4. Climate Sensitivity
Lecture Program of „Climate Engineering“

Part 1: Introduction to the Climate System (4 sessions)
1. Introduction and scope of the lecture
2. The Climate System – Radiation Balance
3. Elements of the Climate System – Greenhouse gases, Clouds, Aerosol
4. Climate System: Sensitivity, Predictions

Part 2: Climate Engineering Methods – SRM (4 sessions)
1. SRM – Reflectors in space
2. SRM – Aerosol in the Stratosphere
3. SRM – Cloud Whitening
4. SRM – Anything else

Part 3: Climate Engineering Methods – CDR (4 sessions)
1. Direct (Carbon dioxide) removal from air
2. Alkalinity to the ocean (enhanced weathering)
3. Ocean fertilization
4. Other greenhouse gases

Part 4: CE – Effectiveness, Side Effects (3 sessions)
1. Comparison of Techniques, characterisation of side effects
2. Other parameters than temperature
3. Summary
Literature

Textbooks

Online Resources
Contents of Today's Lecture

Climate Sensitivity, Feedbacks, and Predictions

• Climate sensitivity and feedbacks
• Heat capacity and response time
• Climate predictions
Global Annual Mean Radiative Forcing

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IPCC AR4 2007

Radiative Forcing (W m⁻²)

Global [1.49 to 1.83]
0.48 [0.43 to 0.53]
0.16 [0.14 to 0.18]
0.34 [0.31 to 0.37]
-0.05 [-0.15 to 0.05]
0.35 [0.25 to 0.65]
0.07 [0.02 to 0.12]
-0.2 [-0.4 to 0.0]
0.1 [0.0 to 0.2]
-0.5 [-0.9 to -0.1]
-0.7 [-1.8 to -0.3]
0.01 [0.003 to 0.03]
0.12 [0.06 to 0.30]
1.6 [0.6 to 2.4]
Climate Sensitivity

Anthropogenic changes (greenhouse gases, aerosols,…) lead to a radiative forcing $F$ \([\text{W/m}^2]\) of the climate system. Big question: How strongly (and how fast) will the climate system (global mean temperature $T$) react to the forcings?

Measure:

**Equilibrium climate sensitivity** $\lambda$:  
$$
\lambda = \frac{dT}{dF} \left[ \frac{\text{K}}{\text{Wm}^{-2}} \right]
$$

- Often the equilibrium temperature change for a doubling of atmospheric CO$_2$ (from 280 to 560 ppm) is referred to as climate sensitivity. We will call this quantity $\Delta T_{2\times\text{CO}_2}$.

- $\Delta T_{2\times\text{CO}_2}$ can be calculated from $\lambda$, using the radiative forcing for CO$_2$ doubling of $F_{2\times\text{CO}_2} \approx 3.7 \ \text{W/m}^2$

$$
\Delta T_{2\times\text{CO}_2} = \lambda F_{2\times\text{CO}_2}
$$
Climate Sensitivity in the „Black-Body“ (BB) Model

Radiative equilibrium: \[ \pi R^2 S_0 (1 - A) = 4\pi R^2 \sigma_{SB} T^4 \]

\[ \frac{S_0}{4} (1 - A) = \sigma_{SB} T^4 \quad \Rightarrow \quad T_{BB} = \left( \frac{S_0 (1 - A)}{4\sigma_{SB}} \right)^{\frac{1}{4}} = \left( \frac{S}{\sigma_{SB}} \right)^{\frac{1}{4}} \]

S: Net solar input per m\(^2\)  E: IR emission per m\(^2\)  With A = 0.3 one obtains \( T_{BB} = 255 \) K

