Département de Géosciences

ÉCOLE NORMALE SUPÉRIEURE

Changement Climatique

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Concepts Clés (1)
Forçages,
Sensibilité climatique
& rétroactions

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Radiative forcing ; forcing – response framework

Radiative forcing **aims to compare the magnitude of different perturbations** that impact climate.

If the change in global mean surface temperature is a measure of the change in climate, and if the change in surface temperature is driven by the change in the net radiative flux at the top of atmosphere then

the radiative forcing is the **change in the net radiative flux** (expressed in $W.m^{-2}$) at the top of atmosphere due to a change in an external forcing (an driver of climate change) **before surface temperature adjusts** to this perturbation (temporary definition).

$$\Delta R = \Delta Q + \lambda \Delta T_s$$

Change in global mean **surface** temperature

Change in net flux at the TOA

radiative forcing

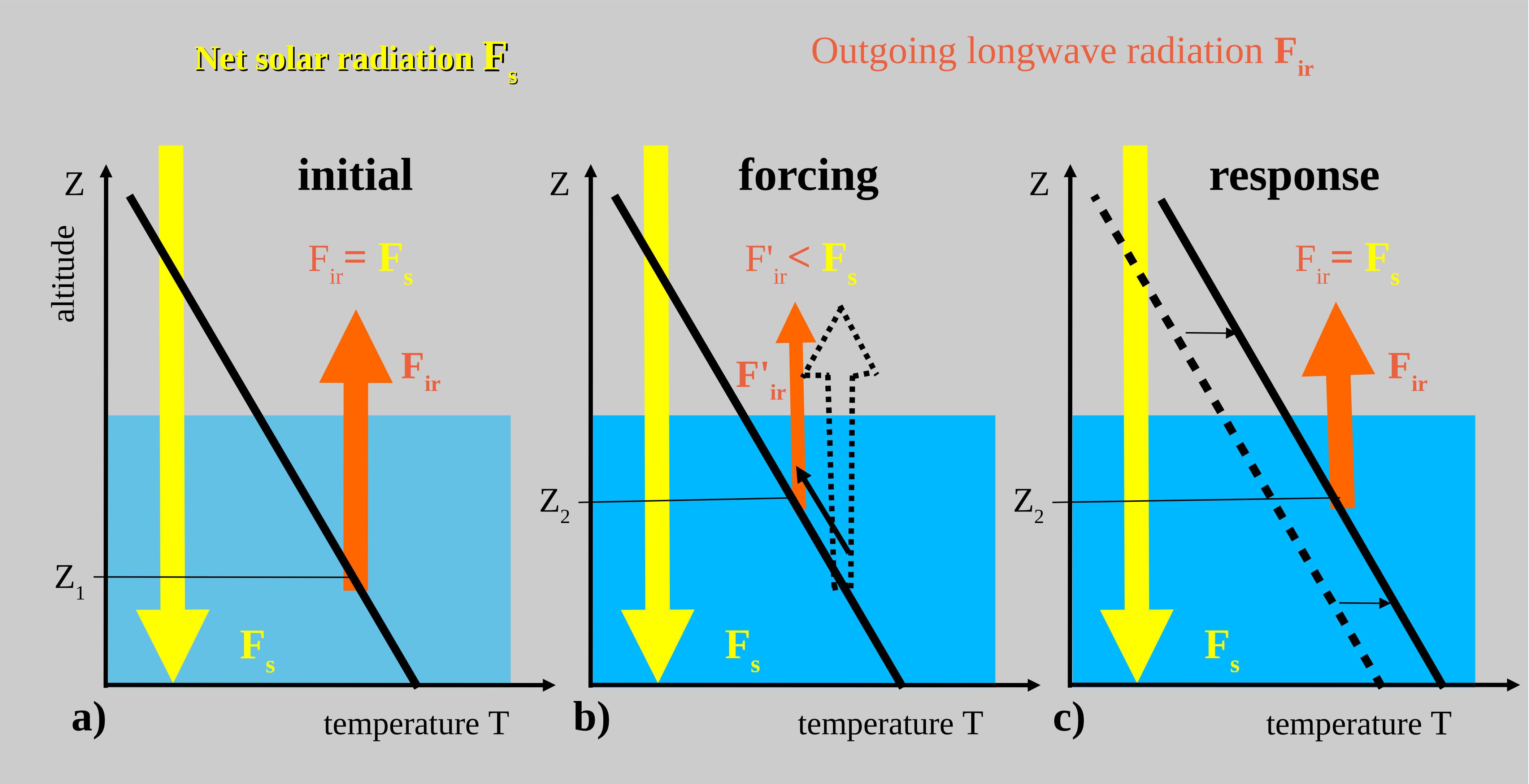
“climate feedback parameter”

