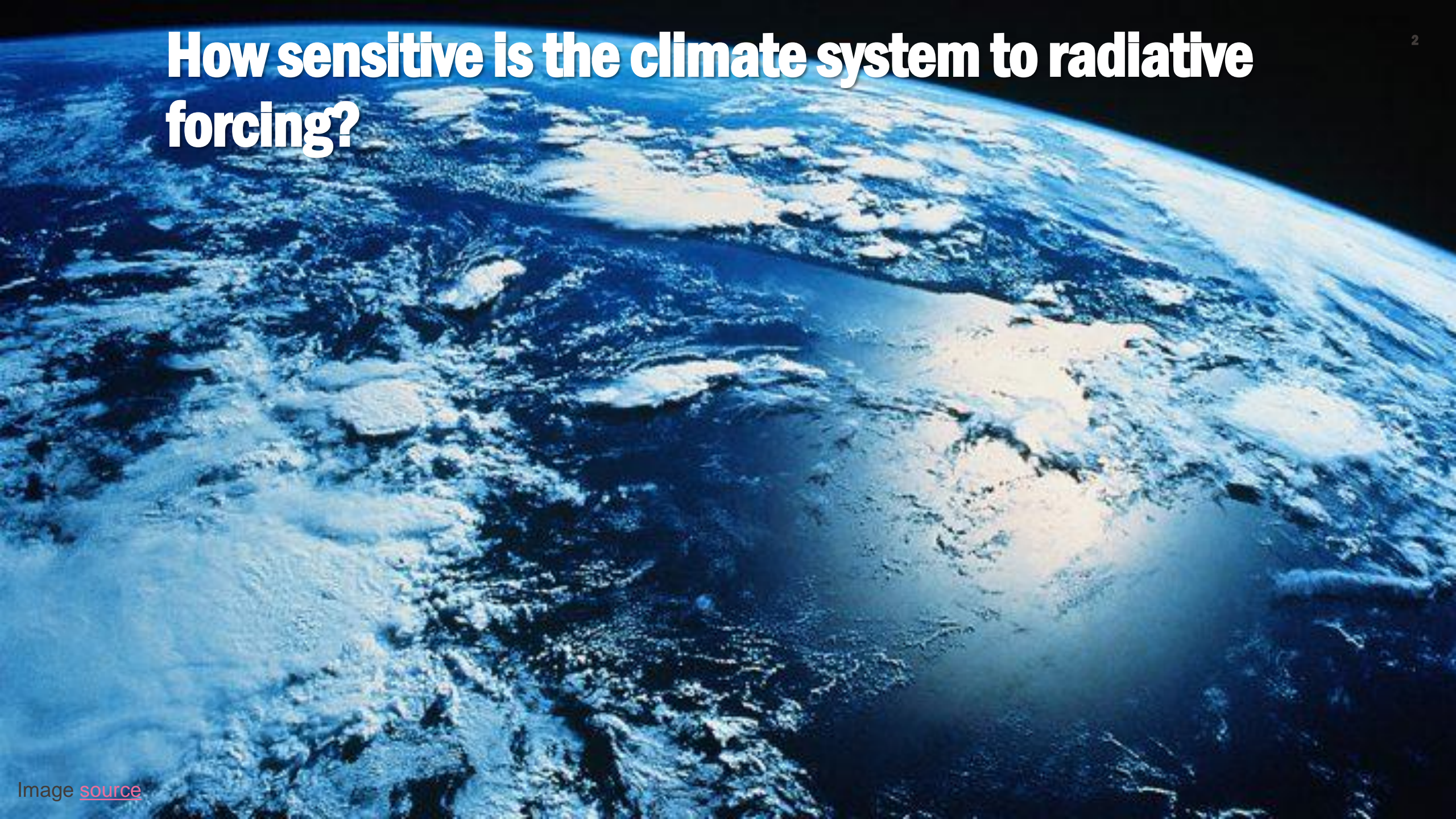


	No.	Date	Topics	Deadlines / tentative
Basics	1.	11.09.2025	Introduction to the climate system	Questionnaire (not graded)
	2.	18.09.2025	Climate System, Radiation	
	3.	25.09.2025	Radiation, Earth's Energy balance, Greenhouse effect	launch of first assignment
	4.	02.10.2025	Aerosols & clouds, Radiative Forcing	Launch of poster project
	5.	09.10.2025	Feedback mechanisms, Climate Sensitivity	Video recordings instead of lecture
	6.	16.10.2025	Paleoclimate	submission of Poster proposal (graded)
Present and future Climate change	7.	30.10.2025	Climate variability	
	8.	06.11.2025	Paris Agreement, IPCC – report, Climate scenarios (RCPs, SSPs),	
	9.	13.11.2025	Tipping elements, 1.5 vs 2.0°C vs warmer, Emissions, Carbon budget, Emissions Gap	submission of Poster draft (graded)
	10.	20.11.2025	Carbon budget, Emissions Gap, Metrics	
	11.	27.11.2025	Metrics, Extreme Events	submission of assignment (graded)
Actions	12.	04.12.2025	Polar climate change	
	13.	11.12.2025	Mitigation measures	Poster Conference (graded)
	14.	18.12.2025	Climate engineering, questions and answers session	fill in Questionnaire in exercises (not graded)

How sensitive is the climate system to radiative forcing?



Generally, climate sensitivity refers to the amount of global mean surface warming (in °C or K) that will occur in response to a change of atmospheric CO₂ concentrations compared to preindustrial levels.

- «Magic» single number, which tells us how severe climate change will be?
- It's not that easy.
- But very important:
 - Hot or very hot? Makes a huge economic difference, health...

Climate sensitivity is a temperature.

Climate Sensitivity Definitions

Equilibrium climate sensitivity (ECS) is the equilibrium annual global mean temperature response to a doubling of equivalent atmospheric CO₂ from pre-industrial levels and is thus a measure of the strength of the climate system's eventual response to greenhouse gas forcing. It takes into account changes in water vapour, lapse rate, clouds and surface albedo. The carbon cycle and other biogeochemical feedbacks, chemistry feedbacks, and slow feedback-like changes in vegetation types and ice sheets are deliberately not included in the concept of equilibrium climate sensitivity.

IPCC AR5: ECS of 1.5°C to 4.5°C;
CMIP6: ECS of 1.8°C to 5.6°C, **increased**

The **Earth system sensitivity (ESS)** includes very long-term Earth system feedbacks, such as changes in ice sheets or changes in the distribution of vegetative cover.

Transient climate response (TCR) is the annual global mean temperature change at the time of CO₂ doubling in a climate simulation with a 1% yr⁻¹ compounded increase in CO₂ concentration. CO₂ doubling is reached after 70 years.

TCR is a measure of the strength and rapidity of the climate response to greenhouse gas forcing, and depends in part on the rate at which the ocean takes up heat. It differs from ECS because the distribution of heat between the atmosphere and oceans will not yet have reached equilibrium.

IPCC AR5: TCR of 1C to 2.5C;
CMIP 6: 1.7°C (1.3°C to 3.0°C), **increased**

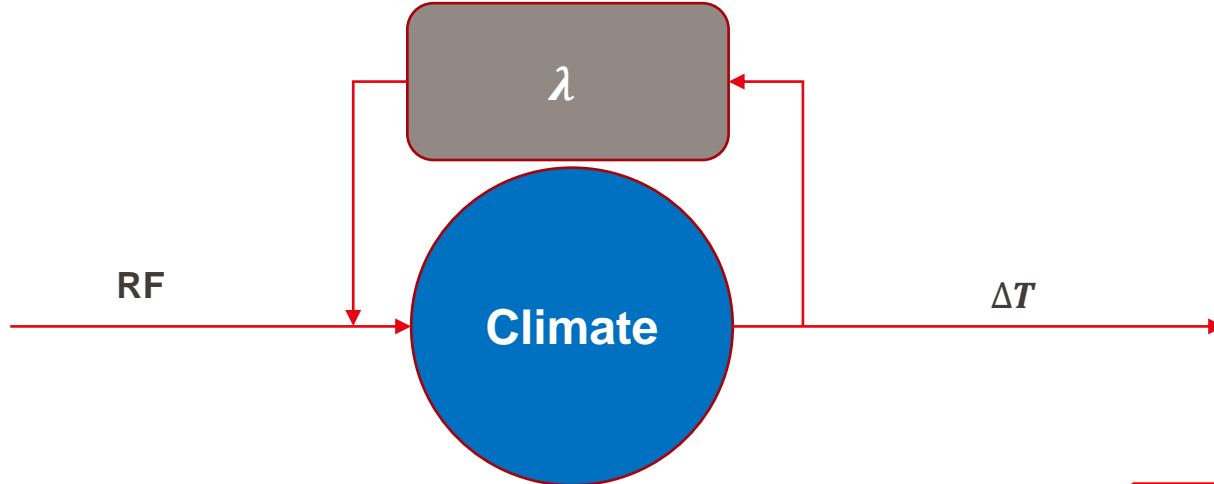
TCR < ECS because of oceanic heat uptake, which is a slow process. In TCR experiments, the surface ocean remains cooler and hence IR emission remains lower.

Forcing, climate sensitivity and feedback

$$N = RF + \lambda \Delta T$$

N : net top of atmosphere energy balance,
 RF : radiative forcing,
 ΔT : global surface temperature response, climate sensitivity
 λ : feedback factor

Positive feedback amplifies the response
Negative feedback dampens the response



Forcing, climate sensitivity and feedback are fundamental concepts to understand climate change.

To derive the climate sensitivity, we need to know the feedback factor.

Backbone
of any
climate
model!

1. Net downward flux at TOA

$$F_{TOA} = (1 - \alpha)Q - \sigma T_e^4$$

σ Boltzmann constant ($5.67 \cdot 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$)

T_e equivalent temperature

Q area-weighted mean incoming solar flux (341.3 Wm^{-2})

α planetary albedo (0.3)

2. Planetary energy budget

$$C \frac{dT_s}{dt} = F_{TOA}$$

T_s average surface temperature

C atmosphere-ocean column effective heat capacity ($\text{Jm}^{-2}\text{K}^{-1}$)

3. Adding radiative forcing

$$C \frac{d\Delta T_s}{dt} = RF + \Delta F_{TOA}$$

ΔT_s change of global mean surface temperature

RF = radiative forcing

T_s changes because of RF and resulting changes in radiative processes (internal to the climate system) ΔF_{TOA}

4. The **key assumption** in climate feedback analysis is that *changes in radiative flux are proportional to surface temperature changes*:

$$\Delta F_{TOA} = \lambda * \Delta T_s$$

λ is a constant of proportionality: climate feedback factor ($\text{W m}^{-2} \text{K}^{-1}$)

$$C \frac{d\Delta T_s}{dt} = RF + \lambda * \Delta T_s$$

How much warming do we expect with a given radiative forcing?

Or, how much warming do we expect if we double the CO_2 concentration, which is about 3.7 W m^{-2} ?

5. With sufficient time the system will equilibrate:

$$C \frac{d\Delta T_s}{dt} = 0 = RF + \lambda * \Delta T_s$$

$$\Delta T_s = -\frac{RF}{\lambda}$$

$$\lambda = \lambda_0 + \lambda_1 + \lambda_2 + \dots = \sum_{i=0}^n \lambda_i$$

Many different climate feedbacks

$\lambda > 0$, positive feedback

$\lambda < 0$, negative feedback

What's the sign of λ ?

What is the sign of λ ?

$$\Delta T_s = -\frac{RF}{\lambda}$$

- A. Positive
- B. Negative

Previous slide

$$C \frac{dT_s}{dt} = F_{TOA} = (1 - \alpha)Q - \sigma T_e^4$$

Need to reconcile T_s and T_e

6. Parameterize with T_s only.

$$C \frac{dT_s}{dt} = (1 - \alpha)Q - \sigma(\beta T_s)^4$$

β measures the proportionality between the surface and emission temperature
 $\beta = T_e/T_s = 255 \text{ K} / 288 \text{ K} = 0.885$

7. Defining λ

$$C \frac{d\Delta T_s}{dt} = RF + \lambda * \Delta T_s$$

This is a simple climate model (only physics)!

8. Calculate λ

$$\lambda = -3.3 \text{ W m}^{-2} \text{ K}^{-1}$$

What does this mean?

For every 1 W m^{-2} radiative forcing, our planet must warm by $-1/\lambda = 0.3 \text{ K}$ to establish equilibrium.

