„Deep dive into perspectives and challenges“

Nico Bauer
with help from Jiarui Chong and Inga Sauer

Potsdam Institute for Climate Impact Research
PIK

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Passo dello Stelvio, Italy.

Two dimensions of equity and fairness – Are they separate?

Intragenerational equity and fairness

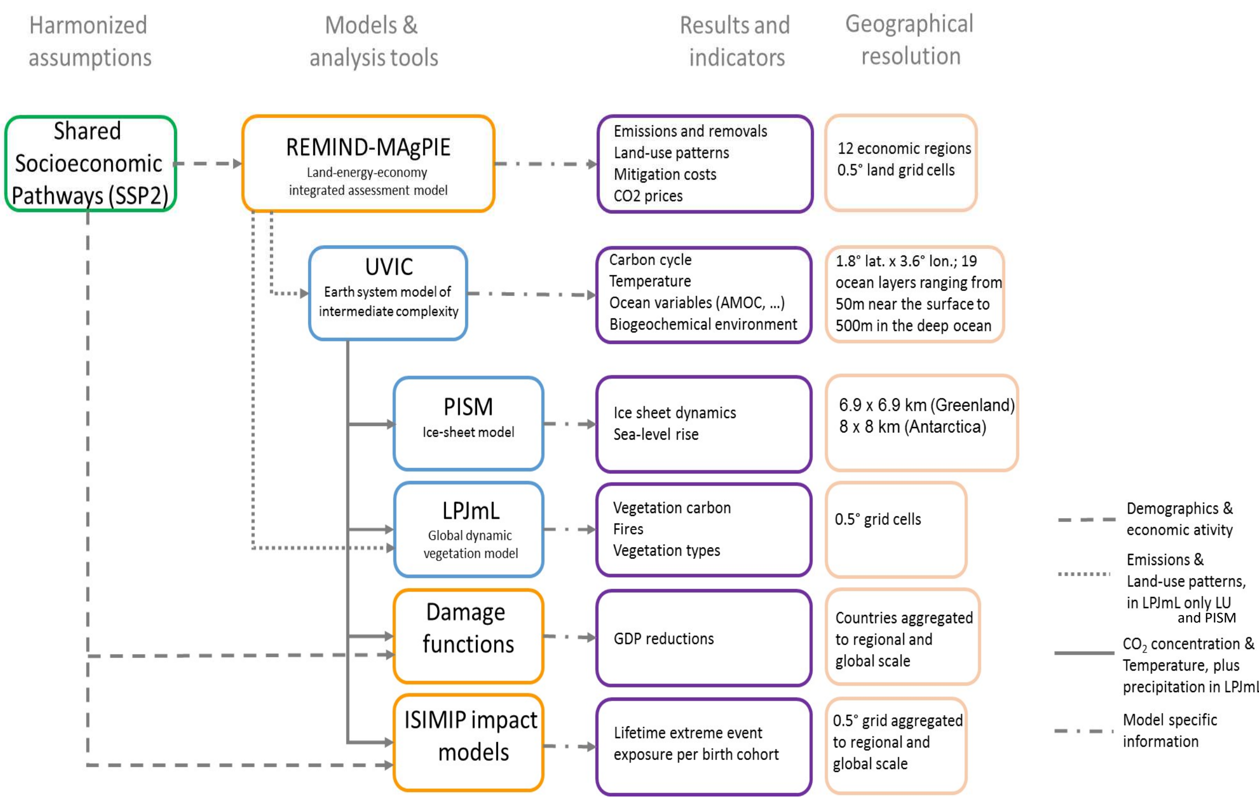
Mostly related to mitigation

Intergenerational equity and fairness

Formula for the fair wage *A* equals the square root of minimum consumption *a* times value of produced goods *p* on grave stone of Johann Thünen (1783-1850). Source: own!

Cookie monster consumes everything he gets immediately
Cookie monster’s pure rate of time preference 100% per second, consequently, his savings rate is zero.

The cause-effect-chain and the models



Bauer et al. (2023)
https://iopscience.iop.org/article/10.1088/1748-9326/accd83

Exploring risks and benefits of overshooting a 1.5 °C carbon budget over space and time

Nico Bauer[1,*], **David P Keller**[2], **Julius Garbe**[1,3], **Kristine Karstens**[1], **Franziska Piontek**[1], **Werner von Bloh**[1], **Wim Thiery**[4], **Maria Zeitz**[1,3], **Matthias Mengel**[1], **Jessica Strefler**[1], **Kirsten Thonicke**[1] and **Ricarda Winkelmann**[1,3]

[1] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany
[2] GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany
[3] Institute of Physics and Astronomy, University of Potsdam, Potsdam, Germany
[4] Vrije Universiteit Brussel, Department of Hydrology and Hydraulic Engineering, Brussels, Belgium
[*] Author to whom any correspondence should be addressed.

E-mail: nico.bauer@pik-potsdam.de

Keywords: carbon dioxide removal, mitigation and impacts, integrated assessment models, Earth system model of intermediate complexity, global south, carbon budget overshoot

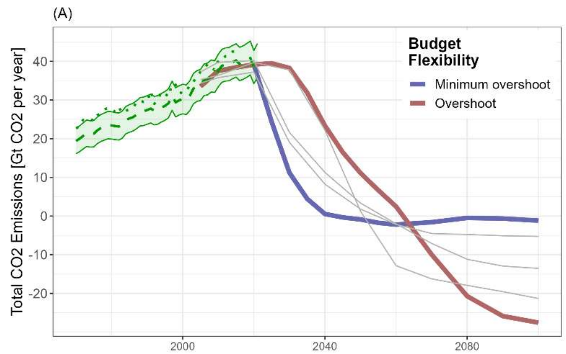
Supplementary material for this article is available online

Abstract

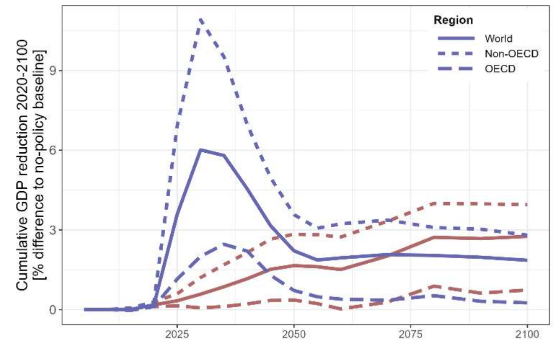
Temperature targets of the Paris Agreement limit global net cumulative emissions to very tight carbon budgets. The possibility to overshoot the budget and offset near-term excess emissions by net-negative emissions is considered economically attractive as it eases near-term mitigation pressure. While potential side effects of carbon removal deployment are discussed extensively, the additional climate risks and the impacts and damages have attracted less attention. We link six models for an integrative analysis of the climatic, environmental and socio-economic consequences of temporarily overshooting a carbon budget consistent with the 1.5 °C temperature target along the cause-effect chain from emissions and carbon removals to climate risks and impact. Global climatic indicators such as CO_2-concentration and mean temperature closely follow the carbon budget overshoot with mid-century peaks of 50 ppmv and 0.35 °C, respectively. Our findings highlight that investigating overshoot scenarios requires temporally and spatially differentiated analysis of climate, environmental and socioeconomic systems. We find persistent and spatially heterogeneous differences in the distribution of carbon across various pools, ocean heat content, sea-level rise as well as economic damages. Moreover, we find that key impacts, including degradation of marine ecosystem, heat wave exposure and economic damages, are more severe in equatorial areas than in higher latitudes, although absolute temperature changes being stronger in higher latitudes. The detrimental effects of a 1.5 °C warming and the additional effects due to overshoots are strongest in non-OECD countries (Organization for Economic Cooperation and Development). Constraining the overshoot inflates CO_2 prices, thus shifting carbon removal towards early afforestation while reducing the total cumulative deployment only slightly, while mitigation costs increase sharply in developing countries. Thus, scenarios with carbon budget overshoots can reverse global mean temperature increase but imply more persistent and geographically heterogeneous impacts. Overall, the decision about overshooting implies more severe trade-offs between mitigation and impacts in developing countries.

Mitigation under a 600 $GtCO_2$ C-budget (2010-2100)

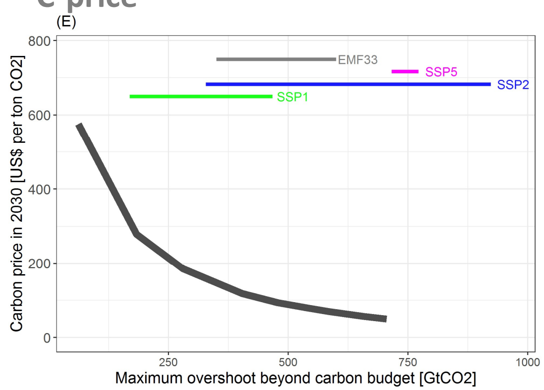
Global net CO_2 emissions



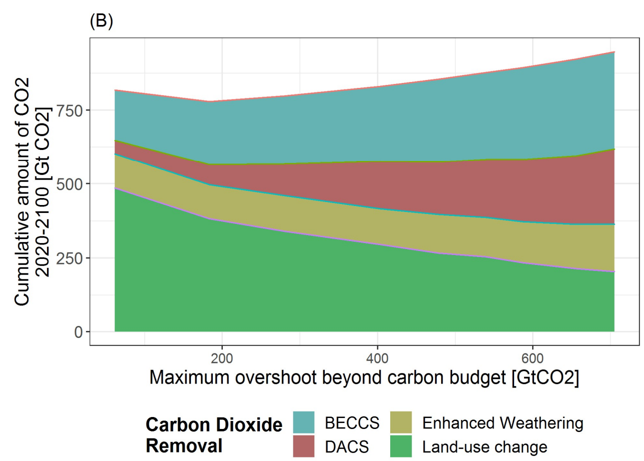
GDP losses (mitigation only)