When a new equilibrium is reached, *ΔR=0*

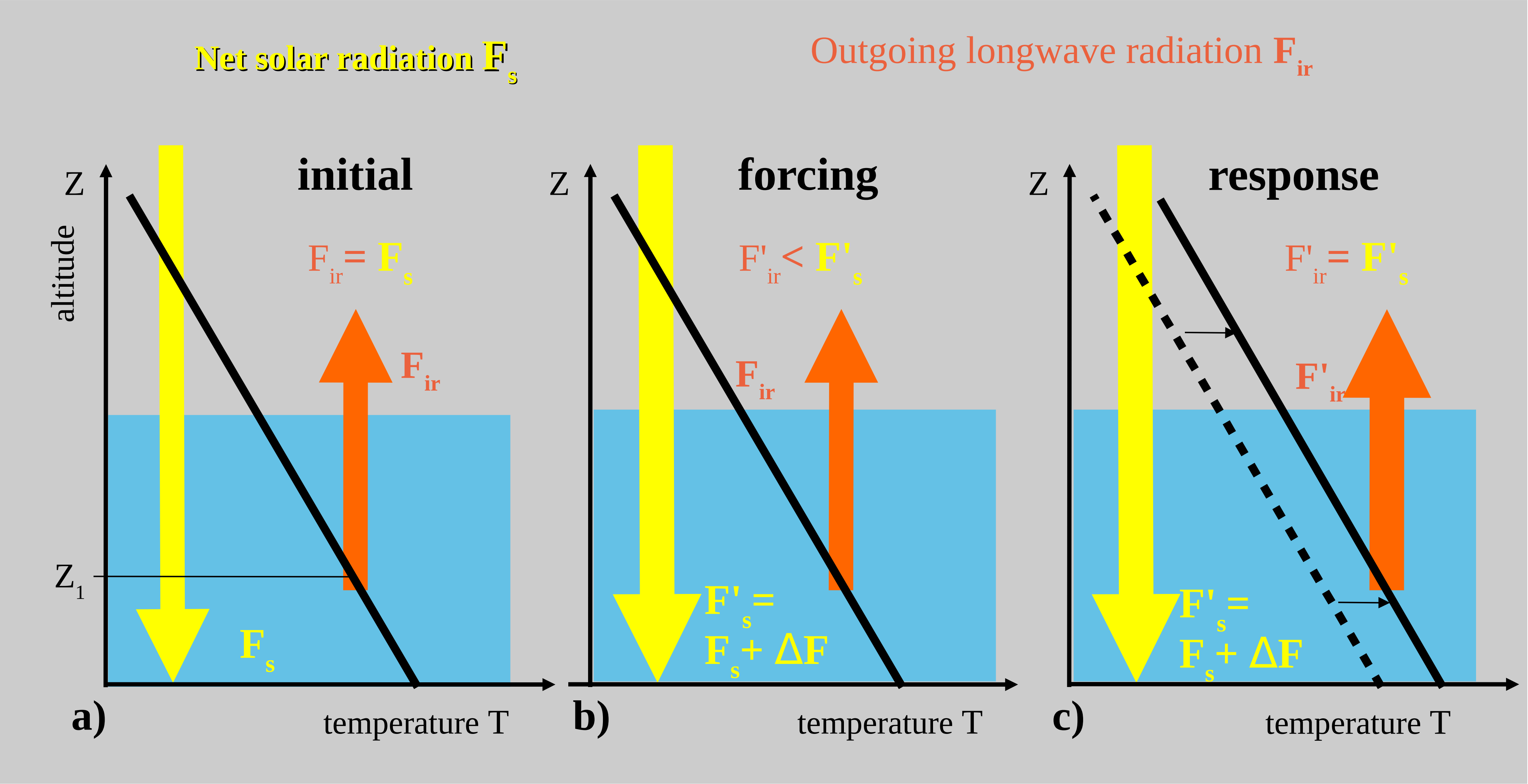
$$\Delta T_s^e = \frac{-\Delta Q}{\lambda}$$