Note:

This model only represents a **single feedback process**: the increase in longwave emission to space with surface warming.

This is called the **Planck feedback** because it is fundamentally due to the Planck blackbody radiation law (warmer temperatures = higher emission).

$$\lambda_0 = -3.3 \text{ W m}^{-2} \text{ K}^{-1}$$

$$N = RF + \lambda \Delta T$$

N : net top of atmosphere energy balance,
 RF : radiative forcing,
 ΔT : global surface temperature response,
 λ : feedback factor

What is the value of λ approximately?

- A. $0 \text{ W m}^{-2} \text{ K}^{-1}$
- B. $3 \text{ W m}^{-2} \text{ K}^{-1}$
- C. $-3 \text{ W m}^{-2} \text{ K}^{-1}$
- D. $\sim -2 \text{ W m}^{-2} \text{ K}^{-1}$

1. Assume the climate system equilibrates after some time.
2. Use the information from the lecture to derive λ . *E.g. figures with RF and some value on global warming.*

Types of feedback – fast physical

Atmospheric thermodynamic feedbacks (most certain quantification)

- 1 Planck response (black body radiation)
- 2 The combined water vapour and lapse rate feedback

Cloud feedbacks (complex and large source of uncertainty)

- 1 Rise of cloud top feedback
- 2 Tropical low -cloud feedback
- 3 Mid-latitude cloud reflectance feedback
- 4 Cloud water phase feedback

Fast surface feedbacks

- 1 Snow albedo feedback
- 2 Soil moisture evapotranspiration feedback and CO₂ stomata-water feedback

Fast ocean feedbacks

- 1 ocean mixed-layer and ocean thermocline feedbacks
- 2 Tropical circulation responses to a warming climate

Sea ice feedbacks

- 1 Sea ice albedo feedback

Color legend

Thermal longwave (LW) heat redistribution including water vapour and moisture

Shortwave (SW) reflectivity / albedo

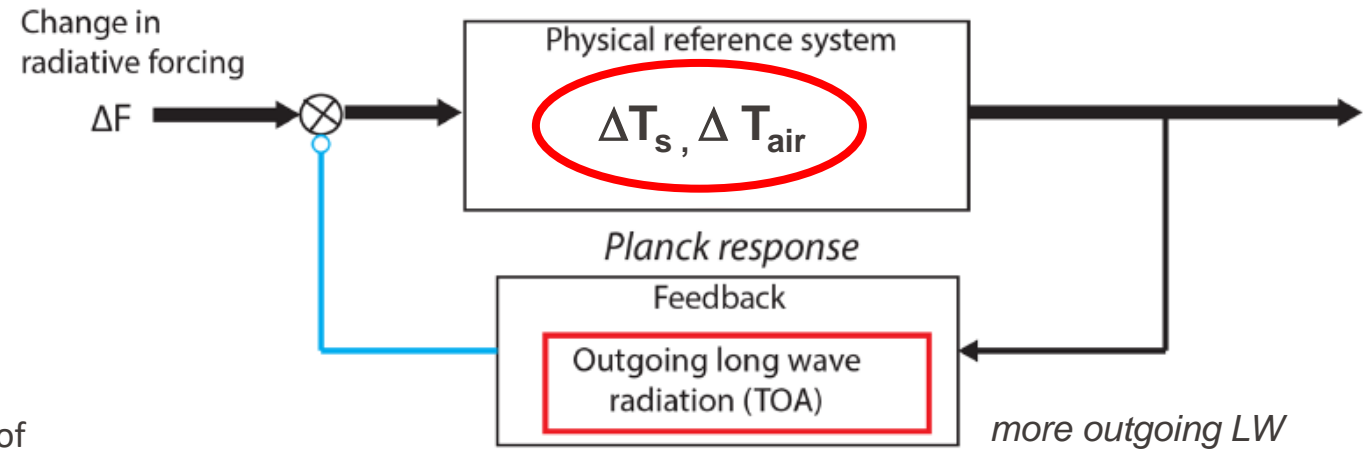
Both LW and SW effects

Planck response

Arrows indicate positive coupling;
open circles indicate negative coupling.
Changes in state variables are indicated in ellipses.

Red indicates increasing variable values, strengthening of processes, or positive feedback; blue indicates the opposite.

ΔT_s change in surface temperature
 ΔT_{air} change in air temperature



Planck response:

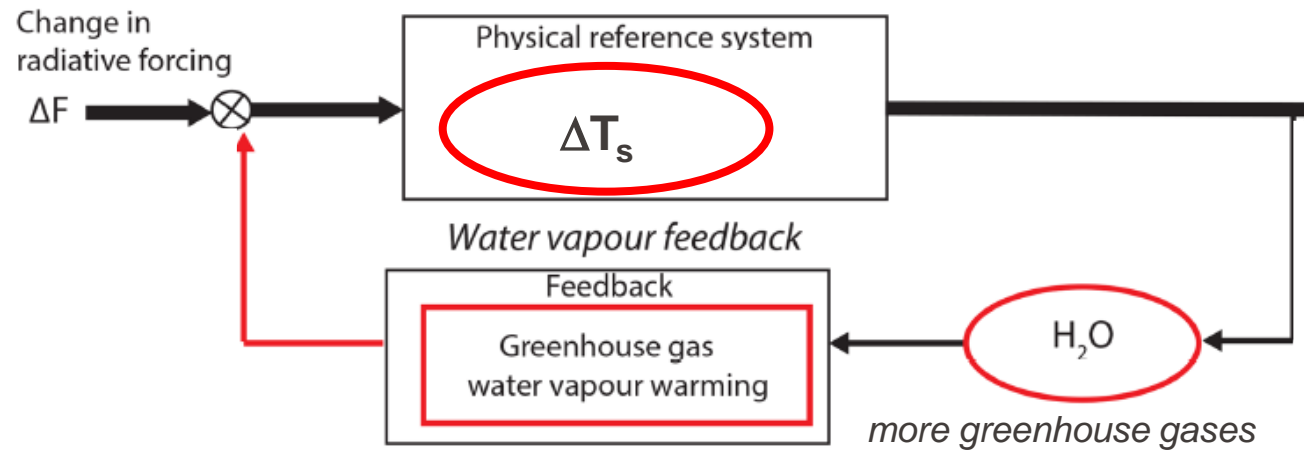
- Single largest and negative feedback. Based on Stefan-Boltzmann law. Increase of LW radiation to space due to surface warming. Only if the Planck feedback is overcome by other positive feedbacks, a runaway greenhouse effect can be expected.

Arrows indicate positive coupling;
open circles indicate negative coupling.
Changes in state variables are indicated in ellipses.

Red indicates increasing variable values, strengthening of
processes, or positive feedback; blue indicates the opposite.

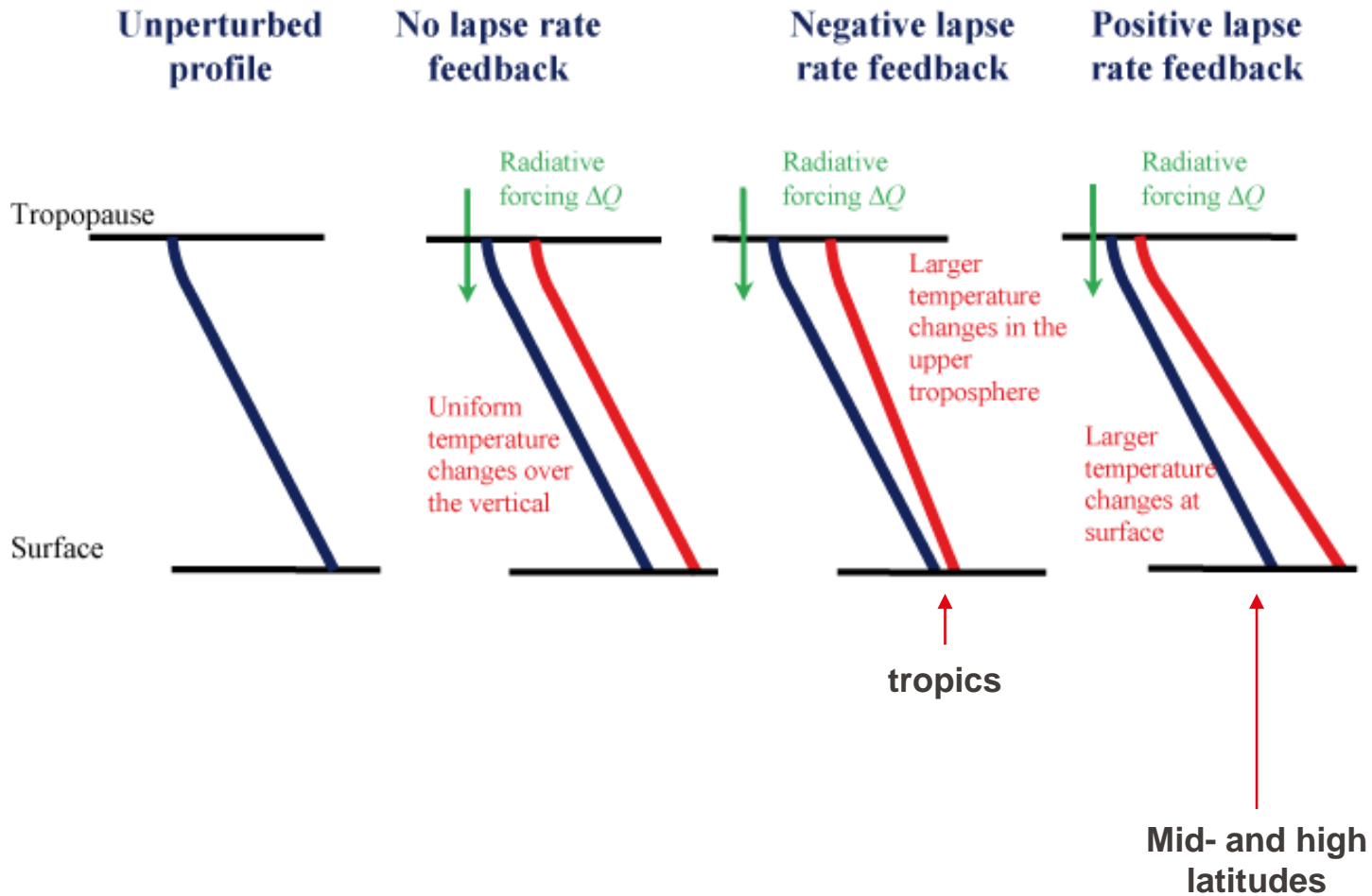
ΔT_s change in surface temperature

ΔT_{air} change in air temperature



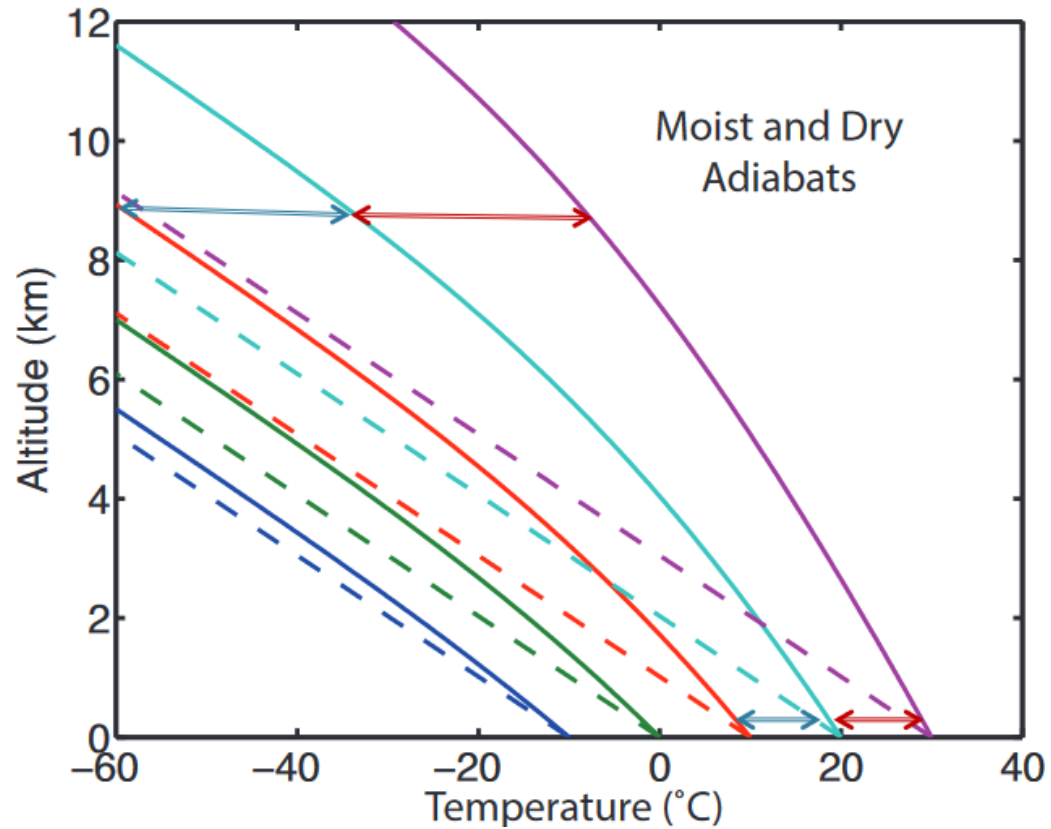
■ Water vapour feedback:

- The warmer the atmosphere, the more water vapour it can hold. Water vapour is a greenhouse gas. The RF resulting from water vapour is roughly proportional to the logarithm of its concentration. Hence more warming occurs, where the unperturbed situation is rather dry (higher troposphere, cold regions).