New equilibrium with forcing:

\[ S + F = E(T) = \sigma_{SB} T^4 \quad \Rightarrow \quad T = \left( \frac{S + F}{\sigma_{SB}} \right)^{\frac{1}{4}} \]

\[ S \approx \frac{1368}{4} (1 - 0.3) = 342 \cdot 0.7 \approx 239.4 \text{ W m}^{-2} \]

\[ \Rightarrow \lambda = \frac{dT}{dF} = \frac{1}{4} \cdot \left( \frac{S + F}{\sigma_{SB}} \right)^{\frac{1}{4} - 1} \cdot \left( \frac{1}{\sigma_{SB}} \right) = \frac{1}{4\sigma_{SB}} \cdot \left( \frac{S + F}{\sigma_{SB}} \right)^{\frac{1}{4}} \cdot \left( \frac{S + F}{\sigma_{SB}} \right)^{-1} = \frac{1}{4\sigma_{SB} T^3} \]

\[ \text{For } F \rightarrow 0: \quad \lambda = \frac{1}{4\sigma_{SB}} \cdot \left( \frac{S}{\sigma_{SB}} \right)^{\frac{3}{4}} = \frac{1}{4\sigma_{SB} T_{BB}^3} \approx 0.27 \frac{K}{\text{W m}^{-2}} \]
Better way to calculate $\lambda$:

$$S + F = E(T) \implies F = E(T) - S = R(T)$$

$$\implies \lambda^{-1} = \frac{dF}{dT} \approx \frac{dR}{dT} = \frac{d}{dT}(E(T) - S) = \frac{dE(T)}{dT} = 4\sigma_{SB} T^3$$

$$\implies \lambda = \frac{1}{4\sigma_{SB} T^3} \text{ (see above)}$$

Note: $\lambda \propto \frac{1}{T^3}$ However, Change in $T$ is small!
Climate Sensitivity in Two-Layer Model

Radiative equilibrium for surface:

\[
\frac{S_0}{4}(1-A) + \varepsilon_a \sigma_{SB} T_a^4 = \sigma_{SB} T_s^4
\]

S: Solar input  B: Backradiation  E: Emission

New equilibrium with forcing (using \( T = T_s = 2^{1/4}T_a = 288 \) K and \( \varepsilon_a = 0.77 \)):

\[
S + B + F = E \quad \Rightarrow \quad F = R = E - S - B = \sigma_{SB} T^4 - \frac{S_0}{4}(1-A) + \frac{1}{2} \varepsilon_a \sigma_{SB} T^4
\]

\[
\Rightarrow \quad \lambda_{\text{tot}}^{-1} = \frac{dF}{dT} = \frac{dR}{dT} = \frac{dE}{dT} - \frac{dS}{dT} - \frac{dB}{dT} = \lambda_{E}^{-1} - \lambda_{S}^{-1} - \lambda_{B}^{-1}
\]

with \( \lambda_{E}^{-1} = 4\sigma_{SB} T^3 = 5.41 \frac{W}{m^2} K \); \( \lambda_{S}^{-1} = 0 \); \( \lambda_{B}^{-1} = 2\varepsilon_a \sigma_{SB} T^3 = 2.08 \frac{W}{m^2} K \)

\[
\Rightarrow \quad \lambda_{\text{tot}} = \frac{1}{\lambda_{E}^{-1} - \lambda_{B}^{-1}} = \frac{1}{5.41 - 2.08} = \frac{1}{3.33} = 0.30 \frac{K}{Wm^{-2}} \equiv \lambda_0
\]

The sensitivity for pure radiative forcing is \( \lambda_0 = 0.30 \text{ K/(W/m}^2) \)
Climate Sensitivity and Feedbacks

With $\lambda = 0.3 \text{ K/(W/m}^2\text{)}$ and $F_{2\times CO_2} \sim 3.7 \text{ W/m}^2$ we obtain:

$$\Delta T_{2\times CO_2} = \lambda F_{2\times CO_2} \approx 0.3 \cdot 3.7 \approx 1.1 \text{ K}$$

So what!?

IPCC: $\Delta T_{2\times CO_2} = 2.0 - 4.5 \text{ K} \text{ (best estimate: 3.0 K)}$

What's wrong?