If λ is constant, ΔT is proportional to the radiative forcing

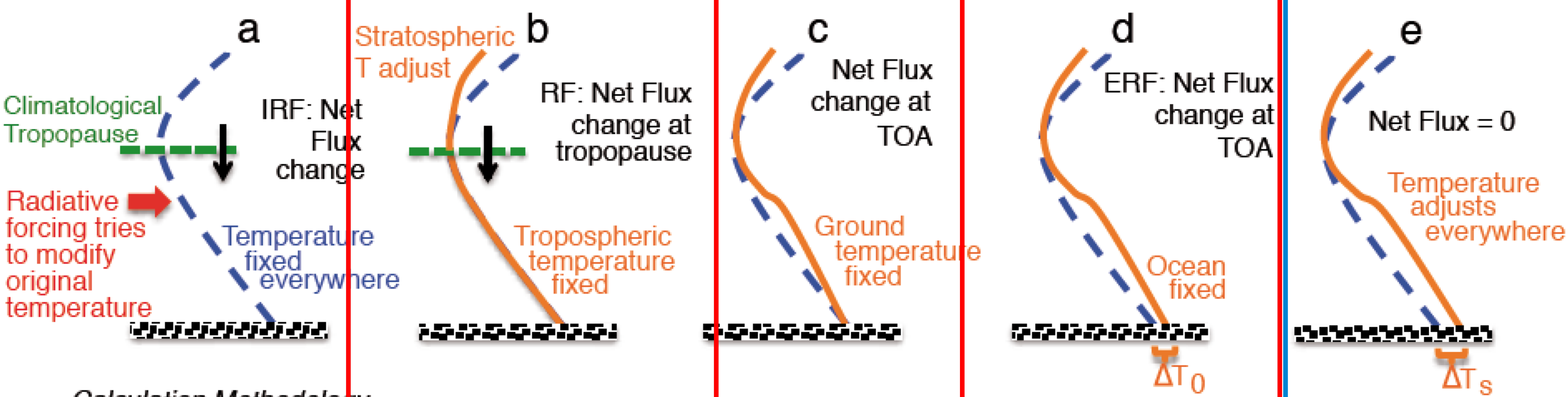
Forcing and response for a CO_2 increase with a uniform temperature response



Forcing and response to a solar absorption increase with a uniform temperature response



Radiative forcing: evolution of the definition to improve the proportionality between *ΔQ* and *ΔT*



Calculation Methodology

a	b	c	d	e
Online or offline pair of radiative transfer calculations within one simulation	Difference between two offline radiative transfer calculations with prescribed surface and tropospheric conditions allowing stratospheric temperature to adjust	Difference between two full atmospheric model simulations with prescribed surface conditions everywhere or estimate based on regression of response in full coupled atmosphere-ocean simulation	Difference between two full atmospheric model simulations with prescribed ocean conditions (SSTs and sea ice)	Difference between two full coupled atmosphere-ocean model simulations