- Lapse rate: the moist adiabatic lapse rate is expected to decrease with warming tropospheric temperature. This means the outgoing LW radiation to space increases (loss of energy). → **First order effect.**
 - Above is particularly true **for tropical regions** where greenhouse gases lead to tropospheric warming (further aloft) due to increased convection from the surface.
- In the **mid- to high latitudes**, the surface tends to warm relatively more such that the lapse rate becomes steeper and results in a positive feedback (colder troposphere and less LW radiation loss to space).
- Overall, for the water vapour and lapse rate feedbacks the exact changes of temperature and humidity in high altitudes are not yet well known, but since the effects cancel each other out, their combined uncertainty is nevertheless relatively small.

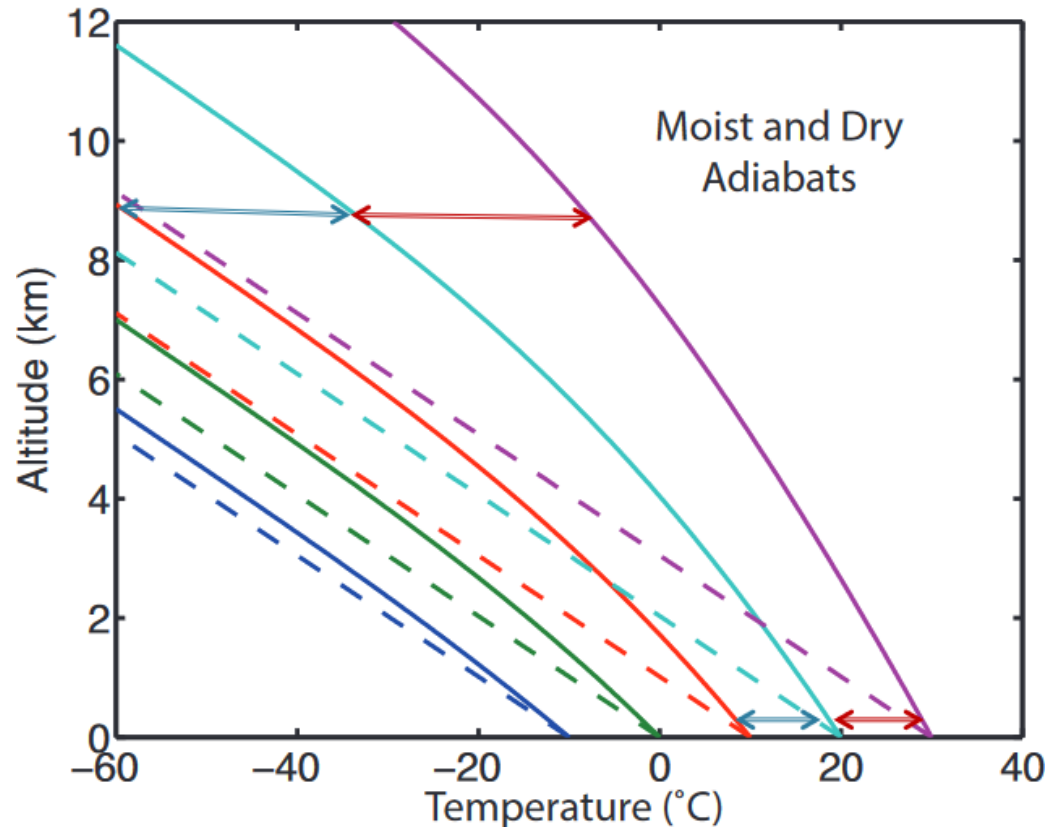
Which line is the moist adiabat?



A. Dashed

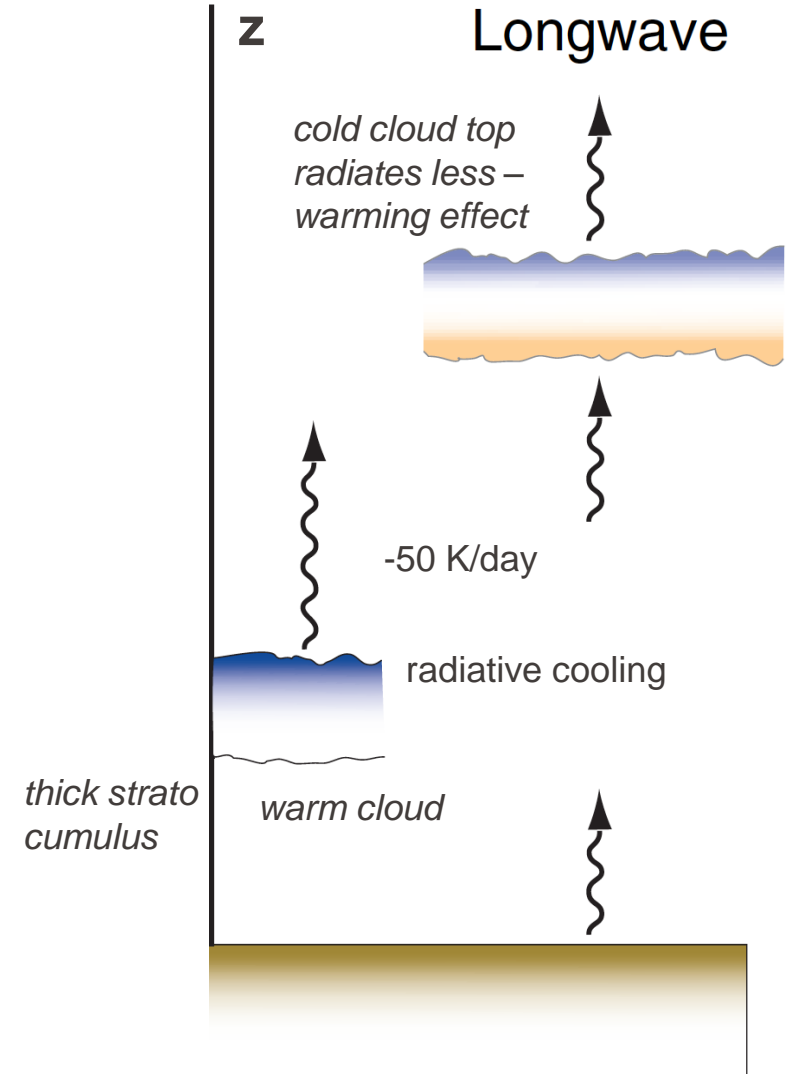
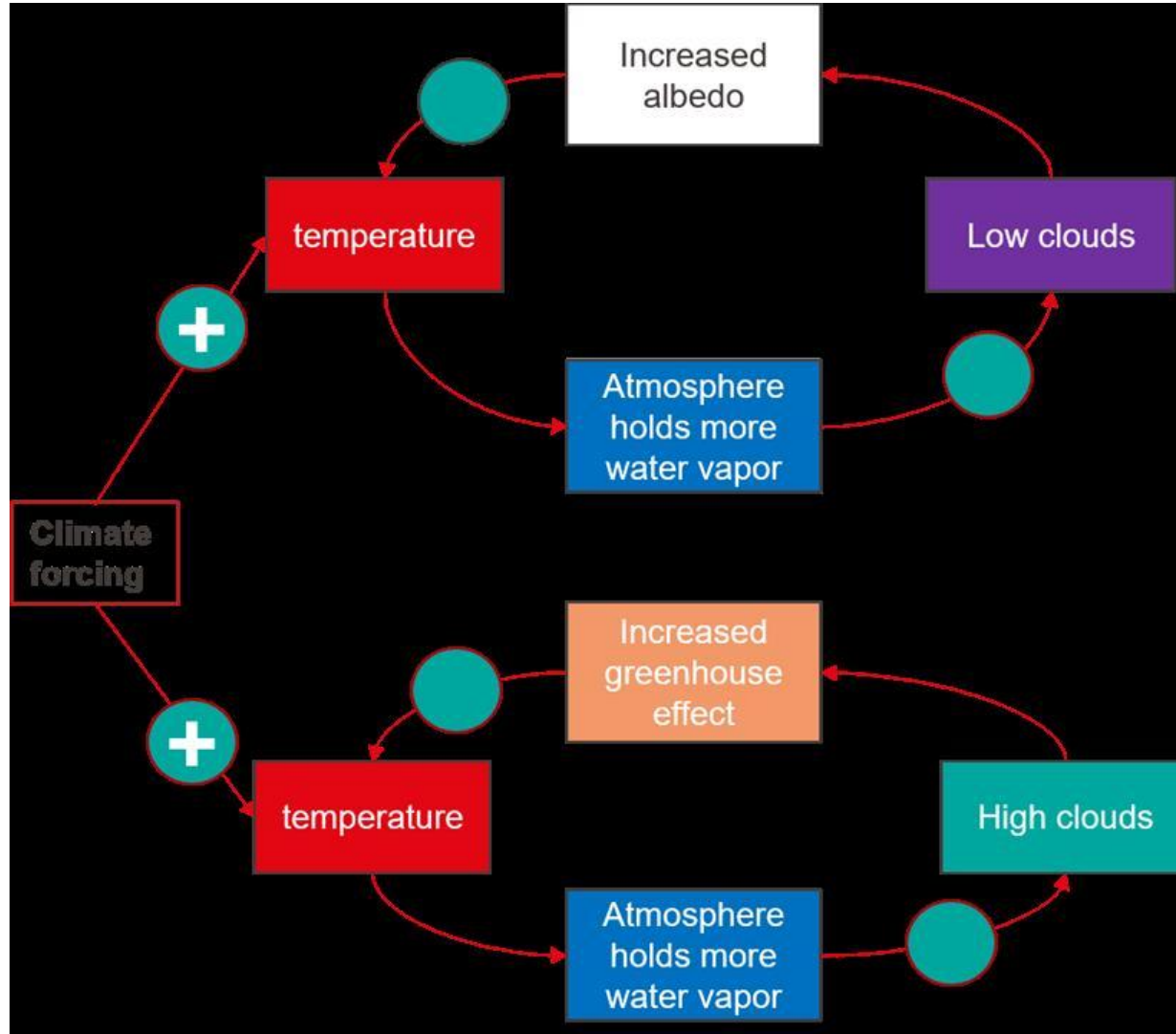
B. Solid

