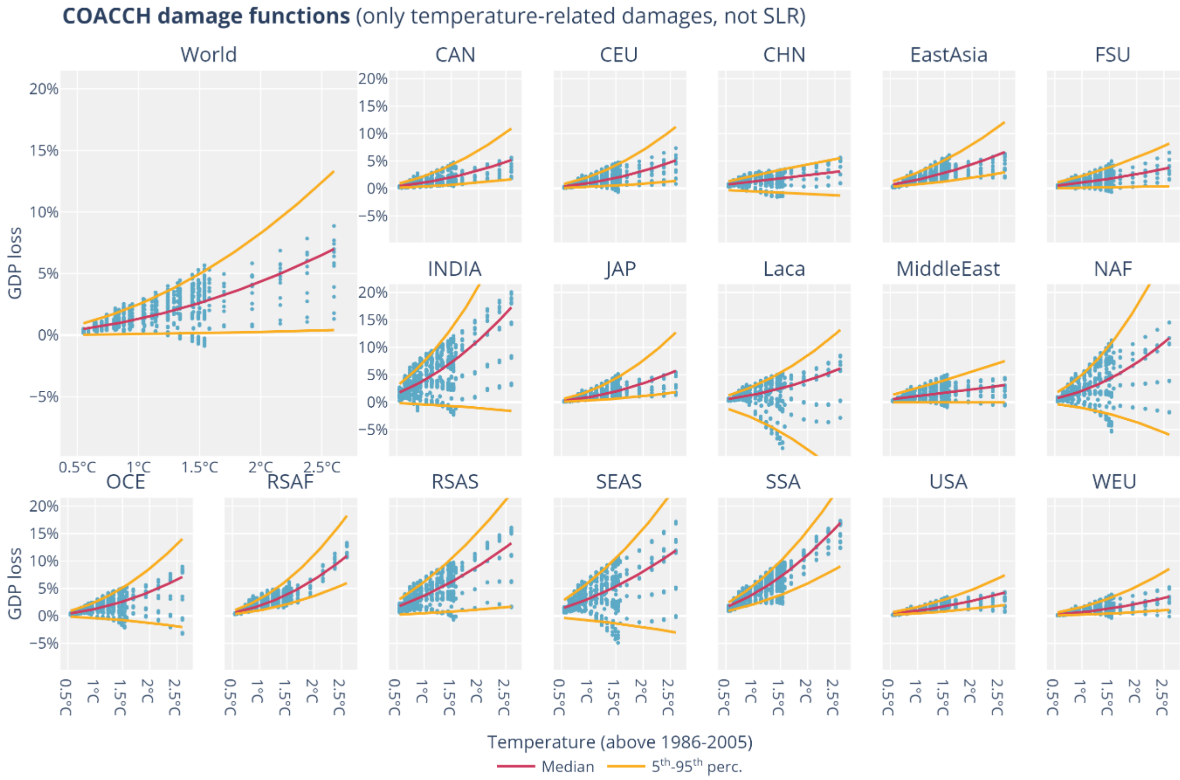
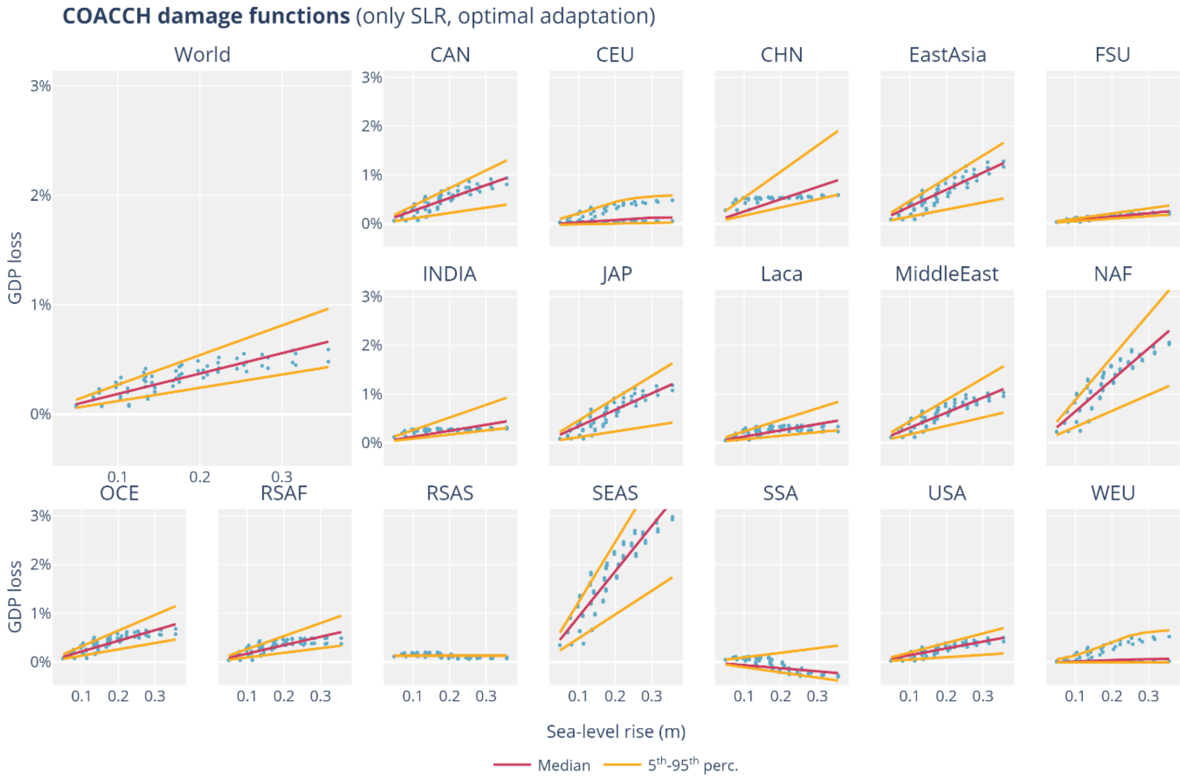
