The Integrated Assessment of Climate Change

Thomas Kleinen
09/03/06

Outline

1) The paradigms of integrated assessment modeling
   - Policy evaluation modeling
   - Policy optimization modeling
   - Policy guidance modeling

2) Uncertainty in integrated assessment
   - The probabilistic Tolerable Windows Approach

3) Modeling impacts of climate change
   - Changes in flooding probability

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- The probabilistic Tolerable Windows Approach

3)Modeling impacts of climate change
- Changes in flooding probability

The general problem

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  - Consider the **entire** chain of cause-and-effect of climate change

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Emissions of greenhouse gases

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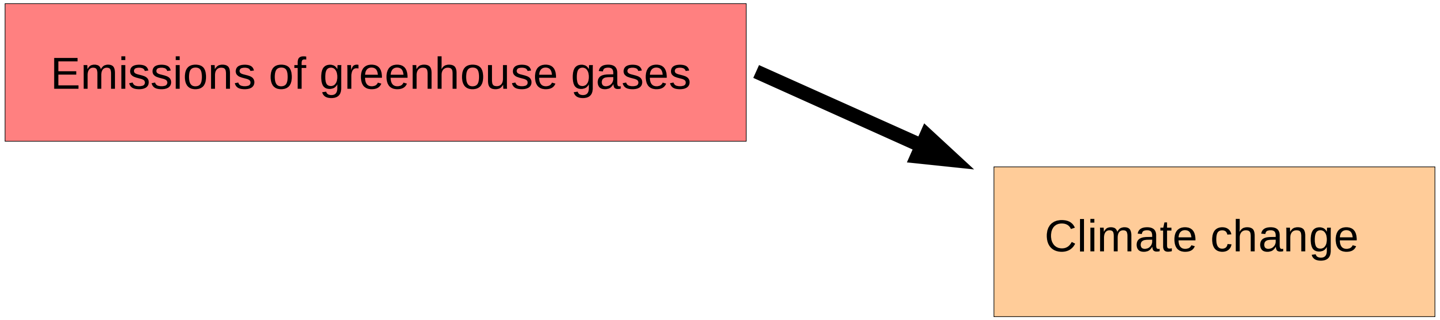

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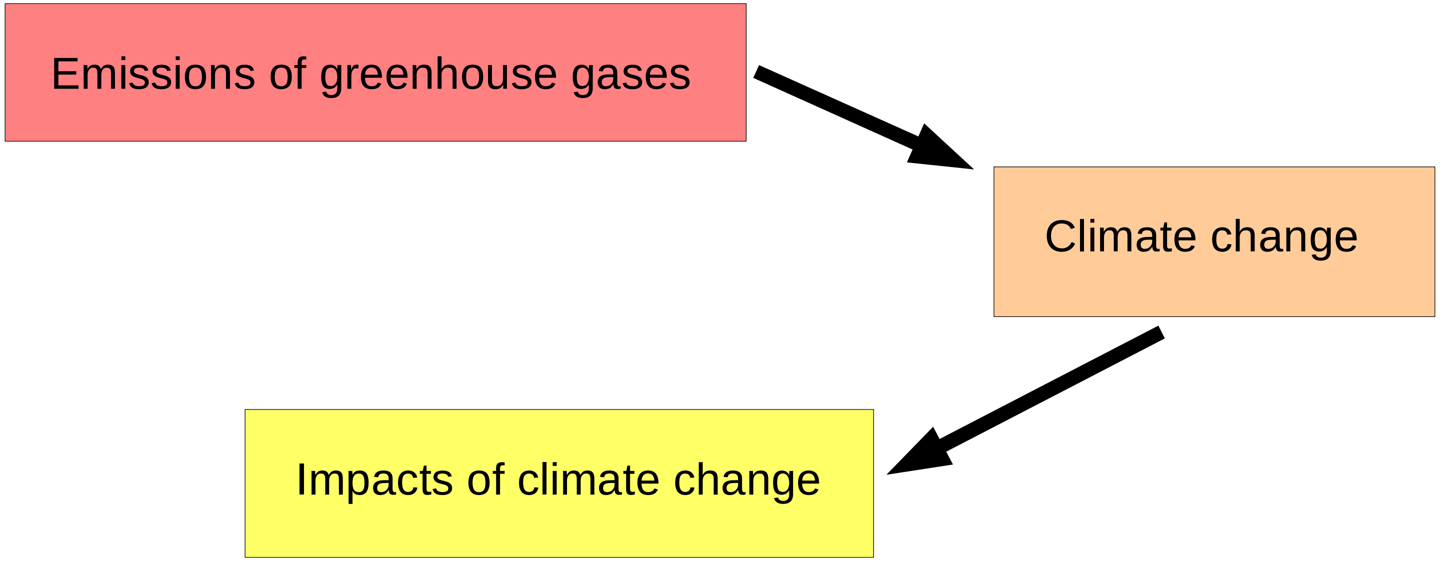

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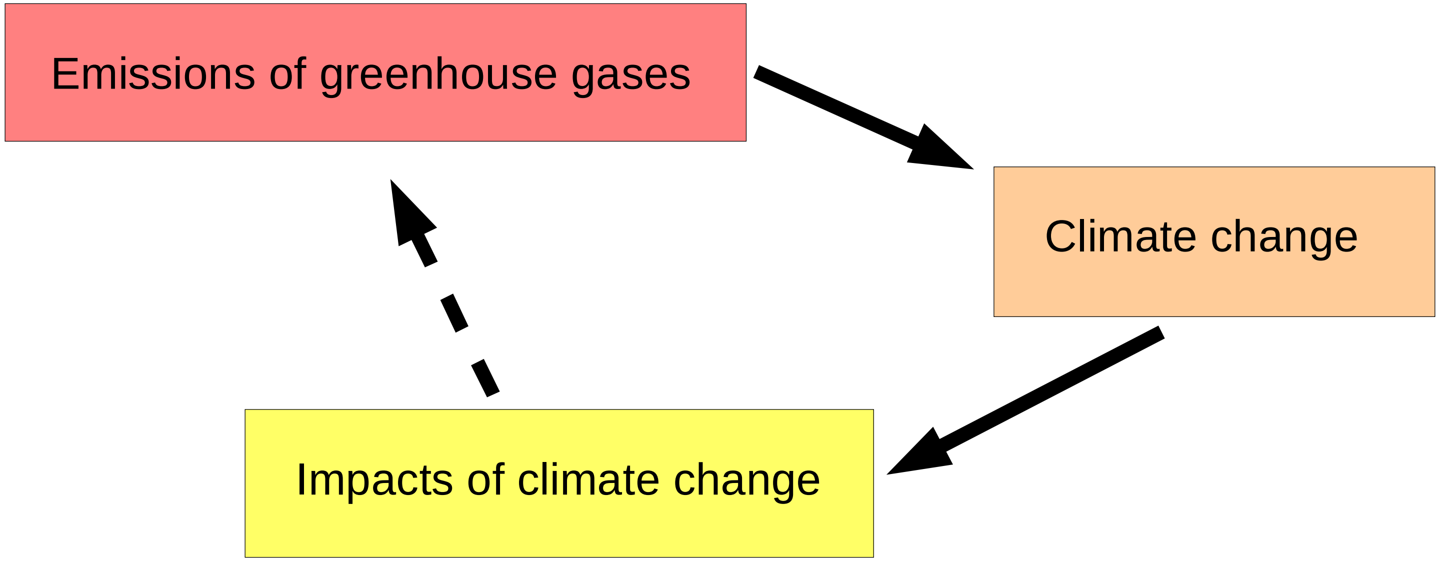

  - Assessment conducted in **integrated** framework

Three paradigms

- Mathematically integrated assessment is a *control problem*

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, t; \boldsymbol{u})$$

- Evolution of system state $\boldsymbol{x}$ also depends on *control vector* $\boldsymbol{u}$
- Three general approaches to handle this kind of problem:

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   - ***Policy guidance modeling***

Policy evaluation modeling

- The general approach:
  - Predefine control path, e.g. GHG emissions, investment decisions, R&D
  - Evaluate consequences
- Example: IMAGE family of IA models, e.g. Rotmans et al. 1990

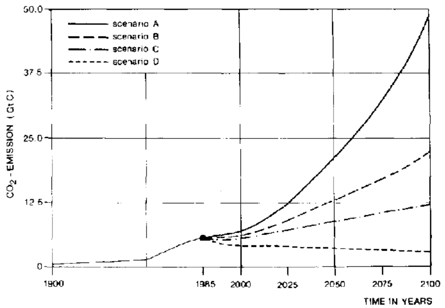

Fig. 2. Emisison of CO_2.

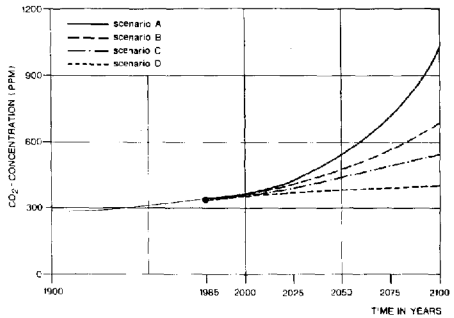

Fig. 8. Concentration of CO_2.

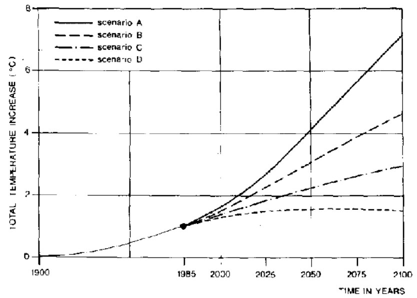

Fig. 13. Total temperature increase.

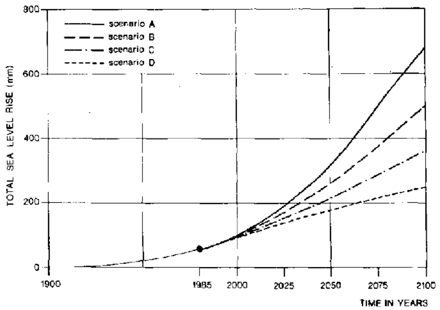

Fig. 15. Total sea level rise.

The IMAGE model

- IMAGE = **I**ntegrated **m**odel for the **a**ssessment of the **g**reenhouse **e**ffect

Emissions of greenhouse gases

Climate change

Impacts of climate change

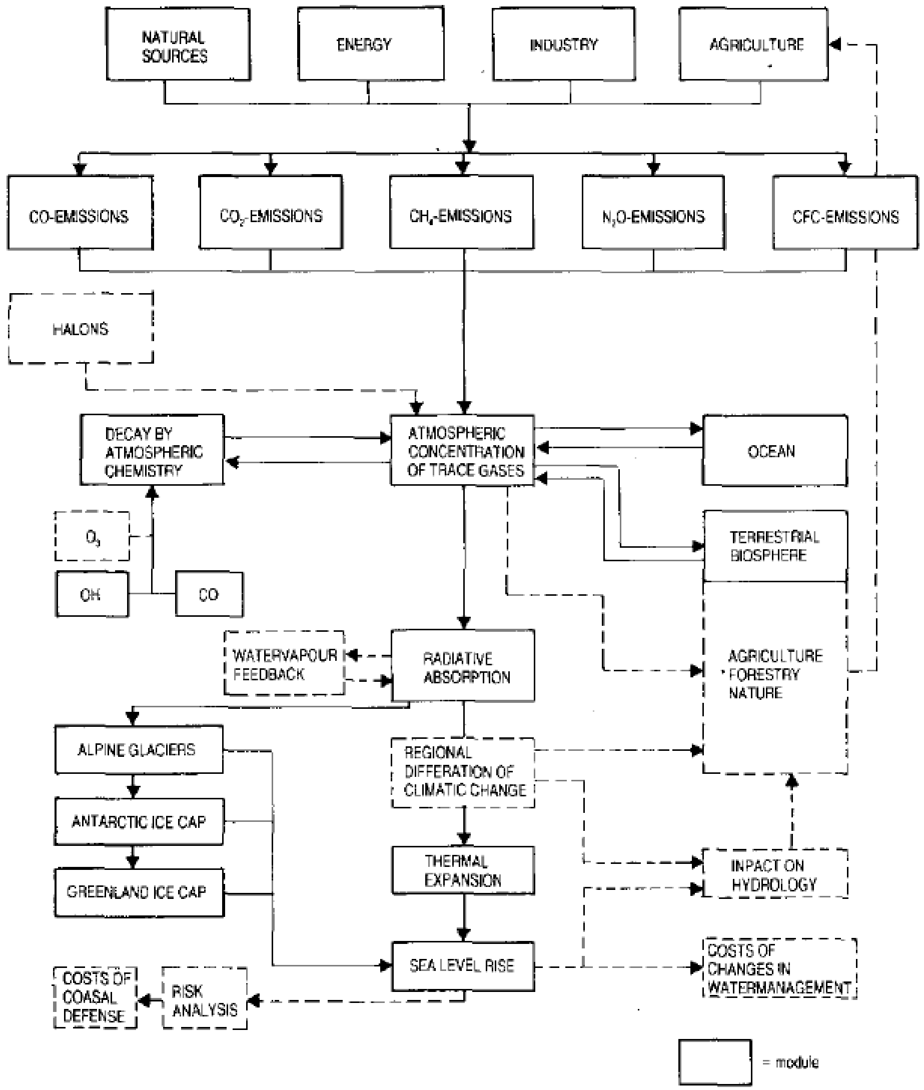

Fig. 1. Extended integrated model for the assessment of the greenhouse effect.

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Emissions of greenhouse gases

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Climate change

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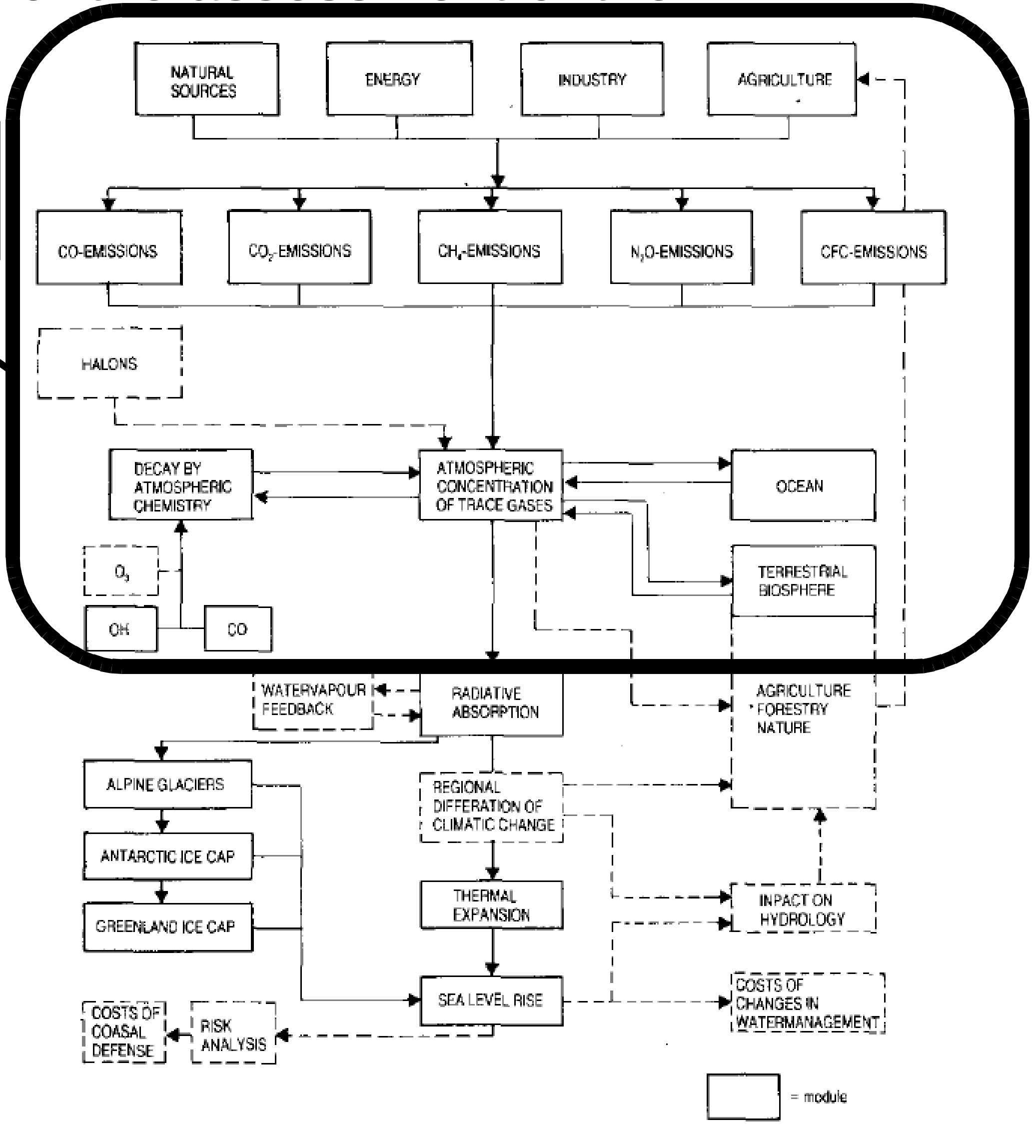