Moist adiabatic lapse rate in a warming climate

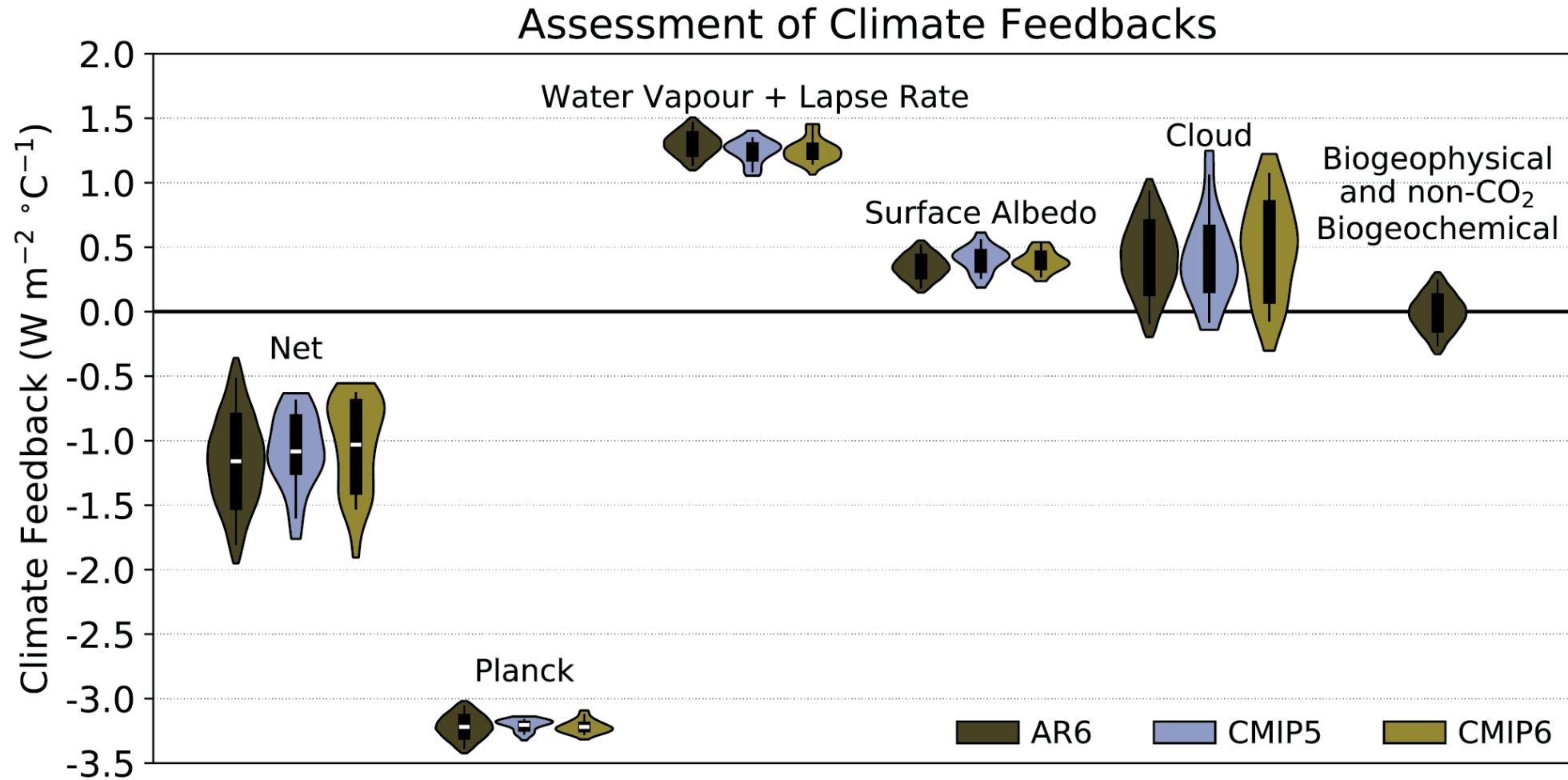


- The warmer the surface the smaller the moist adiabatic lapse rate.
- There is a warming amplification with altitude.

Cloud feedback: Where is the negative feedback?



Summary of physical feedback factors



Types of feedback – fast physical

Atmospheric thermodynamic feedbacks (most certain quantification)

- 1 Planck response (black body radiation)
- 2 The combined water vapour and lapse rate feedback

Cloud feedbacks (complex and large source of uncertainty)

- 1 Rise of cloud top feedback
- 2 Tropical low -cloud feedback
- 3 Mid-latitude cloud reflectance feedback
- 4 Cloud water phase feedback

Fast surface feedbacks

- 1 Snow albedo feedback
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Color legend

Thermal longwave (LW) heat redistribution including water vapour and moisture

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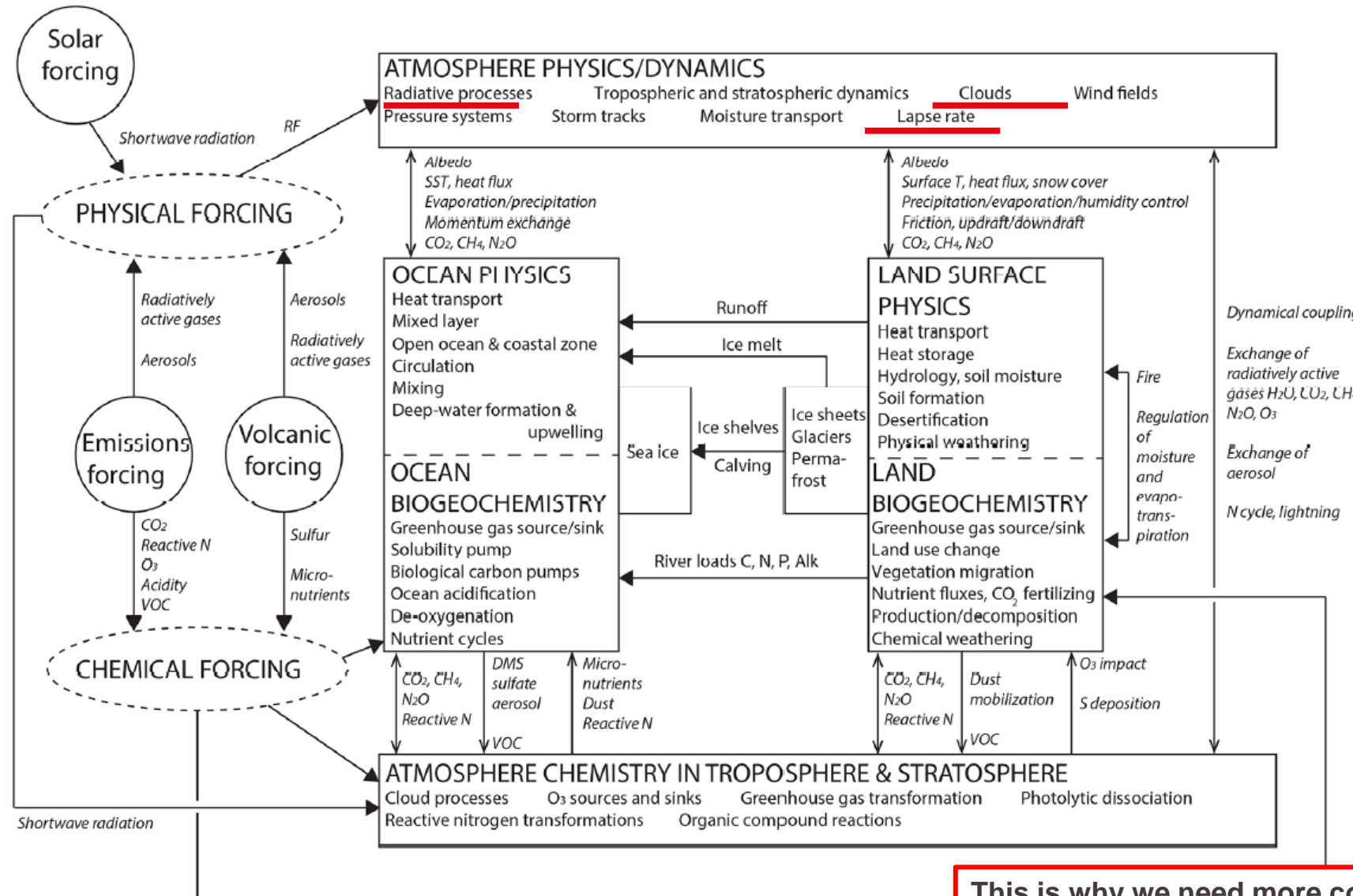
Both LW and SW effects

There are slower and non-physical feedbacks as well.

Upper ocean feedback

- Fundamental physical properties of the ocean are very different compared to the atmosphere: heat capacity, viscosity, and timescales of motion.
- The evolution of climate change depends critically on the penetration rate of the global warming signal into the ocean and the capacity of the ocean to uptake heat from the atmosphere.
- Ocean–climate feedback timescales range from the synoptic to seasonal, decadal, or even centennial.

There are many more feedbacks



Long time scale effects:

- Deep ocean
- Ice sheets

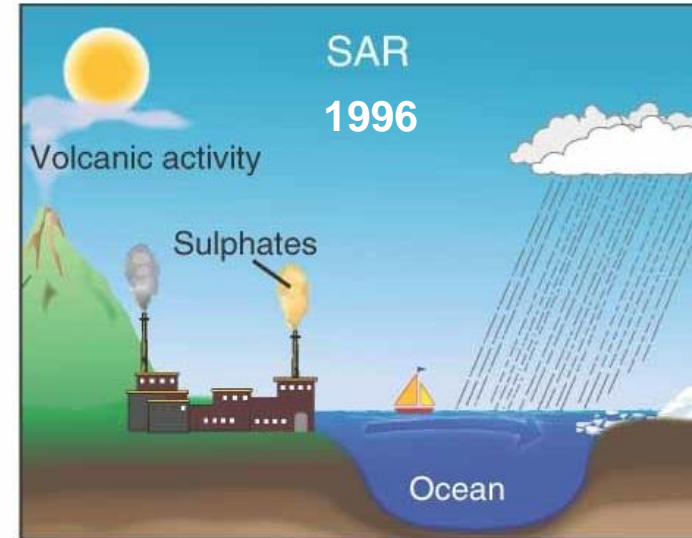
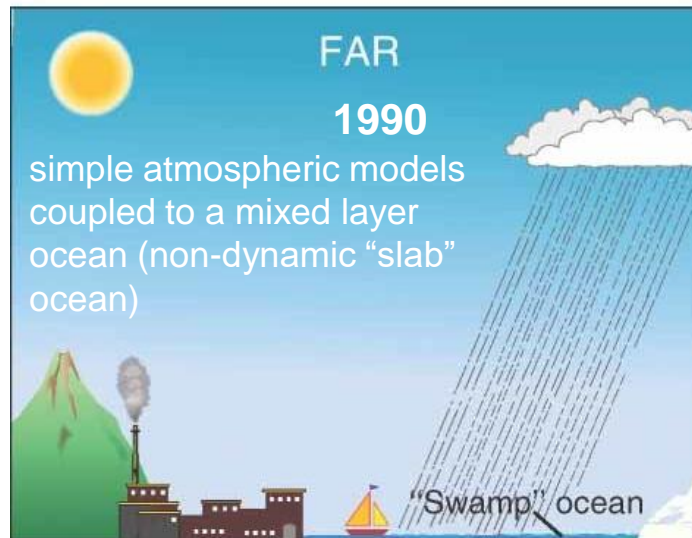
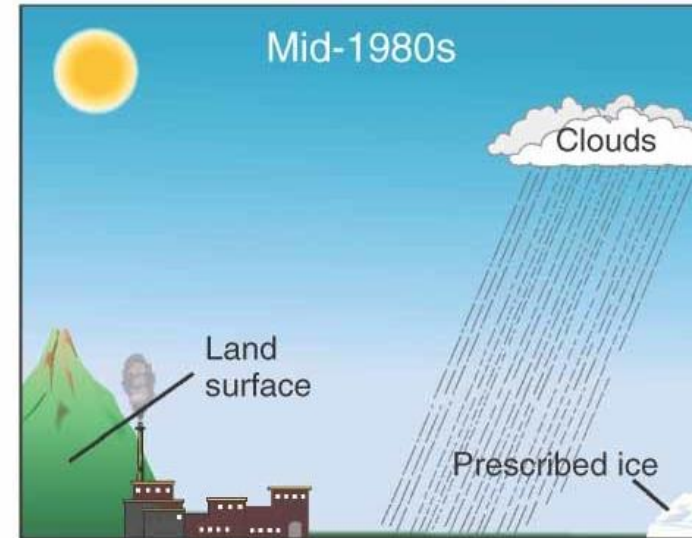
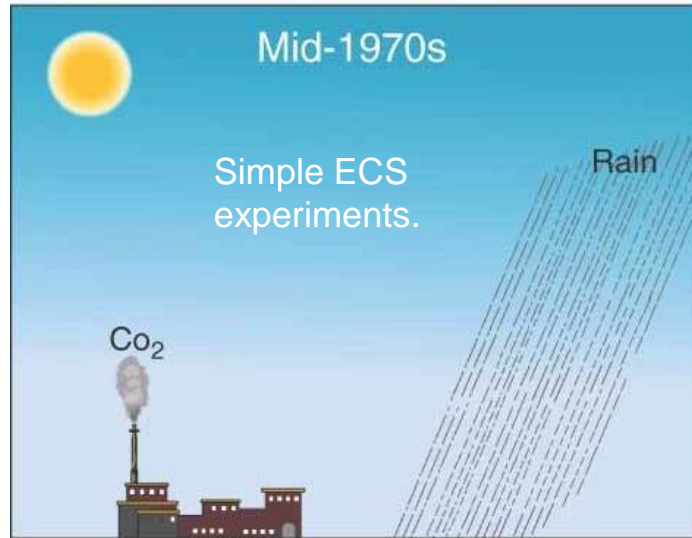
Biogeochemical effects

- Vegetation growth
- fires
- Marine emissions
- Inorganic ocean carbon cycle
- Aerosol effects

This is why we need more complex climate models including also biogeochemical processes.