Problem: Amplifying feedbacks!
- Some climate system parameters such as Albedo $A$ and IR-emissivity of the atmosphere $\varepsilon_a$ are $T$-dependent
- $\rightarrow$ re-write balance equation:

$$F = R = E - S - B = \sigma_{SB} T^4 - \frac{S_0}{4} (1 - A(T)) - \frac{1}{2} \varepsilon_a(T) \sigma_{SB} T^4$$

Now:

$$\lambda_S^{-1} = \frac{dS}{dT} = - \frac{S_0}{4} \frac{dA}{dT}$$

and

$$\lambda_B^{-1} = \frac{dB}{dT} = 2 \varepsilon_a \sigma_{SB} T^3 + \frac{1}{2} \sigma_{SB} T^4 \frac{d\varepsilon_a}{dT}$$

$\lambda_w^{-1}$

$\uparrow$

$\rightarrow$

ice-albedo feedback

cloud feedback

water vapour feedback
The Ice-Albedo Feedback

Parametrisation of $A(T)$ proposed by Sellers, 1969 (J. Appl. Meteor. 8: 392-400):

$$A = 0.30 - 0.009 \cdot (T - 283) K, \quad 222 K \leq T \leq 283 K$$

Thus:

$$\lambda_S^{-1} = -\frac{S_0}{4} \frac{dA}{dT} = 342 \frac{W}{m^2} \cdot 0.009 K^{-1} = 3.08 \frac{W}{Km^2}$$

$$\Rightarrow \lambda_{tot} = \frac{1}{\lambda_0^{-1} - \lambda_S^{-1}} = \frac{1}{3.33 - 3.08} = \frac{1}{0.25} = 4.0 \frac{K}{Wm^{-2}}$$

This is much too high!

after Stocker, 2009. Introduction to Climate Modelling. Lecture notes, University of Bern
Water Vapour Feedback

Water vapour pressure increases by 7 % per °C warming. $\varepsilon_a$ should also increase, but it is difficult to estimate by how much (non-linear relationship and $\varepsilon_a$ in two-layer model is not a realistic parameter).

$$d\varepsilon_a/dT = 0.009 \text{ K}^{-1}$$ yields a result that is in agreement with results of complex climate models:

Thus:

$$\lambda_w^{-1} = \frac{1}{2} \sigma_{SB} T^4 \frac{d\varepsilon_a}{dT} = 1.75 \text{ W/Km}^2$$

$$\Rightarrow \lambda_{tot} = \frac{1}{\lambda_0^{-1} - \lambda_w^{-1}} = \frac{1}{3.33 - 1.75} = \frac{1}{1.58} = 0.63 \text{ K/Wm}^{-2}$$

Climate models have a significant sensitivity-enhancement due to the water vapour feedback. Verified by modeling effect of volcanoes.
Cloud Feedbacks

Climate models don't agree on the sign of the net cloud feedback. Figure: Cloud feedback (LW/SW/net) for 2xCO$_2$ in 10 GCMs. From IPCC 2007 and Stocker 2009.
Changes of the lapse rate (T-gradient in the troposphere) also produce a feedback on radiative forcing. Overall estimated to be a negative feedback.
Feedbacks in Climate Models

\[ \lambda_{\text{All}}^{-1} \approx 2 \frac{\text{W m}^{-2}}{\text{K}} \]

\[ \lambda_{\text{tot}} = \frac{1}{\lambda_{0}^{-1} - \lambda_{\text{All}}^{-1}} \approx \frac{1}{3.33 - 2} = \frac{1}{1.33} = 0.75 \frac{\text{K}}{\text{W m}^{-2}} \]

\[ \Delta T_{2 \times \text{CO}_2} = \lambda_{\text{tot}} \cdot 3.7 \text{ W m}^{-2} = 2.8 \text{ K} \]
Effect of CO₂ Doubling without Feedbacks

No feedback:

Anthropogenic forcing: (CO₂ doubling) 4 W/m²  \(\Delta T = 1.1^\circ C\)

Without feedbacks, climate prediction would be rather simple.