Max C-budget overshoot and 2030 C-price

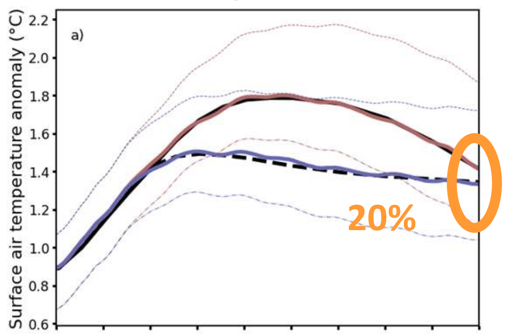


Global cumulative CDR

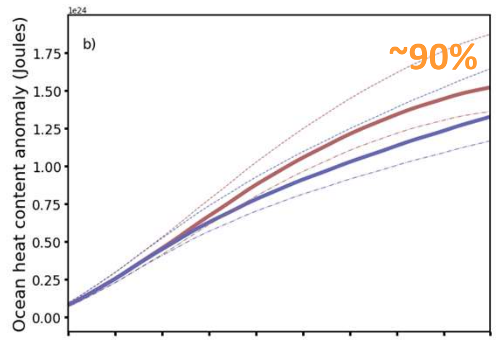


Climate System and key components

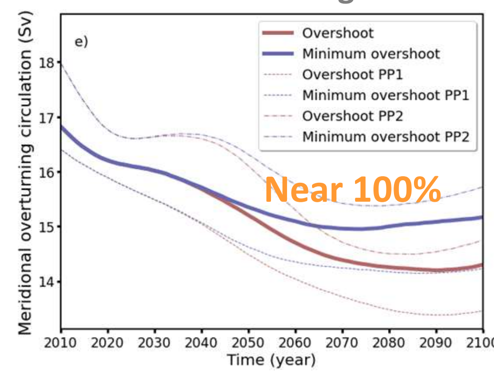
Global Air Temperature



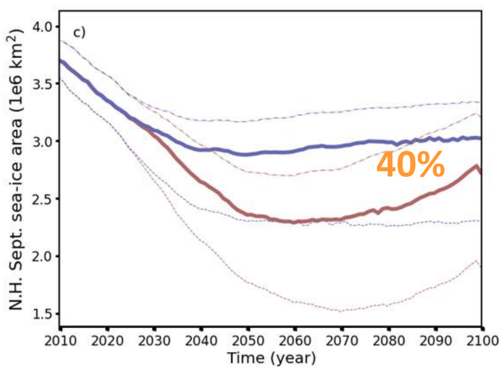
Ocean heat content



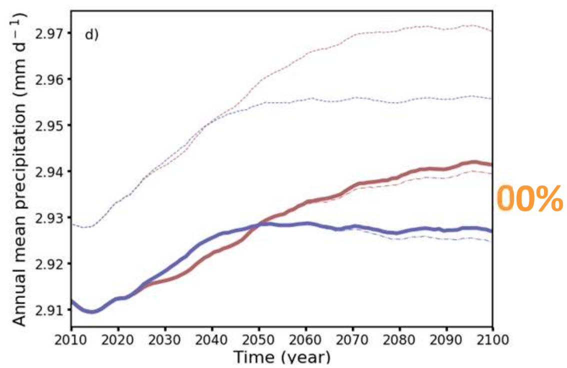
Meridional overturning



Arctic sea-ice area

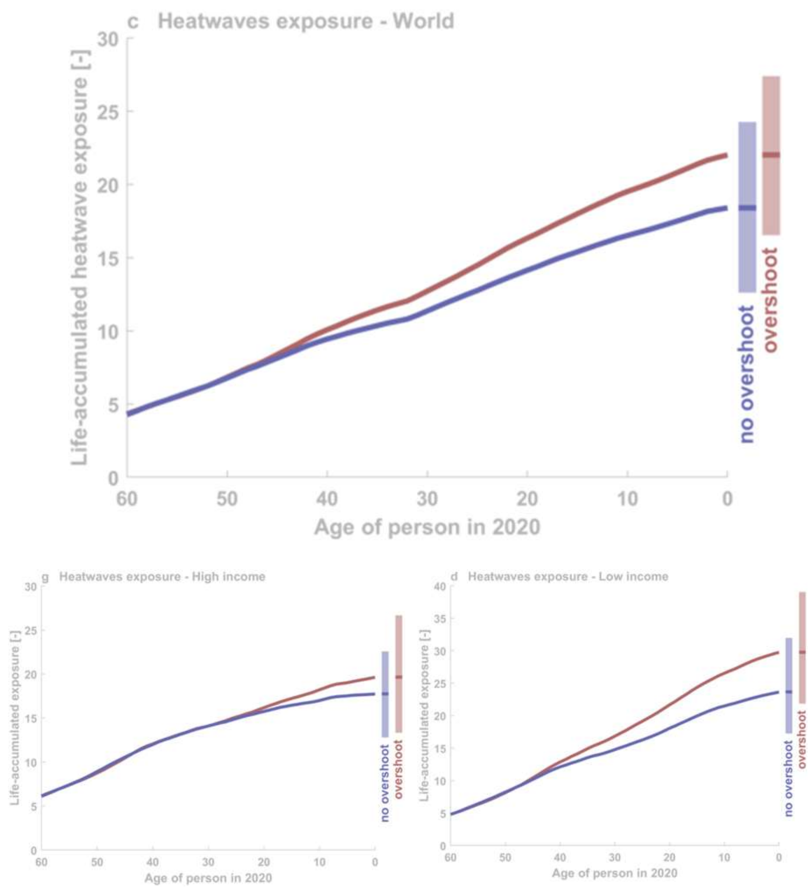


Global precipitation



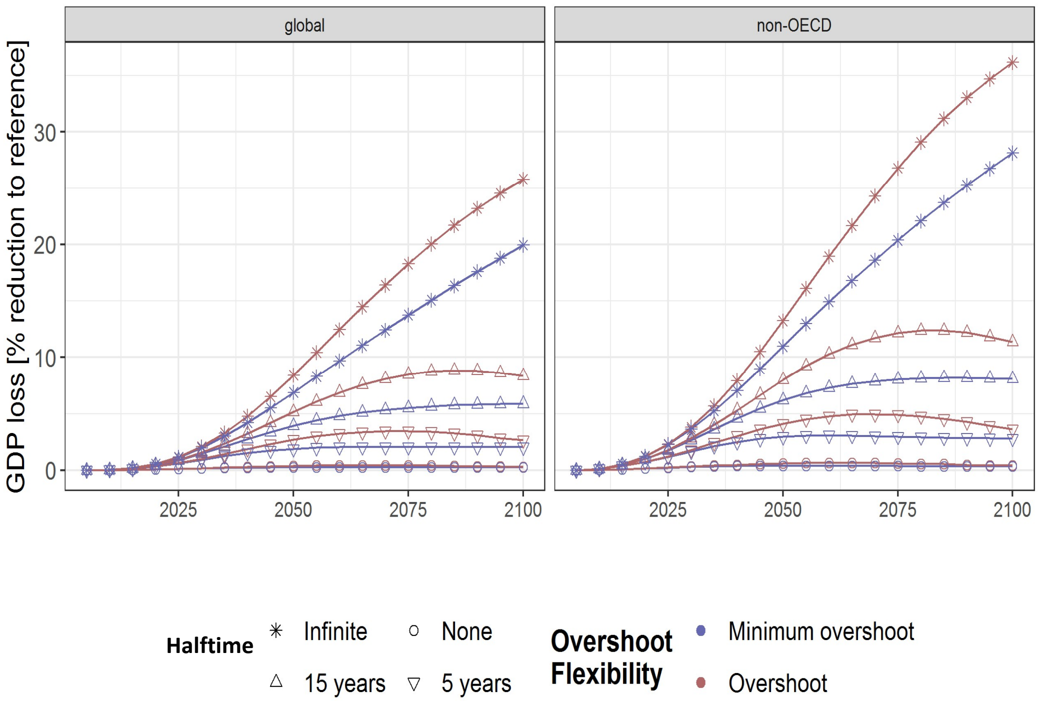
Metric:
X% of peak difference still observed in 2100

Impacts on (expected) biographies

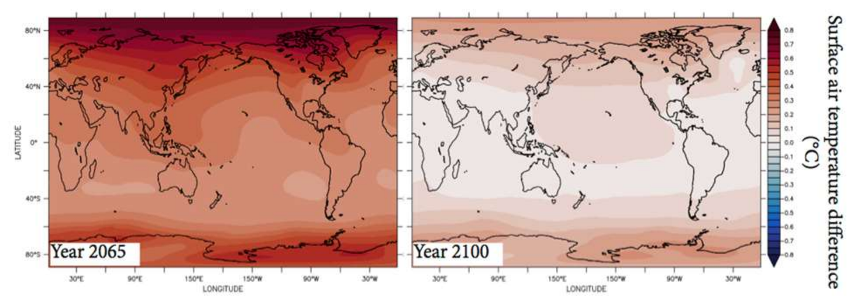


- Likelyhoods of extreme events increases and can be associated to
  - Age cohorts
  - Countries (groups of countries)
- Higher lifetime exposure most substantial regarding heatwaves
- Low income, high temperature countries:
  - most affected w/o overshoot
  - largest increase w/ overshoot

Impacts on GDP



- Halftime with which immediate GDP shock vanishes
- Larger halftime implies:
  - Stronger overall GDP impact
  - Stronger effect of overshoot
- GDP impacts larger around equator, despite polar amplification



The intertemporal dimension of climate change

Intergenerational equity - discounting

- How to aggregate damages and utilities over time?
- Key issue in (environmental) economics
- Climate change mitigation is a long-term challenge
- General economics argument: present consumption values more than future consumption
- Empirical research found very different results
- In environmental and climate economics exponential discounting is common
- This means that the annual discount rate is constant ρ
- Discount Factor $DF = 1 / (1 + \rho)^t$

Intergenerational equity - discounting

PRESENT VALUE OF A CASH FLOW OF $1000 RECEIVED AFTER *T* YEARS					
t	Value ($) of $1000 at a discount rate of				Certainty equivalent (%)
	1%	**4%**	**7%**	**Equally likely 1% or 7% expected value**	
1	990.05	960.79	932.39	961.22	3.94
10	904.84	670.32	496.59	700.71	3.13
50	606.53	135.34	30.20	318.36	1.28
100	367.88	18.32	0.91	184.40	1.02
150	223.13	2.48	0.03	111.58	1.01
200	135.34	0.34	0.00	67.67	1.01
300	49.79	0.01	0.00	24.89	1.01
400	18.32	0.00	0.00	9.16	1.01

Arrow et al. (2014),
DOI 10.1126/science.1235665

Intergenerational equity – Social Cost of Carbon

- Why is it so important?
- The social cost of carbon SCC are the net present value of all damages caused by a ton of carbon emitted:

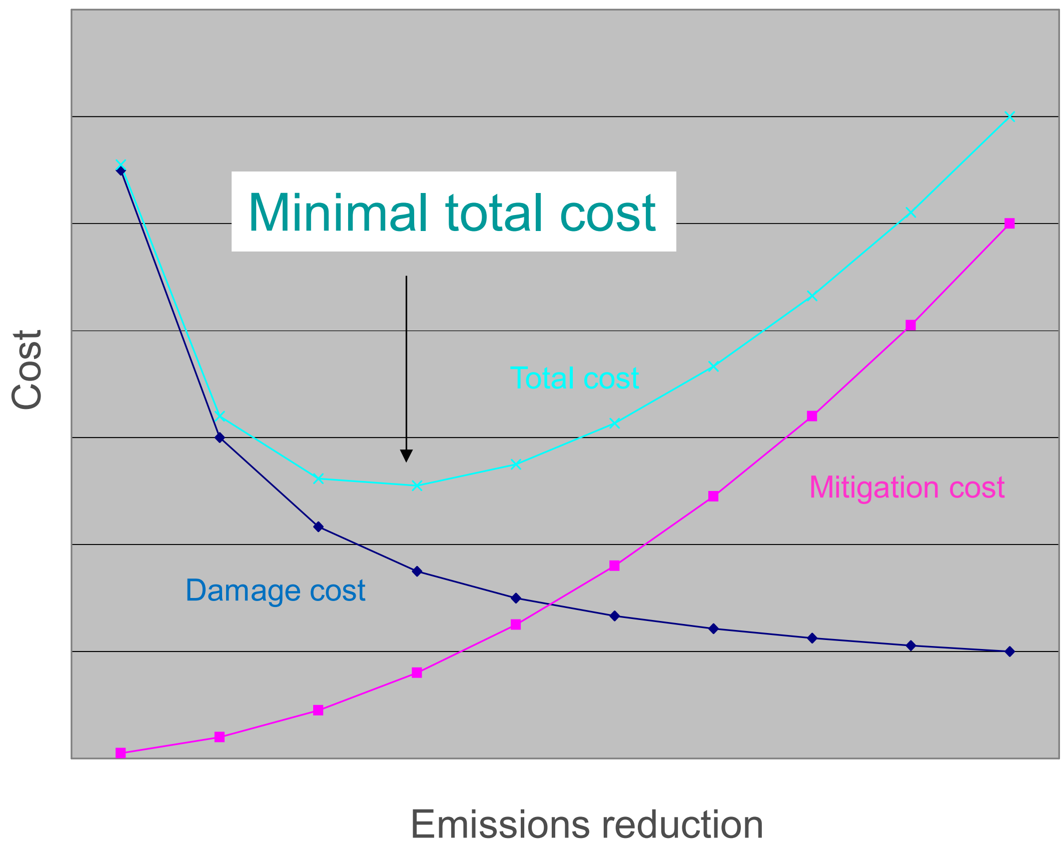
$$\mathrm{SCC} = \sum_{t=r}^{T} \sum\nolimits_{i=1}^{n} D_R(t, i)\,(1+\rho)^{-t}$$

- The discount rate is crucial for this cumulative value

Intergenerational equity – SCC derived from a model

- The economic back-bone of DICE (and REMIND) is the Ramsey model of optimal growth
- Ramsey asked: how much a society should save?
- Intertemporal trade-off of consumption today and tomorrow
- Savings used for investment to increase capital stock *K* to produce *Y*
- For the general capital accumulation problem the Keynes-Ramsey rule is derived for steady-state growth
- Wellfare function: $W = \sum_{r,t} U(c) * e^{\rho t} dt$
- Long-term interest rate $r = \frac{\partial Y}{\partial K} - \delta = \rho + a + n$
- The net interest rate *r* is the marginal product of capital corrected by capital depreciation δ
- Interest rate *r* is determined by the pure rate of time preference ρ, technological progress *a* and population growth *n*
- Most debate is about ρ (e.g. Stern vs. Nordhaus)

Intergenerational equity – SCC derived from a model



The optimum requires that marginal damage and marginal mitigation cost equalize

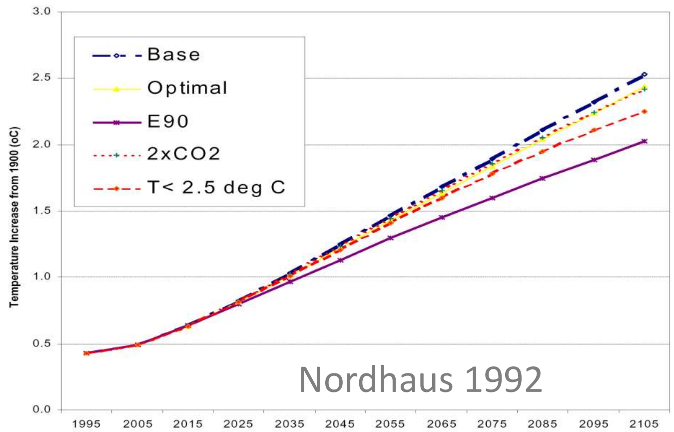
Setting an environmental target leads to cost-effectiveness analysis

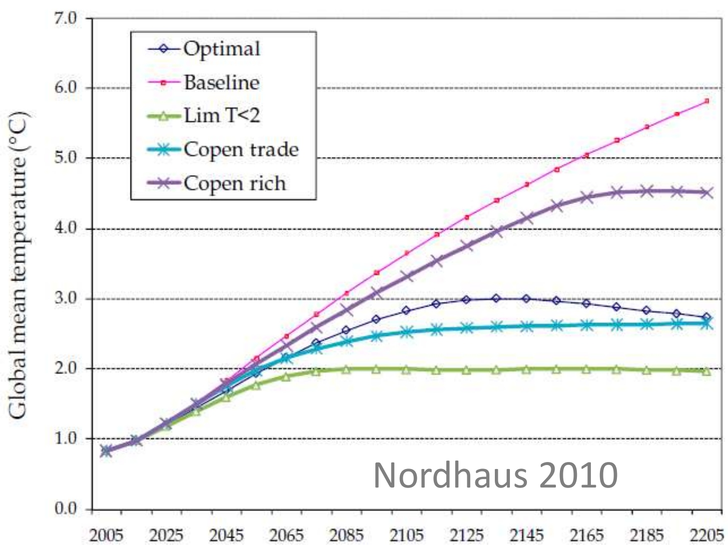
CBA and CEA are strongly disputed

Implementation in the DICE model

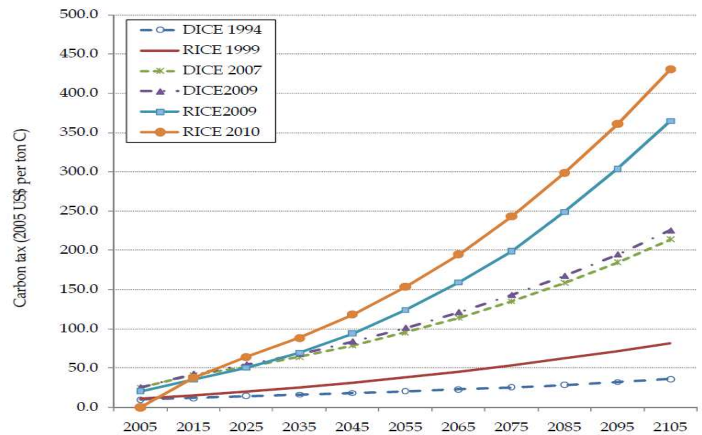
$$Q(t) = \frac{1-V(\mu(t))}{1+D(T(t))} \cdot A(t) \cdot K(t)^{\gamma} \cdot L(t)^{1-\gamma}$$