General circulation models (GCMs):

- «Dynamical core» simulates large-scale fluidic motion using primitive equations.
- «Model physics» simulate climate-relevant physical processes (e.g. radiative transfer).

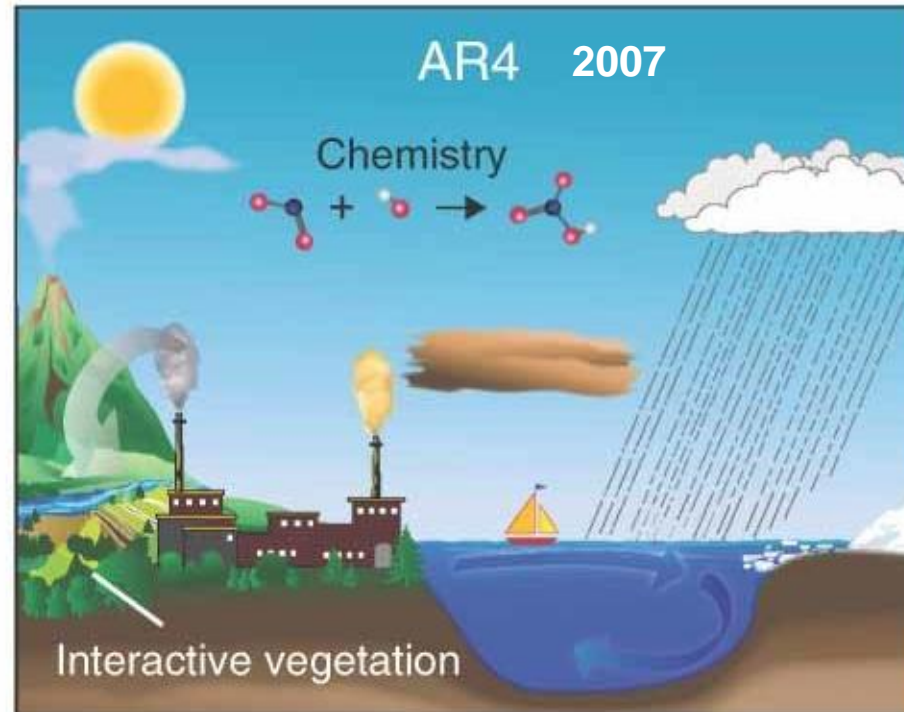
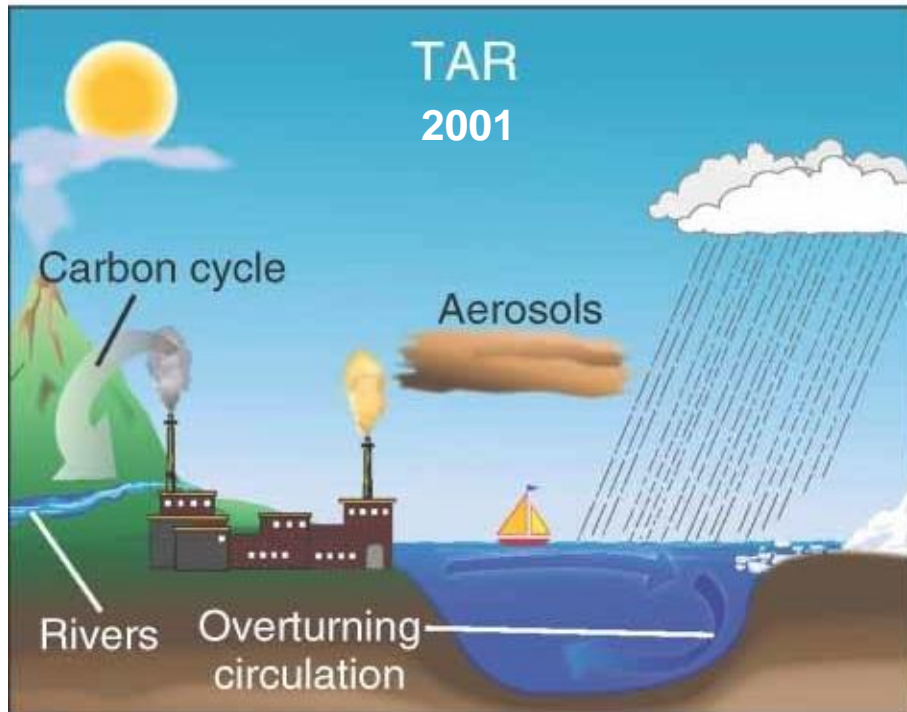


First estimate of transient climate response: increase CO₂ by 1% each year until doubled (ca. 70 years): TCR

Established CMIP 2 for intercomparison of transient responses. CMIP: coupled model intercomparison project

FAR: First assessment report
SAR: Second AR

Creation of time-dependent emission scenario runs.
Establish TCR experiments.



Atmosphere-ocean general circulation model

How do we now derive climate sensitivity?

$$N = RF + \lambda \Delta T$$

N : net top of atmosphere energy balance,
 RF : radiative forcing,
 ΔT : global surface temperature response,
 λ : feedback factor

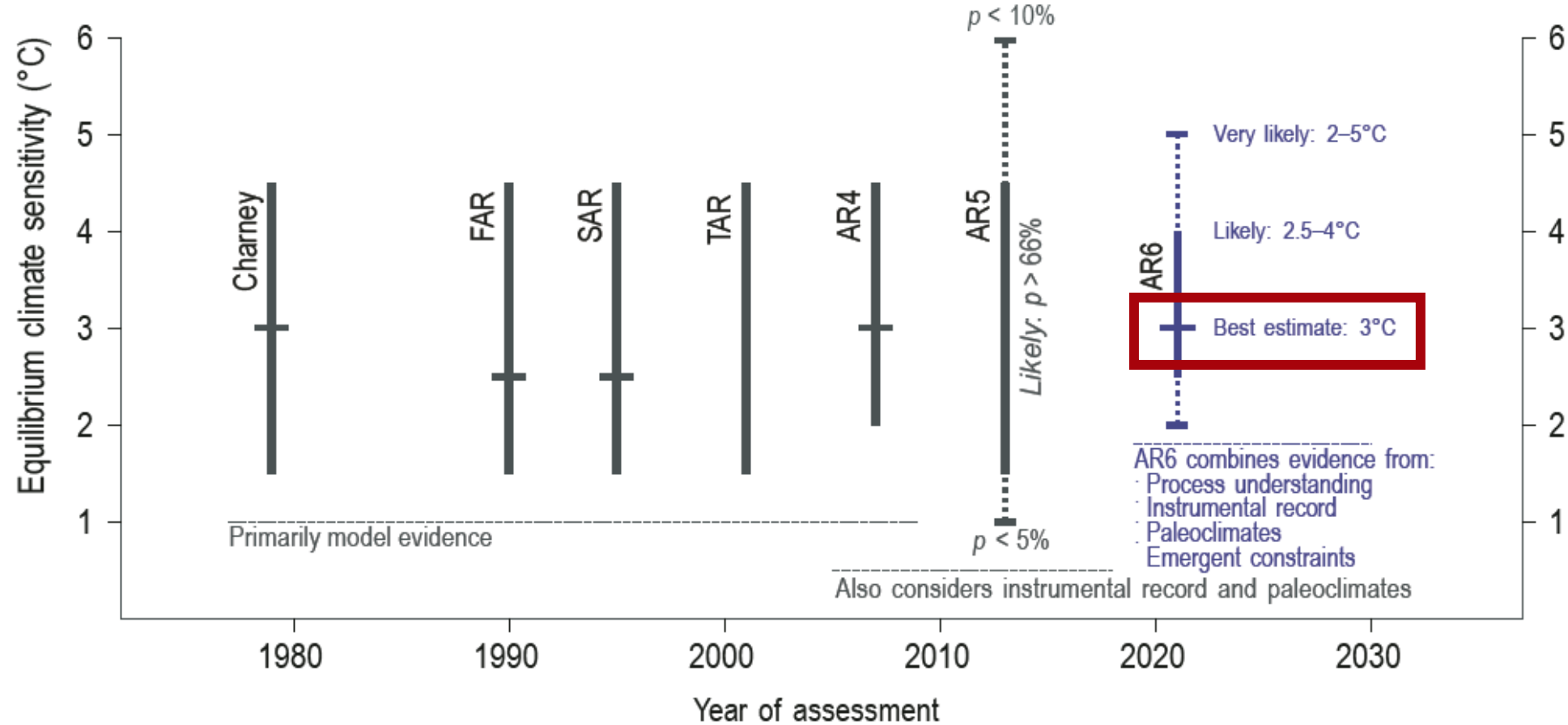
- For a given forcing associated with a doubling of atmospheric CO₂ concentration (with a radiative forcing of about 3.7 W m⁻²), at equilibrium $N = 0$, we can solve for ΔT , a quantity known as the “equilibrium climate sensitivity” (ECS).
- **Gregory method:**
 - The ECS calculated by the **Gregory method** is derived from a fully coupled Earth system model and does not require equilibrium to actually be achieved.
 - In the Gregory method, **CO₂ is instantaneously quadrupled** in a fully coupled Earth system model and **run for 150 years**.
 - As the surface temperature asymptotes toward equilibrium, the slope of the time-evolving curve of the net top-of-atmosphere radiance against the surface temperature is calculated to extrapolate the eventual temperature increase at equilibrium some time far in the future for a doubling of CO₂, assuming that there is a roughly linear response that is half of the warming from a quadrupling of CO₂.

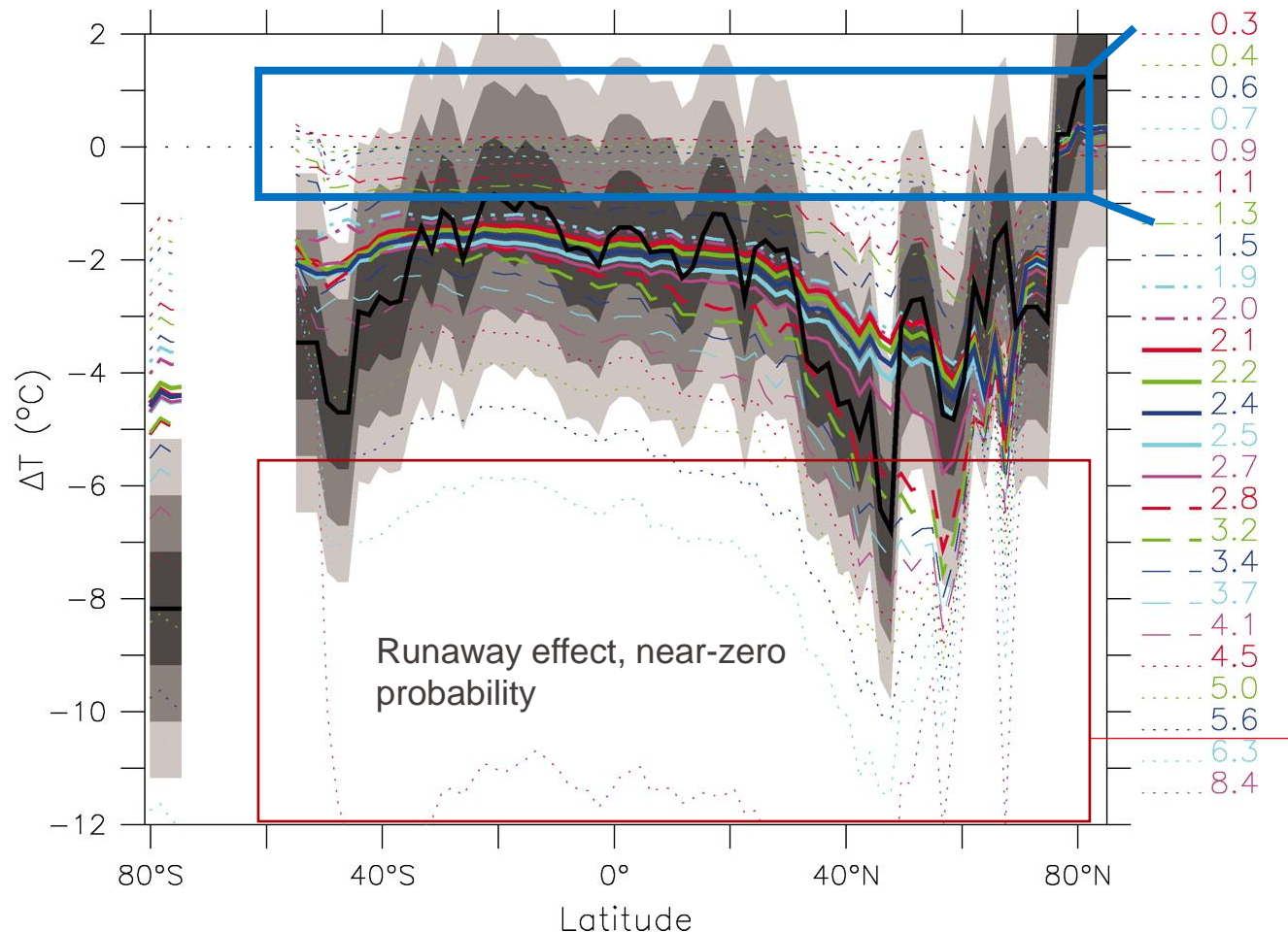
What is the unit of ECS?