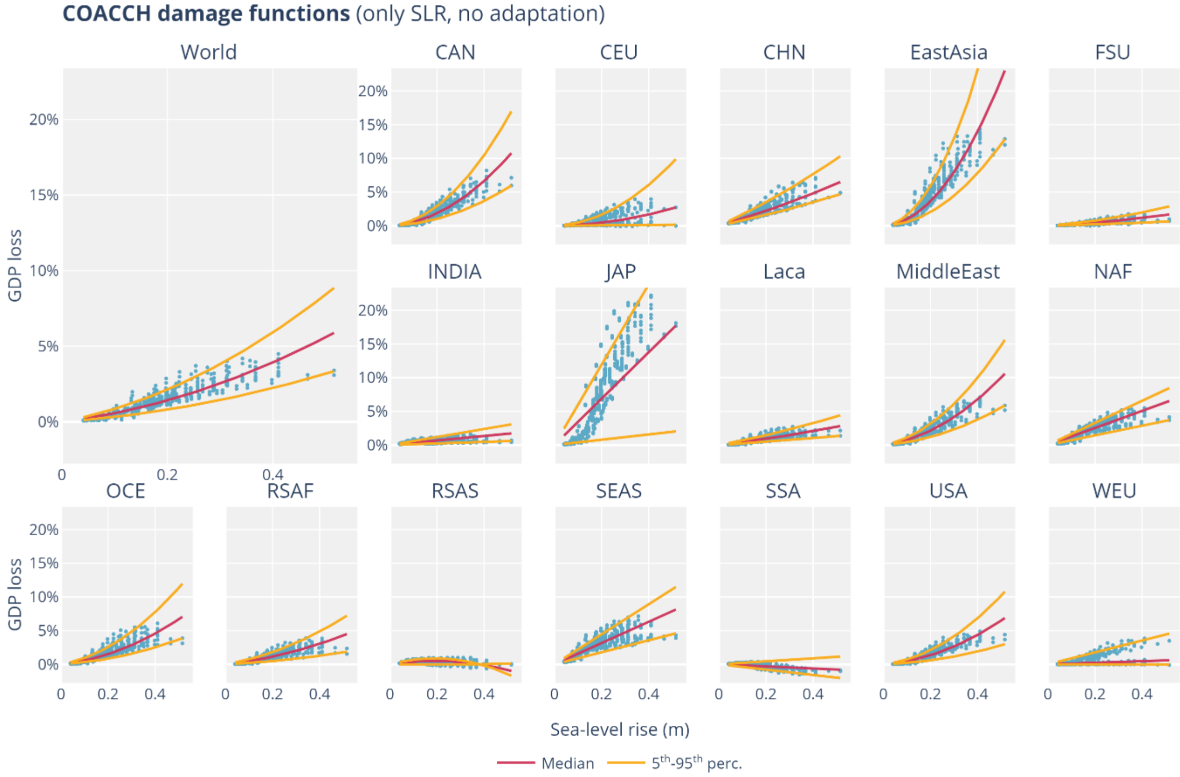


