Low Risk Emissions Corridors for Safeguarding the Atlantic Thermohaline Circulation

Thomas Bruckner* and Kirsten Zickfeld**

*Institute for Energy Engineering
Technical University of Berlin, Germany

**Potsdam Institute for Climate Impact Research
Potsdam, Germany

*Correspondence: bruckner@iet.tu-berlin.de  Website: www.iet.tu-berlin.de/~bruckner
Introduction

- stability of the North Atlantic thermohaline circulation (THC)

Integrated assessment of the thermohaline circulation with dimrise

- model overview
- dynamic THC module
- reduced-form climate module
- aggregate economic module

Model application schemes and first results

- cost-effectiveness analysis
- Tolerable Windows Approach (TWA)
North Atlantic thermohaline circulation

Short-term business-as-usual evolution

Simulated strength of the Atlantic overturning relative to the 1961–1990 mean — with future-forcing under the IS92a scenario

\[ \Delta F(t) = h \Delta T^{\text{NH}}(t) \]

\( \Delta T^{\text{NH}}(t) \) is atmospheric temperature change in the northern hemisphere.

\( \Delta F(t) \) is change of freshwater flux into the Atlantic, north of 50°N.

\( 1 \text{ Sv} = 1 \text{ Sverdrup} = 10^6 \text{m}^3/\text{s} \)

Key sources of uncertainty

- initial THC overturning \( m_{\text{init}} \)
- climate sensitivity \( T_{2xCO2} \)
- hydrological sensitivity \( h \)

Source: IPCC, TAR, WGI (2001)
Long-term sensitivity analysis for hydrological sensitivity $h$

Source: Rahmstorf and Ganopolski, Climatic Change (1999)
Integrated Assessment of the thermohaline circulation

Integrated assessment model *dimrise* –
dynamic integrated model of
regular impacts and singular events

Components
- dynamic model of the Atlantic overturning
- reduced-form multi-gas climate model
- aggregate model of the world economy

Features
- dynamic, fully coupled, computationally fast GAMS model
- able to derive least-cost emissions paths and emissions corridors
Dynamic model of the Atlantic overturning

- dynamic four-box interhemispheric extension of the seminal Stommel model
- calibrated against results of the CLIMBER 2 climate model of intermediate complexity

\[ \dot{T}_1 = \frac{m}{V_1} \cdot (T_4 - T_1) + \lambda_1 \cdot (T_1^* - T_1) + \frac{S_0 \cdot F_1}{V_1} \]
\[ \dot{T}_2 = \frac{m}{V_2} \cdot (T_3 - T_2) + \lambda_2 \cdot (T_2^* - T_2) + \frac{S_0 \cdot F_2}{V_2} \]
\[ \dot{T}_3 = \frac{m}{V_3} \cdot (T_1 - T_3) + \lambda_3 \cdot (T_3^* - T_3) + \frac{S_0 \cdot (F_1 - F_2)}{V_3} \]
\[ \dot{T}_4 = \frac{m}{V_4} \cdot (T_2 - T_4) \]
\[ m = \frac{k \cdot (\rho_2 - \rho_1)}{\rho_0} = k \cdot [\beta \cdot (S_2 - S_1) - (\alpha \cdot (T_2 - T_1))] \]

Source: Zickfeld, Slawig, and Rahmstorf, Ocean Dynamics 54, 8-26 (2004)
Dynamic THC model: hydrological sensitivity $h$

Response of the Atlantic overturning for different values of the hydrological sensitivity $h$ — given in Sv °C$^{-1}$

Source: Zickfeld, Slawig, and Rahmstorf, Ocean Dynamics 54, 8-26 (2004)
Dynamic THC model: rate of temperature change sensitivity

Stability diagram of the THC for different values of the hydrological sensitivity

The stable (unstable) domains are located to the left (right) of the respective curves

'SS' indicates the stability curve from Stocker and Schmittner (1997)

Response of the Atlantic overturning for different rates of temperature increase — measured in °C century⁻¹ (hydrological sensitivity $h = 0.046$ Sv °C⁻¹)

Source: Zickfeld, Slawig and Rahmstorf, Ocean Dynamics 54, 8-26 (2004)
Reduced-form multi-gas climate model

► ICLIPS climate module (ICM)

► Component of the ICLIPS (Integrated Assessment of Climate Protection Strategies) suite

► CO₂-cycle: differential-impulse-response representation of the 3-dim Hamburg Model of the Oceanic Carbon Cycle (HAMOCC)

► Climate system: differential-impulse-response representation of ECHAM 3

► Non-CO₂ greenhouse gas atmospheric chemistry for CH₄, N₂O, halocarbons, SF₆ and aerosols according to MAGICC (Wigley et al.1988-1996)

Aggregate model of the world economy


► Ramsey-type intertemporal optimal growth model with endogenous investment decisions and capital accumulation cycle
► Cobb-Douglas production function with exogenous technological change
► applied to assess emissions mitigation costs in terms of global welfare losses
► computationally fast GAMS model
► well-known and widely used in the integrated assessment community
► conceptual model used for proof-of-concept application
► to be replaced by a sophisticated multi-regional model
Aggregate model of the world economy

**Global welfare:** discounted flow of global utility

\[
W = \sum_{t} \frac{1}{(1+i)^t} \cdot U(c(t), L(t))
\]

**CO₂-emissions:**

\[
E(t) = [1 - \mu(t)] \cdot \sigma(t) \cdot Q(A(t), K(t), L(t))
\]

active emissions reduction  output dependence

**Percentage output loss due to active emissions mitigation:**

\[
\left| \frac{\Delta Q}{Q} \right| = b_1 \cdot \mu(t)^{b_2}
\]