Feedbacks complicate climate modeling and add uncertainty to predictions of global warming.
Effect of CO$_2$ Doubling with Feedbacks

Anthropogenic forcing

4 W/m$^2$

Climate system

$\Delta T \approx 3 \, ^oC$

Increased water vapour

+5 W/m$^2$

Less snow and ice

+1 W/m$^2$

Change in cloudiness

+1.5 W/m$^2$

Change in vertical T profile

-1.5 W/m$^2$

Total feedback forcing: +6W/m$^2$ > initial 2xCO$_2$-forcing!

Rounded numbers, uncertainties omitted

New result
Transient Temperature Response

Equilibrium warming for doubling of CO$_2$ is estimated at about 3 °C (2 to 4.5 °C, IPCC, AR4, 2007)

But how quickly does the climate system respond?

Assume a system at equilibrium at $T_0$: $R(T_0) = E(T_0) - S - B(T_0) = 0$

For $t \geq 0$, a constant forcing $F$ is applied $\rightarrow$ temperature $T = T_0 + \Delta T(t)$

Net heat input $Q$ to climate system is given by radiation imbalance:

$$Q = F - R(T_0 + \Delta T) \approx F - \left[R(T_0) + \frac{dR}{dT} \Delta T\right] = F - \frac{\Delta T}{\lambda}$$

linearisation

$0$ \hspace{1cm} $\lambda^{-1}$ (total sensitivity)

This heat input leads to warming, with $C = $ effective heat capacity:

$$\frac{dE_{th}}{dt} = C \frac{d(\Delta T)}{dt} = Q = F - \frac{\Delta T}{\lambda} \quad \text{or} \quad \frac{d}{dt} \Delta T = \frac{F}{C} - \frac{1}{\lambda C} \Delta T$$

Solution: $\Delta T(t) = \lambda F \left(1 - e^{-\frac{t}{\lambda C}}\right) = \Delta T_\infty \left(1 - e^{-\frac{t}{\tau}}\right)$

$\Delta T_\infty = \lambda F$

$\tau = \lambda C$
Effective heat capacity, sensitivity, and response time of the climate system are coupled through

\[ \tau = \lambda C \]

**What is the heat capacity of the climate system?**

C is the heat capacity per unit surface area \([J \text{ m}^{-2} \text{ K}^{-1}]\). For a uniform material with density \(\rho\) and height \(h\) it is given by

\[ C = h \rho c_p \]

with \(c_p\) = heat capacity of the material \([J \text{ kg}^{-1} \text{ K}^{-1}]\)

Atmosphere: \(h \approx 8000 \text{ m}, \rho \approx 1.3 \text{ kg m}^{-3}, c_p \approx 1000 \text{ J kg}^{-1} \text{ K}^{-1}\):

\[ C = 1.0 \cdot 10^7 \text{ J m}^{-2} \text{ K}^{-1} \]

\(\rightarrow\) with \(\lambda = 0.30 \text{ K W}^{-1} \text{ m}^2\): \(\tau = 3.0 \cdot 10^6 \text{ s} \approx 35 \text{ d}\)

\(\rightarrow\) with \(\lambda = 0.75 \text{ K W}^{-1} \text{ m}^2\): \(\tau = 7.5 \cdot 10^6 \text{ s} \approx 90 \text{ d}\)

Upper ocean: \(h \approx 100 \text{ m}, \rho \approx 1000 \text{ kg m}^{-3}, c_p \approx 4180 \text{ J kg}^{-1} \text{ K}^{-1}\):

\[ C = 4.2 \cdot 10^8 \text{ J m}^{-2} \text{ K}^{-1} \]

\(\rightarrow\) with \(\lambda = 0.30 \text{ K W}^{-1} \text{ m}^2\): \(\tau = 1.3 \cdot 10^8 \text{ s} \approx 4 \text{ a}\)

\(\rightarrow\) with \(\lambda = 0.75 \text{ K W}^{-1} \text{ m}^2\): \(\tau = 3.1 \cdot 10^8 \text{ s} \approx 10 \text{ a}\)

Simple model: If the effective heat capacity and the response time of the climate system were known, climate sensitivity could be determined.