Figure SI.3.1. SSP-RCP scenario combinations examined

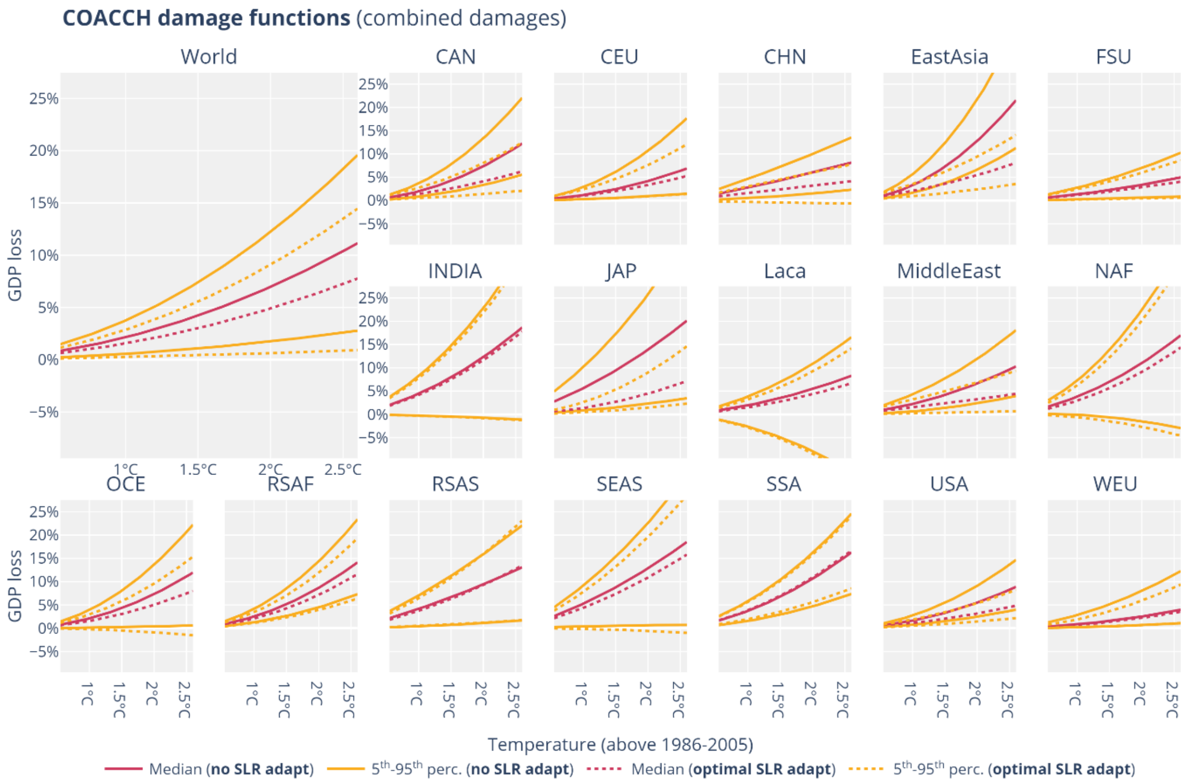
SI.3.2. Regional COACCH damage functions and CGE output