- A. K or °C
- B. W m⁻²
- C. °C m⁻²

Evolution of climate sensitivity

(a) Evolution of equilibrium climate sensitivity assessments from Charney to AR6

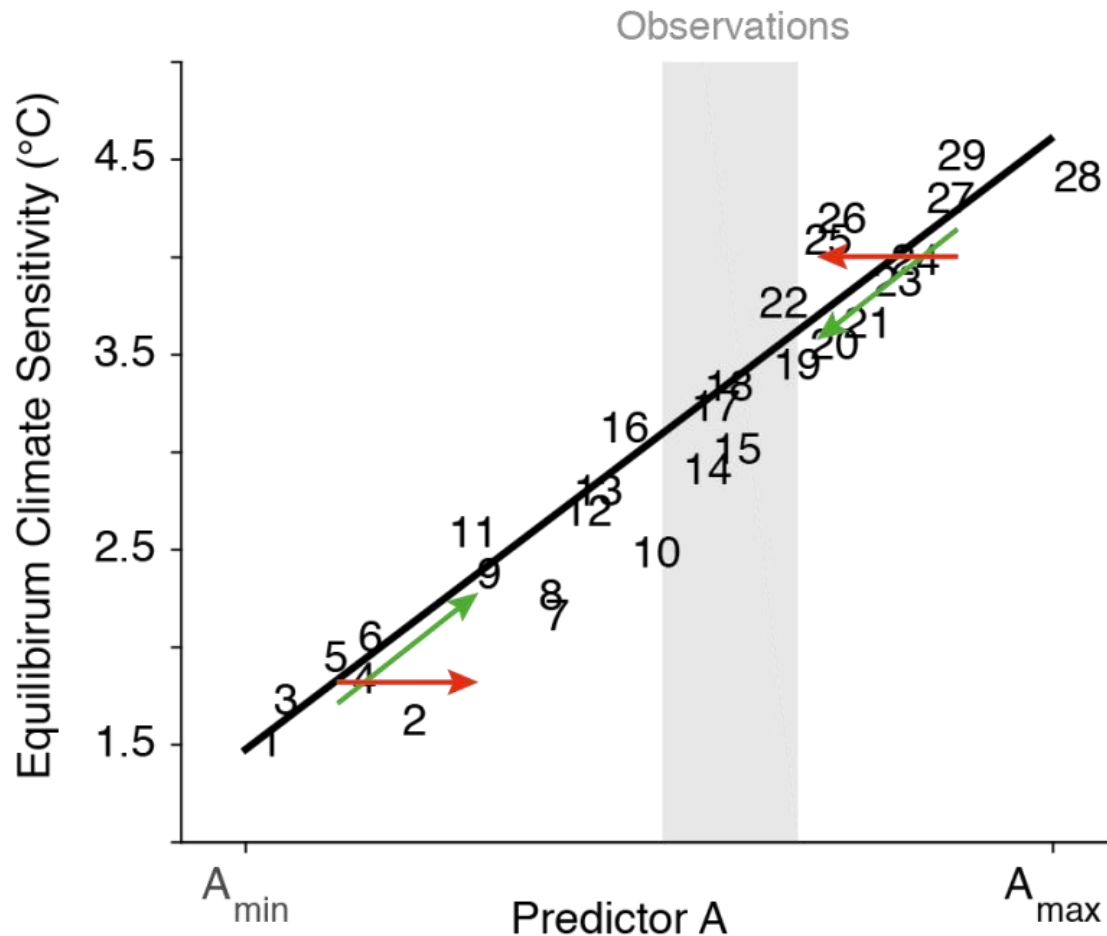




- Models with $ECS_{2xC} < 1.3$ K underestimate the cooling at the LGM almost everywhere, particularly at mid-latitudes and over Antarctica,
- Models with $ECS_{2xC} > 4.5$ K overestimate the cooling almost everywhere, particularly at low latitudes.
- High-sensitivity models ($ECS_{2xC} > 6.3$ K) show a runaway effect resulting in a completely ice-covered planet. Once snow and ice cover reach a critical latitude, the positive ice-albedo feedback is larger than the negative feedback because of reduced longwave radiation (Planck feedback), triggering an irreversible transition.
- During the LGM, Earth was covered by more ice and snow than it is today, but continental ice sheets did not extend equatorward of $\sim 40^\circ\text{N/S}$, and the tropics and subtropics were ice free except at high altitudes.
- **Results thus suggest that large climate sensitivities ($ECS_{2xC} > 6$ K) cannot be reconciled with paleoclimatic and geologic evidence and hence should be assigned near-zero probability.**

Zonally averaged surface temperature change between the Last Glacial Maximum and modern. Thick black line denotes the climate reconstructions, the gray shading the ± 1 , 2, and 3 K intervals around the observations. Modeled temperatures, averaged using only cells with reconstructions are shown as colored lines labeled with the corresponding ECS_{2xC} values.

Constraining with emergent constraints (the concept)



Hypothetical relationship between a predictor A and the equilibrium climate sensitivity (ECS) for 29 climate models.

Predictor A may represent, for example, the variability of the surface temperature over time. On the y-axis, ECS may be replaced by any climate-change projection. The black line is the linear regression, and the grey vertical bar is the observed value of predictor A (with its uncertainty).

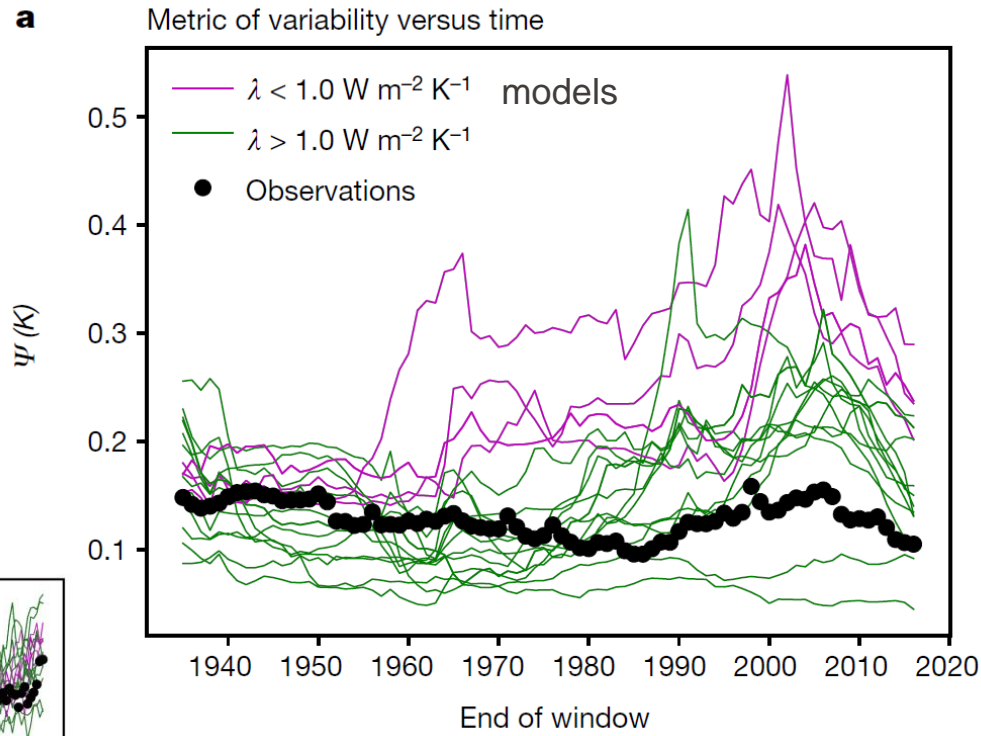
Arrows show the evolution of ECS after improving the representation of predictor A for two climate models having low (4) and high (24) ECS values.

If these climate models evolve following the red arrows, the relationship may have been found by chance. If they evolve following the green arrows, mechanisms underlying the relationship gain credibility.

Since predictor A can be observed, this relationship can be considered as an emergent constraint.

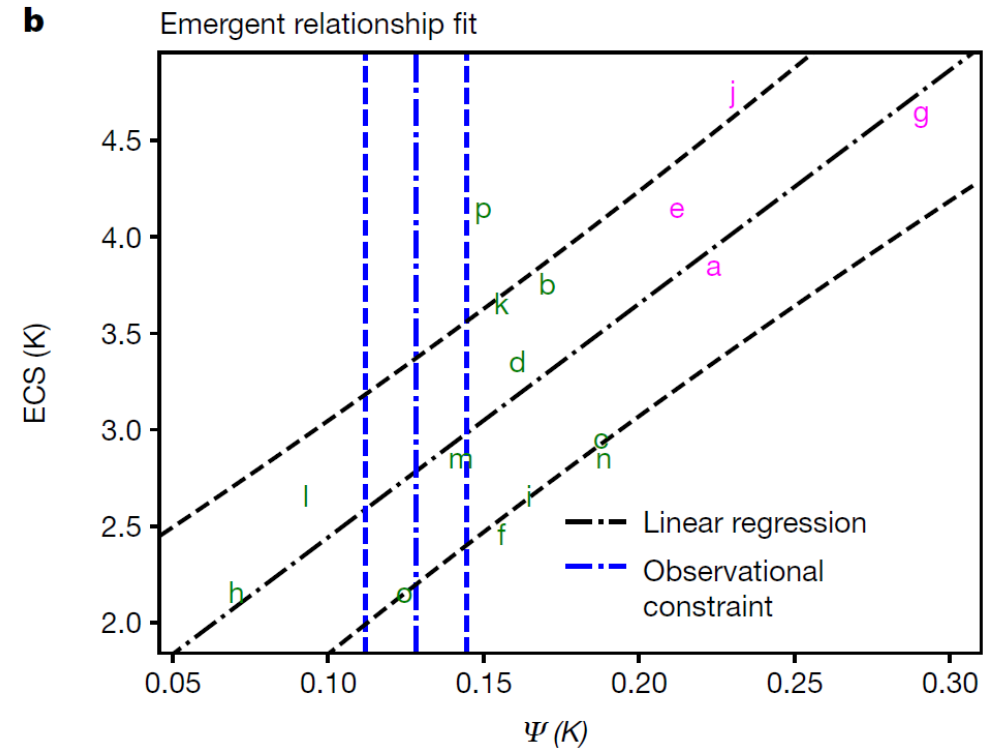
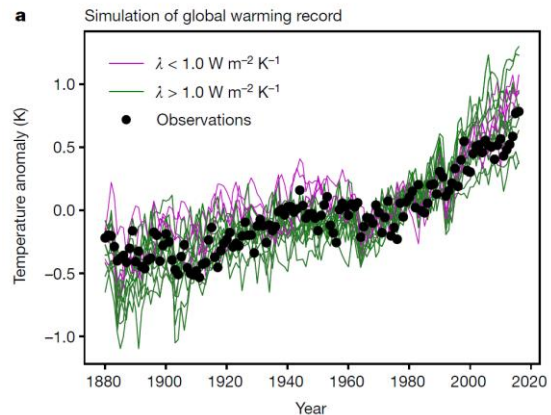
Constraining with emergent constraints

Temporal variability (Ψ) of the surface air temperature as observable metric to constrain ECS.