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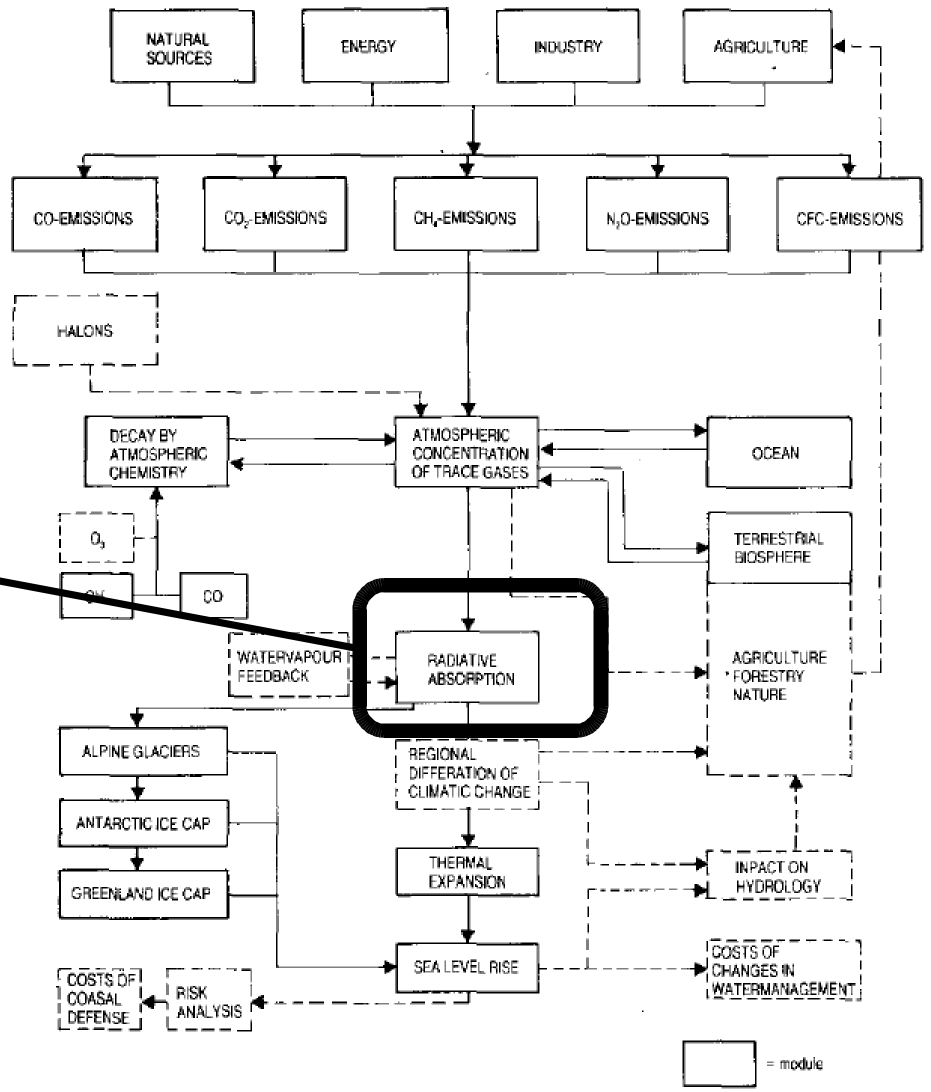

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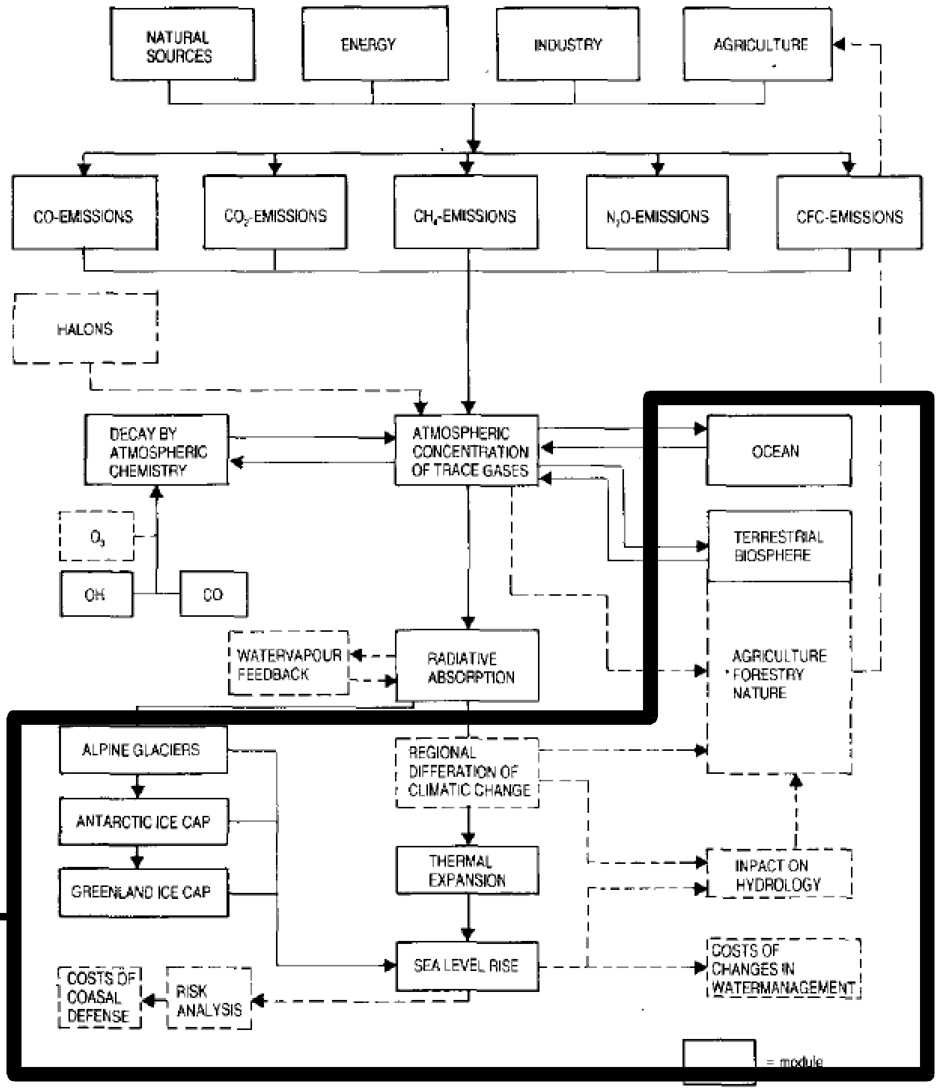

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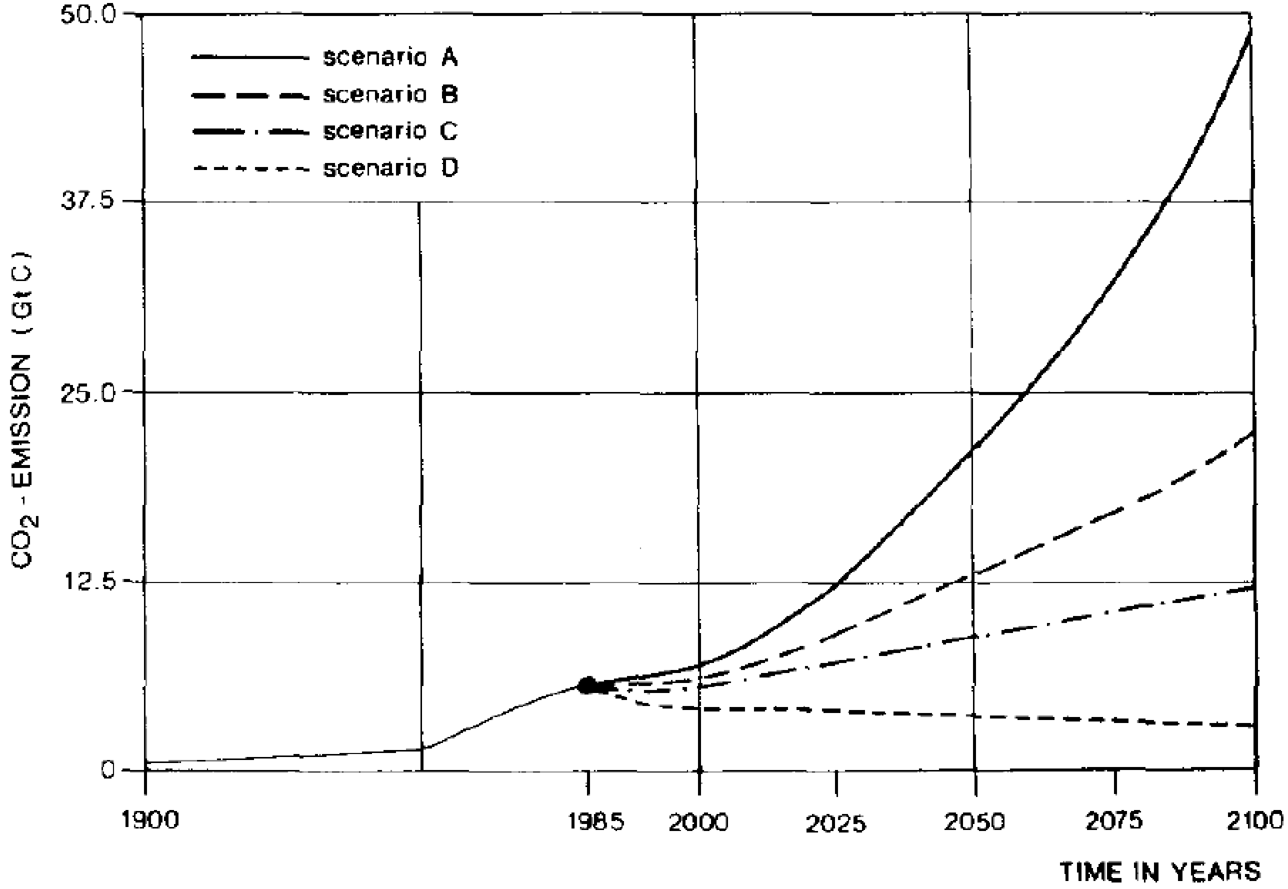
Policy evaluation modeling



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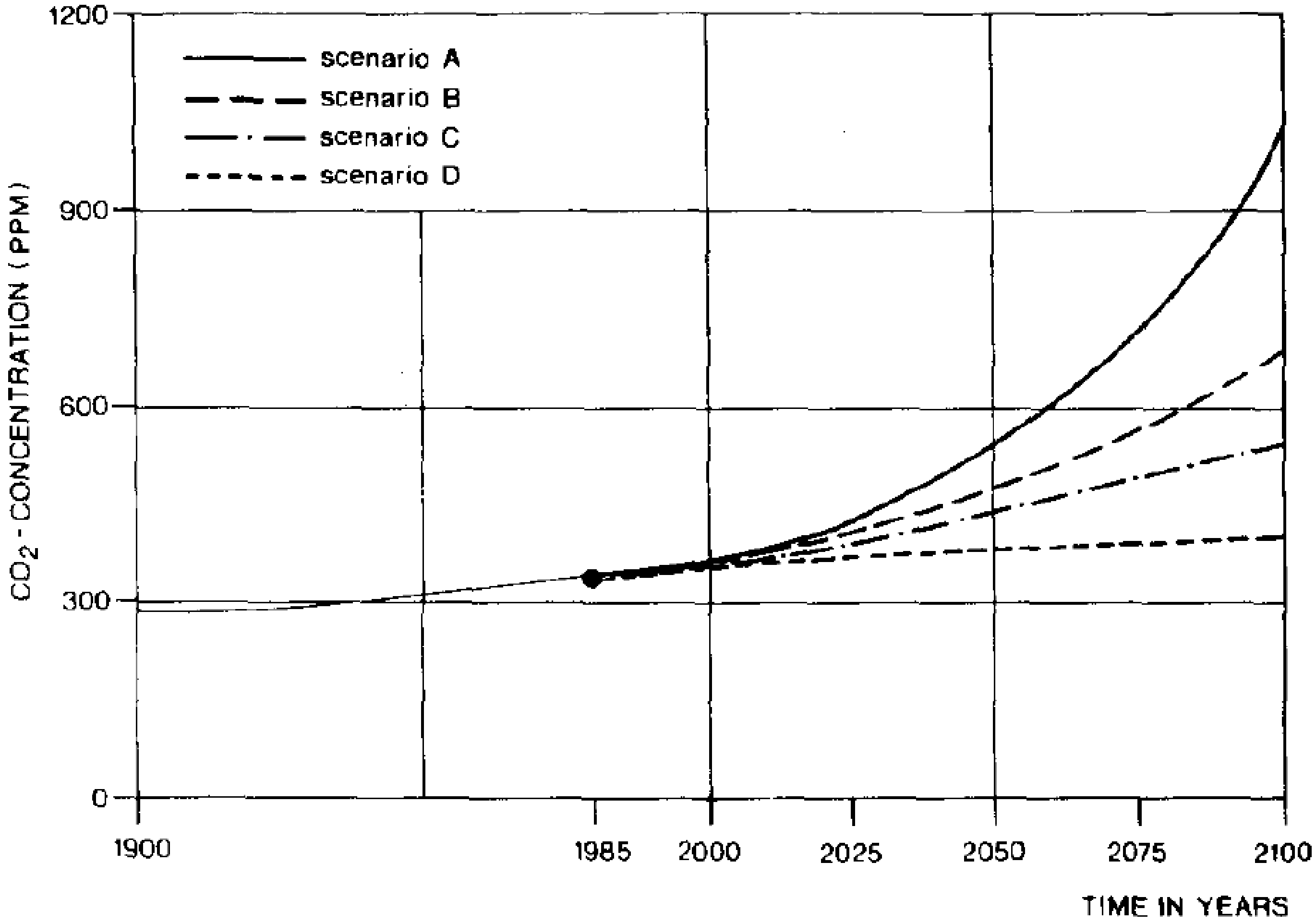