Intergenerational equity – Social Cost of Carbon





Social Cost of Carbon

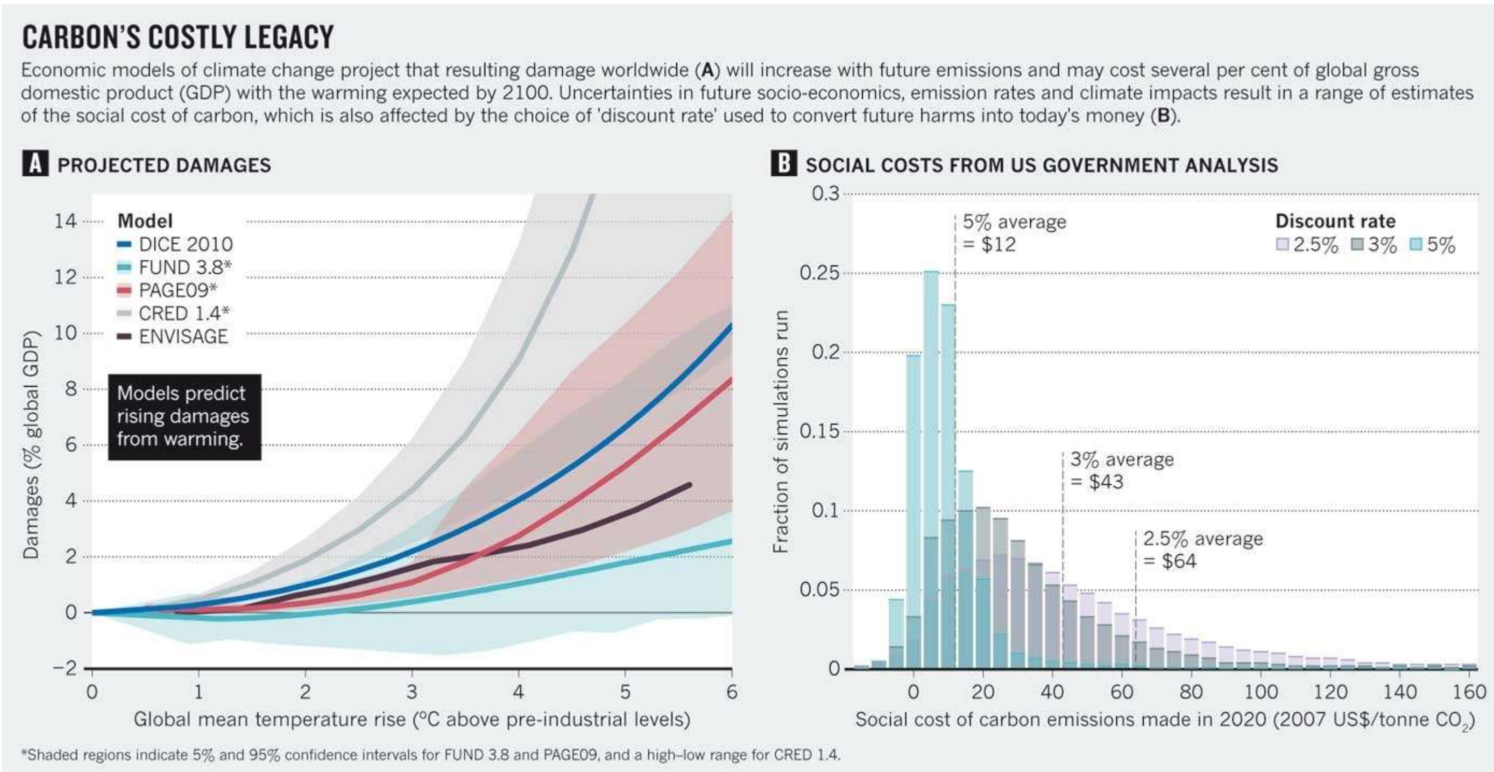


Def.: Social cost of carbon in year r

$$\mathrm{SCC} = \sum_{t=r}^{T} \sum_{i=1}^{n} D_R(t,i)\,(1+\rho)^{-t}$$

Social Cost of Carbon – Practical Example

Results from the US EPA study on SCC [carbon pollution]



Estimating the impacts of climate change

Two main approaches for impact assessment

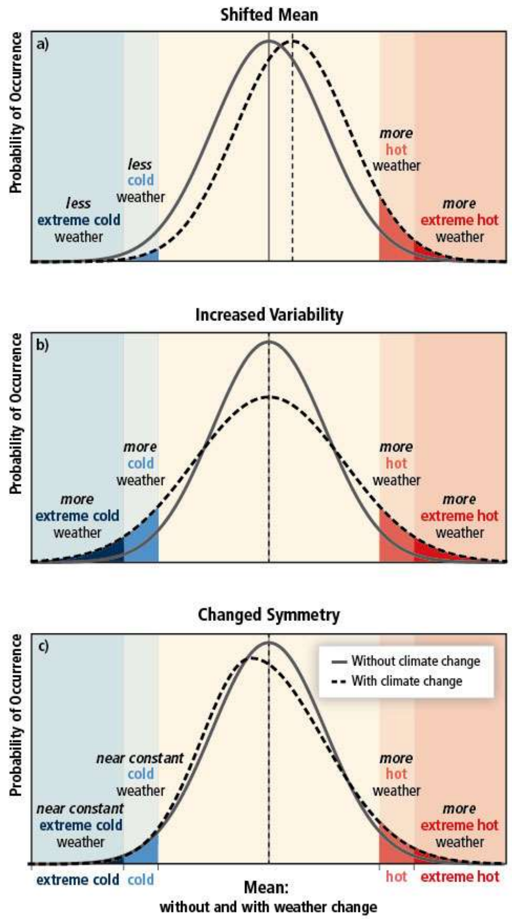
Process based modeling approach

- Climate change leads to impacts that are valued
- E.g. increasing temperature lead to yield losses in agricultural production (ton pre ha)
- Impacts are monetized
  - Valuation of a bundle of changes; e.g. lower yield is multiplied with price
  - Include impacts into a model to derive the economy wide effects after price changes and market based adaptation (trade); impact on GDP

Econometric approach

- Take data on weather and economic activity (i.e. GDP)
- What are the significant effects of weather anomalies on GDP?
- E.g. if warmer years have negative impacts on GDP, then increases in average temperature will have negative effects also on average
- Solomon Hsiang (2016): 10.1146/annurev-resource-100815-095343

Probability and Classification of Impacts



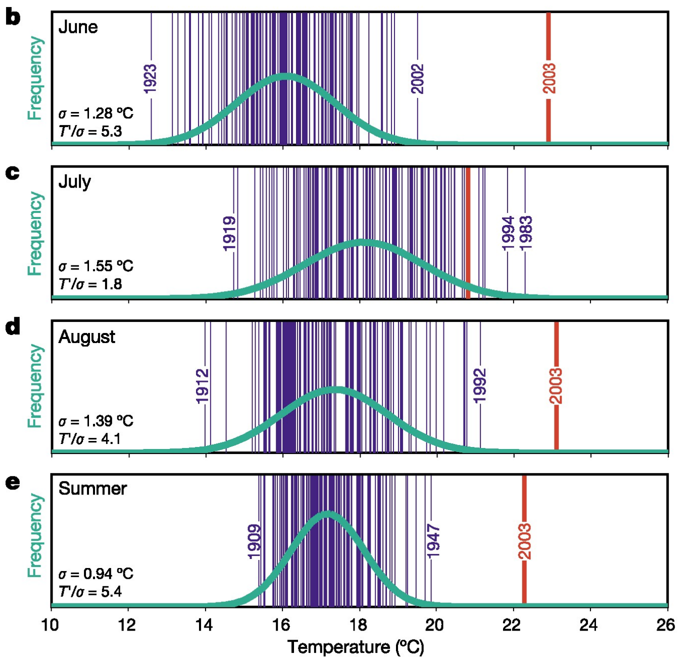
- Regular shift of probability density function
- High-end event probability increases
- Low-end event probability decreases

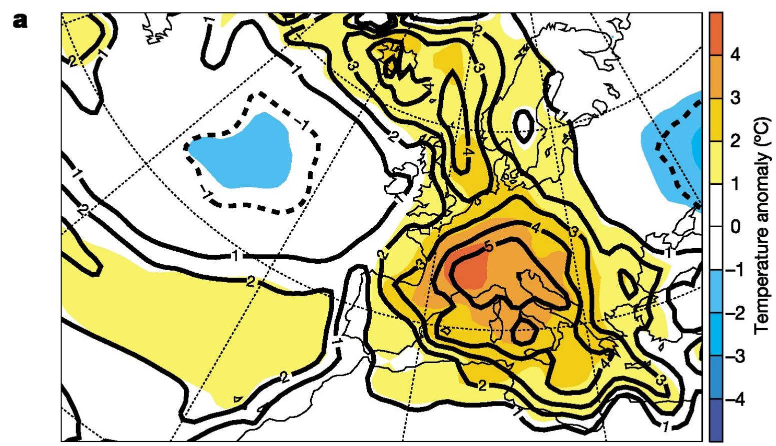
- Variability increases, predictability decreases
- High-end event probability increases
- Low-end event probability increases
- Both tails become fatter

- Shape of the function changes
- High-end event probabiility increases
- The tail becomes fatter

IPCC, SREX SPM

Health and heat stress – The 2003 European heat wave





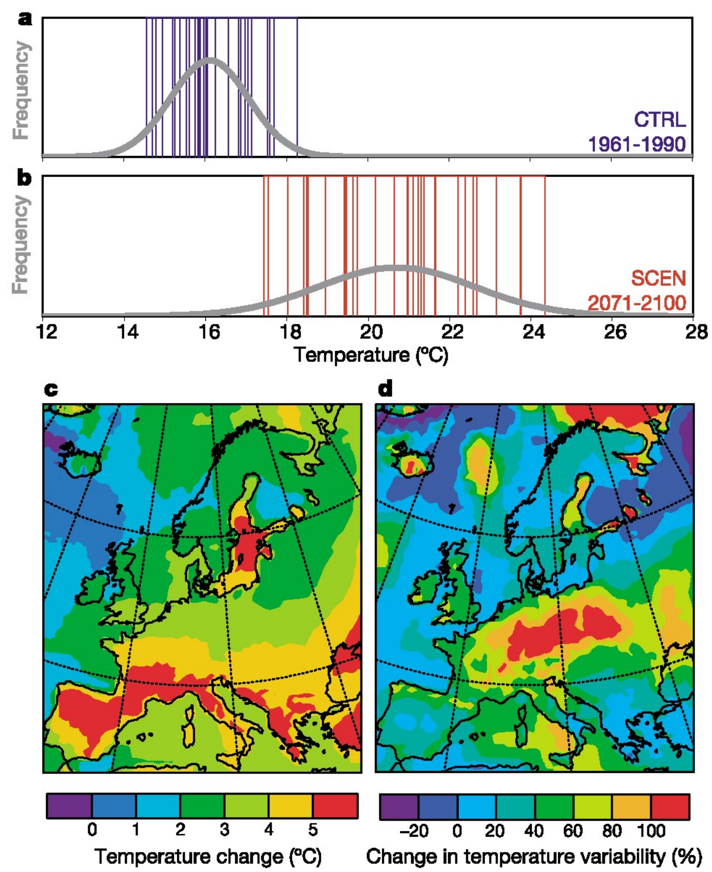
Comparison of the 2003 extreme values with the distribution of preceding summer temperatures (measured in the years 1864 – 2003) for Switzerland

2003 temperature deviation from the mean: > 5 standard deviations

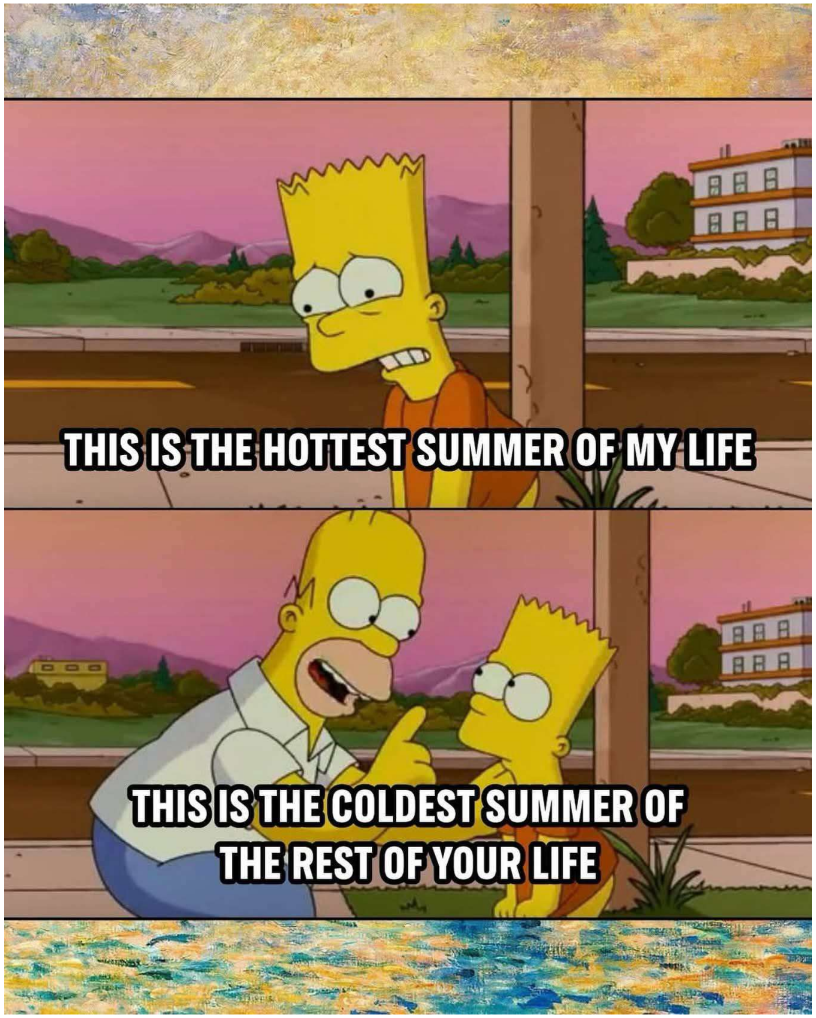
Return period (with respect to the reference period „1864-2000“): **several million years**