COACCH damage functions (only SLR, no adaptation)
World
CAN
CEU
CHN
EastAsia
FSU
INDIA
JAP
Laca
MiddleEast
NAF
OCE
RSAF
RSAS
SEAS
SSA
USA
WEU
GDP loss
0%
5%
10%
15%
20%
0
0.2
0.4
Sea-level rise (m)
Median
5th-95th perc.



COACCH damage functions (combined damages)
World
CAN
CEU
CHN
EastAsia
FSU
INDIA
JAP
Laca
MiddleEast
NAF
OCE
RSAF
RSAS
SEAS
SSA
USA
WEU
GDP loss
25%
20%
15%
10%
5%
0%
−5%
1°C
1.5°C
2°C
2.5°C
Temperature (above 1986-2005)
Median (no SLR adapt)
5th-95th perc. (no SLR adapt)
Median (optimal SLR adapt)
5th-95th perc. (optimal SLR adapt)

SI.4. Details on the MIMOSA model

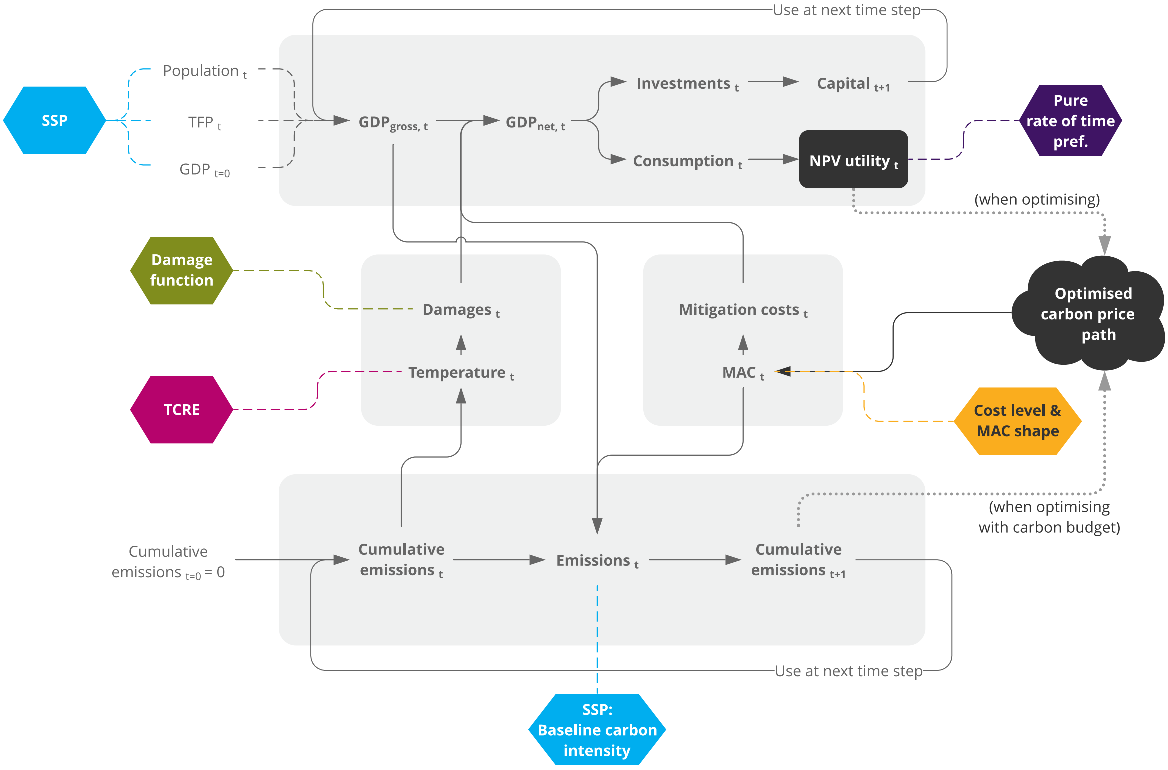


Figure SI.4.1. Overview of the MIMOSA model (reproduced from [2]).

The MIMOSA model is a relatively simple, transparent, open-source IAM based on FAIR [1]. The global version of this model is detailed in [2]. An overview of the model is shown in Fig. SI.4.1. For this paper, we updated the model to become regional, using the 26 macro-regions from FAIR/IMAGE[3]. Specifically, the following aspects were updated compared to [2]:

- Regional population and baseline emission projections, and regional Total Factor Productivity calibration based on baseline GDP projections. We used the Ref-SPA0-V17 IMAGE scenarios for each SSP. In this paper, we only used the SSP2 calibration.

- Regional mitigation cost curves: each region uses the same global Marginal Abatement Cost (MAC) curve as in the global model, with a region-specific scaling factor κ_r:

$$\mathrm{MAC}_{\mathrm{region}\ r}(a;\cdot) = \kappa_r \cdot \mathrm{MAC}_{\mathrm{global}}(a;\cdot)$$

  The values of κ_r are calibrated using SSP2 MAC curves from the TIMER model (the energy submodule of IMAGE), see [3]. By comparing the carbon price per region required to reach 75% CO2 reduction in 2050 compared to baseline, relative to the world average, we obtain a scaling factor for the MAC. This is shown in Fig. SI.4.2a.