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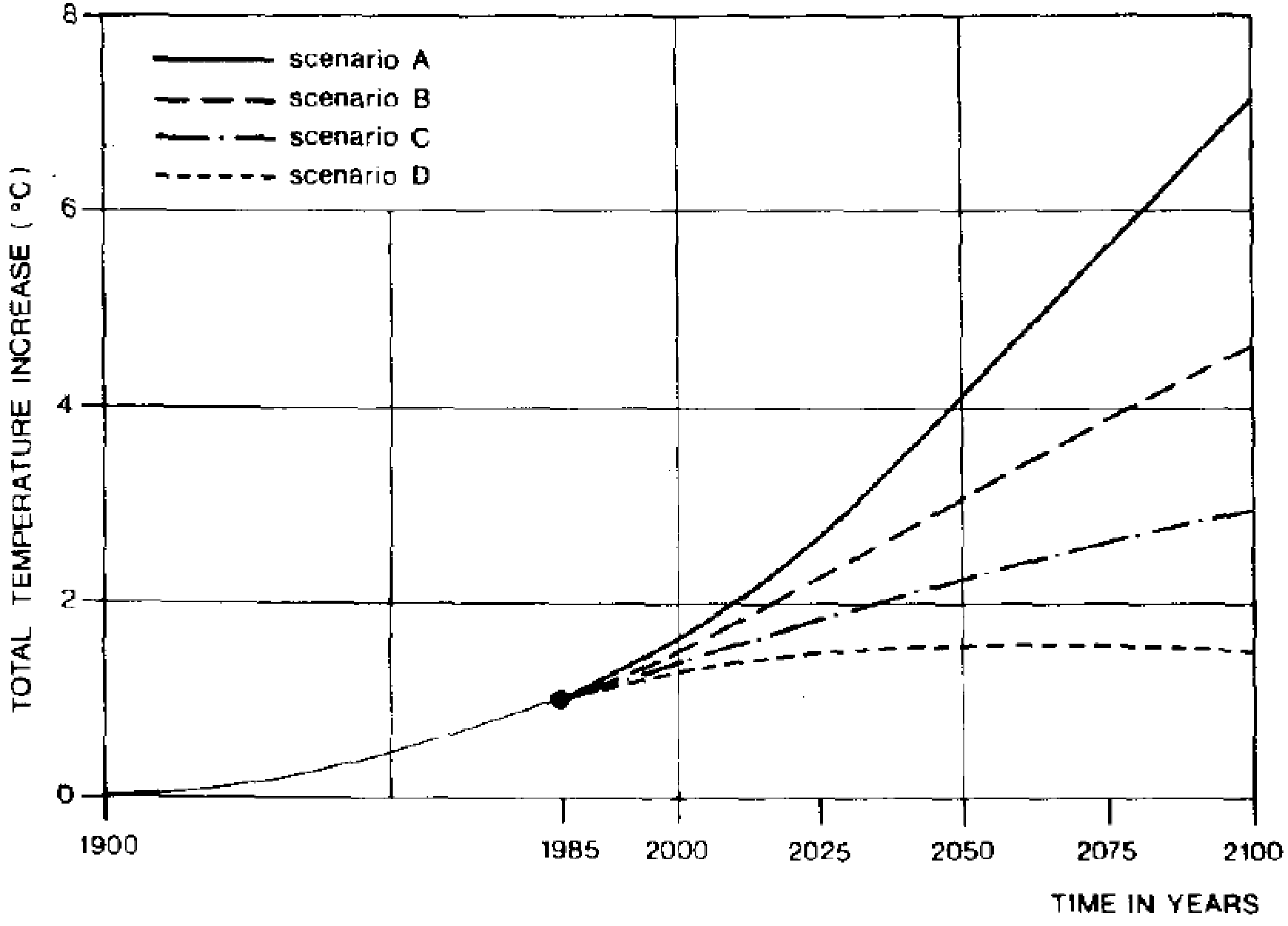

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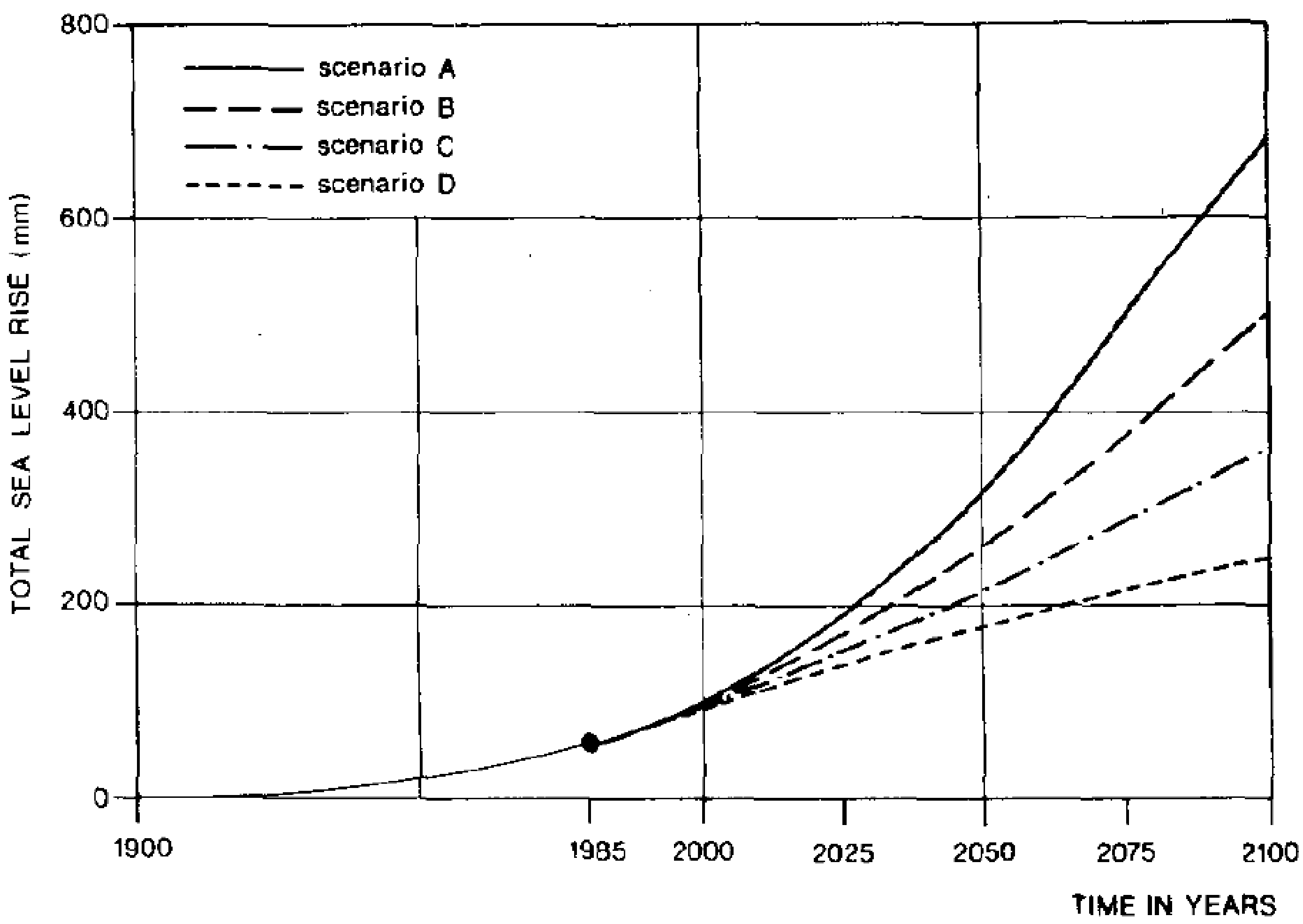

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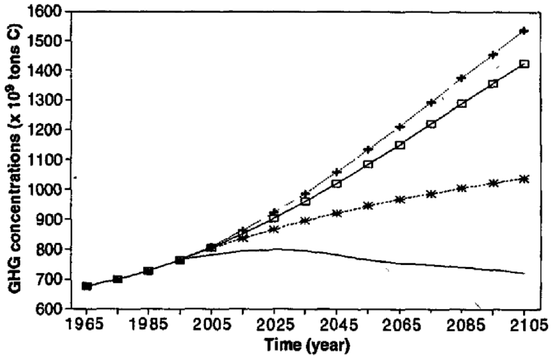
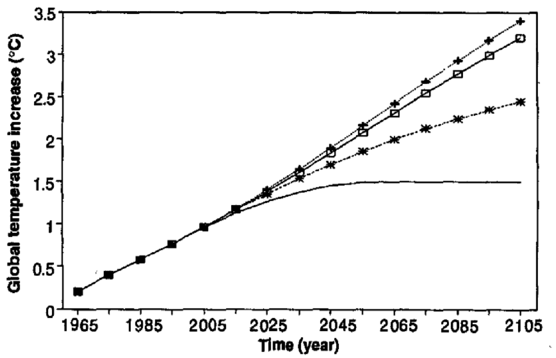
Policy evaluation modeling II

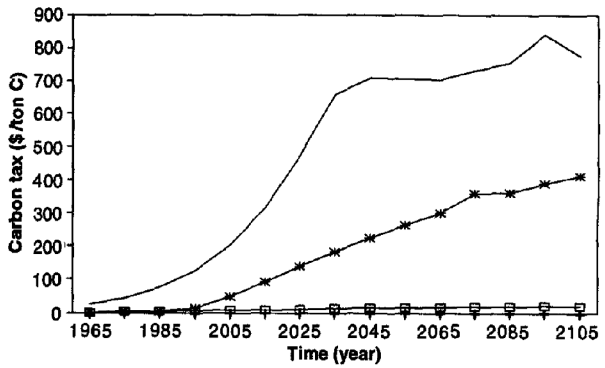
- Advantages:
  - Allows use of process-based models well established in natural sciences
  - High resolution possible, very detailed assessment
  - Any impact(s) that can be described by a model can be considered
- Disadvantages:
  - Search for policy recommendation by trial and error

Policy optimization modeling

- Aim: determine *optimal* control path
- Two flavors: cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA)
- CEA: Determine cost-efficient controls to reach target
- CBA: Determine control path that maximizes global welfare while considering costs and benefits of climate change
- Example: DICE / RICE models, Nordhaus 1992

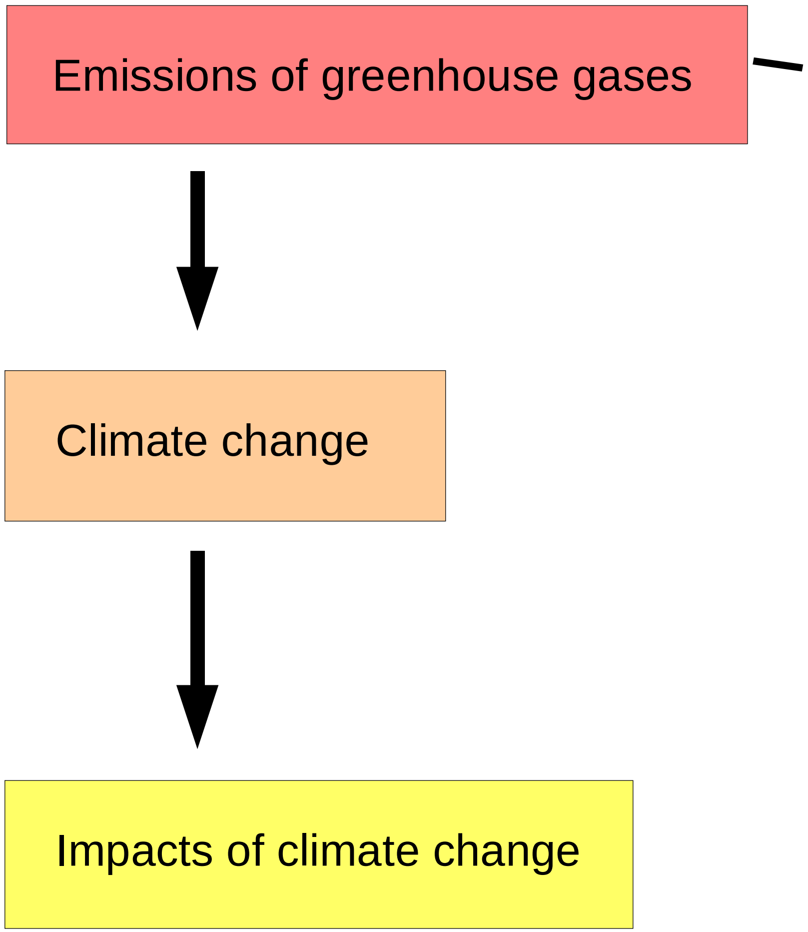






The DICE model

- DICE = **D**ynamic **i**ntegrated **c**limate **e**conomy



- Economic submodel
  - ➔ Economic utility over time
  - ➔ Utility dependent on economic output
  - ➔ Again dependent on capital, labor, investment
  - ➔ Emissions dependent on Output
  - ➔ Cost of GHG reductions: simple function, obtained from studies

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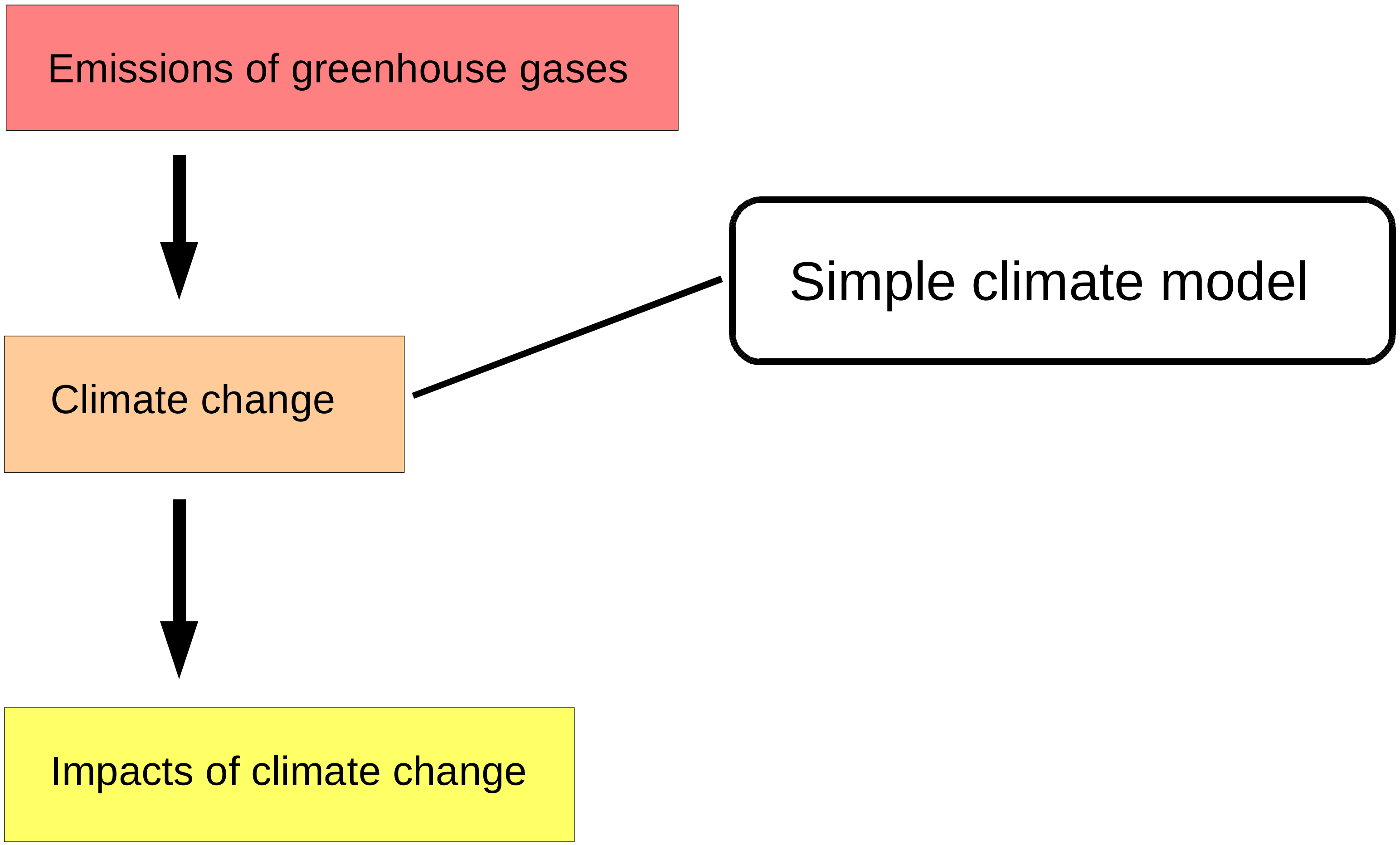

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Emissions of greenhouse gases