Source: Schär et al., Nature, 2004

Health and heat stress – The 2003 European heat wave

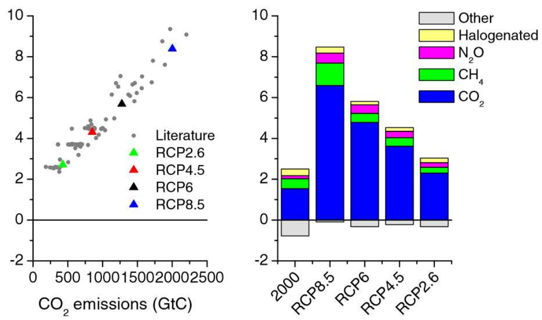


Source: Schär et al., Nature, 2004



Process based impacts

Climate forcers from IAMs



Van Vuuren et al (2011)
http://link.springer.com/10.1007/s10584-011-0148-z

Threshold values for weather extremes

Table 1
Extreme Event Definitions Used in This Study

Event category	Event type	Definition of land area exposed	Definition of population exposed
River flood	Confined (by topography)	Flooding is assumed to occur whenever daily discharge (0.5° resolution) exceeds the preindustrial 100-year return level; to derive the associated land area exposed per grid cell, simulated runoff is translated into inundation areas (2.5′ resolution) by CaMaFlood (Yamazaki et al., 2011, 2013).	Land area fraction exposed multiplied by total population of grid cell.
Tropical cyclone	Confined (to storm track)	Fraction of grid cell exposed to 1-min sustained hurricane-force winds (at least 64 kt) at least once a year (0.1° resolution); information required about wind fields is derived from center location and minimum pressure/maximum wind speed (Emanuel, 2013; Geiger et al., 2018).	Land area fraction exposed multiplied by total population of grid cell.
Crop failure	Confined (to agricultural land)	Fraction of grid cell where one of the considered crops (maize, wheat, soybean, and rice) is grown and the corresponding crop yield falls short of the 2.5th percentile of the preindustrial baseline distribution; crop-specific land area fractions exposed are added up.	Land area fraction exposed multiplied by employment in agriculture as a fraction of total employment, divided by grid cell area fraction used for agriculture.
Wildfire	Confined (to vegetated land)	Annual aggregate of monthly burned land area simulated by global vegetation models.	Burned land area fraction multiplied by total population of grid cell.
Drought	Extensive (can occur everywhere)	Entire grid cell if monthly soil moisture falls below the 2.5th percentile of the preindustrial baseline distribution for at least seven consecutive months.	Rural population (Klein Goldewijk et al., 2017) of exposed grid cell.
Heatwave	Extensive (can occur everywhere)	Entire grid cell if both, a relative indicator based on temperature (Russo et al., 2015, 2017) and an absolute indicator based on temperature and relative humidity (Masterton & Richardson, 1979) exceed their respective threshold value.	Total population of exposed grid cell.

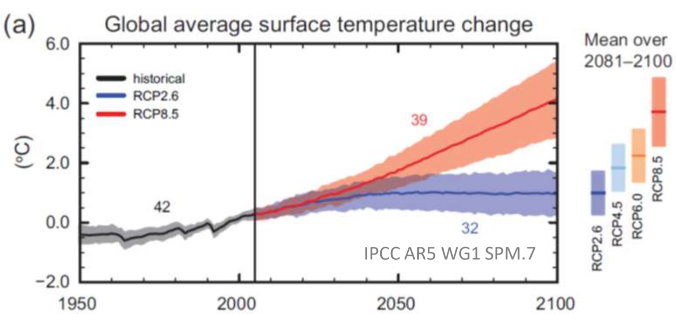
Lange et al (2020)
https://onlinelibrary.wiley.com/doi/10.1029/2020EF001616

Population development

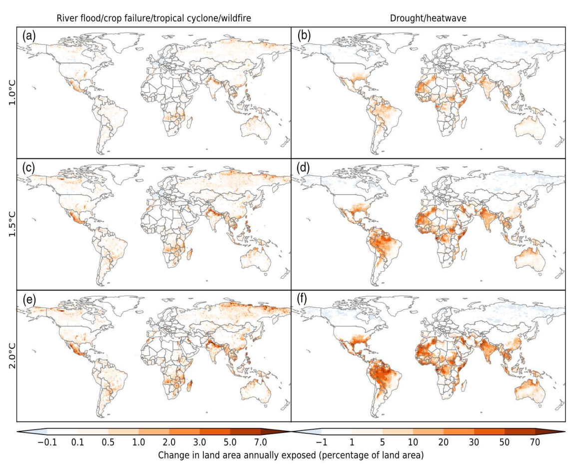
Region	Year	Population (in millions)		
		SSP1	SSP2	SSP3
World	2010	6871	6871	6871
	2050	8461	9166	9951
	2100	6881	9000	12,627
Africa	2010	1022	1022	1022
	2050	1764	2011	2333
	2100	1865	2630	3947
Asia	2010	4141	4141	4141
	2050	4734	5140	5656
	2100	3293	4417	6712
Europe	2010	738	738	738
	2050	769	762	681
	2100	657	702	543

KC and Lutz (2017)
https://linkinghub.elsevier.com/retrieve/pii/S0959378014001095

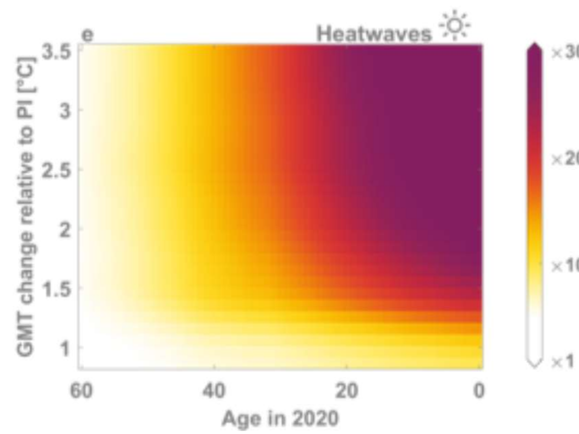
Climate response from ESMs



Exceedance of thresholds for ΔT

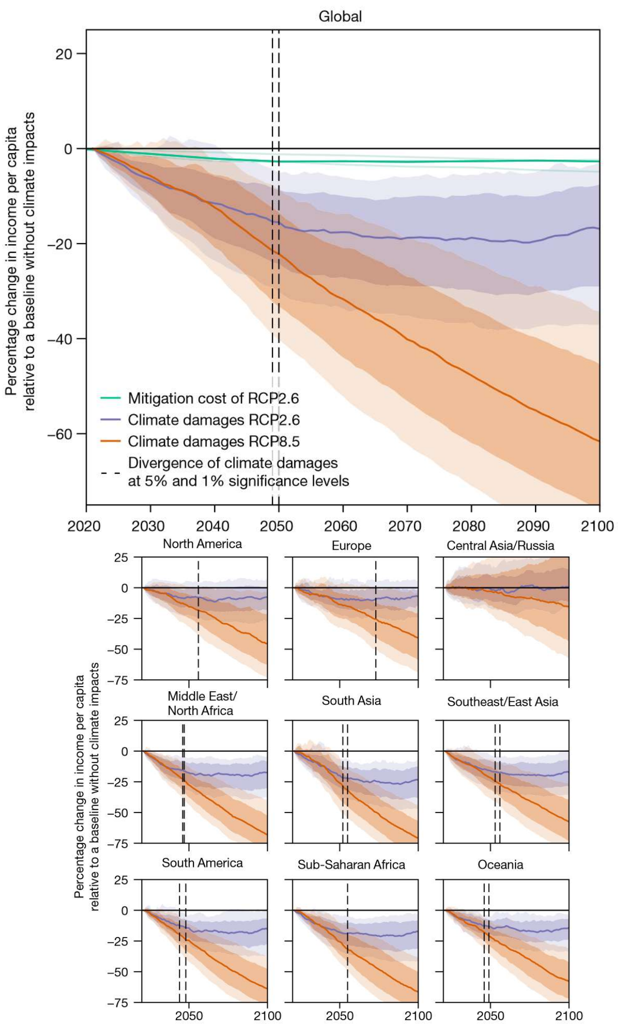


Heat wave life time exposure



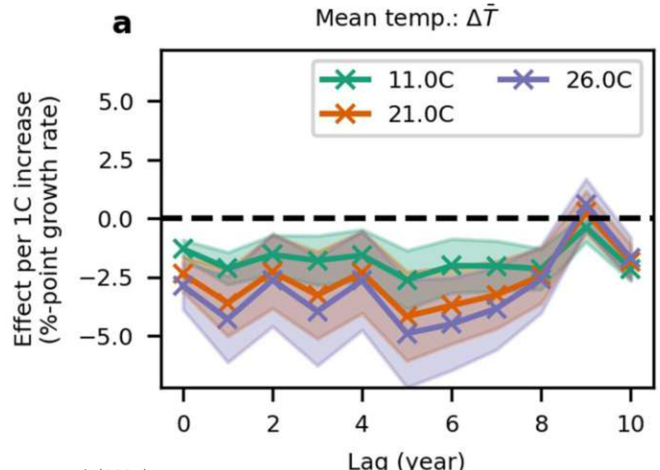
Thiery et al (20210)
https://www.science.org/doi/10.1126/science.abi7339

Climate econometric approach



Fixed effects and distributed lags

$$\Delta \mathrm{lgrp}_{r,y} = \mu_r + \eta_y + k_r y + \sum_{L=0}^{N} (\alpha_{1,L}\Delta\overline{T}_{r,y-L} + \alpha_{2,L}\Delta\overline{T}_{r,y-L}\times\overline{T}_r)$$

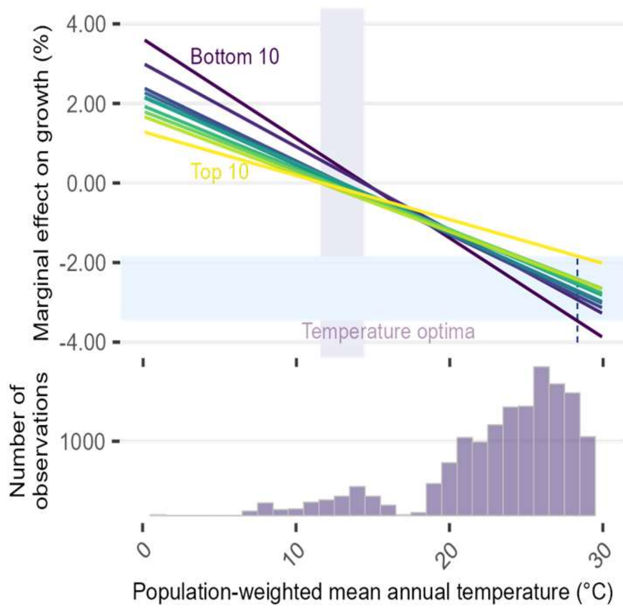


Kotz et al. (2024)
https://www.nature.com/articles/s41586-024-07219-0

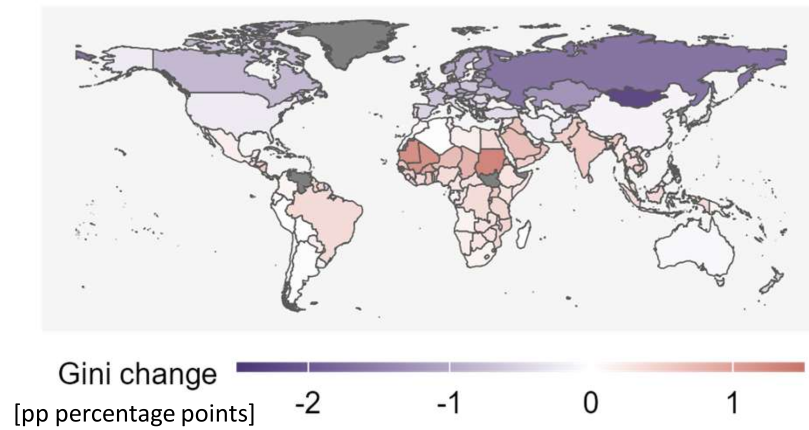
- Estimated parameters do not explain the underlying cause-effect chain
- The 10 year lag structure suggests that
  - Direct destruction is miniscule
  - Knock-on effects dominate
- Working hypothesis: macroeconomic effects during recovery and rebuild need be taken into account