[3] See https://models.pbl.nl/image/index.php/Region_classification_map

- Initial capital stock: while GDP and capital stock are endogenous variables through the Cobb-Douglas equation, the initial capital stock needs to be calibrated. For this, we use the Investment and Capital Stock Data (ICSD) from IMF[4] and follow these steps:
    1. The total capital stock is calculated as sum of general government capital stock, private capital stock and public-private partnership capital stock.
    2. This data is summed for all countries within each region
    3. The regional total capital stock is divided by the regional GDP to obtain capital stock as factor of initial GDP.
    4. We use data from 2013 as this is the latest available data from IMF.

    The resulting regional initial capital factors are shown in Fig. SI.4.2b.

- Regional emission reduction constraints: besides the already existing global inertia and minimum emission level constraints, we add regional inertia (each region cannot reduce more than 5% of 2020 emission level per year) and a regional minimum emission level of -10 $GtCO_2$/year.

- Since damages are not expressed exclusively in terms of temperature change anymore, a sea-level rise module has been added. We have used the same SLR module as DICE [4].

- The welfare function has been updated. Yearly and regional utility is defined as:

$$U(t,r) = \left(\left(\frac{\text{consumption}_{t,r}}{L_{t,r}}\right)^{(1-\text{elasmu})} - 1\right)/(1-\text{elasmu}) - 1,$$

with $L_{t,r}$ the population (labour force) and elasmu the elasticity of marginal utility (equal to 1.001). The optimization goal is to maximise the Net Present Value of the summed utility:

$$\text{NPV} = \int_0^T e^{-rt} \sum_r U(t,r) \cdot L_{t,r} dt$$

[4] https://data.imf.org/?sk=0e0209d8-1115-4e84-a419-baa0256b32fb&hide_uv=1

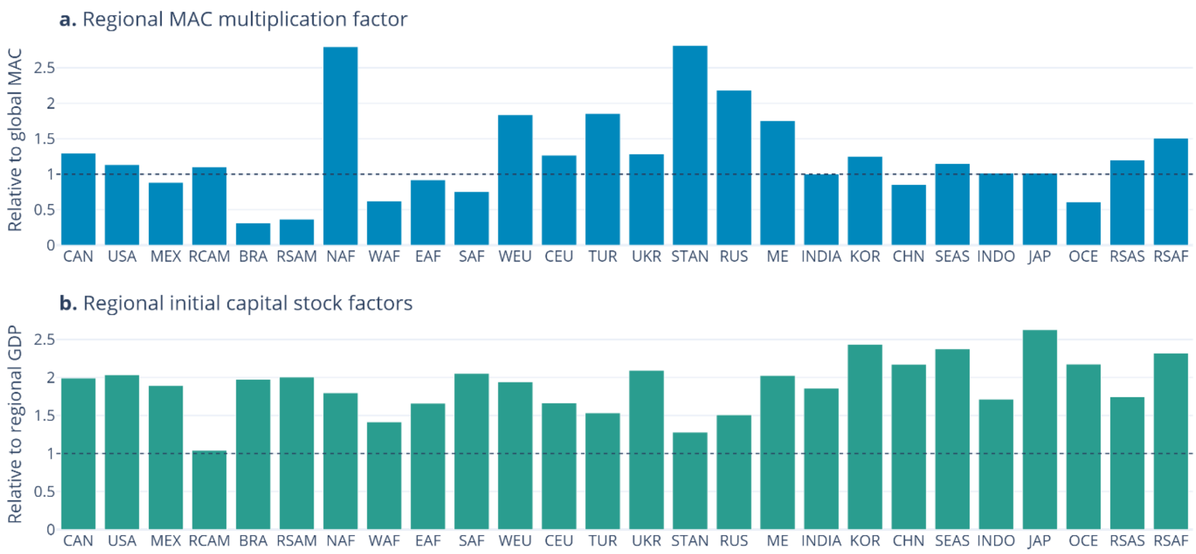
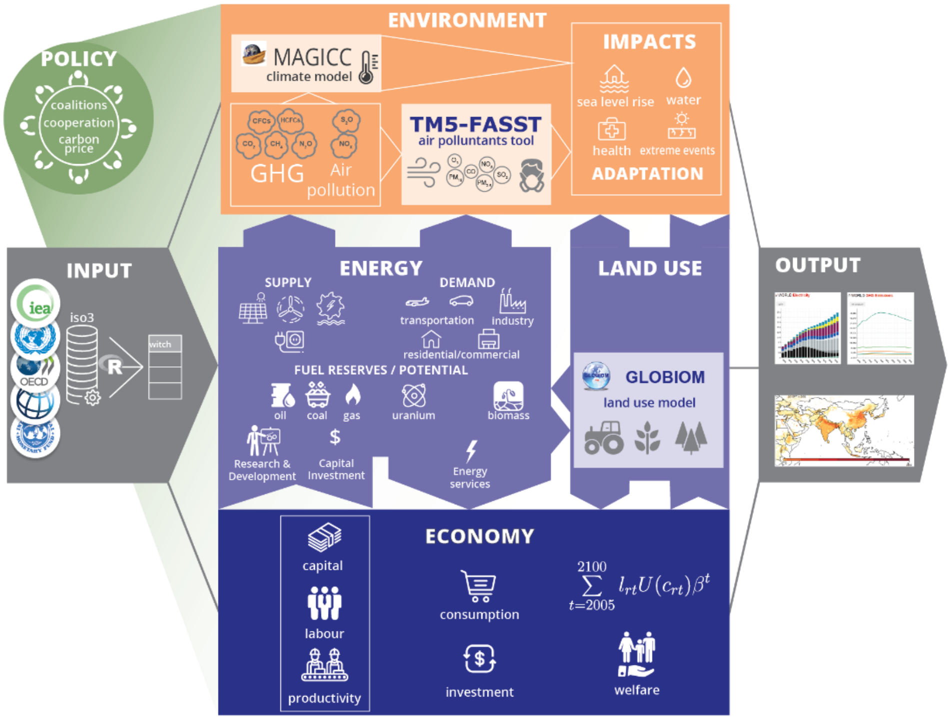