↓

Climate change

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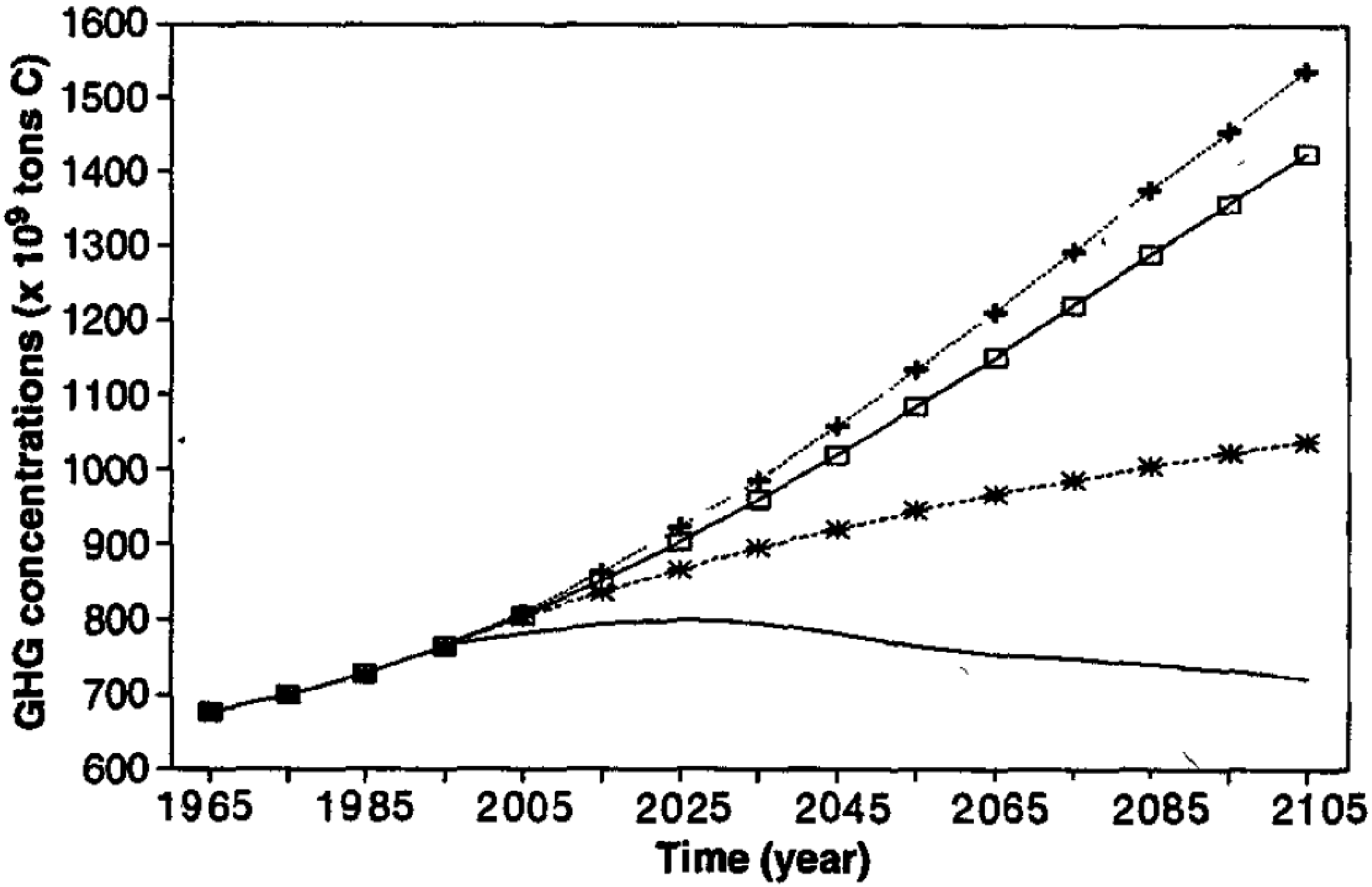
Impacts of climate change

- Climate change impacts:
  - Simple function
  - Function determined from case studies
  - Relates warming to costs / benefits
  - Globally aggregated

Policy optimization modeling



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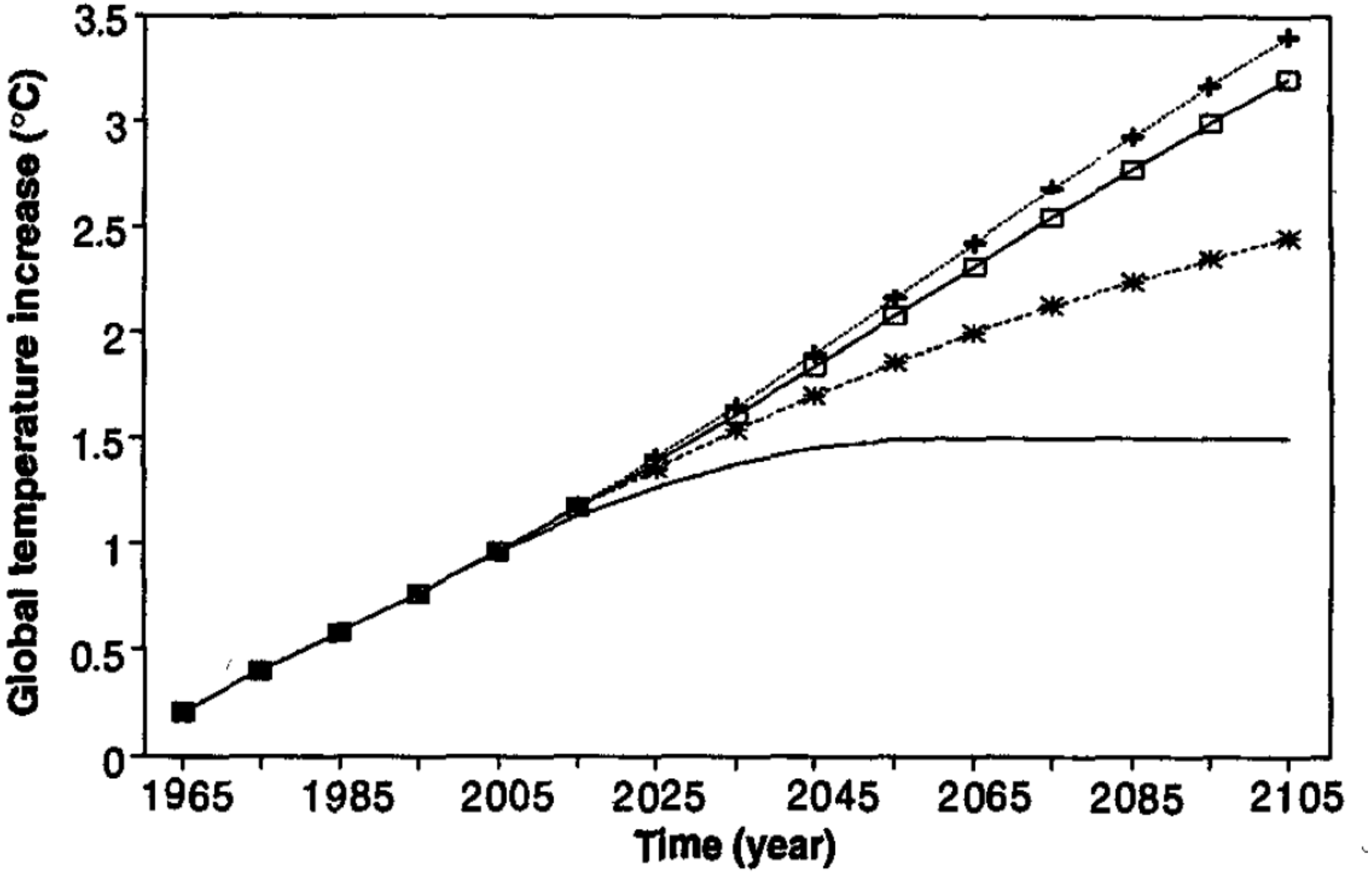

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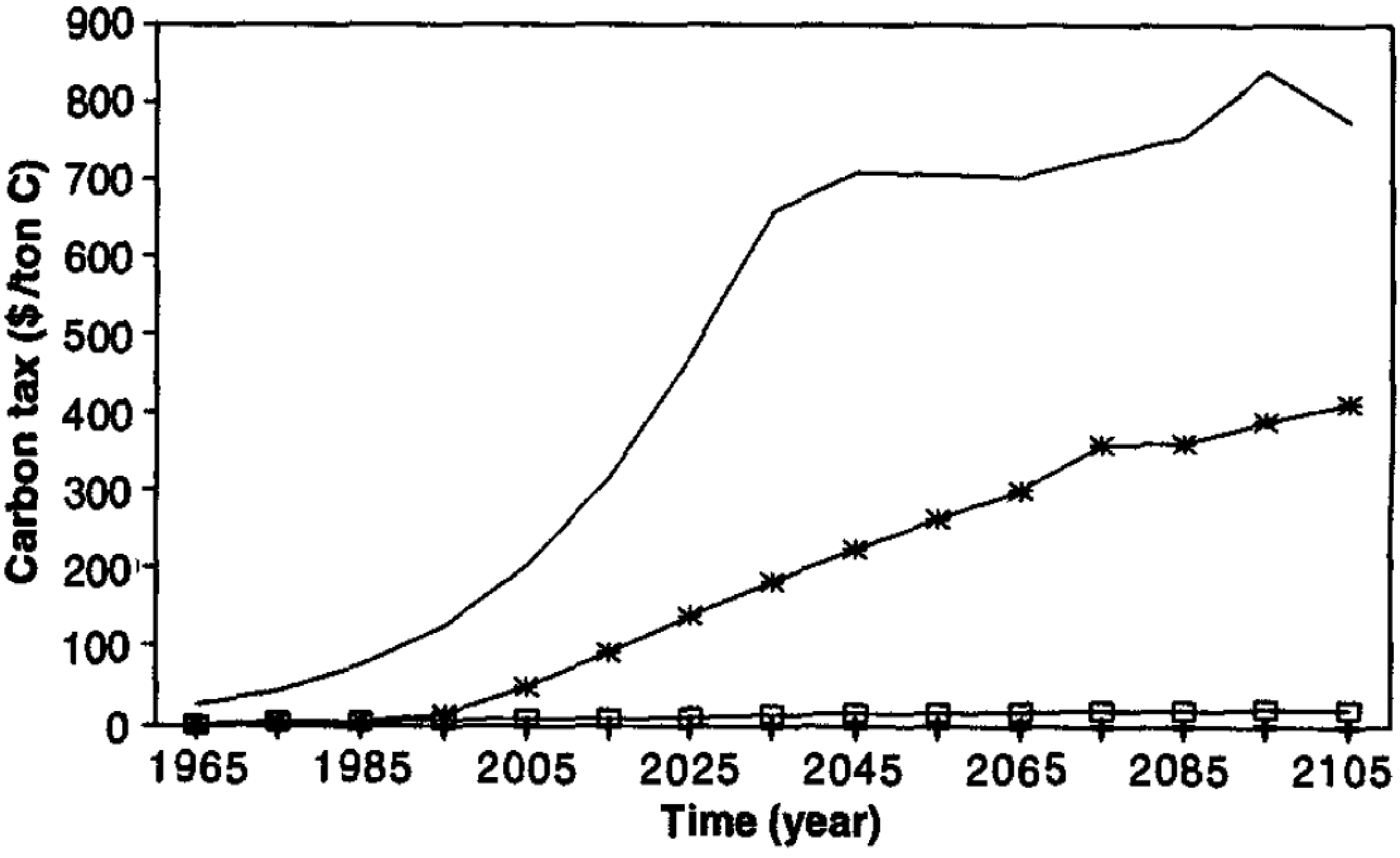


Optimization modeling II

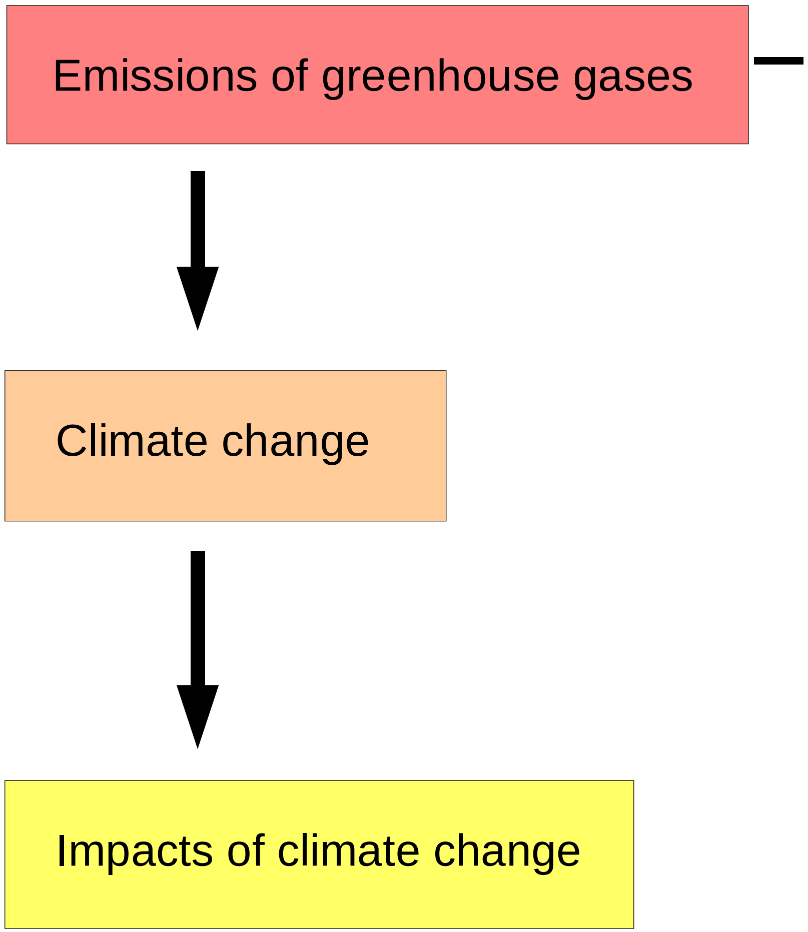
- Advantages:
  - Comparison in single metric
  - Allows determination of policy recommendations
- Disadvantages:
  - Global aggregation masks winners and losers of climate change
  - Cost / benefit studies mainly for industrialized countries
  - Costing of non-market impacts very uncertain, possibly ethically non-desirable
  - Discounting leads to low valuation of future impacts

Policy guidance modeling

- Aim: determine control strategies that are compatible with climate change policy objectives
- General approach:
  - Introduce additional constraints (“guardrails”) to exclude undesirable consequences of climate change or undesirable climate protection strategies
  - Determine set of emission strategies that violate none of the introduced guardrails
- Example: Tolerable Windows Approach (TWA), Bruckner et al. 1999

Tolerable Windows Approach

- TWA = **T**olerable **w**indows **a**pproach



- No sub-model for emissions, since set of allowed emission strategies is determined

Tolerable Windows Approach

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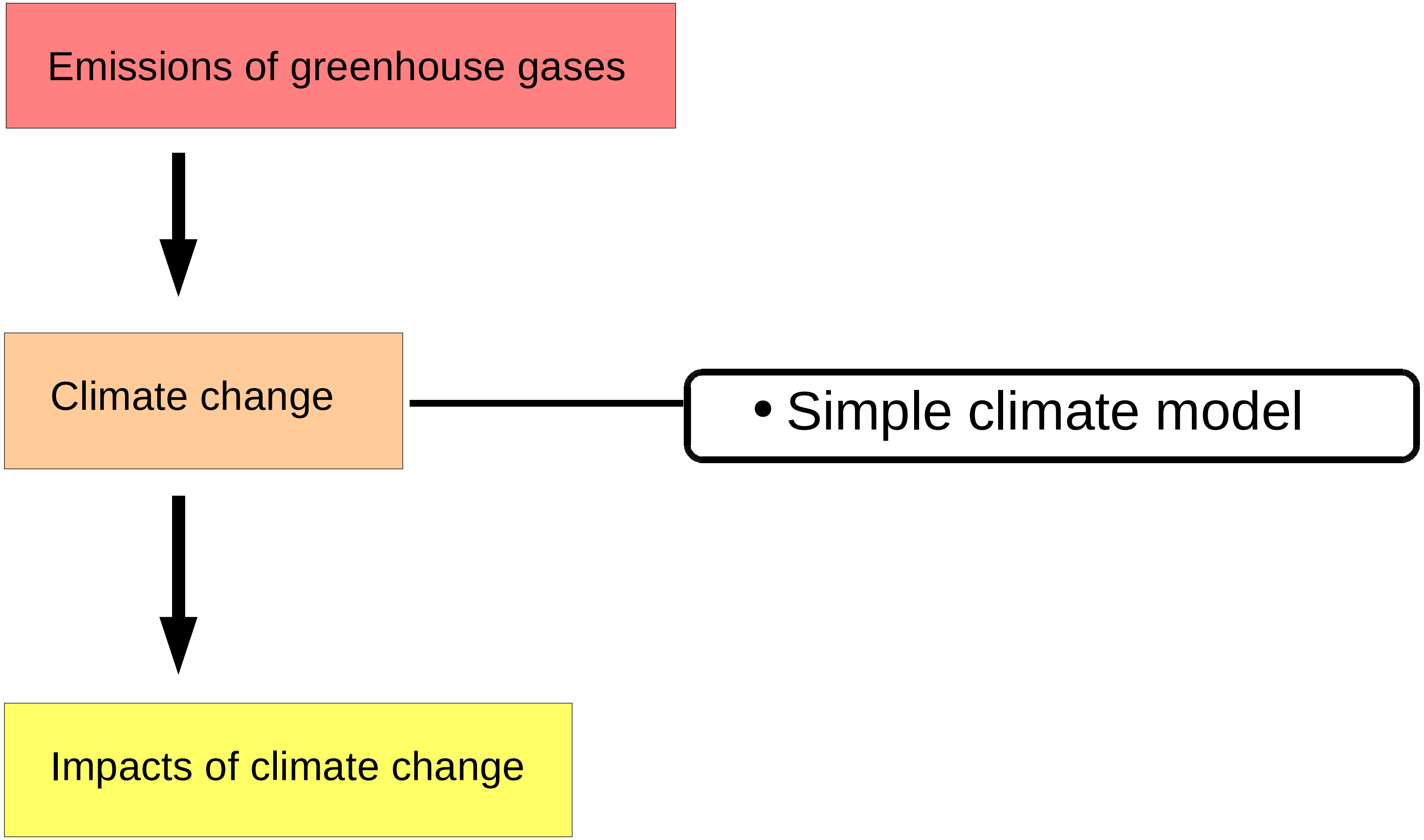