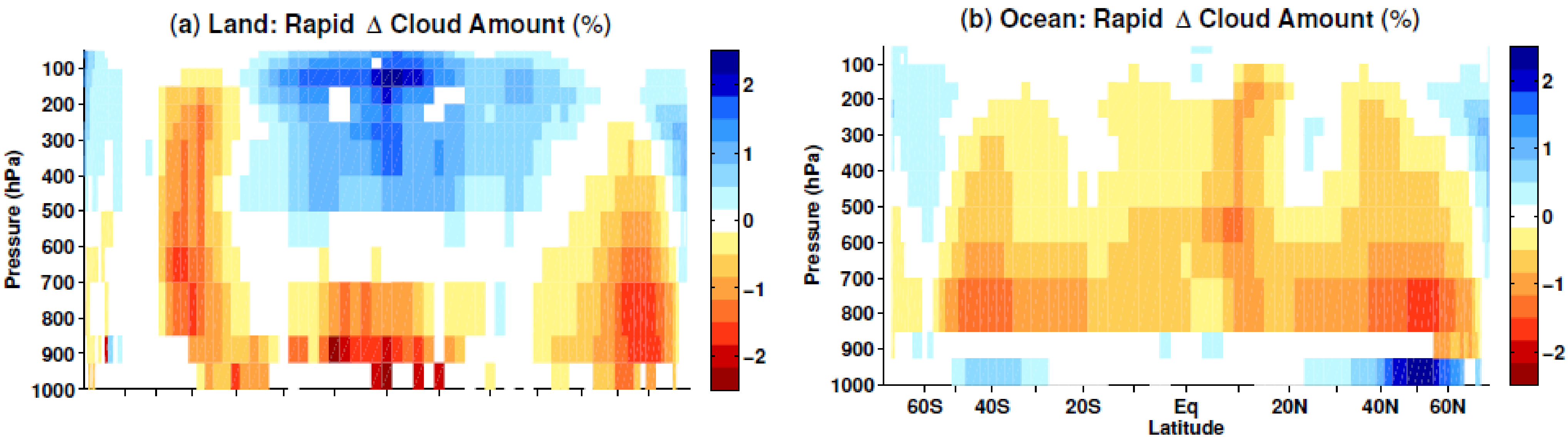
climate response

Radiative Forcing

Effective Radiative Forcing

Hansen 2005, updated IPCC 2013)

Clouds respond to CO2 even in the absence of Ts changes (4xCO2 experiments with fixed SSTs)



Zelinka et al., 2013

Underlying physical processes ?

Increased CO2 reduces the radiative cooling of the troposphere, and thus radiatively warms the troposphere, leading to :

- Change in planetary boundary layer (PBL)

- CO2 radiative forcing induces a low-tropospheric warming, RH and stability changes

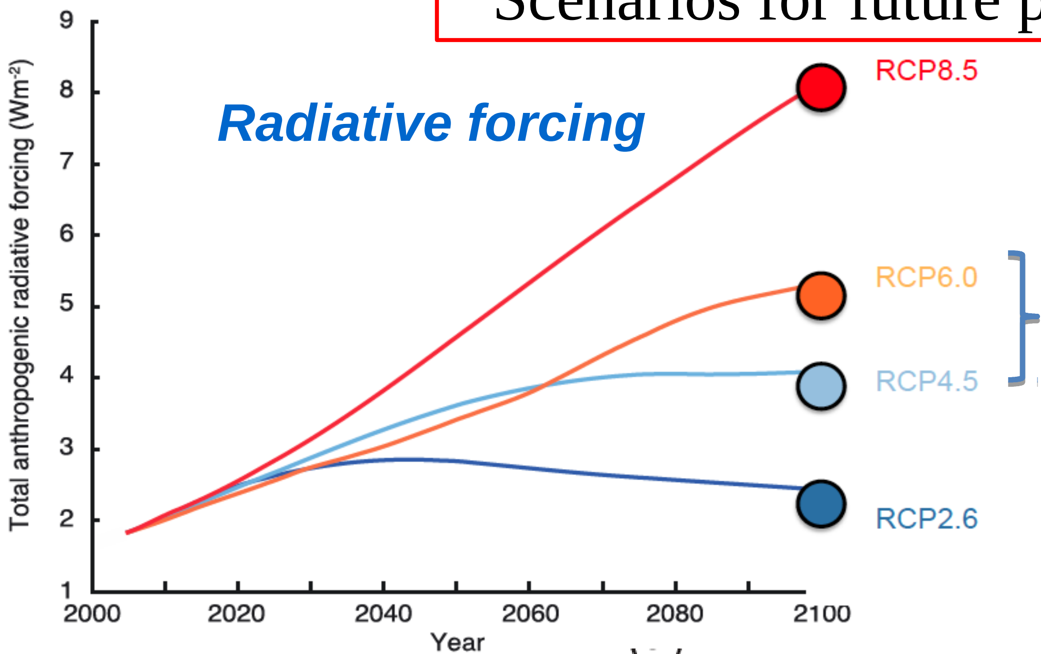
- Change in the strength of the overturning circulation

- weakening of large-scale rising motions over ocean, strengthening over land
- weakening of large-scale subsidence over both land and ocean

Kamae & Watanabe, 2012
Bony et al., NGS, 2013

How do climate models respond?