Climate econometric approach

Marginal impacts of temperature change on income growth in Low Income Countries



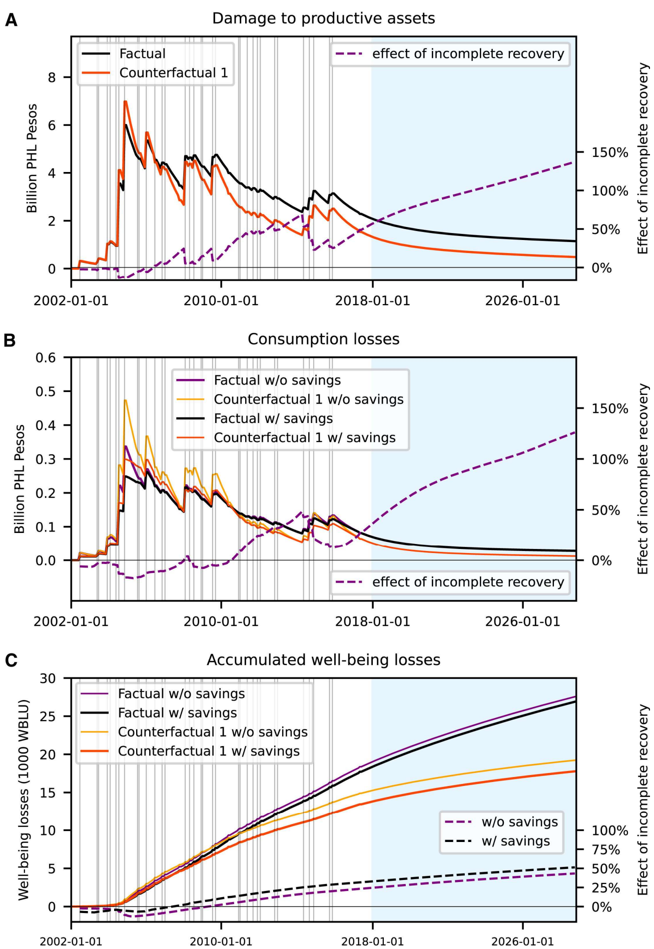
Accumulated inequality impacts of climate change from 1980 to 2019



Empiric model:

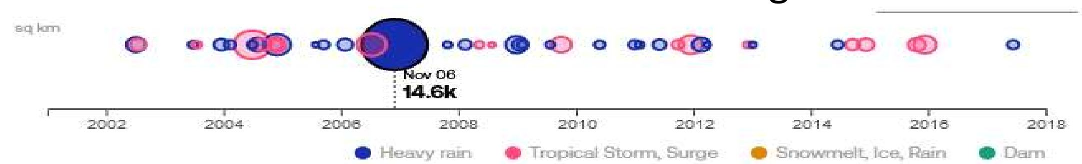
$$g_{ipt} = \gamma_1 T_{it} + \gamma_2 T_{it}^2 + \beta_1 P_{it} + \beta_2 P_{it}^2 + Lo_{it}(\delta_1 T_{it} + \delta_2 T_{it}^2) + Lm_{it}(\delta_3 T_{it} + \delta_4 T_{it}^2) + Um_{it}(\delta_5 T_{it} + \delta_6 T_{it}^2) + Lo_{it}(\alpha_1 P_{it} + \alpha_2 P_{it}^2) + Lm_{it}(\alpha_3 P_{it} + \alpha_4 P_{it}^2) + Um_{it}(\alpha_5 P_{it} + \alpha_6 P_{it}^2) + \varphi_p + \nu_t + \theta_{1i} t + \theta_{2i} t^2 + \varepsilon_{ipt} \quad [4]$$

Hybrid approach – Floods in the Philippines



Sauer et al. (2025)
https://doi.org/10.1016/j.isci.2024.111733

- Households with assets and income, decision making in a equilibrium model
- History of Tropical Cyclones 2000 – 2018
- Cyclones hit the Philipines every year
- Some households hit more than once during one season



- Poor households have
  - Lower building standard
  - Can fall below poverty line
- Thus, only partial recovery before next shock
- Partial recovery increases damage and hits the poor most
- Thus, income losses not only result from the immidiate event, but depend on context

Fun fact: abstract claims an Agent Based Model is developed, but it is an economic equilibrium model with intertemporal optimization

Modeling of damages in Integrated Assessment Models

Modeling damages and persistency of GDP effects

- Most models assume climate change reduces GDP directly
- This assumption is not necessarily given
- CES production function in capital and labour

$$Y_t^G = a_0\left[\alpha K_t^\sigma + (1-\alpha)\left(\chi_t^L L_t\right)^\sigma\right]^{1/\sigma}$$

- A given reduction in GDP can be caused by
  - Reduction of total factor productivity *a*
  - Destruction of capital *K*
  - Reduction of labour supply *L*
  - Reduction of labour efficiency χ
- Question does it make a difference how the same GDP chock is modeled?

Modeling damages and persistency of GDP effects

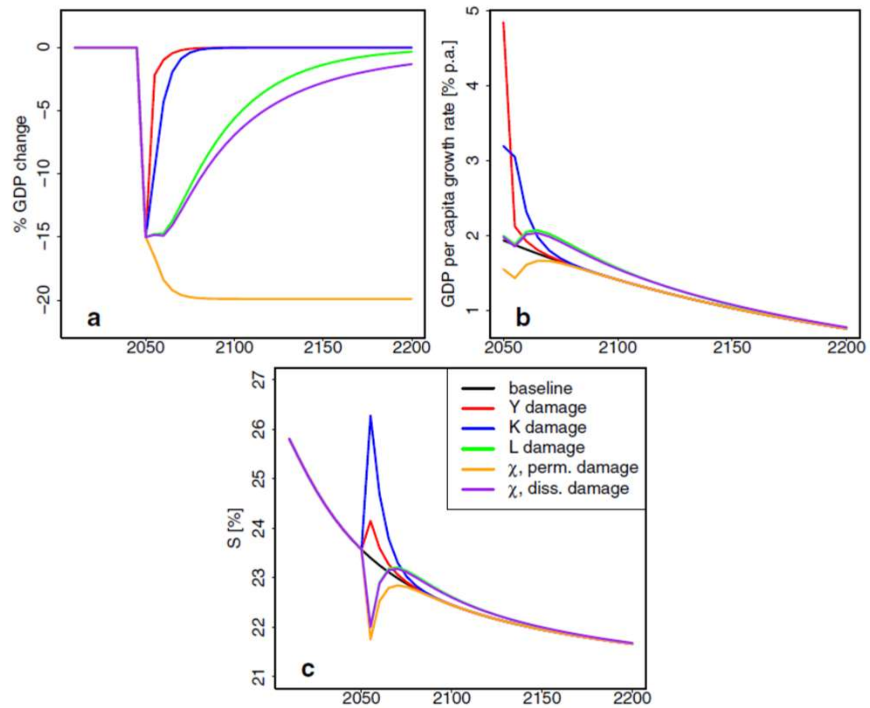


Fig. 2 GDP change (panel **a**), the GDP per capita growth rate after the shock (panel **b**) and the savings rate S (panel **c**) in a comparative shock test for different damage channels (colors). For productivity χ there are two cases: permanent and dissipative damage. (Color figure online)

Modeling damages and persistency of GDP effects

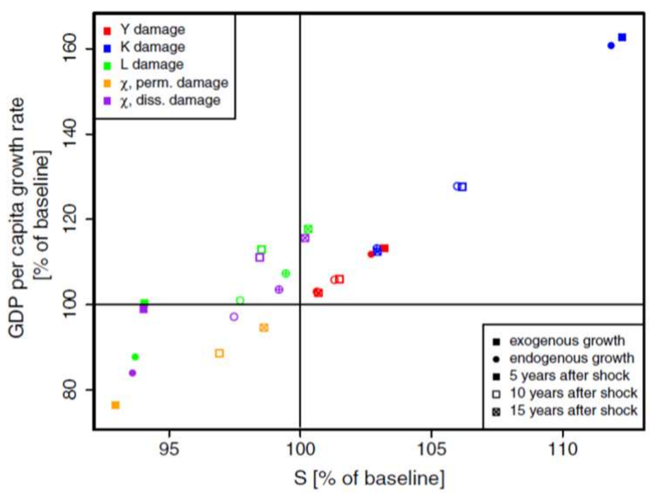


Fig. 12 Typology of the macroeconomic system dynamics in terms of savings rate and per capita GDP growth rate 5, 10 and 15 years after the shock (symbols) in the different impact channels (colors), expressed as % of the baseline values. (Color figure online)

- The shape of GDP change and the persistency depend on modeling of shock
- Via the macroeconomic model there is a interrelationship with the savings rate
- Flexibility of saving can help to buffer a GDP shock

Modeling damages and persistency of GDP effects

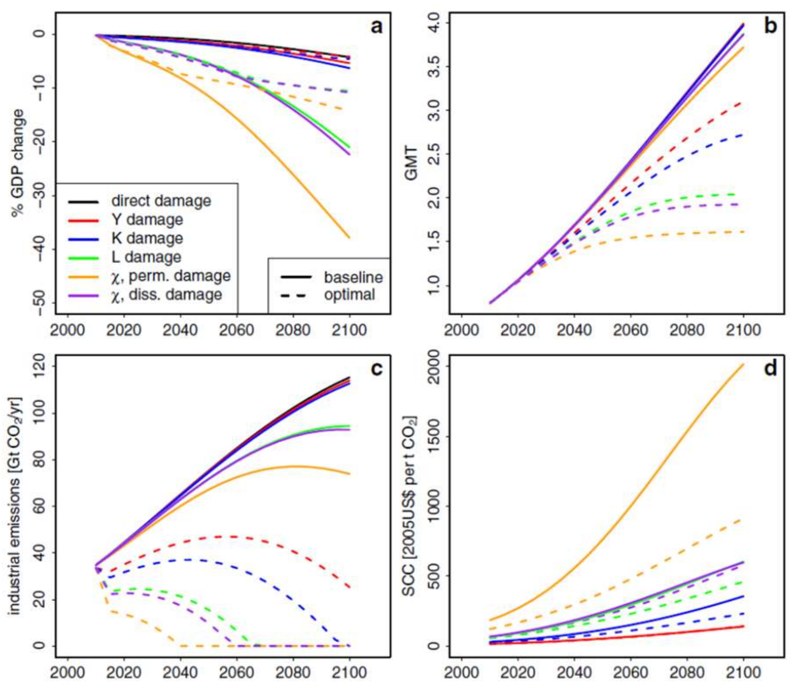


Fig. 10 GDP change (panel **a**), global mean temperature change (panel **b**), industrial emissions (panel **c**) and social cost of carbon (panel **d**), comparing baseline and optimal policy case (solid vs. dashed lines) for the different damage channels (colors) in the standard case (endogenous savings, exogenous growth, endogenous damage function). (Color figure online)

- Modeling of damage function strongly affects model results
- Global mean temperature GMT with optimal policy varies between near baseline and slightly above 1.5°C
- SCC along Baseline path vary more strongly than the optimal

Some insights

- Distinction between inter and intragenerational equity/fairness is a tricky starting point
- Intragenerational equity is mostly discussed regarding mitigation
- Impacts have distributional implications and will so in the future
- Process based and econometric approaches are very different and can be extended for distributional implications
- Both approaches should complement each other
- Big issue is data availability and the merging of different data sets

Process based impacts

Table 1
Extreme Event Definitions Used in This Study

Event category	Event type	Definition of land area exposed	Definition of population exposed
River flood	Confined (by topography)	Flooding is assumed to occur whenever daily discharge (0.5° resolution) exceeds the preindustrial 100-year return level; to derive the associated land area exposed per grid cell, simulated runoff is translated into inundation areas (2.5′ resolution) by CaMaFlood (Yamazaki et al., 2011, 2013).	Land area fraction exposed multiplied by total population of grid cell.
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- Likelyhoods of extreme events increases and can be associated to
    - Age cohorts
    - Countries
- Higher lifetime exposure most substantial regarding heatwaves
- Low income, high temperature countries:
    - most affected w/o overshoot
    - largest increase w/ overshoot

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- Persistent effects?
  - Global aggregates of CO_2 concentration and GMT are fast variables
  - Sub-systems in the climate are more inert and react on longer time scales
  - Socioeconomic systems also react with inertia
- Geographical differences?
  - Mitigation
    - Overshoot reduces mitigation burden particularly in low-income, high temperature countries
  - Impacts and damages
    - Polar amplification is at work and shows persistence
    - Ice-sheet melting mostly dependent on long-term temperature change, overshoot secondary
    - However, impacts are not only a matter of differences, but todays temperature levels
- Trade-offs are strong in low-income, high temperature countries
  - High dependence on energy and food
  - High exposure and vulnerability to increasing temperatures
- Research challenges
  - Fully integrating mitigation and impacts/damages in overshoot scenarios
  - Uncertainty analysis across different models
  - Improved interfacing between models