Figure SI.4.2. Regional parameters for the MIMOSA model. Top row: multiplication factor to create the regional MACs, by scaling the global MAC for each region. Bottom row: initial capital stock factors per region, expressed as factor of 2020 GDP.

SI.5. Description of the WITCH model

WITCH (World Induced Technical Change Hybrid) is an integrated assessment model developed and maintained at the RFF-CMCC European Institute on Economics and the Environment and assesses climate change mitigation and adaptation policies [5]. It is open source and its code and documentation is available at www.witchmodel.org. It is a global dynamic model that integrates into a unified framework the most important drivers of climate change and an inter-temporal optimal growth model captures the long-term economic growth dynamics. In the model, a compact representation of the energy sector is fully integrated (hard linked) with the rest of the economy so that energy investments and resources are chosen optimally, together with the other macroeconomic variables.

WITCH represents the world in a set of a varying number of macro regions – for the present study, the version with seventeen representative regions has been used. For each, it generates the optimal mitigation strategy for the long-term (from 2005 to 2100) as a response to a carbon price compatible with external constraints on emissions. A modelling mechanism aggregates the national policies on emission reduction or on the energy mix into the WITCH regions. Finally, a distinguishing feature of the WITCH model is the endogenous representation of R&D diffusion and innovation processes that allows a description of how R&D investments in energy efficiency and carbon-free technologies integrate the mitigation options currently available. Non-CO2 emissions in energy and industry are endogenously modelled with potentials derived from the literature (marginal abatement cost curves).



credits: icons from flaticon.com made by Freepik, EpicCoders, Chanut is Industries, Nikita Golubev, Eucalyp, Made by Made, Zlatko Najdenovski, OCHA, Madebyoliver, Vectors Market

Figure SI.5.1. Overview of the WITCH model.

[1] den Elzen, M. G. J. & Lucas, P. L. The FAIR model: A tool to analyse environmental and costs implications of regimes of future commitments. *Environmental Modeling and Assessment* **10**, 115–134 (2005).

[2] van der Wijst, K.-I., Hof, A. F. & van Vuuren, D. P. On the optimality of 2°C targets and a decomposition of uncertainty. *Nature Communications* 1–11 (2021) doi:10.1038/s41467-021-22826-5.

[3] van Vuuren, D., Stehfest, E., Gernaat, D., de Boer, H.-S., Daioglou, V., Doelman, J., Edelenbosch, O., Harmsen, M., van Zeist, W.-J., van den Berg, M., Dafnomilis, I., van Sluisveld, M., Tabeau, A., De Vos, L., de Waal, L., van den Berg, N., Beusen, A., Bos, A., Biemans, H., … Zapata Castillo, V. (2021). *The 2021 SSP scenarios of the IMAGE 3.2 model [Preprint]*. Environmental Sciences. https://doi.org/10.31223/X5CG92

[4] Nordhaus, W. Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. *Journal of the Association of Environmental and Resource Economists* **1**, 273–312 (2014).

[5] Emmerling, Johannes, Laurent Drouet, Lara Aleluia Reis, Michela Bevione, Loic Berger, Valentina Bosetti, Samuel Carrara, et al. ‘The WITCH 2016 Model - Documentation and Implementation of the Shared Socioeconomic Pathways’. Working Paper. Fondazione Eni Enrico Mattei, 2016. https://ideas.repec.org/p/fem/femwpa/2016.42.html.