**Control variables:**
emissions control level \( \mu(t) \) and per capita consumption \( c(t) \)
Framework of the Tolerable Windows Approach (TWA)

► Prescription of explicit normative "guard-rails" that cover both
  ► intolerable climate impacts
  ► socio-economically unacceptable mitigation side-effects

► Scientific analysis of the relevant and interconnected elements of the Earth system, including: ecosystems, the climate system, socio-economic systems

► Calculation of the set of admissible policy paths by applying a suitable integrated assessment model

► Selection of a specific policy path by applying quantitative optimization, by referring to qualitative arguments, and/or by relaxing normative constraints after public consultation
Normative guard-rails (constraints)

Climate guard-rail: prevention of a THC collapse

▶ Atlantic overturning \( m(t) \geq m_{\text{min}} = 10 \text{ Sv} \)

Socio-economic guard-rail: acceptable emissions mitigation burden

▶ maximum percentage welfare loss relative to the non-intervention case RC

\[
\frac{W_{\text{RC}} - W}{W_{\text{RC}}} \leq l_{\text{max}}
\]

▶ maximum increase in the emissions control level

\[
0 \leq \dot{\mu}(t) \leq \dot{\mu}_{\text{max}}
\]
Model application schemes

Overarching goal: preservation of the THC

Cost-effectiveness analysis

Min \( \frac{W_{RC} - W}{W_{RC}} \) s.t. \( m(t) \geq m_{\min} \)

Least-cost emissions paths

Tolerable windows approach

- \( m(t) \geq m_{\min} \)
- \( \frac{W_{RC} - W}{W_{RC}} \leq I_{\max} \)
- \( 0 \leq \dot{m}(t) \leq \dot{m}_{\max} \)

Emissions corridors
## First results

<table>
<thead>
<tr>
<th>Model calibration</th>
<th>Standard</th>
<th>Worst case</th>
</tr>
</thead>
<tbody>
<tr>
<td>climate sensitivity $T_{2xCO2}$</td>
<td>2.5 °C</td>
<td>4.5 °C</td>
</tr>
<tr>
<td>hydrological sensitivity $h$</td>
<td>0.03 Sv°C⁻¹</td>
<td>0.05 Sv°C⁻¹</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normative guard-rails</th>
<th>Default values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic overturning</td>
<td>$m_{min}$ 10 Sv</td>
</tr>
<tr>
<td>overall welfare loss</td>
<td>$l_{max}$ 2.0 %</td>
</tr>
<tr>
<td>rate of change in the emissions control level</td>
<td>$\dot{\mu}_{max}$ 1.33 %-Pts/year</td>
</tr>
</tbody>
</table>
Emissions corridors for standard conditions

![Graph showing emissions trends over calendar years from 2000 to 2200, with various lines representing different emission scenarios including upper boundary, lower boundary, and specific paths maximizing emissions in different years. The y-axis represents CO₂ emissions in GtC/yr, and the x-axis represents calendar years from 2000 to 2200.](image-url)
Variation of the climate sensitivity $T_{2xCO2}$
Variation of the hydrological sensitivity $h$

![Graph showing CO₂ emissions and sensitivity levels over calendar years from 2000 to 2200. The graph includes lines and markers indicating upper and cost-effective paths for different sensitivity levels.](image-url)

- Upper boundary for $h_2=0.03$ Sv°C
- Upper boundary for $h_2=0.04$ Sv°C
- Upper boundary for $h_2=0.05$ Sv°C
- Cost-effective path for $h_2=0.03 - 0.04$ Sv°C
- Cost-effective path for $h_2=0.05$ Sv°C
- Lower boundary
Variation of the admissible welfare loss $l_{\text{max}}$
Variation of the max emissions reduction rate $\mu_{\text{max}}$

Lower boundary for $\mu_{\text{max}} = 1\%$
Lower boundary for $\mu_{\text{max}} = 0.5\%$
Lower boundary for $\mu_{\text{max}} = 1.33\%$
Lower boundary for $\mu_{\text{max}} = 2\%$
Lower boundary for $\mu_{\text{max}} = 2.5\%$
Upper boundary for $\mu_{\text{max}} = 0.5-2.5\%$
Variation of the admissible welfare loss $l_{max}$

Worst case emissions corridors and least-cost path

![Graph showing CO\(_2\) emissions over time with different boundary conditions and paths.](image-url)
Variation of the max emissions reduction rate $\mu_{\text{max}}$
Worst case emissions corridors and least-cost path

![Diagram showing CO2 emissions over calendar years with upper and lower boundaries for different emission reduction rates.](image-url)
Conclusions

dimrise

► a fully-coupled dynamic integrated assessment model for investigating THC instability
► suitable for deriving cost-effective emissions paths and emissions corridors (proof-of-concept)

best-guess conditions

► cost-effective emissions path does not deviate from the business-as-usual emissions
► "comfortable" emissions corridors
► sensitive to uncertain climate and hydrological sensitivities

worst-case conditions

► (moderate) business-as-usual path transgresses the upper corridor boundary within the next two decades if future world-wide emissions mitigation capabilities remain low
Thank you for your attention

Contact:

Dr. Thomas Bruckner
Institute for Energy Engineering
Technical University of Berlin
Marchstrasse 18
D-10587 Berlin
Germany

Tel.: +49/30/31424763
Email: bruckner@iet.tu-berlin.de
WWW: http://www.iet.tu-berlin.de/~bruckner
Selected references