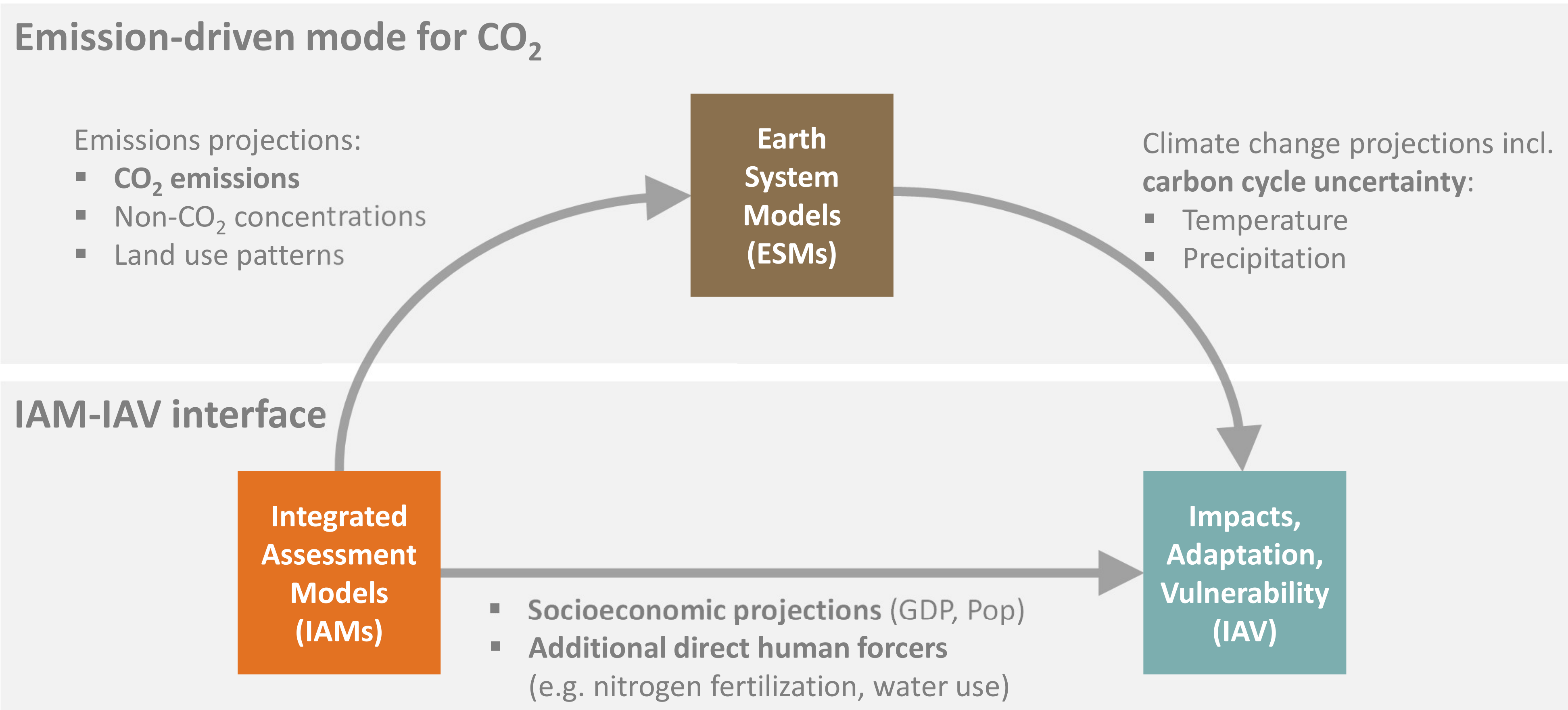
Overview of Work Package

- Task 1.1 Geopolitical risks of transition pathways
  - Conceptual, connect political science and modeling
  - Match risk categories with model variables and scenario assumptions

- Task 1.2 Advance Modeling
  - Capital (cost of financing, capital market fragmentation
  - public finance (pressure on public budgets from many sides)
  - Trade (energy security)

- Task 1.3 Geopolitical risks due to orderly and disorderly transitions
  - What are geopolitical risks implied by different transformation pathways?
  - What are risks from geopolitical developments for transitions?

ScenarioMIP for CMIP7: Improved modelling and integration



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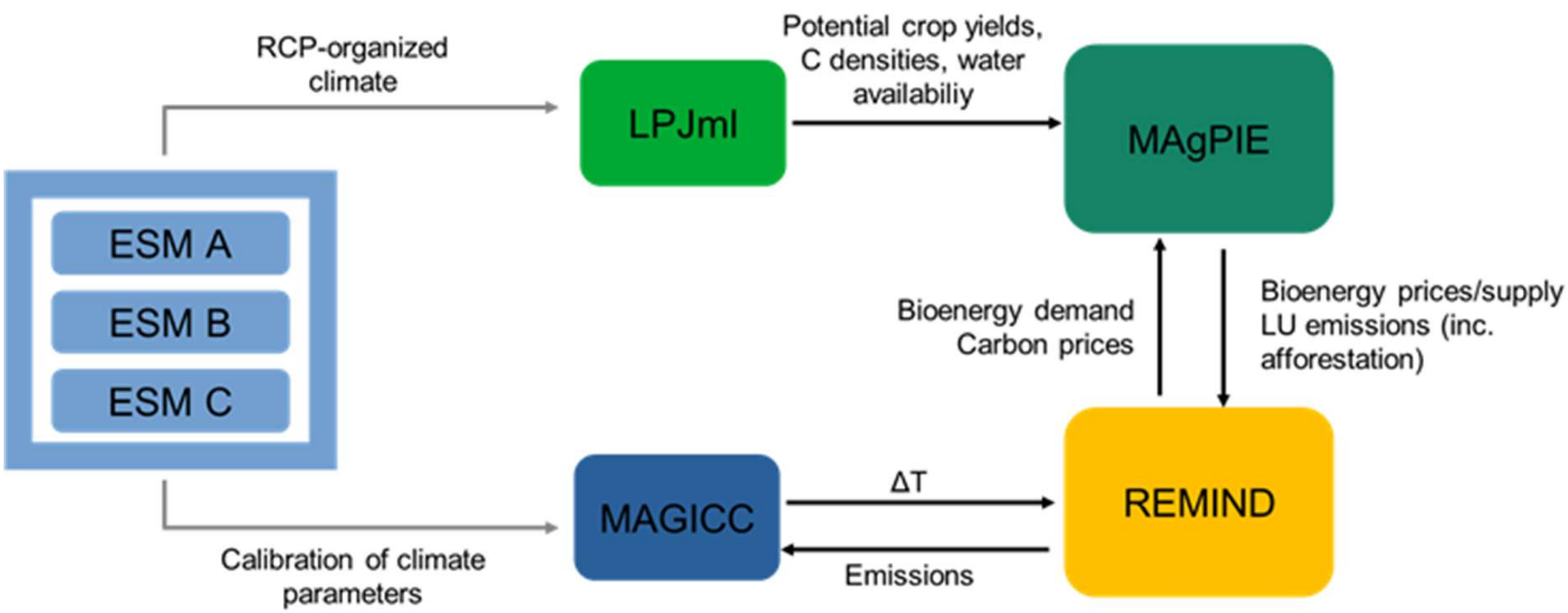
The Potsdam Integrated Assessment Modeling framework (PIAM)



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The REMIND-MAgPIE integrated assessment modeling framework

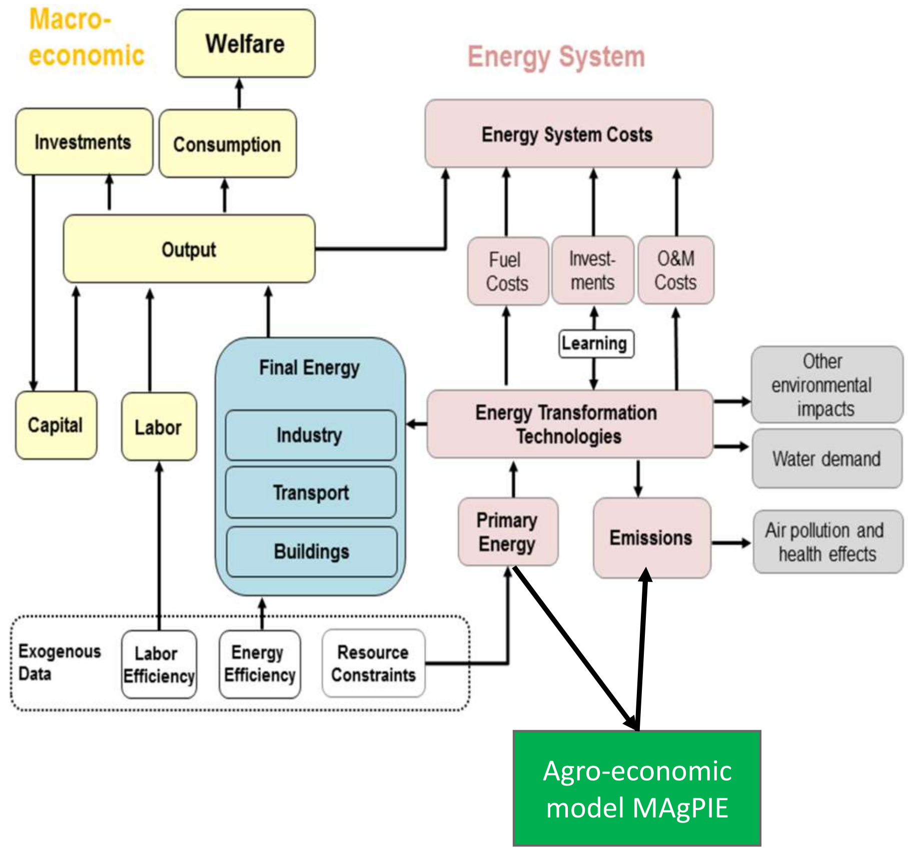
Shared Socioeconomic Pathways

Drivers:

- Population
- Economic development

Narratives:

- Technological development
- Food and energy demand
- Non-climate policies
- Trade liberalization
- ....



Climate policy scenarios

Emission/temperature target

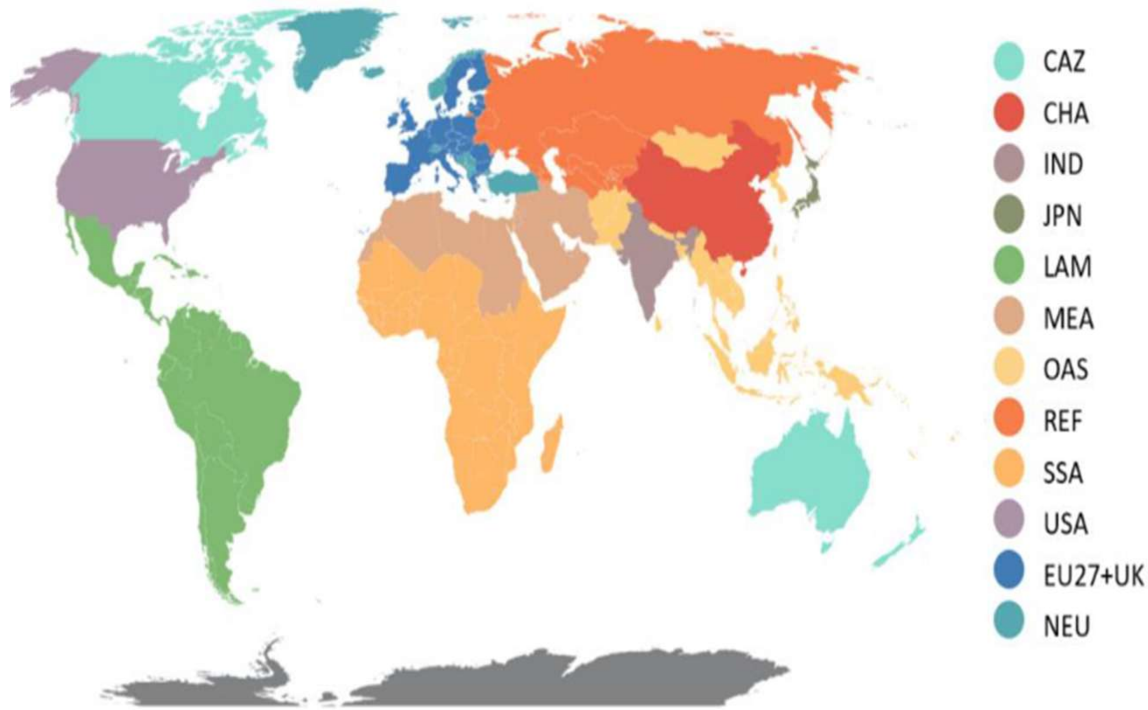
Assumptions about overshoot

Assumptions about carbon prices

The REMIND-MAgPIE integrated assessment modeling framework

12 world regions

Possibility to downscale to country level



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Scenario analysis

Current policy scenario

↓

Orderly/disorderly transition scenarios: e.g. delayed action, policy/technology constraints