But: Real climate system has multiple response times!
Climate Engineering: Response Times

There are two response times:

1) Response of the CE-measure itself, for example:
   - cloud whitening: days
   - Stratospheric aerosol: \(\approx\)1-2 years
   - CO\textsubscript{2}-removal: depends on C-cycle, years to decades

2) Response of the climate system to CE-forcing
   (or no more CE-forcing after CE-measures stopped).
Climatic Effects of Ocean Heat Capacity

Mid-latitudes:
W-coast: maritime
E-coast: continental

Seasonal variation of local radiation balance:
Continents react much faster than oceans.

Marshall and Plumb, 2008
Response Times in Climate Models

Step-forcing experiment with one climate model.

$2\times CO_2$ for $t > 300$ a.

→ No equilibrium at $t = 500$ a.

T-evolution 1950–2100 in 10 climate models.

Forcing ($CO_2$) assumed to be constant after 2000.

Increase in 21st century: "Constant composition warming commitment"

Sensitivity and Response in Climate Models

Equilibrium climate sensitivity (ECS) and transient climate response (TCR) of the AOGCMs assessed in the 4th IPCC report.

Equilibrium climate sensitivity is what we called $\Delta T_{2xCO_2}$.

Transient climate response is defined as the global annual mean surface air temperature change averaged over a 20-year period centred at the time of CO$_2$ doubling in a 1% yr$^{-1}$ CO$_2$ increase scenario.

IPCC AR4, 2007
Emission Scenarios


http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml
Emissions and Concentrations

IPCC-Scenarios for CO\textsubscript{2} emissions and concentrations

\[\text{CO}_2\text{-concentration will increase significantly}\]
Climate Predictions

up to 2100

Global surface warming (°C)

-1.0
0.0
1.0
2.0
3.0
4.0

1900 2000 2100
Year

IPCC, AR4, 2007

These graphs show climate predictions up to 2100 for different emission scenarios. The predictions indicate a temperature increase of 1.8°C, 2.8°C, and 3.4°C for A2, A1B, and B1 scenarios, respectively. The number of models for each scenario is also indicated.
Climate Predictions

Level of CO₂ stabilisation

Global surface warming (°C)

Year

IPCC, AR4, 2007
The "2°C Lottery"

EU Policy:
To prevent the most severe impacts of climate change, ... the world needs to limit global warming to **no more than 2°C** above the pre-industrial temperature.

http://ec.europa.eu/clima/policies/brief/eu/

Black line: probability of peak global mean temperature exceeding 2°C above pre-industrial levels before the year 2100 vs. integrated emissions 2009 to 2049.

Predicted Regional Climate Change

A2: strong CO₂ increase
2100: ~850 ppm

B2: moderate CO₂ increase
2100: ~600 ppm

Annual multi-model mean change of temperature (colour shading) and its range (isolines, units: °C) from OAGCMs, for the period 2071 to 2100 relative to the period 1961 to 1990.

Patterns are similar, even though scenarios are very different. Strong enhancement of warming in high latitudes!

IPCC, TAR, 2001
Predicted Warming Relative to 1980-1999

IPCC, AR4, 2007
Predicted Change in Precipitation

Changes for A1B scenario for the period 2080 - 99 relative to 1980 - 99. Stippled areas: > 80 % of models agree on the sign of change.

Drying in much of the subtropics, more rain at higher latitudes.

IPCC, AR4, 2007
Predicted Changes in Europe

Changes for A1B scenario for the period 2080 - 99 relative to 1980 - 99.