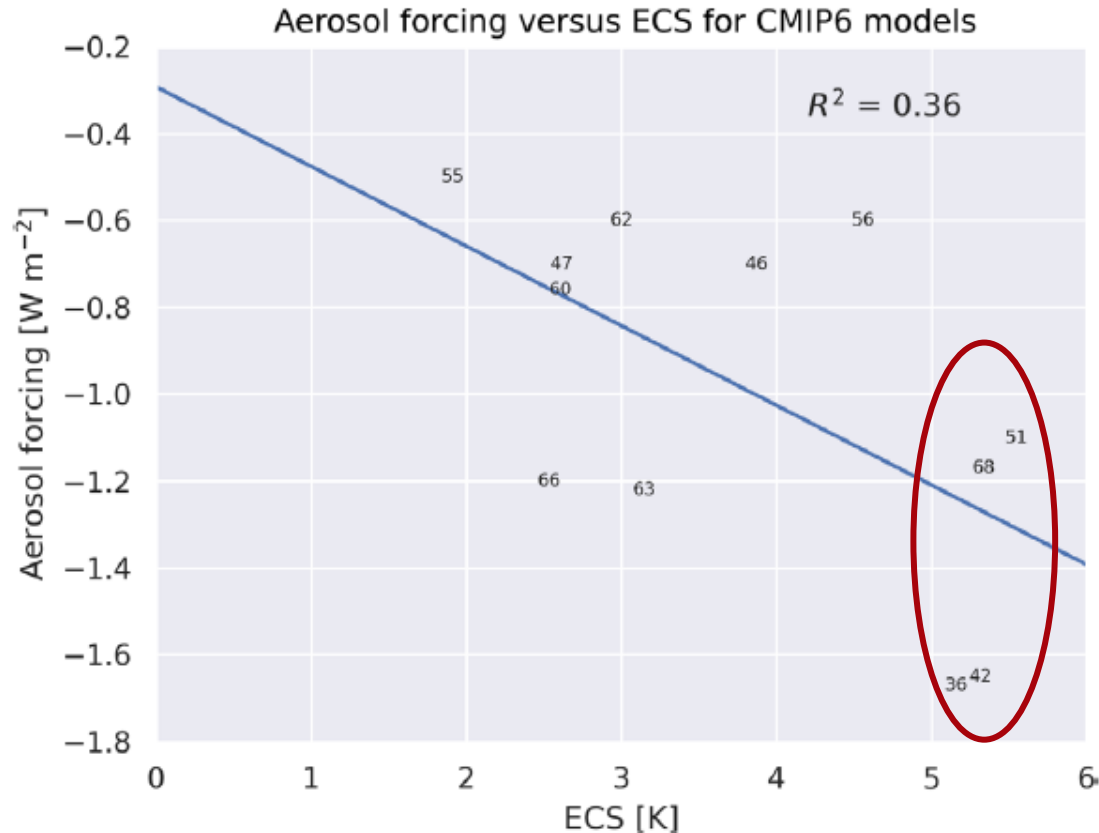
55 years as time windows to derive Ψ

Done for many time windows (not shown)



Reduces the probability of ECS being less than 1.5 degrees Celsius to less than 3 per cent, and the probability of ECS exceeding 4.5 degrees Celsius to less than 1 per cent.

Why larger range of ECS with the newest generation of climate models?



- Newer climate models include more complex treatment of aerosols.
- Aerosols interact with clouds which strongly influence the radiative forcing effect of aerosols.
- If the aerosol forcing is more negative, the climate sensitivity to CO₂ forcing needs to be higher to end up with the same rate of warming.
- However, CMIP6 models only show a weak correlation ($R^2 = 0.36$).

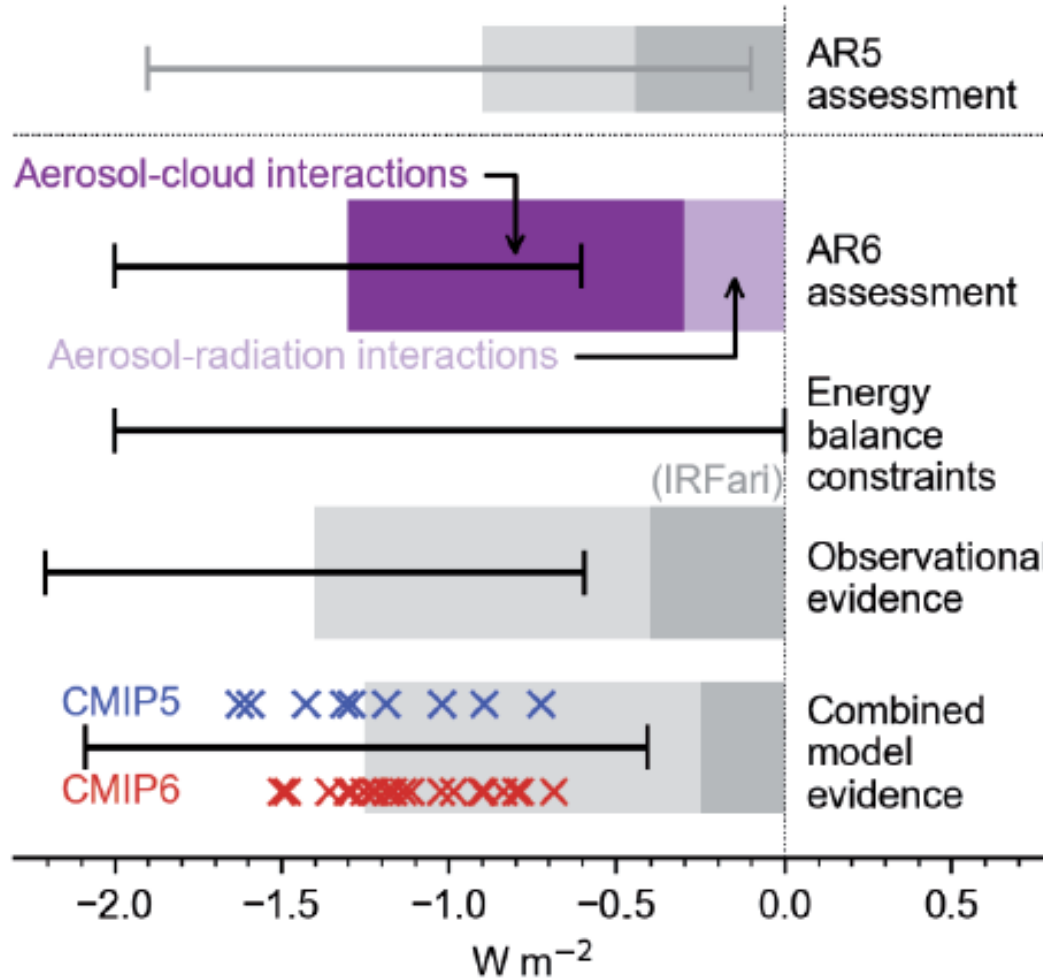
Models with prognostic aerosol schemes and aerosol-cloud interactions. It is difficult to pinpoint the exact feedback mechanisms in the models that lead to high ECS. But overall *"cloud feedbacks and cloud-aerosol interactions in models with prognostic aerosol schemes seem to be playing an important role"*.

Critical to research

Fig. 4. Effective radiative forcing from aerosols versus ECS. Values supplied by the modeling groups (Table 3); black line is linear fit with R^2 of 0.36. The numbers denoting individual models are listed in Table 2.

- Meehl et al., Science Advances, 2021, <https://advances.sciencemag.org/content/6/26/eaba1981/tab-pdf>

Uncertainty from aerosols and clouds

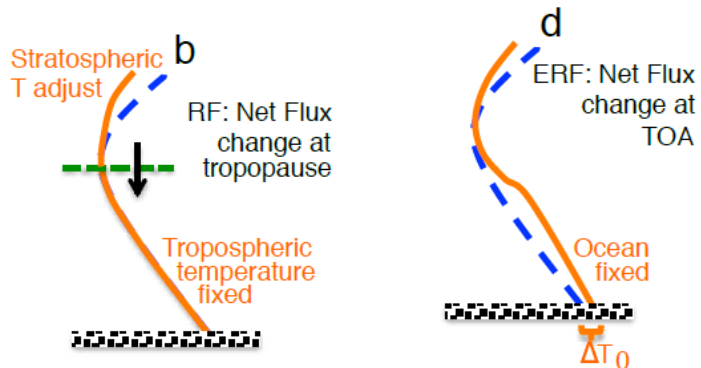
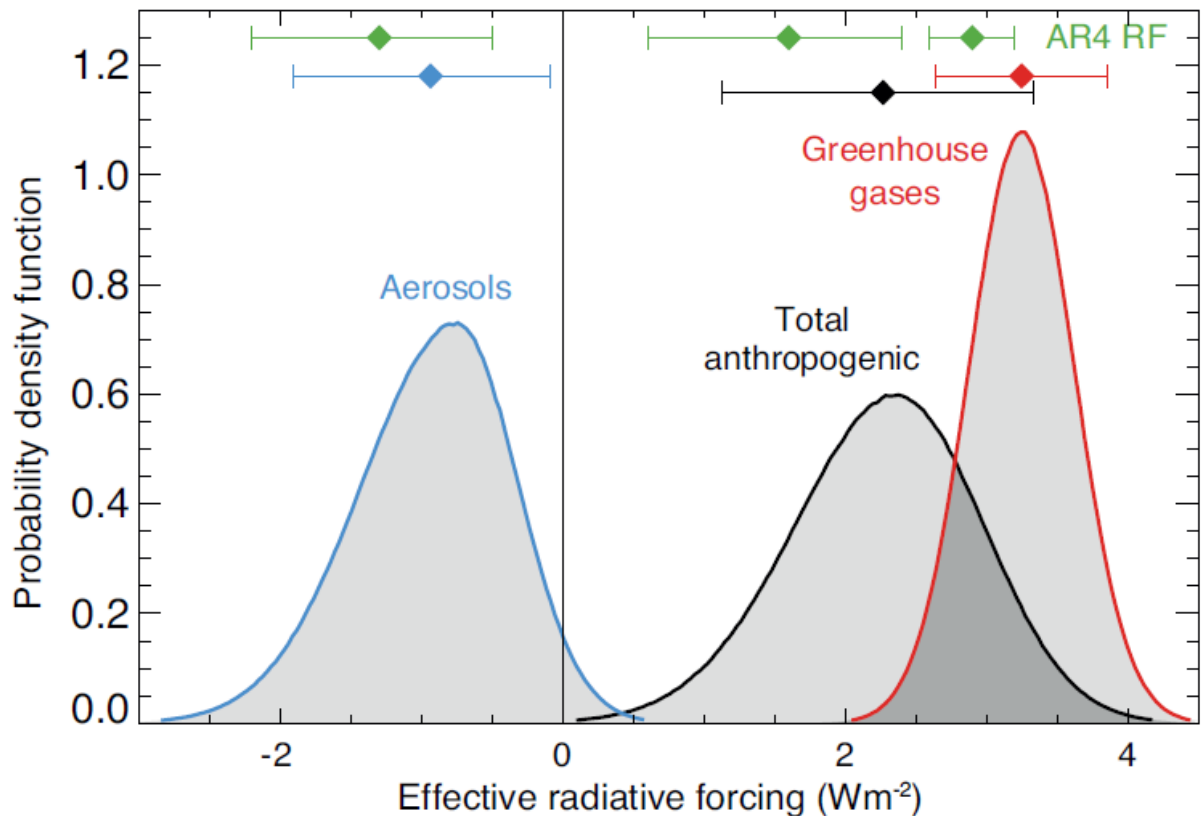


How can we reduce uncertainties from aerosol and cloud forcing?