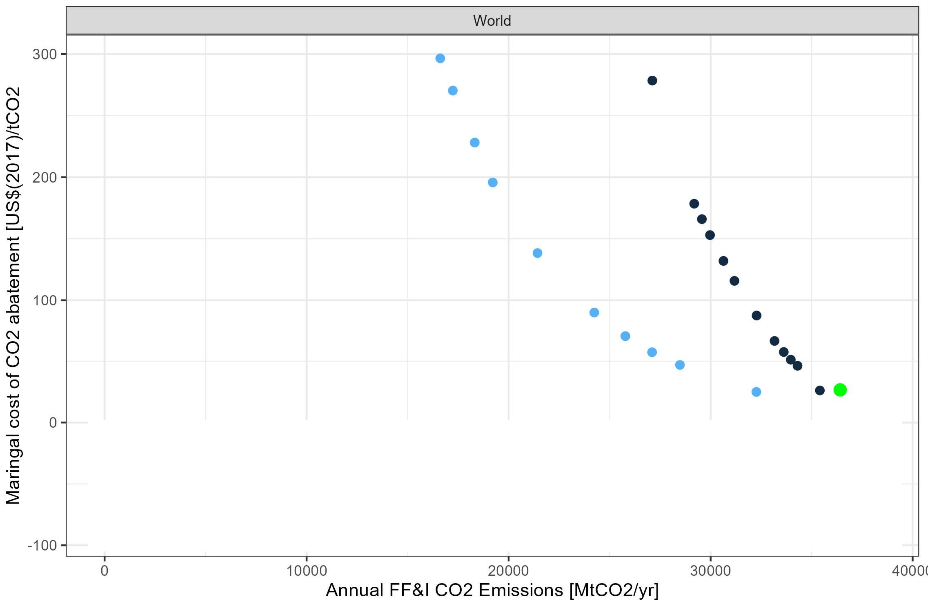
↓

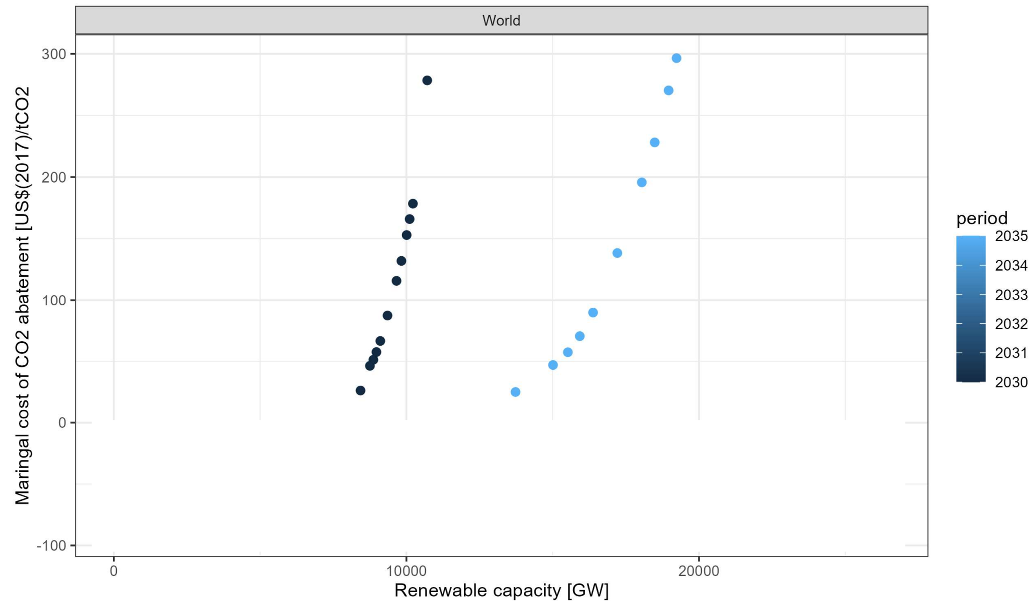
Other constraints, e.g. energy security

↓

Outcomes in terms of costs (GDP/consumption change), emissions, …

Economic potentials for near-term emission reductions – Informing NDCs





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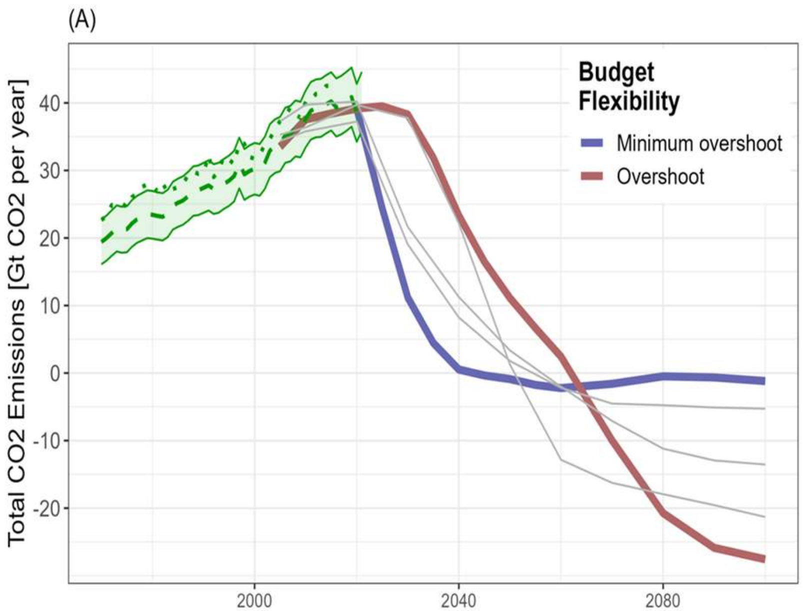
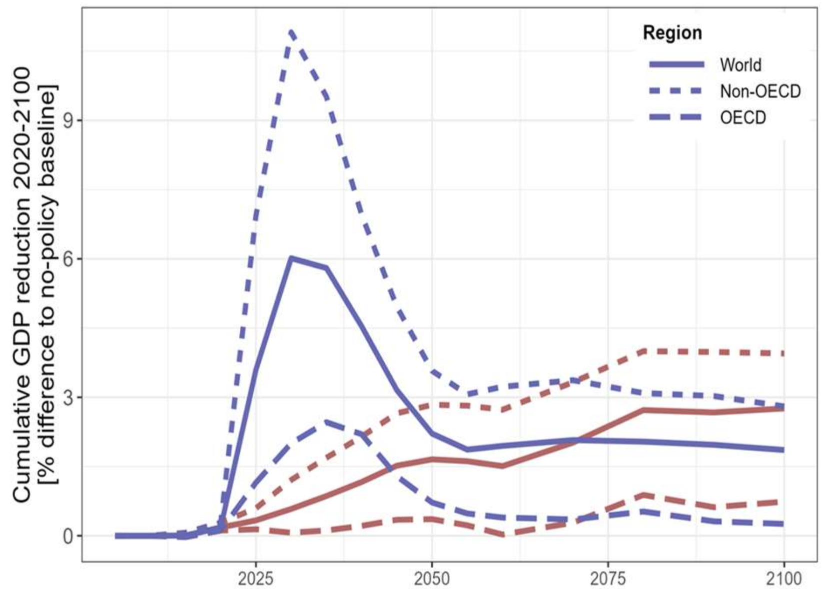
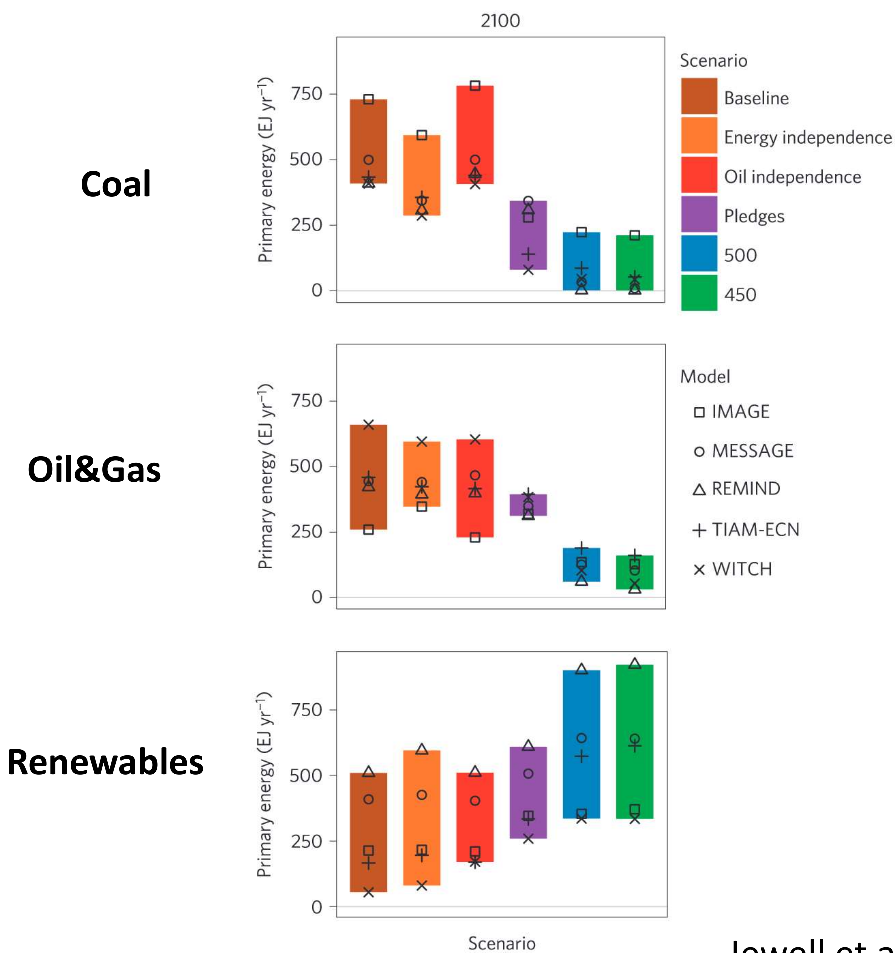
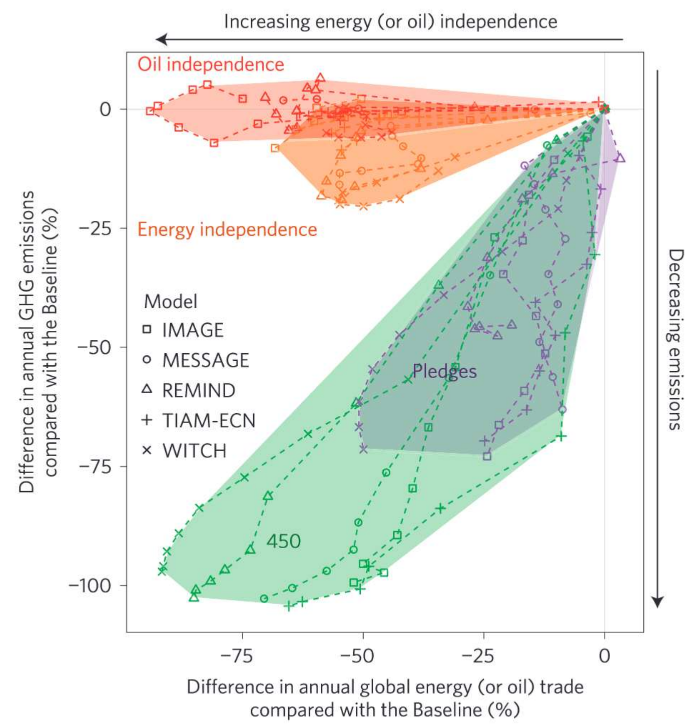
Scenario analysis: climate policy





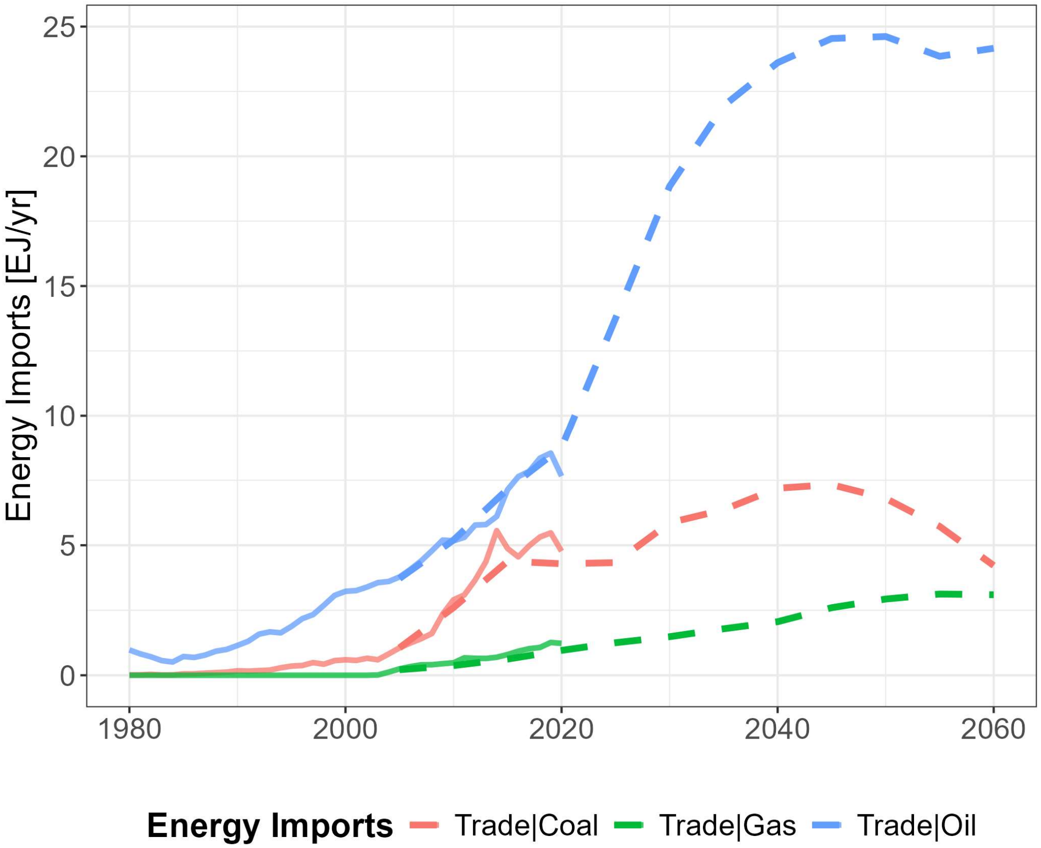
Scenario analysis: energy security





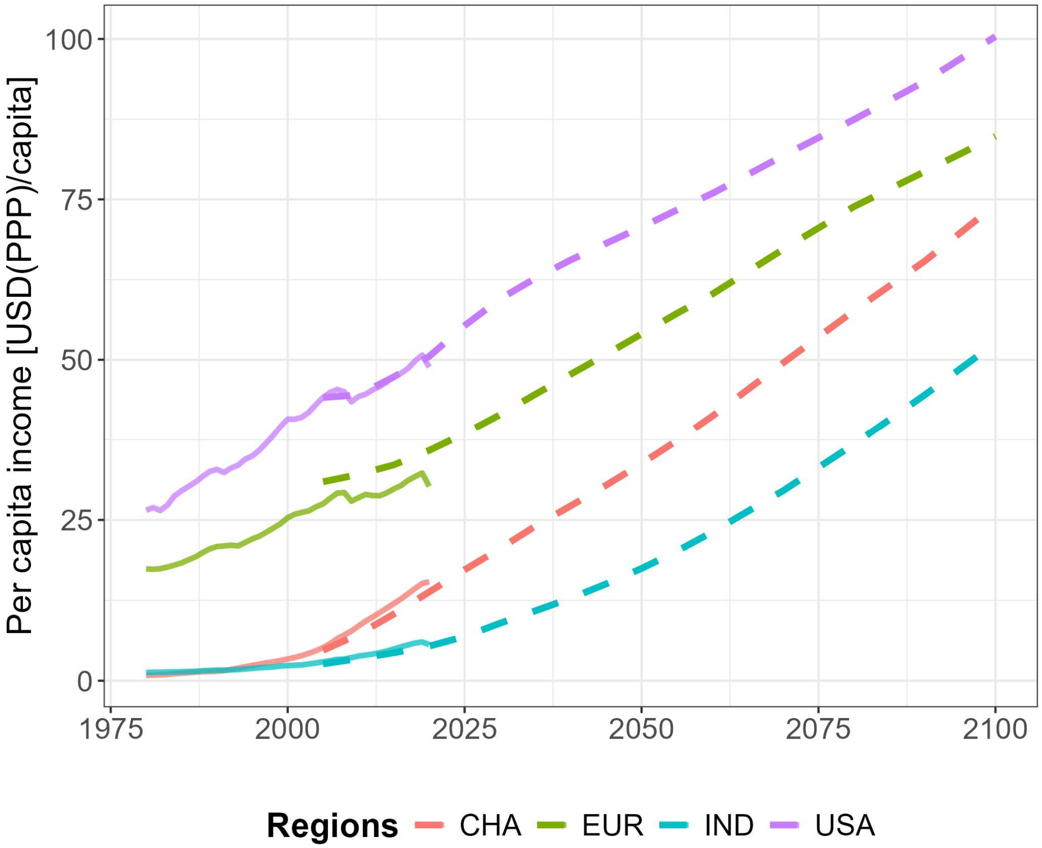
Jewell et al. (2016)

Indian energy imports under Current Policy scenario



- What are realistic short term import developments?
- What are strategic planning targets?
- What is the project-pipeline for infrastructure development?
- Indian energy security policies ?
- What are potential source countries?
- Are supplies subject to physical climate risks?