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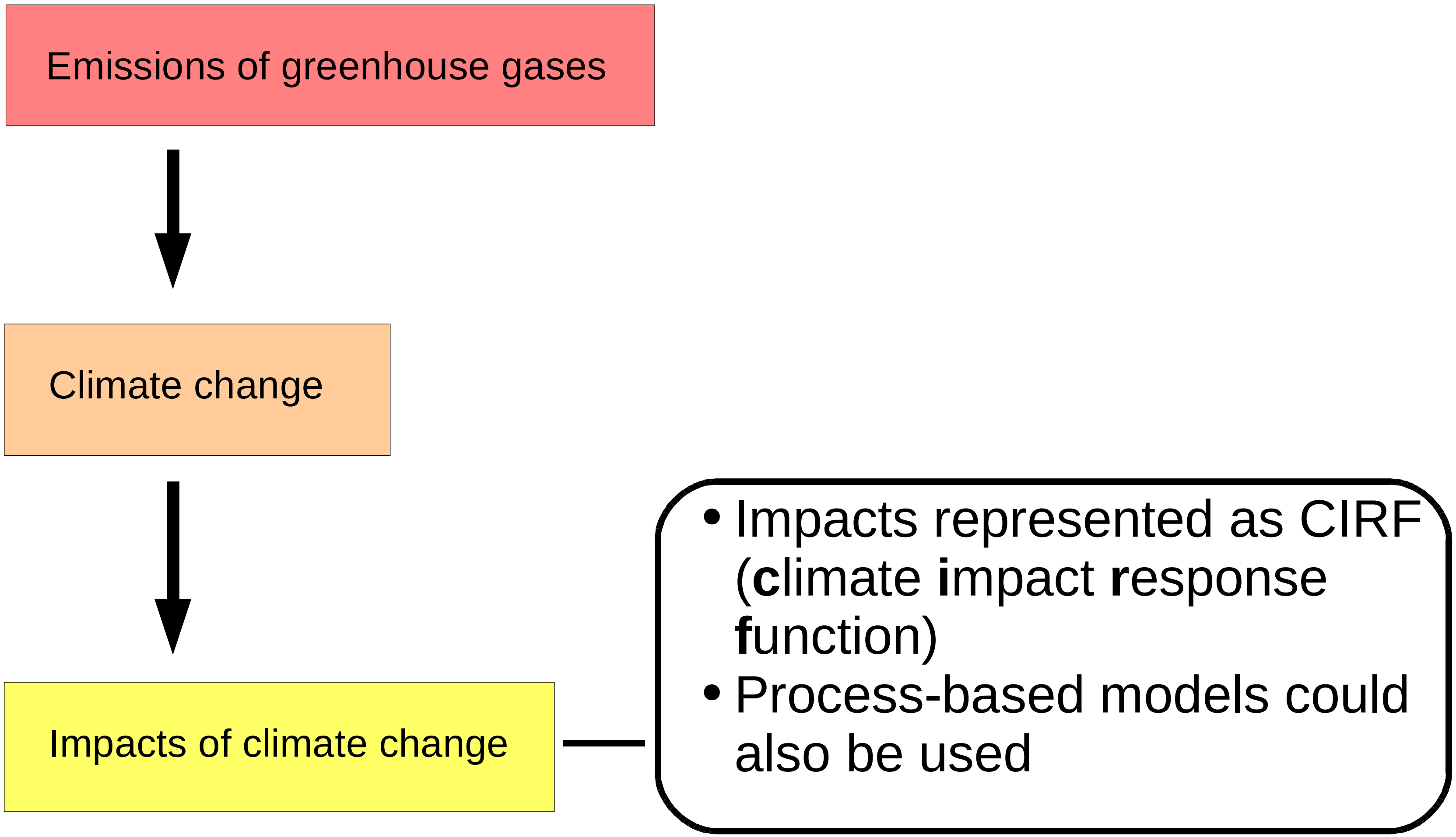
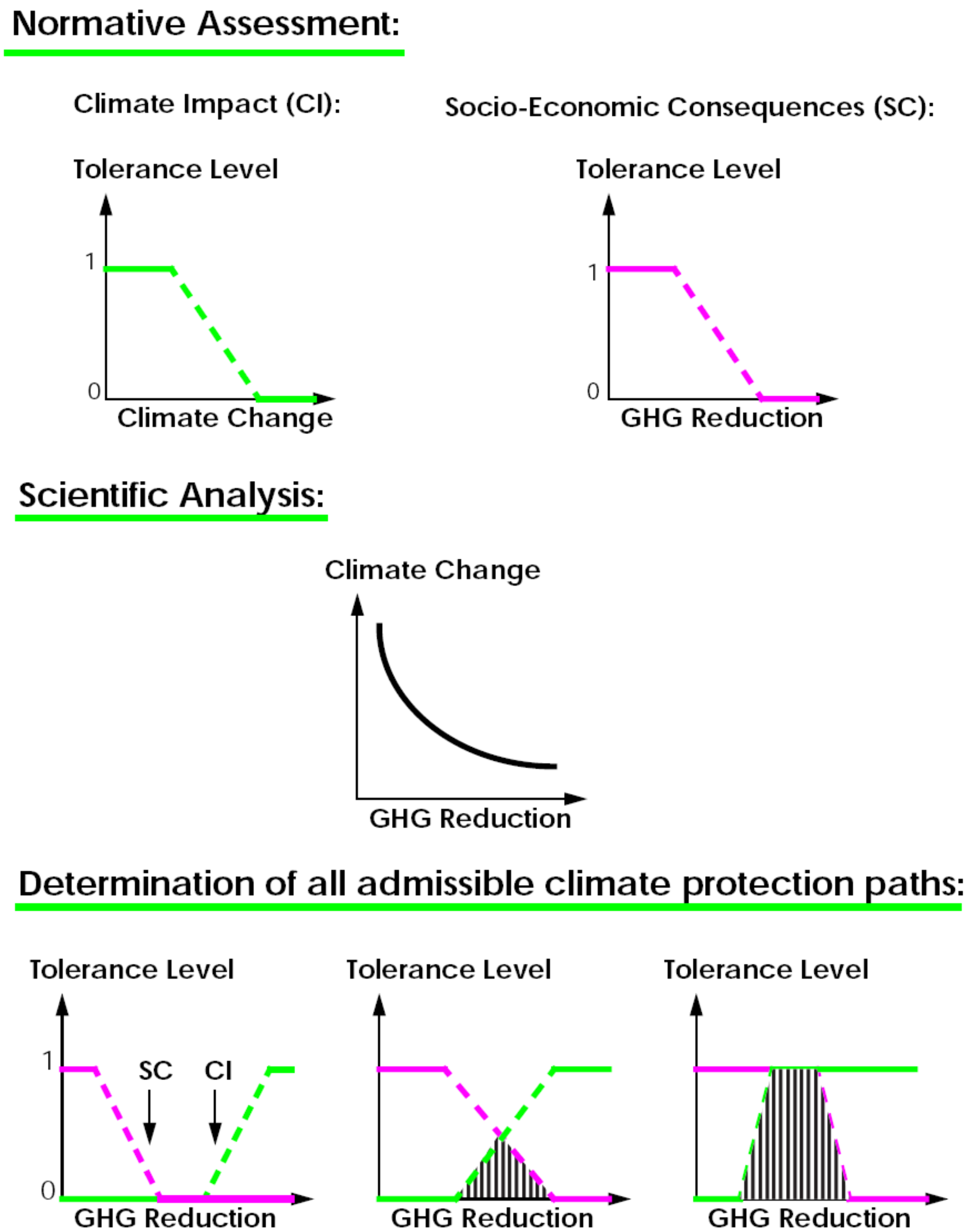


TWA schematically

- In the TWA, assessment starts with “guardrails”
- Guardrails define tolerable climate change impacts / GHG reductions
- Analysis subsequently determines set of admissible protection strategies



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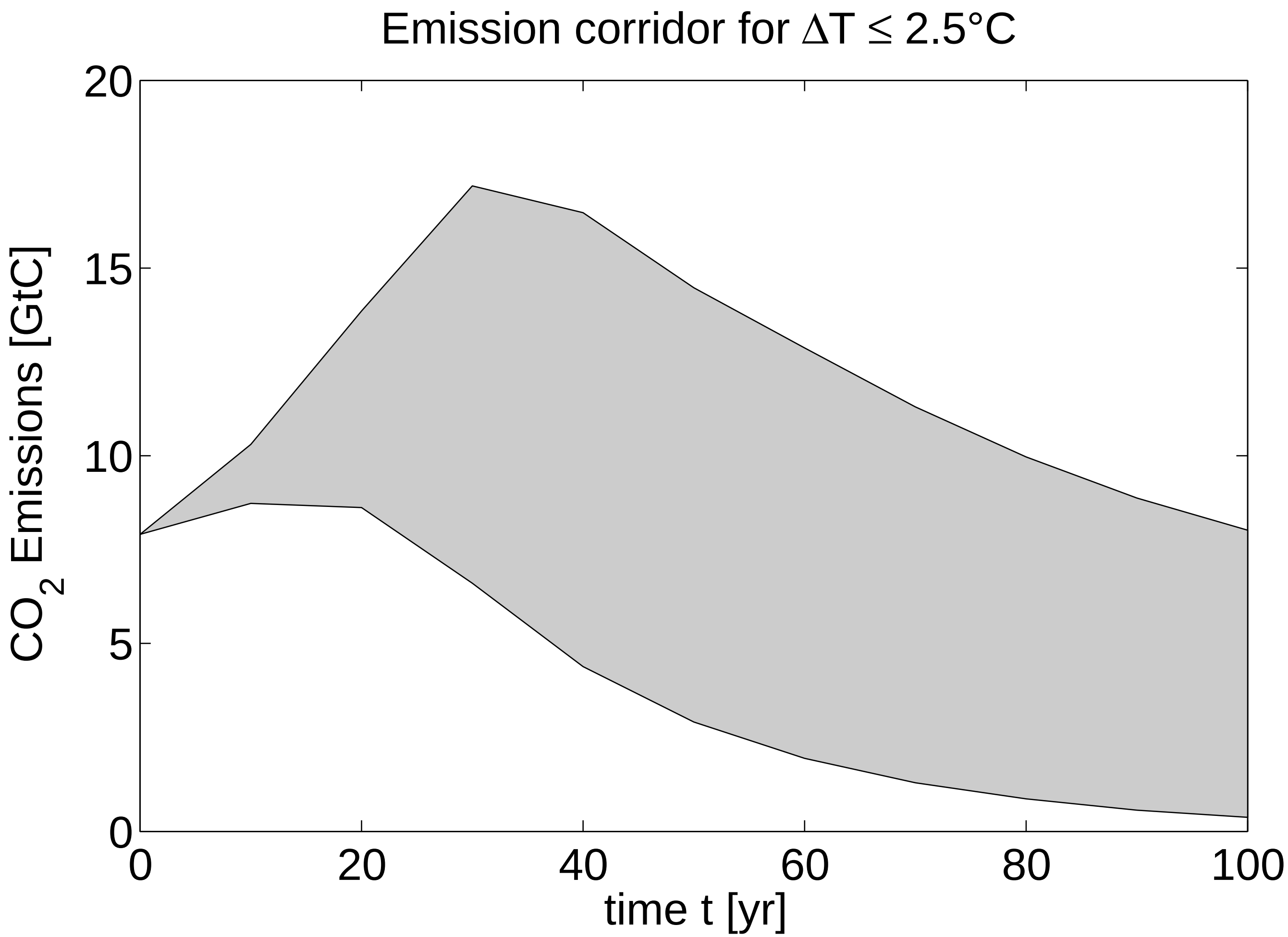
Emission corridor

- Application to climate change: emission corridor
- Guardrail:

$$\Delta T \leq 2.5°C$$

- Further guardrails to admissible emission reductions



Summary

- Three paradigms in integrated assessment
- Distinguished by handling of control vector:
  - Prescribed for policy evaluation modeling
  - Optimized in policy optimization modeling
  - Set compatible with constraints determined in policy guidance modeling
- Approaches are complementary
- Neither takes uncertainty into account explicitly