IPCC, AR4, 2007
Sea level is predicted to continue to increase, but by how much is debated.
The mean of climate variables such as temperature and precipitation is expected to shift. The variability is expected to increase. Both effects lead to a disproportionate increase of the frequency of extreme events (heat waves, floods, droughts,…)

IPCC, TAR, 2001
Consequences of Climate Change

Global mean change from pre-industrial temperatures (°C)

- Peak emissions 2015
- Peak emissions 2025
- Peak emissions 2035

Water
- More water available in moist tropics and high altitudes
- Decreasing water availability and more drought in mid-latitudes and semi-arid low latitudes
- 0.4-1.7 billion
- 1.0-2.0 billion
- 1.1-3.2 billion

Ecosystems
- More amphibian extinction
- About 25-35% of species at high risk of extinction
- Major extinctions around the globe
- More coral bleaching
- Most coral bleached
- Widespread coral mortality
- Increasing species range shifts and wildfire risk
- Terrestrial biosphere tends towards a net carbon source, as 15% of ecosystems affected
- 60% of ecosystems affected

Food
- Low latitudes: decreases for some cereals
- Mid to high latitudes: increases for some cereals
- Crop productivity
- All cereals decrease
- Decrease in some regions

Coast
- More damage from floods and storms
- Additional people affected by coastal flooding each year
- 0-3 million
- 2-15 million
- About 30% loss of coastal wetlands

Health
- Increasing burden from malnutrition, diarrhoea, cardiorespiratory disease and infections
- More morbidity and mortality from heatwaves, floods and droughts
- Changed distribution of some disease vectors
- Substantial burden on health services

Singular events
- Local retreat of ice in Greenland and West Antarctic
- Long term commitment to several metres of sea-level rise due to ice sheet loss
- Ecosystem changes due to weakening of the meridional overturning circulation
- Adaptation needed to cover 10% of risks
- Adaptation needed to cover 50% of risks
- Adaptation needed to cover 90% of risks

Important questions related to climate change predictions:

• How significant is the anthropogenic influence on climate compared to natural drivers?
• Is the warming of the 20th century extraordinary? Can it be attributed to anthropogenic forcing?
• What is the natural variability of the climate system?
• What is the sensitivity of the climate system? How strong are the feedbacks?
• What are the impacts of climate change?

• Answers to these highly debated questions may come from information on the climate in the past (paleoclimate)
Summary

- Climate sensitivity: Measure for warming per forcing
- Sensitivity depends strongly on feedbacks
  - Without feedbacks: $l = 0.30 \text{ K} / (\text{W m}^{-2})$, $\Delta T_{2xCO2} = 1.1 \text{ K}$
  - Main feedbacks: Water vapour, lapse rate, albedo, clouds
  - With all feedbacks (in models): $l \approx 0.75 \text{ K} / (\text{W m}^{-2})$, $\Delta T_{2xCO2} \approx 3 \text{ K}$
- Transient climate response time: $t = lC$ in simple model, but multiple time constants in the real climate system
- Climate predictions (IPCC summary of model results):
  - Warmer, esp. in high latitude regions
  - Dryer in subtropics, wetter in mid to high latitudes
  - Higher variability, more extreme events
Do we see Global Warming?

The observed global Temperature evolution can be well explained by 4 main components (see e.g. Lean and Rind 2009):

1) Anthropogenic Eff.
2) Volcanic aerosol
3) ENSO
4) Solr variability

However: How important is this question?

Vorschau auf 2100 (IPCC 2007)

- 30 GtC/a in 2090
- Zurück zu den Emissionen von 2005 bis 2070

Graph showing global surface warming over time with different emission scenarios (A2, A1B, B1, Year 2000 Constant Concentrations, 20th century).
Rekonstruierte globale Temperatur über Land

Hegerl et al. 2007, Detection of Human Influence on a New, Validated 1500-Year Temperature Reconstruction, J. Climate 20, DOI: 10.1175/JCLI4011.1
Regionale Konsequenzen des Klimawandels

A2: starker CO₂ Anstieg
2100: ~850 ppm

B2: mäßiger CO₂ Anstieg
2100: ~600 ppm

→ Verschiedene Szenarien ergeben erstaunlich ähnliche Verteilungen

IPCC 2007