Income development: India converges, but still a long way to go



- Purchasing power parity measures activity, not money units
- Income reaches China's today levels ~2045
- … EU levels ~2070
- How much will economic growth contribute to poverty eradication and broad mass consumption society
- What are Indian Projections?

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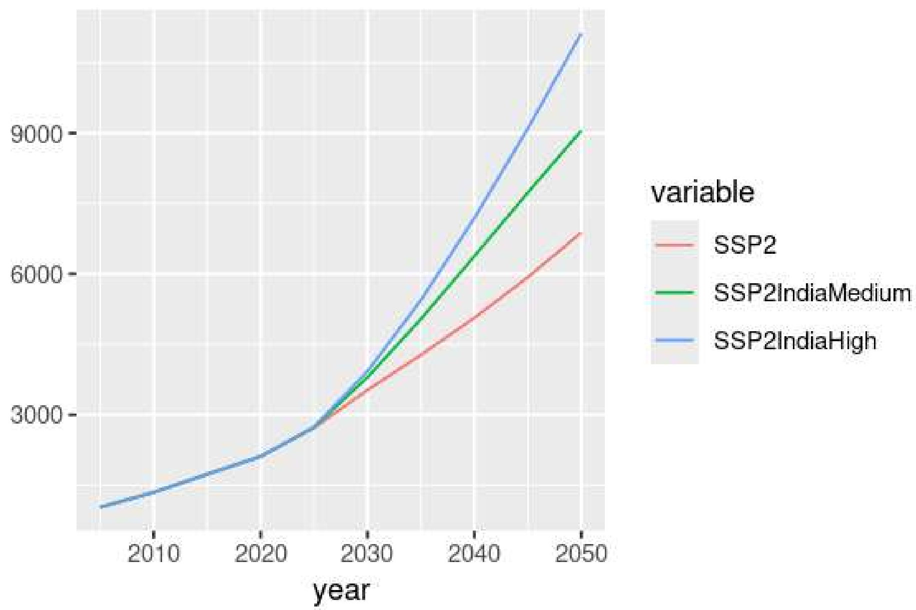
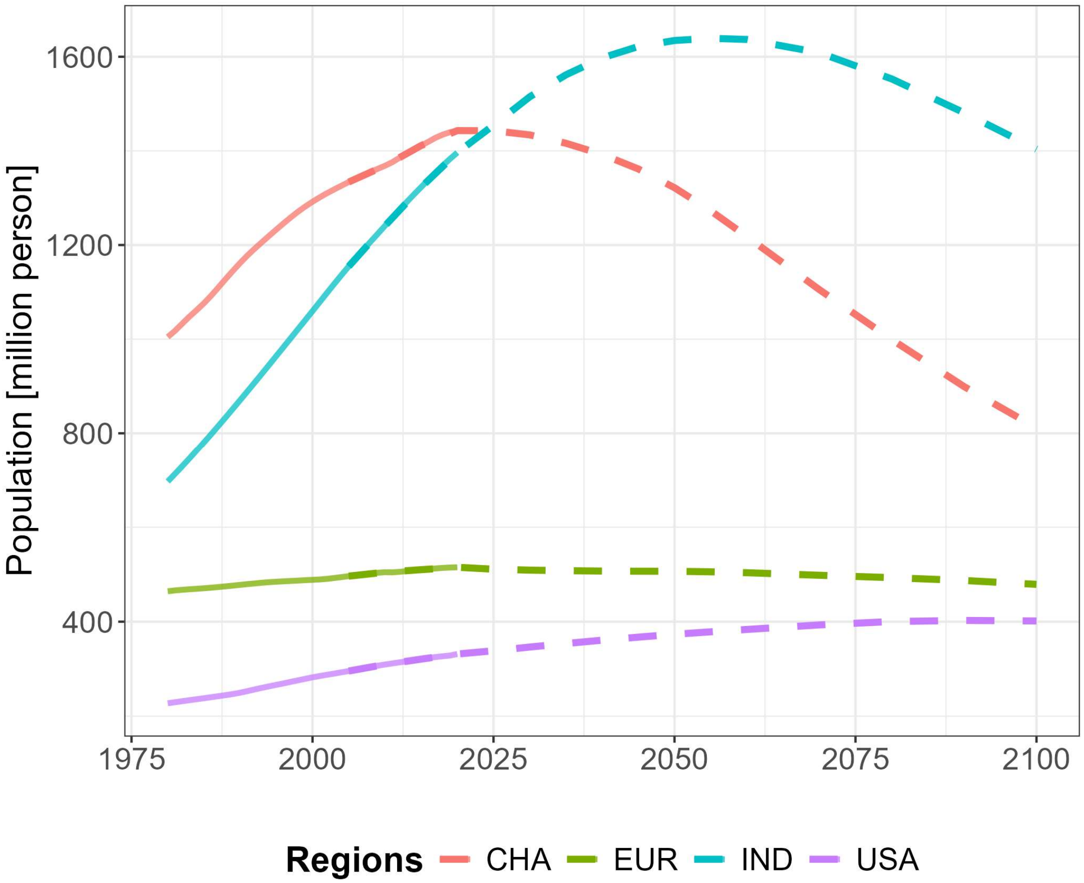
Income development: India converges, but still a long way to go

Indian income projection in USD(MER)/capita



- Purchasing power parity measures activity, not money units
- Income reaches China's today levels ~2045
- … EU levels ~2070
- How much will economic growth contribute to poverty eradication and broad mass consumption society
- What are Indian Projections?
- We investigate the implications for energy, industry, land-use, emissions, etc.

Population: Sharp population peak ahead



- Expected population peak ~2055
- Todays population is young and life expectancy increases
- Demographic transition is accelerated
- Workforce maximum is reached later
- Population peak will be reached at lower per-capita incomes (in MER-Dollars)
- What are Indian Projections?

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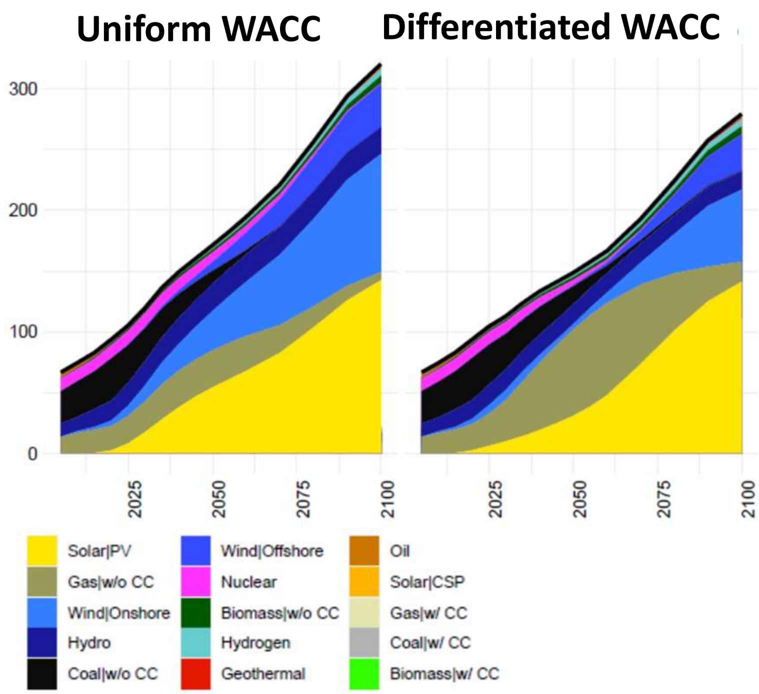
Cost of capital are heterogenous and affect energy transition and trade



Calcaterra et al. (2024), https://doi.org/10.1038/s41560-024-01606-7

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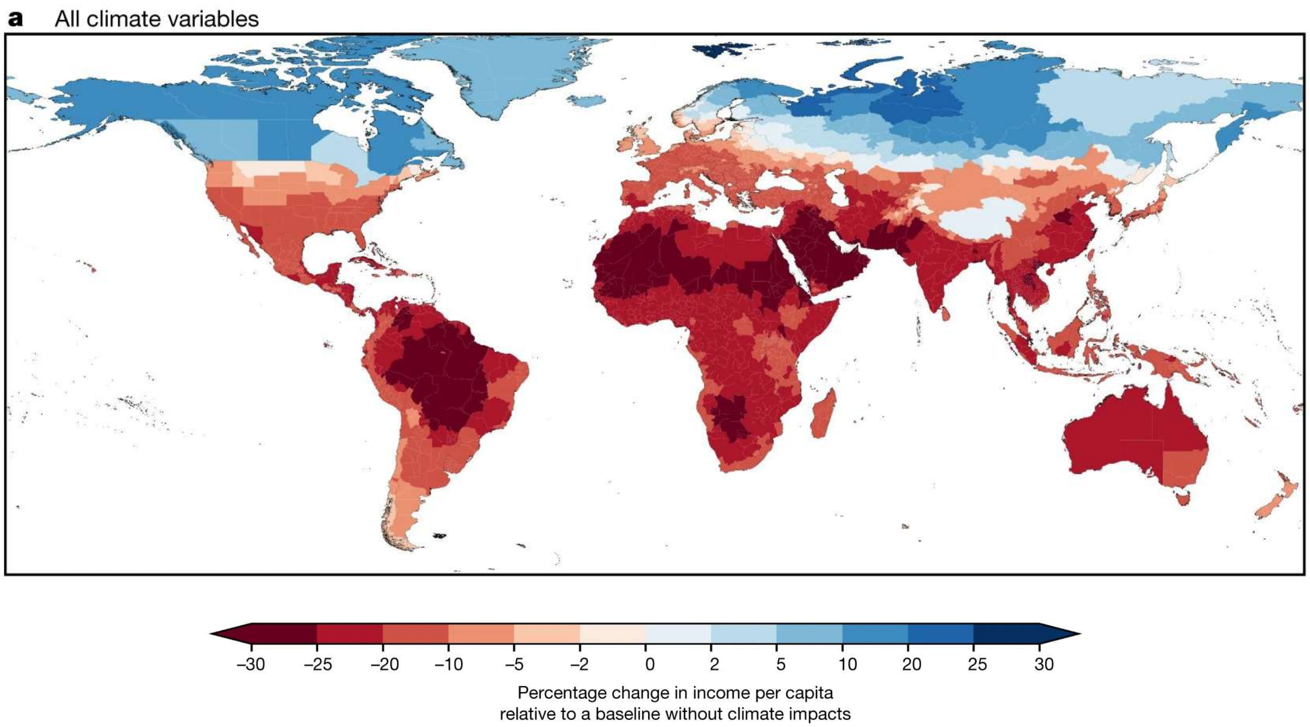
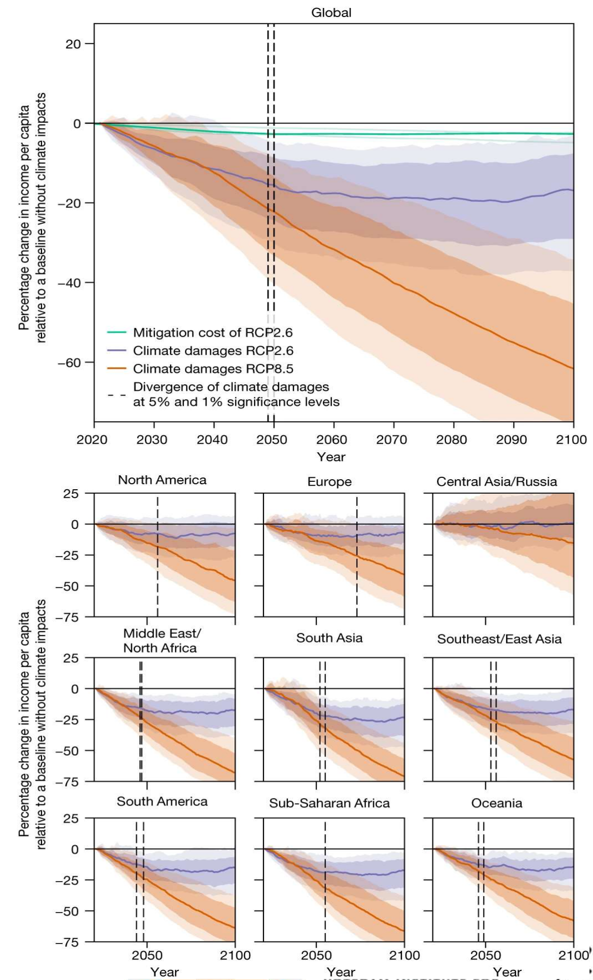
Integration of physical and transition risks (Task 2.1)





Kotz et al. (2024): The economic commitment of climate change

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Focus on finance, capital, trade

Zenios et al. (2024)

Model some of these aspects via:

- Risk mark-ups
- Fragmented capital markets
- Limited capital access
- Trade focus (winners and losers with respect to energy markets/ trade/prices)
- Effects on public budgets
- Multiple pressures (e.g. demographic transition)