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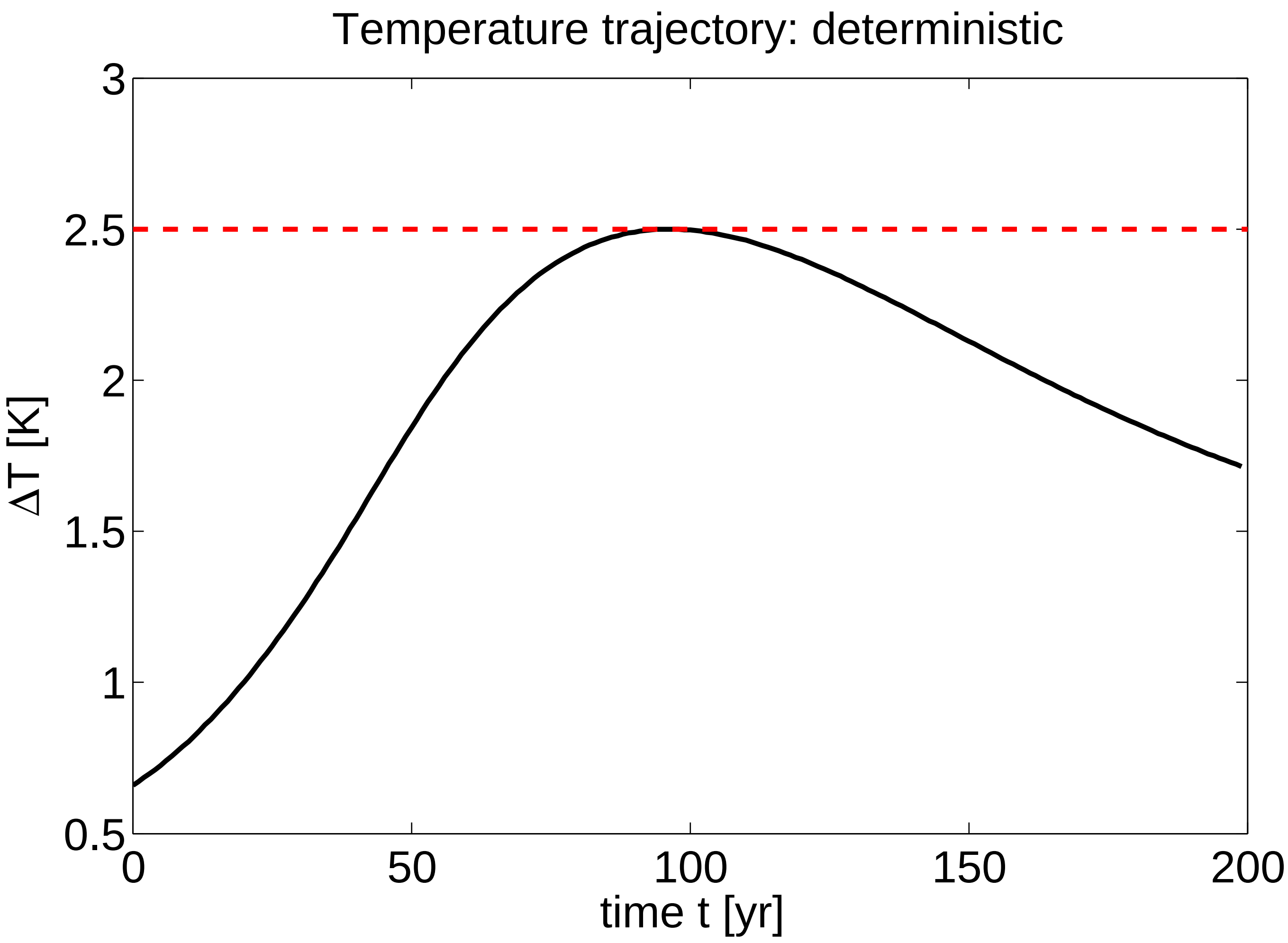
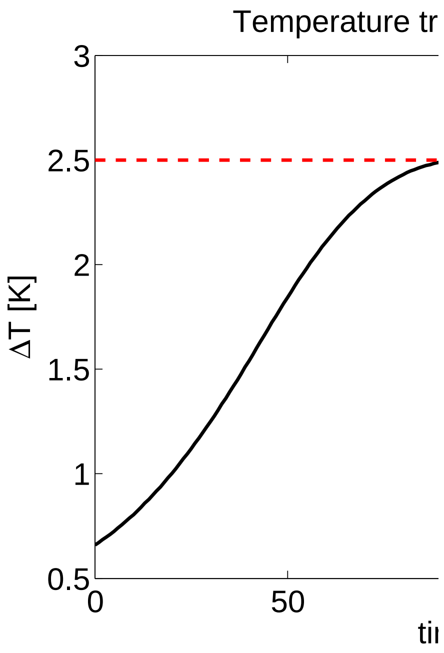
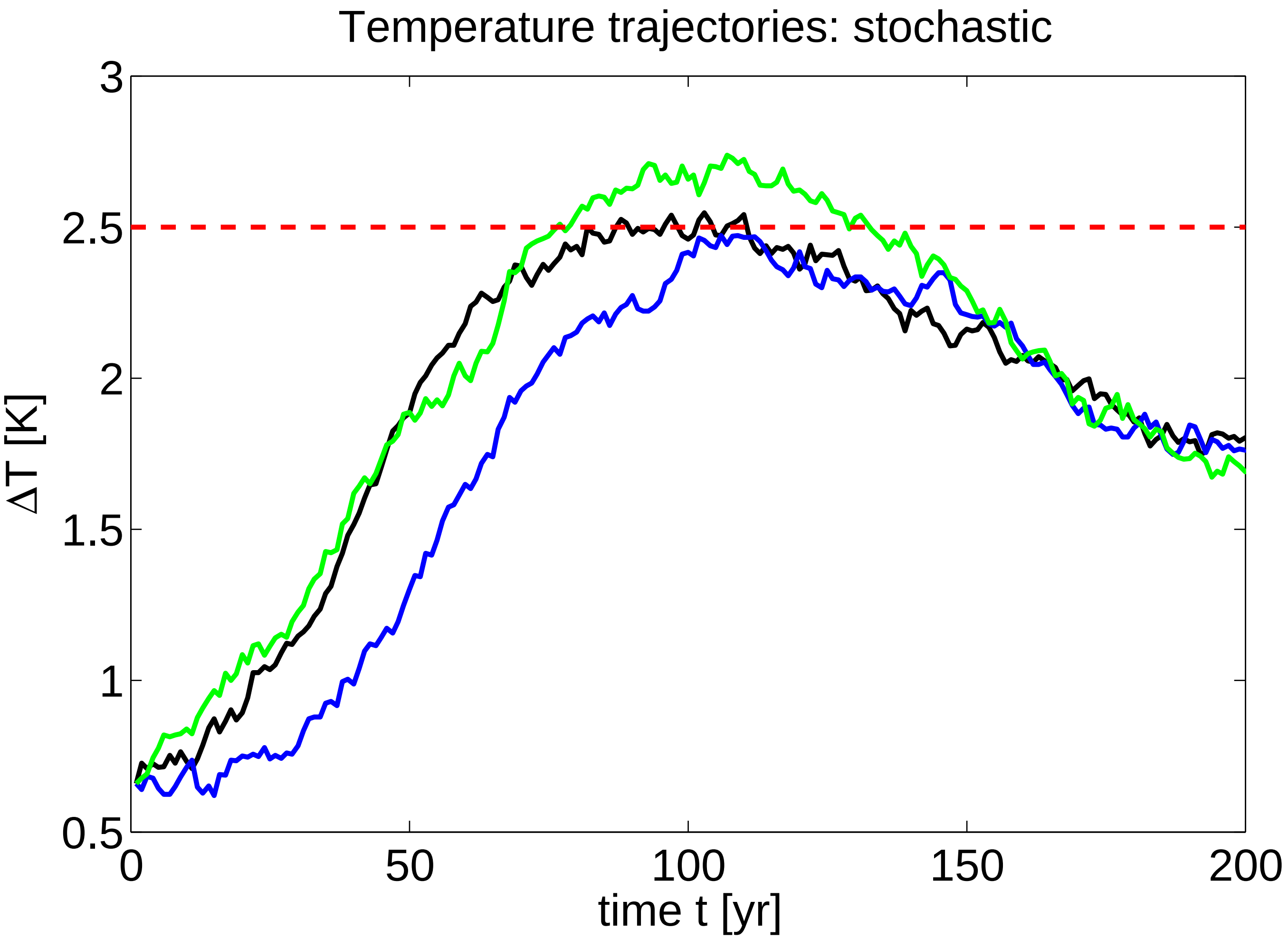
Temperature trajectories



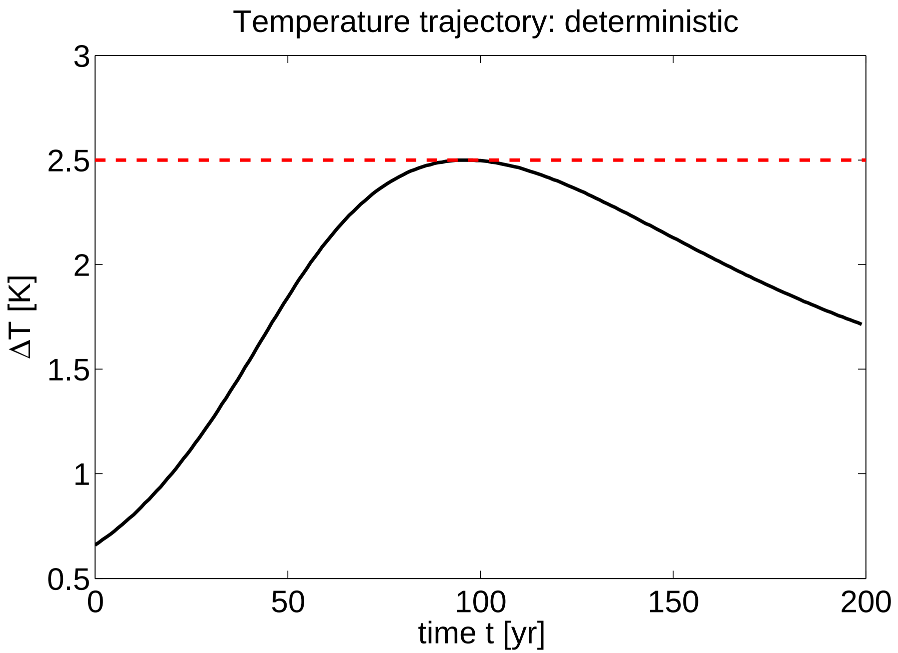
Temperature trajectories with nat. variability

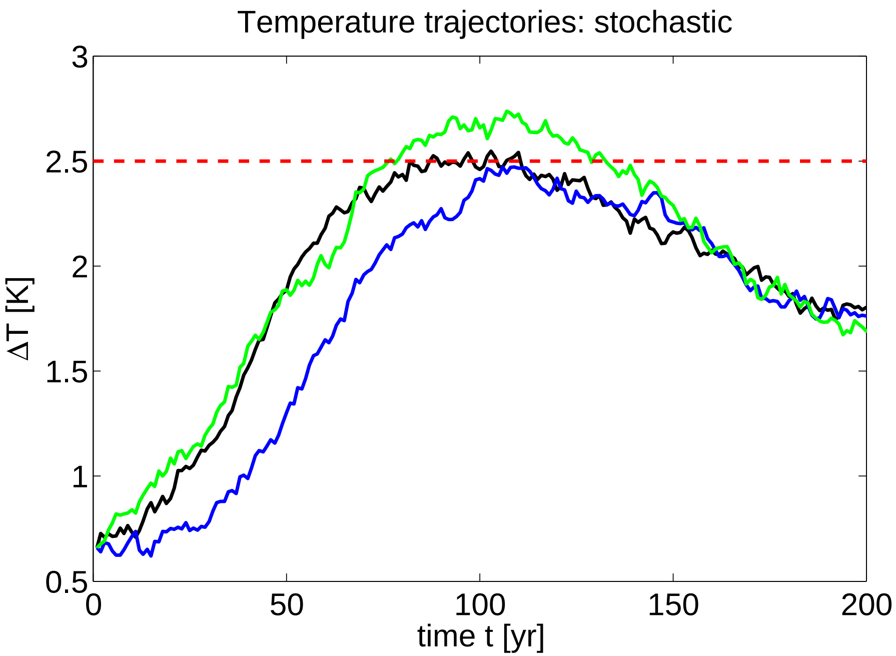




Temperature trajectories with nat. variability

- Consideration of natural variability possible in stochastically modified climate model
- Result: observing guardrail dependent on *realization* of stochastic process => nonzero probability that guardrail is exceeded





Uncertainty

- Uncertainty ever present factor in entire chain of cause-and effect of climate change
- Sensible classification for our purposes by causes of uncertainty:
  1)Uncertainty caused by the freedom of human decisions
  2)Uncertainty caused by natural variability
  3)Uncertainty caused by insufficient knowledge

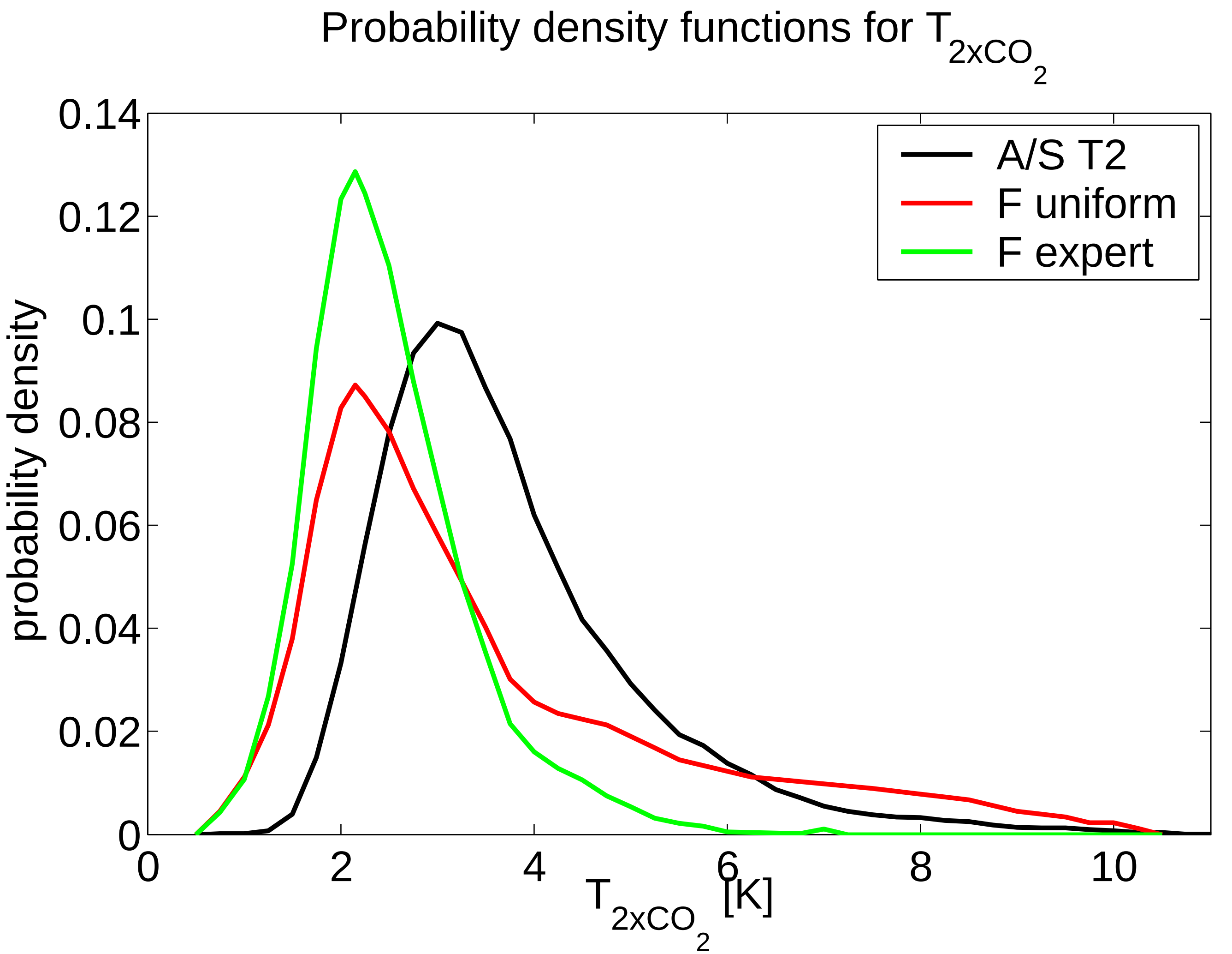
- TWA partly anticipates 1) since human decisions are not *predicted*, but the *maneuvering space for human decisions* is determined instead
- 2) and 3) subject of the probabilistic TWA

Uncertainty in climate sensitivity

- *Climate sensitivity* is one of the key uncertain factors for future climate change
- Climate sensitivity T_{2xCO_2} warming to be expected for doubling of preindustrial CO_2 - concentration
- IPCC: $T_{2xCO_2} \in [1.5°C, 4.5°C]$
- Other authors: probability distributions for T_{2xCO_2}, i.e. from expert elicitations, comparisons of historical climate with model results