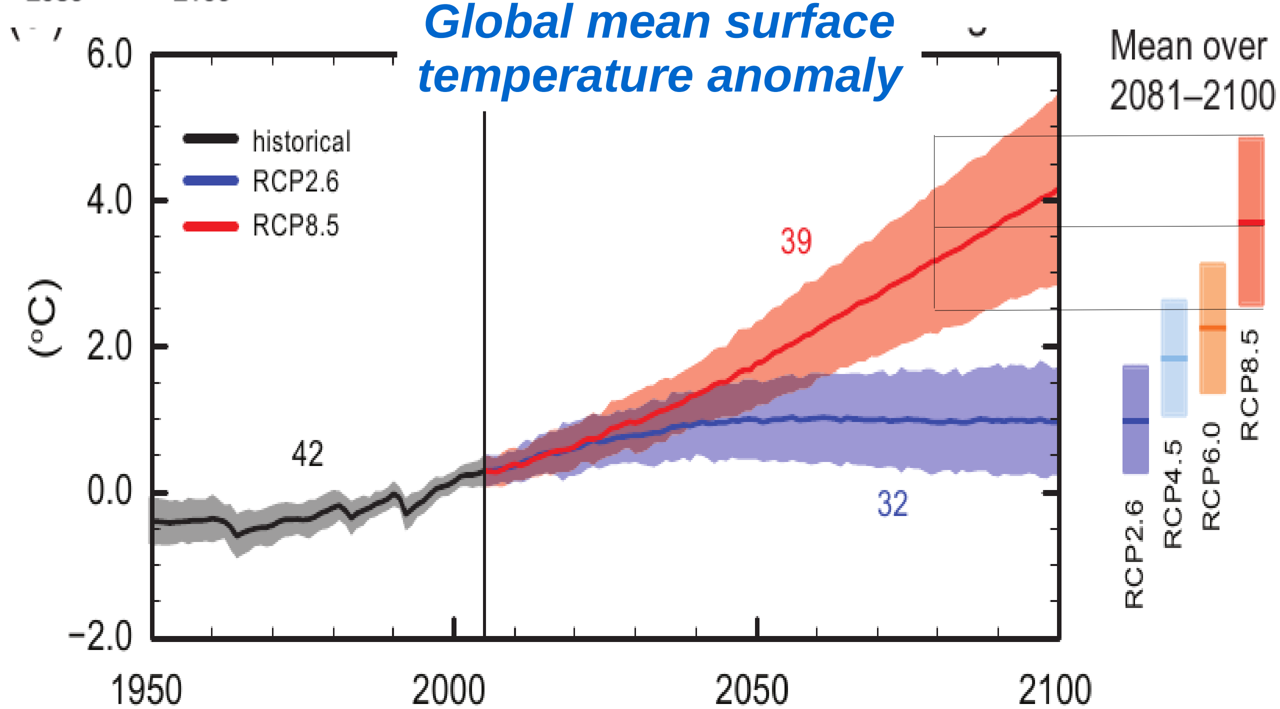
Scenarios for future projections



Strong emissions

Stabilisation

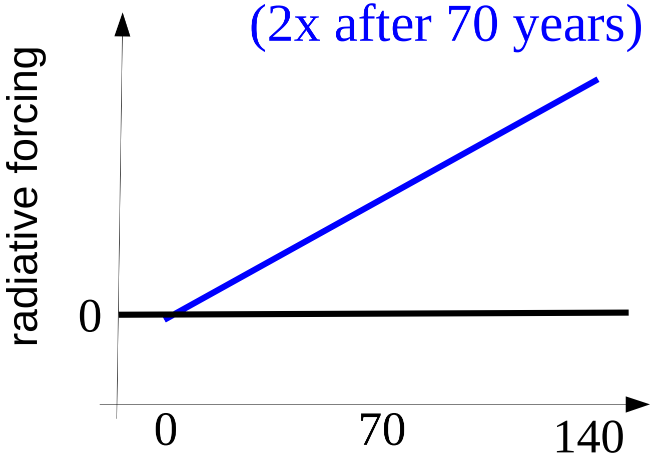
Emission control



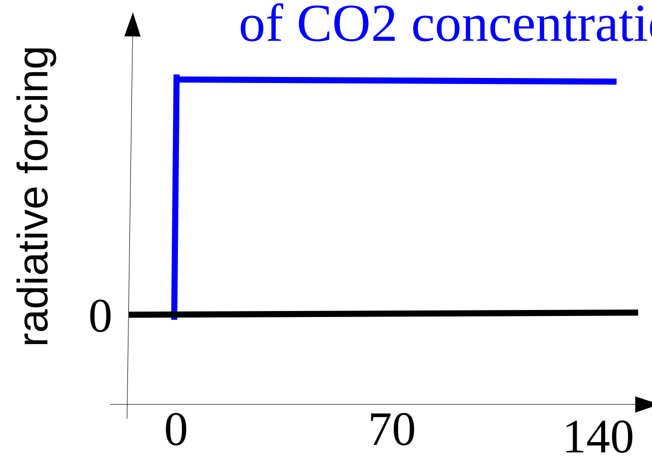
How do climate models respond?