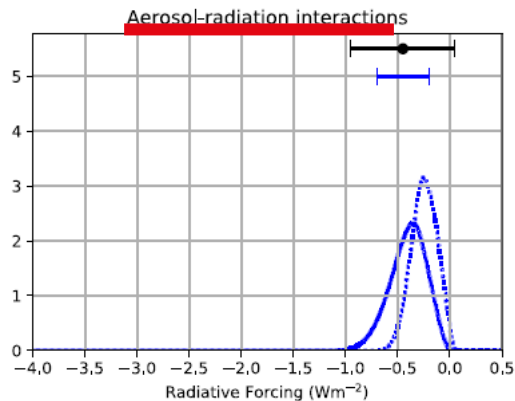
➔ defining the preindustrial

ERF from ARI and ACI

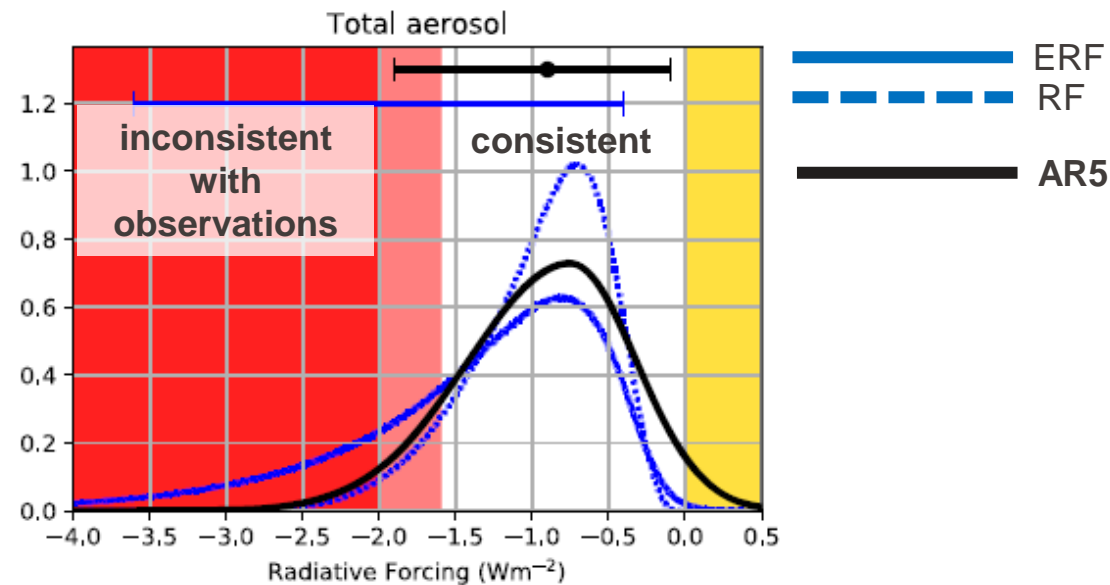
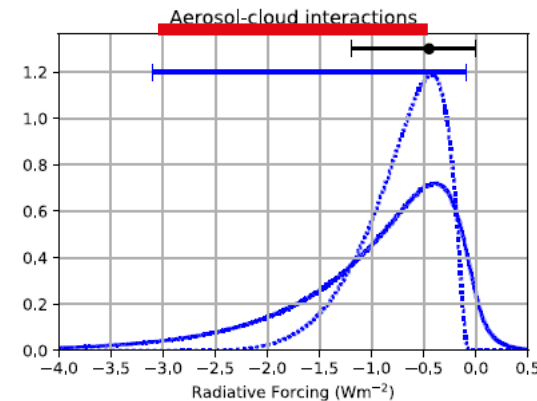
IPCC, 2013, chapter 8, Fig. 8.16



AR5 vs now:
better constrained
 (less strong rapid adjustments)



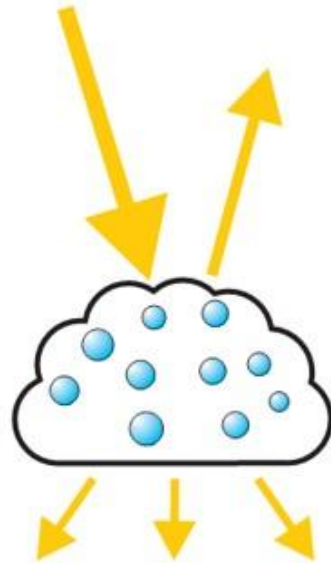
AR5 vs now:
less constrained
 (wider assessment of rapid adjustments)



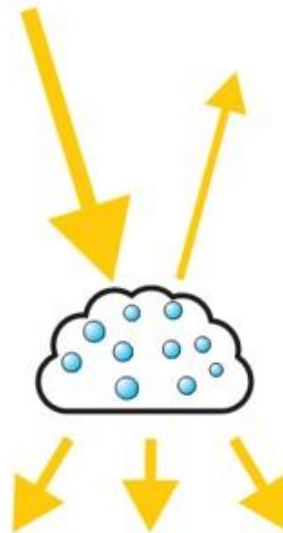
Incoming solar radiation



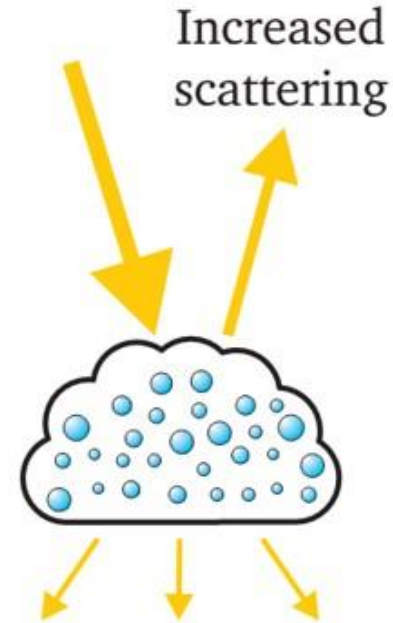
Direct Effect
Scattering/
absorption



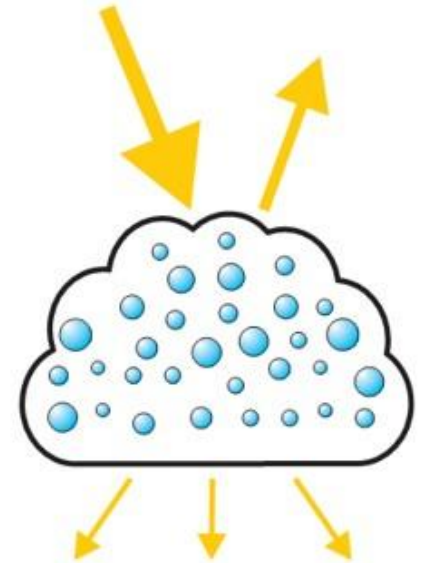
**Unperturbed
cloud**



**Semi-direct
Effect**
Cloud burn-off

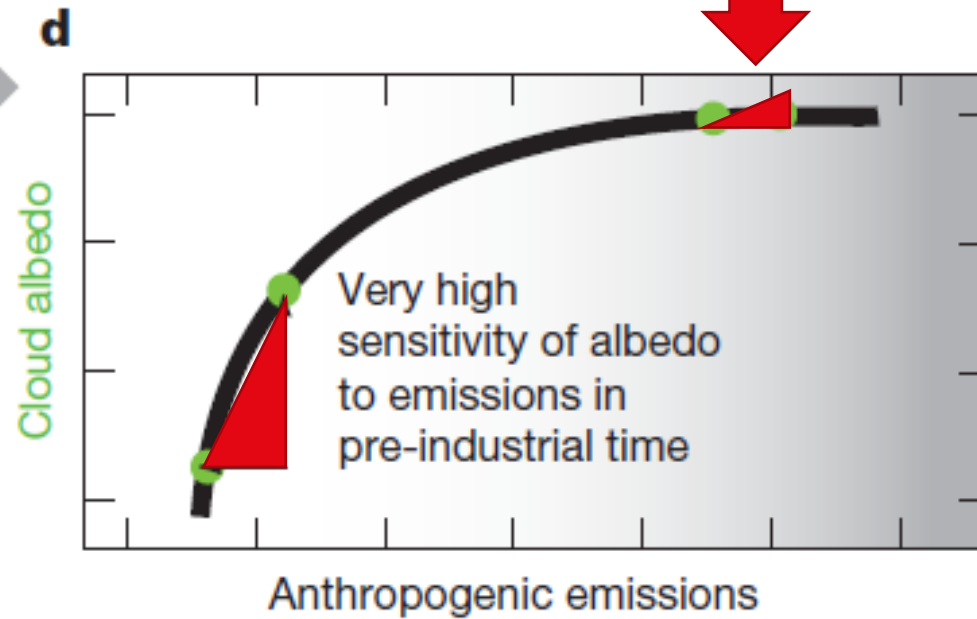
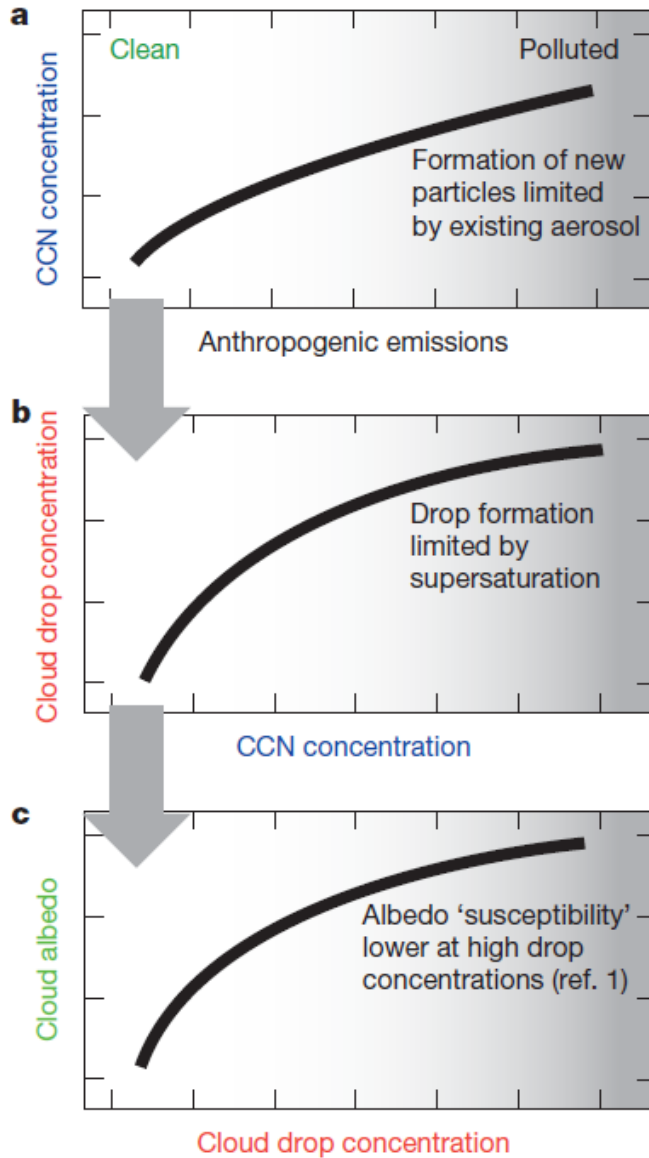


**1st Indirect
Effect**
Increased CDNC



2nd Indirect Effects
Drizzle suppression
Increased cloud height
Increased cloud lifetime

Determining the aerosol-cloud radiative effects



Very difficult to determine the difference in cloud albedo → introduces large uncertainties



What does it mean if there is larger negative forcing by aerosol-cloud interactions?

- A. It will lead to less global temperature increase in the future.
- B. The warming by GHG is actually stronger than we anticipated.

The challenge of climate science: small relative quantities!

- We deal with small magnitudes of the changes in radiative fluxes and global temperature relative to the magnitudes of the initial, unperturbed quantities to determine current and future climate change.
- The observed change in global mean surface temperature of about $1.3\text{ }^{\circ}\text{C}$ represents a change of about 0.3% relative to the initial $287\text{ }^{\circ}\text{C}$. Even the $1.5 / 2\text{ }^{\circ}\text{C}$ increase represents a change of less than 1%.
- The challenge to the climate change research community is to gain quantitative understanding of the changes in quantities influencing climate change and the expected response of the system to the accuracy necessary for informed decision making regarding prospective controls on future emissions of climate influencing substances.
- Such quantitative understanding is essential to answering “what if” questions regarding the consequences of future emissions of climate influencing substances.