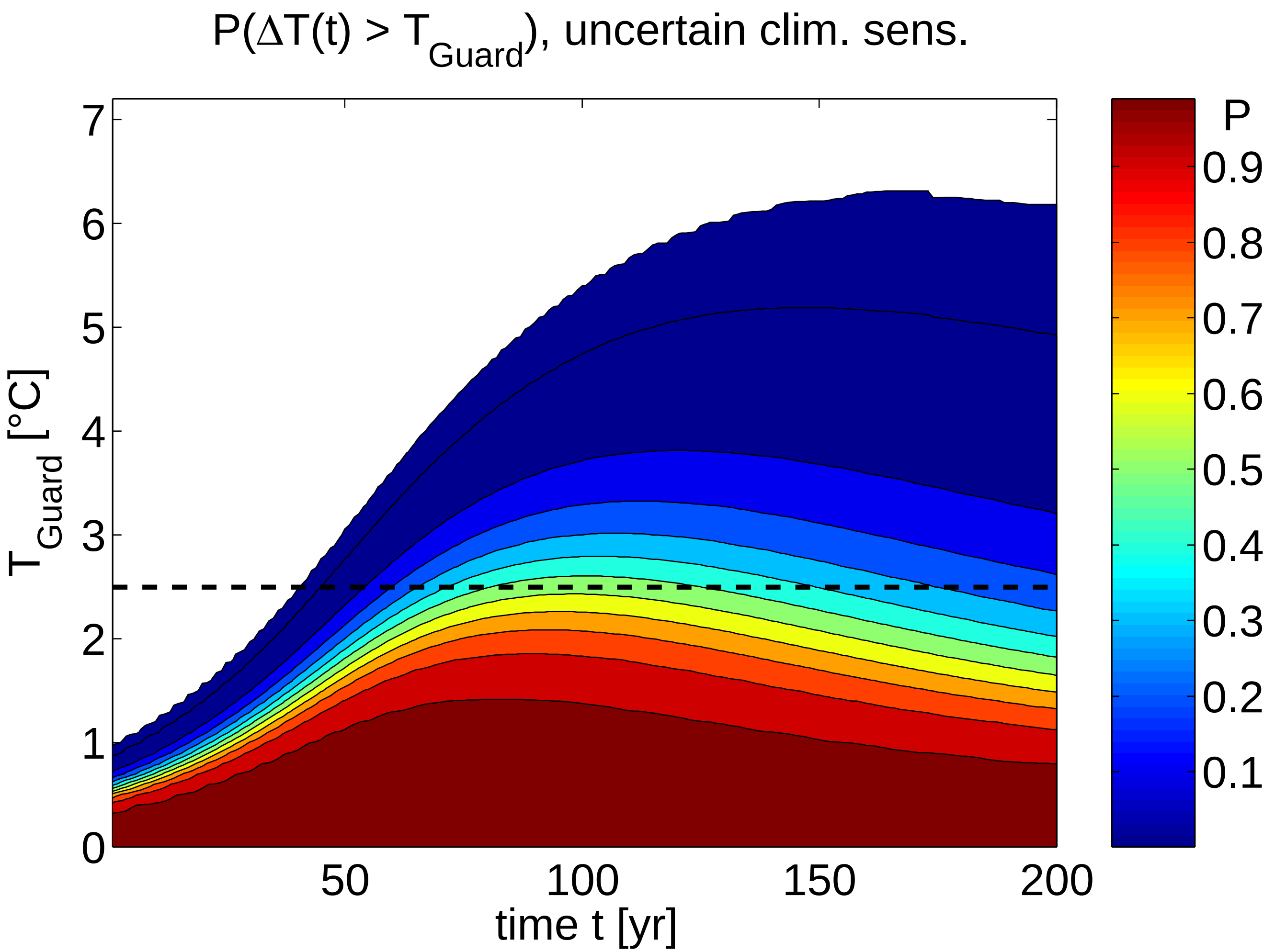
Probability distributions climate sensitivity

- Andronova & Schlesinger (2001) (black)
- Forest et al. (2002) (red, green)



Consequences of uncertainty climate sensitivity

- Climate sensitivity Andronova & Schlesinger
- Leads to probability $P > 0$ that guardrail cannot be observed



The probabilistic TWA

- Uncertainties imply: Extension of TWA necessary
- Deterministic guardrail for impact I defined as

$$I \leq I_{Guard} \;\Rightarrow\; P\left(I \leq I_{Guard}\right) \in \{0,1\}$$

- If probabilistic uncertainty considered:

$$P\left(I \leq I_{Guard}\right) \in [0,1]$$

- Therefore additional probability guardrail necessary

$$I \leq I_{Guard} \;\Rightarrow\; P\left(I \leq I_{Guard}\right) \geq P_{Guard}$$

Solution algorithm

- Problem to be solved: generally stochastic differential inclusion

$$d\boldsymbol{\xi} \in \mathbb{F}(\boldsymbol{\xi}, dt \oplus d\boldsymbol{W})$$

with $\mathbb{F} := \{ \boldsymbol{f}(\boldsymbol{\xi}, t; \boldsymbol{u}) dt + \boldsymbol{g}(\boldsymbol{\xi}, t; \boldsymbol{u}) d\boldsymbol{W} \,|\, \boldsymbol{u} \in \mathbb{U} \}$

under $P(\boldsymbol{h}(\boldsymbol{\xi}, t; \boldsymbol{u}) \leq \boldsymbol{0}) \geq P_{Guard} \quad \forall t \in [0, t_e]$

- Determination of the upper (lower) boundary of emission corridors:

$$\forall t_i \in \{t_1, \ldots, t_n\}: \quad max(min) E(t_i)$$

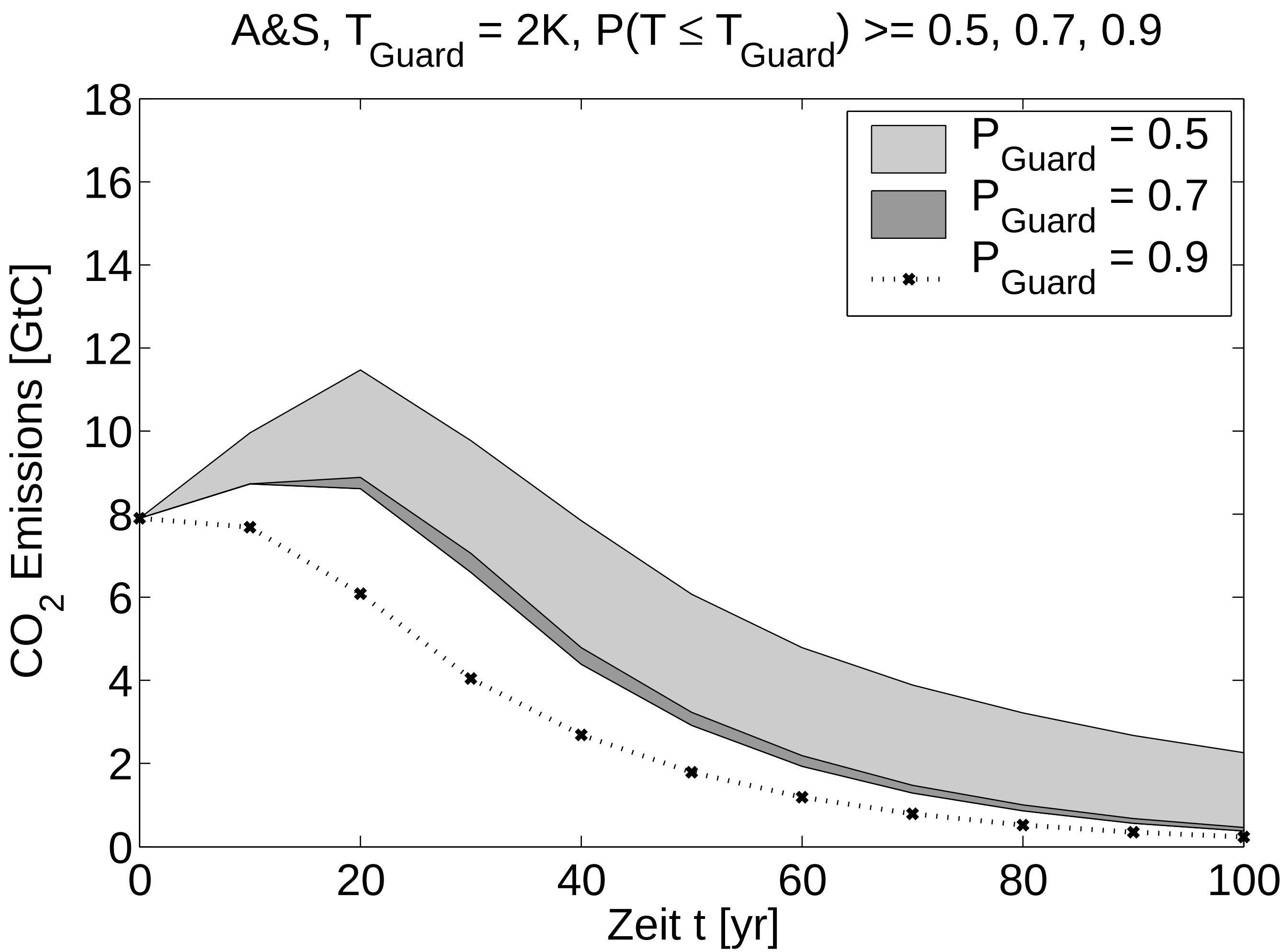
under $P(\boldsymbol{h}(\boldsymbol{\xi}, t; \boldsymbol{u}) \leq \boldsymbol{0}) \geq P_{Guard} \quad \forall t \in [0, t_e]$

- Standard algorithms for constrained optimization can be used
- P-guardrails can be evaluated using Monte-Carlo approach

Results: uncertain climate sensitivity I

- Climate sensitivity: Andronova & Schlesinger
- $\Delta T \leq 2°C$ (EU-target)
- Further constraints for allowed emission paths
- Emission corridors for probability guardrails

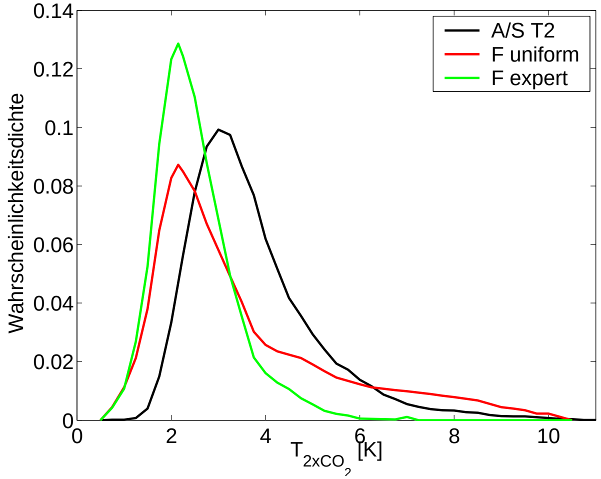
$P_{Guard} = 0.5, 0.7, 0.9$



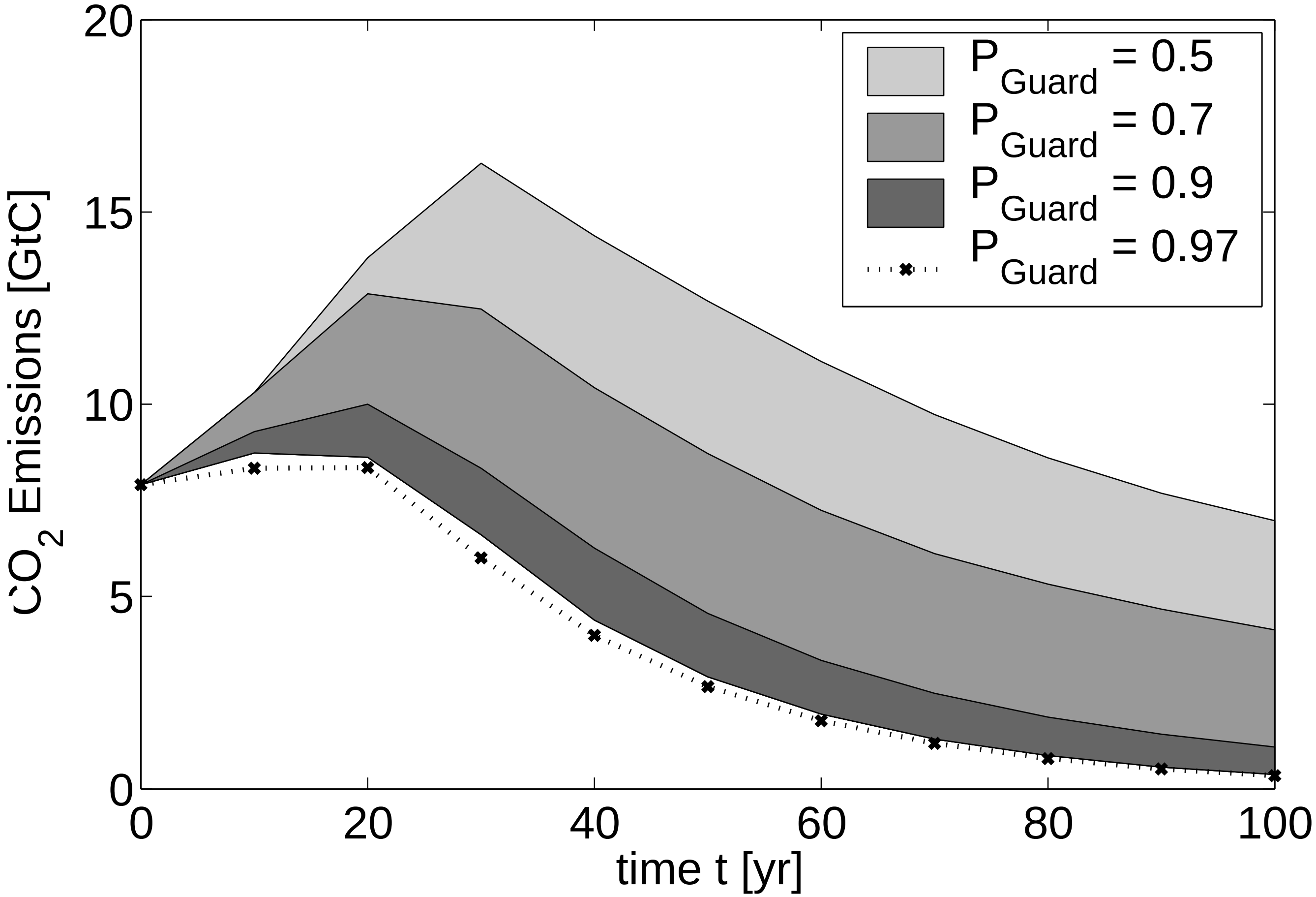
Results: uncertain climate sensitivity II

- Climate sensitivity Forest et al., prior expert elicitation
- $\Delta T \leq 2°C$ (EU-target)
- Constraints on emission paths
- Emission corridors for

$P_{Guard} = 0.5, 0.7, 0.9, 0.97$

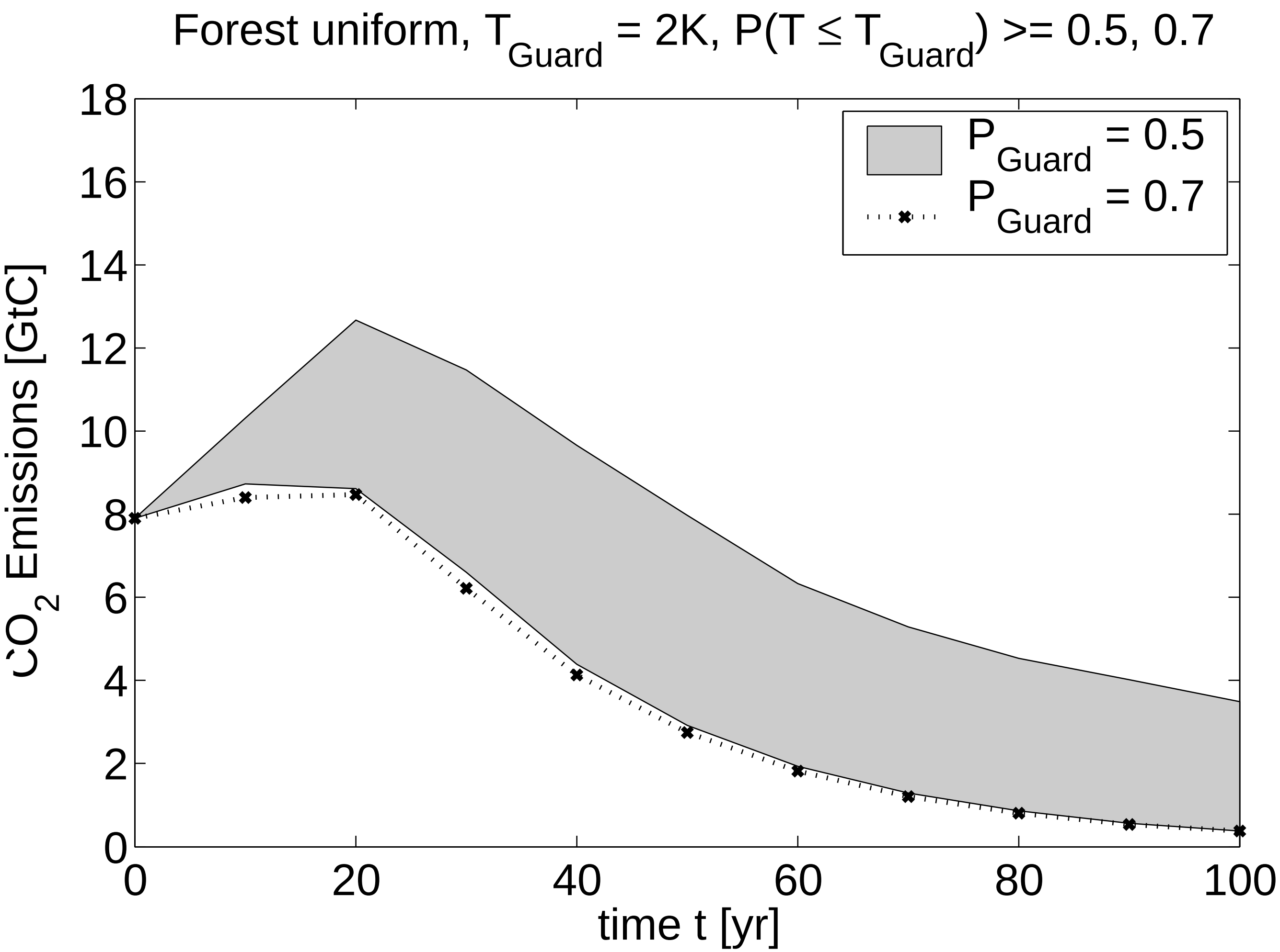


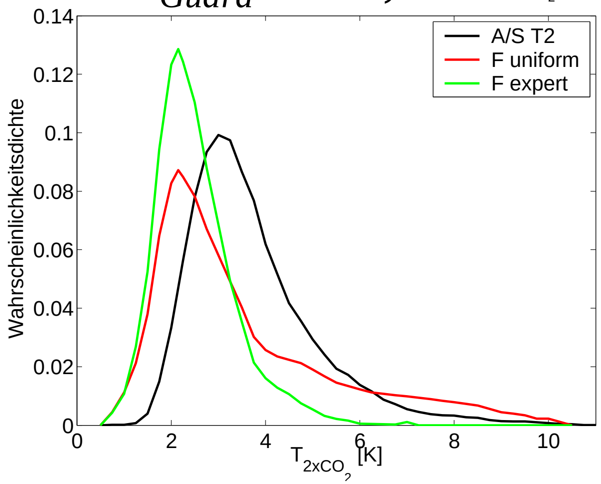
Forest expert, T_{Guard} = 2K, $P(T \leq T_{Guard})$ >= 0.5, 0.7, 0.9, 0.97