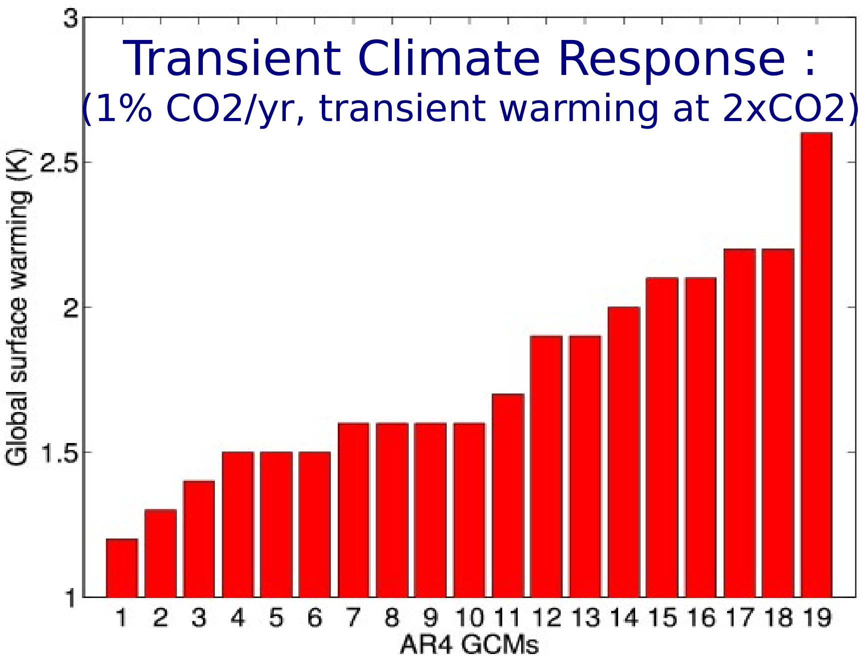
Idealized climate change experiments

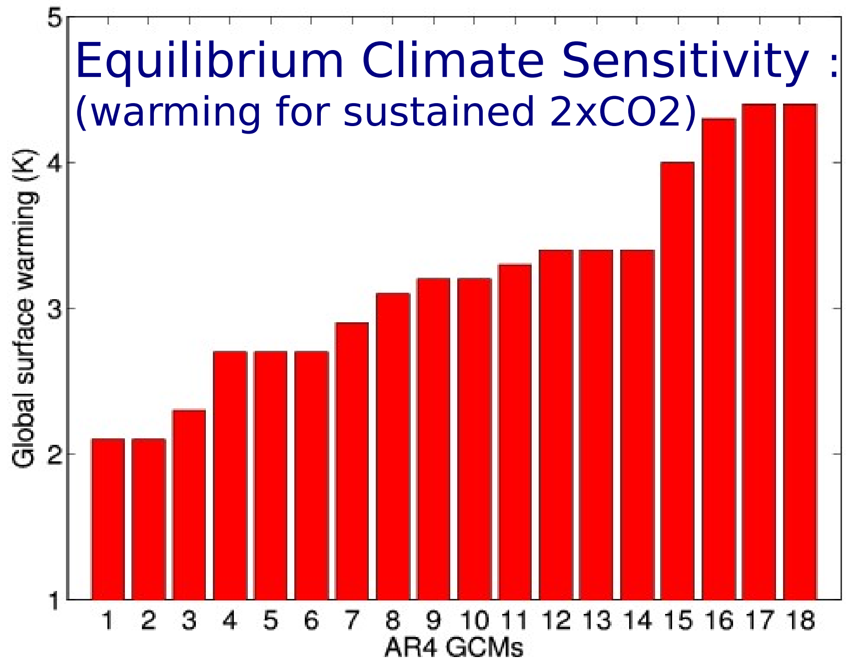
1%/year CO_2 increase
(2x after 70 years)



Instantaneous quadrupling
of CO_2 concentration

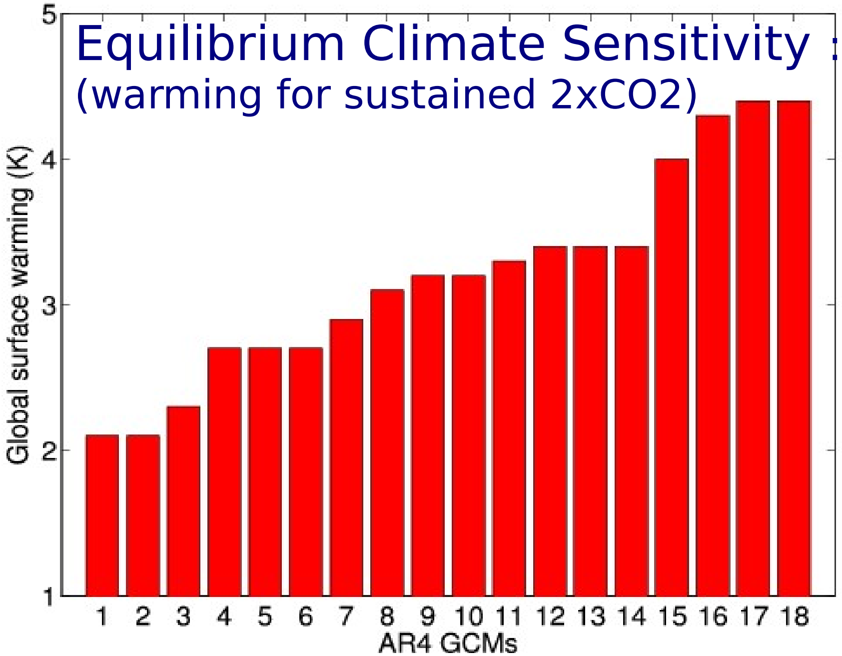






Climate sensitivity and climate feedback parameters

Definition and ranges



Equilibrium climate sensitivity (ECS) is the equilibrium change in global and annual mean surface air temperature after doubling the atmospheric concentration of CO2 relative to pre-industrial levels.

At equilibrium: $\Delta Te = - \Delta Q/\lambda = S' \Delta Q$ (in K)

ΔQ : radiative forcing (in $W.m^{-2}$)

λ : climate feedback parameter (in $W.m^{-2}.K^{-1}$) ; range [-0.9 ; -1.8]

$S' = -1/\lambda$: climate sensitivity parameter (in $K.W^{-1}.m^{2}$); range [0.55 ; 1.1]

ECS = $- \Delta Q(2xCO_2)/\lambda$: climate sensitivity (in K) ; range [2 ; 4.5]

Concepts Clés (1)

- Forçage Radiatif et sensibilité climatique
- Rétroactions climatiques

Réponse à une perturbation du flux solaire incident

Si l'albédo est **indépendant** de la température: A = Cte

$$\epsilon\sigma T^4 = (1-A)I_s$$

$$\delta I_s \Rightarrow \epsilon\sigma(T+\delta T)^4 = (1-A)(I_s+\delta I_s)$$

$$\epsilon\sigma(T+\delta T)^4 \approx \epsilon\sigma\left(T^4 + 4T^3\delta T\right)$$

