The Integrated Assessment of Climate Change
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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   - Changes in flooding probability
The general problem

• Aim of Integrated Assessment (IA):
  – Consider the entire chain of cause-and-effect of climate change
The general problem

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

Emissions of greenhouse gases
The general problem

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![Diagram showing the relationship between emissions of greenhouse gases and climate change.](image)
The general problem

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![Diagram](https://example.com/diagram.png)
The general problem

- Aim of Integrated Assessment (IA):
  - Consider the entire chain of cause-and-effect of climate change

- Assessment conducted in integrated framework
Three paradigms

• Mathematically integrated assessment is a *control problem*
  \[ \dot{x} = f(x, t; u) \]

• Evolution of system state \( x \) also depends on *control vector* \( u \)

• Three general approaches to handle this kind of problem:
Three paradigms

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- Three general approaches to handle this kind of problem:
  1) Use predefined control path \( u \) and evaluate consequences
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     - *Policy evaluation modeling*
  2) Determine “best” control path $u$
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  3) Determine sets of control paths that conform to additional criteria
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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
The IMAGE model

- IMAGE = Integrated model for the assessment of the greenhouse effect

Emissions of greenhouse gases

Climate change

Impacts of climate change

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

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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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- **IMAGE = Integrated model for the assessment of the greenhouse effect**

**Emissions of greenhouse gases**

**Climate change**

**Impacts of climate change**

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*Fig. 1. Extended integrated model for the assessment of the greenhouse effect.*
Policy evaluation modeling

Fig. 2. Emission of CO\textsubscript{2}.
Policy evaluation modeling

![Graph showing CO₂ concentration over time for different scenarios.]

**Fig. 8.** Concentration of CO₂.

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

Fig. 13. Total temperature increase.
Policy evaluation modeling

Fig. 15. Total sea level rise.
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 = Dynamic integrated climate economy

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

Emissions of greenhouse gases

Climate change

Impacts of climate change
The DICE model

- DICE = Dynamic integrated climate economy

Emissions of greenhouse gases → Climate change → Impacts of climate change → Simple climate model
The DICE model

- DICE = Dynamic integrated climate economy

Emissions of greenhouse gases → Climate change

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

![Graph showing GHG concentrations (x 10^9 tons C) over time from 1965 to 2105.](image)
Policy optimization modeling

Global temperature increase (°C)

Time (year)

1965 1985 2005 2025 2045 2065 2085 2105
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
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 = Tolerable windows approach

Emissions of greenhouse gases

Climate change

Impacts of climate change

• No sub-model for emissions, since set of allowed emission strategies is determined
Tolerable Windows Approach

- TWA = Tolerable windows approach

- Emissions of greenhouse gases
- Climate change
- Impacts of climate change
- Simple climate model

Integrated Assessment of Climate Change
Tolerable Windows Approach

• TWA = Tolerable windows approach

Emissions of greenhouse gases

Climate change

Impacts of climate change

• Impacts represented as CIRF (climate impact response function)
• Process-based models could also be used
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

**Normative Assessment:**

- Climate Impact (CI):
  - Tolerance Level vs. Climate Change
- Socio-Economic Consequences (SC):
  - Tolerance Level vs. GHG Reduction

**Scientific Analysis:**

- Climate Change vs. GHG Reduction

**Determination of all admissible climate protection paths:**

- Tolerance Level vs. GHG Reduction
• Application to climate change: emission corridor
• Guardrail: $\Delta T \leq 2.5 ^\circ C$
• 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 trajectory: deterministic

\[ \Delta T \, [K] \]

\[ \text{time } t \, [yr] \]
Temperature trajectories with nat. variability

Temperature trajectories: stochastic

Result: observing guardrail dependent on realization of stochastic process => nonzero probability that guardrail is exceeded
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: $T_{2xCO_2} \in [1.5 \degree C, 4.5 \degree C]$
- 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

$P(\Delta T(t) > T_{\text{Guard}})$, uncertain clim. sens.
The probabilistic TWA

• Uncertainties imply: Extension of TWA necessary
• Deterministic guardrail for impact $I$ defined as
  \[ I \leq I_{Guard} \Rightarrow P(I \leq I_{Guard}) \in [0,1] \]

• If probabilistic uncertainty considered:
  \[ P(I \leq I_{Guard}) \in [0,1] \]

• Therefore additional probability guardrail necessary
  \[ I \leq I_{Guard} \Rightarrow P(I \leq I_{Guard}) \geq P_{Guard} \]
Solution algorithm

• Problem to be solved: generally stochastic differential inclusion

\[ d \xi \in F(\xi, dt \oplus d W) \]

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

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

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

\[ \forall t_i \in \{ t_1, ..., t_n \} : \quad \max(\min) E(t_i) \]

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

• 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
- $\Delta T \leq 2^\circ C$ (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
- $\Delta T \leq 2^\circ C$ (EU-target)
- Constraints on emission paths
- Emission corridors for $P_{Guard} = 0.5, 0.7, 0.9, 0.97$

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

CO$_2$ Emissions [GtC]

Integrated Assessment of Climate Change
Results: uncertain climate sensitivity III

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

Forest uniform, $T_{\text{Guard}} = 2K$, $P(T \leq T_{\text{Guard}}) >= 0.5, 0.7$
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°C 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 $\Delta T_{GM}$ 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: $\Delta x = 0.5^\circ$, $\Delta t = 1$ month
- Min. basin size: $2.5 \times 10^4 km^2$
### Downscaling scheme

- IA models typically determine \( \Delta T_{GM} \) only
- Changes in mean climate: pattern scaling

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

- 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: $\Delta P(Q_{50\text{yr}})$

- Climate Impact Response Function (CIRF): simplified representation of relation impact <-> climate change
- Here: Fraction world population (2100) affected by $P(Q_{50\text{yr}}) = 1/40, 1/25, 1/10$ based on ECHAM3 patterns

ECHAM 3: affected: 50 yr. event becomes...
Climate Impact Response Function: $\Delta P(Q_{50\text{yr}})$

- Here: Fraction world population (2100) affected by $P(Q_{50\text{yr}}) = 1/40, 1/25, 1/10$ based on HadCM2 patterns

![Graph showing the fraction of world population affected by different 50-year events vs. temperature change ($\Delta T$).]

HadCM 2: affected: 50 yr. event becomes...

- 40 yr. event
- 25 yr. event
- 10 yr. event
Emission corridor: flooding

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