Results: uncertain climate sensitivity III

- Climate sensitivity Forest et al., prior uniform
- $\Delta T \leq 2°C$ (EU-target)
- Constraints on emission paths
- Emission corridors for $P_{Guard} = 0.5, 0.7$





Summary

- Uncertainty ever-present in IA modeling
- TWA can be extended to probabilistic approach
- Allows consideration of uncertainty through natural variability and through uncertain parameters

- EU's target of max. 2℃ warming very ambitious
- GHG emissions need to be reduced quickly and strongly

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Changes in flooding probability

- Aim: develop representation of changes in flooding probability (large river basins) in integrated assessment model
- Requirements:
  - Global scale
  - Low computational cost

- Model needs:
  - Downscaling scheme from ΔT_{GM} to $\Delta P, \Delta E$ on river basin scale
  - Representation of natural variability in P, E
  - Hydrological model to aggregate change in P, E to river basin scale

- Resolution chosen: $\Delta x = 0.5°$, $\Delta t = 1\ month$
- Min. basin size: $2.5 \times 10^4 km^2$

Downscaling scheme

- IA models typically determine ΔT_{GM} only
- Changes in mean climate: pattern scaling

- Changed mean climate

$$\bar{T}(r,m,t) = T_C(r,m) + k\,\Delta T_{GM}(t) \times T_P(r,m)$$
$$\bar{P}(r,m,t) = P_C(r,m) \times (1 + k\,\Delta T_{GM}(t) \times P_P(r,m))$$

- Natural variability: deviation patterns from CRU-TS (PIK modification) data
- Representation of nat. variability

$$T(r,m,t) = T_C(r,m) + k\,\Delta T_{GM}(t) \times T_P(r,m) + T'(r,m,t')$$
$$P(r,m,t) = (P_C(r,m) \times (1 + k\,\Delta T_{GM}(t) \times P_P(r,m))) \times P'(r,m,t')$$

Hydrological model

- Most simple model possible:
  - Determine P,E at all grid points belonging to river basin
  - Sum up total $R = P - E - \Delta S$ $(\Delta S=0)$ over all grid points

- Model validation using gauge records and historical CRU-TS(PIK) data:

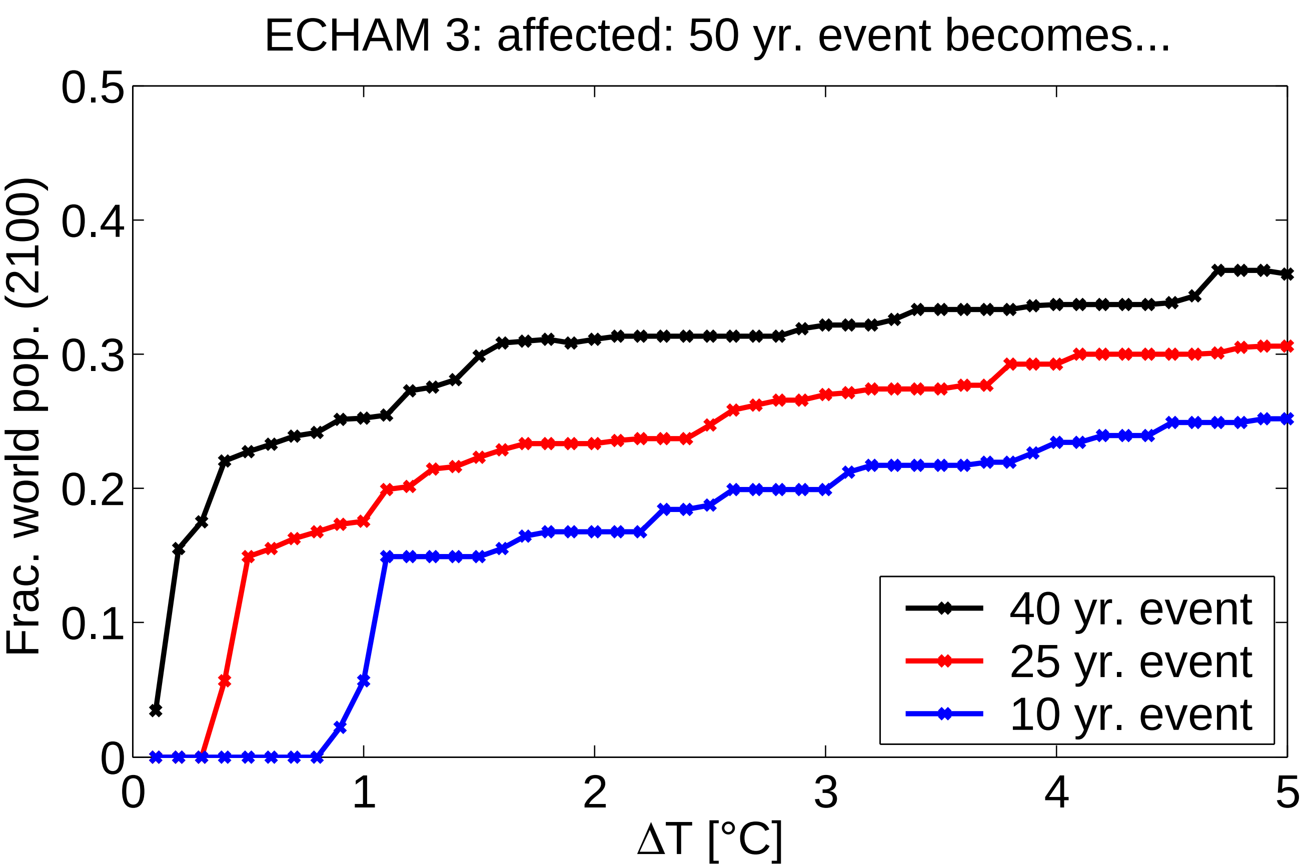
  Model performance is comparably good (or rather: bad) as performance of other models on these scales.

- Aggregation measure for setting of guardrails:

  Population (2100) affected by positive change in probability of 50 year flood event Q_{50yr}

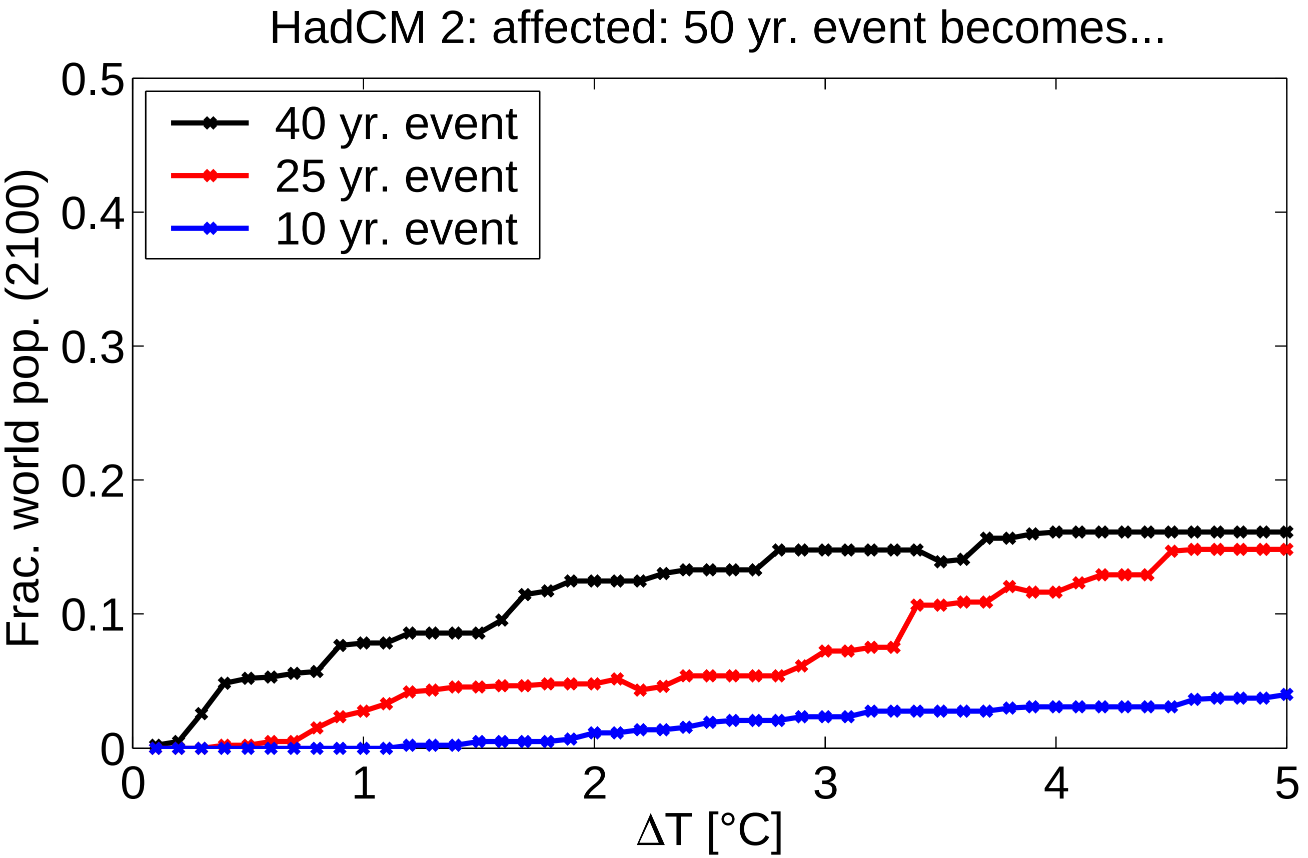
Climate Impact Response Function: $\Delta P(Q_{50yr})$

- Climate Impact Response Function (CIRF): simplified representation of relation impact <-> climate change
- Here: Fraction world population (2100) affected by $P(Q50yr) = 1/40, 1/25, 1/10$ based on ECHAM3 patterns



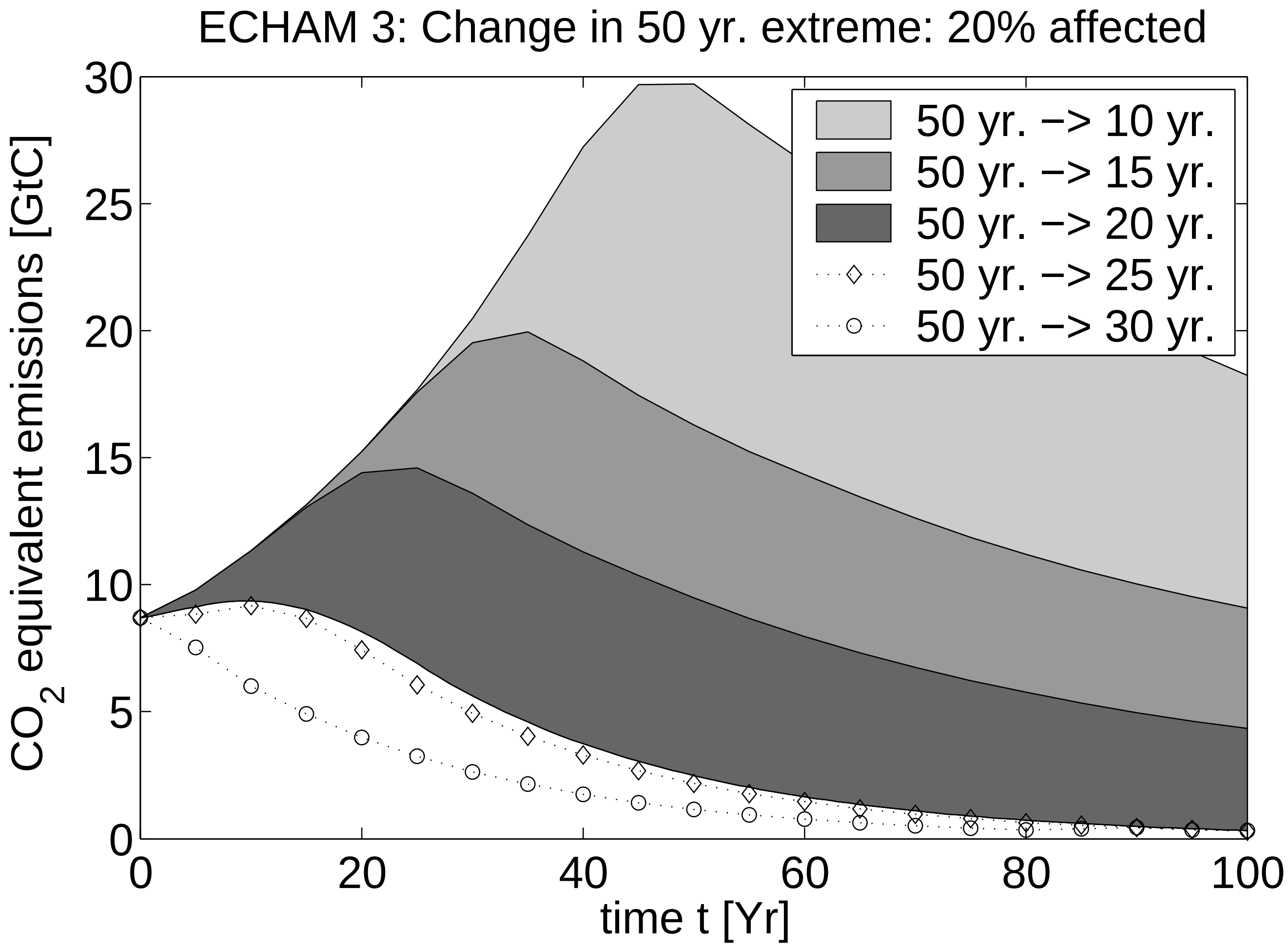
Climate Impact Response Function: $\Delta P(Q_{50yr})$

- Here: Fraction world population (2100) affected by *P(Q50yr) = 1/40, 1/25, 1/10* based on HadCM2 patterns



Emission corridor: flooding

- Climate change patterns: ECHAM3
- guardrail: max. 20% world pop. (2100) affected by change in
  $$P(Q_{50yr}) > \frac{1}{50}$$
- Emission corridors for various
  $$P(Q_{50yr})$$



Summary

- Climate change will change probability of large flood events in river basins
- Changed probability can be determined using simple flooding model consisting of downscaling scheme and hydrological model
- This model can be used to determine CIRF for changes in flooding probability
- Depending on changes to monsoon climate, large proportions of population may already be affected for small climate change
- Limiting population fraction affected will be big challenge