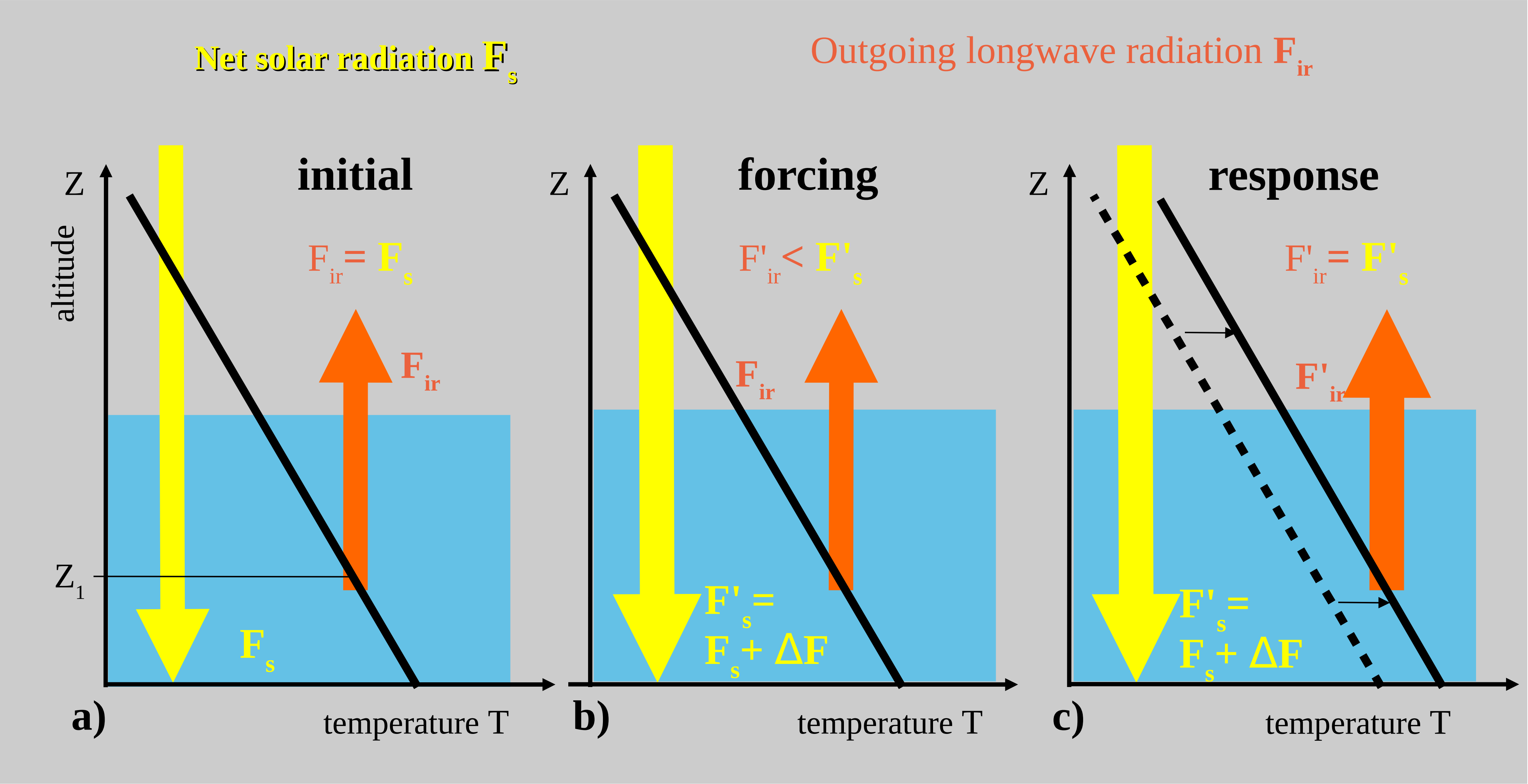
$$\boxed{\lambda_p\delta T \approx -(1-A)\delta I_s} \quad \text{avec} \quad \boxed{\lambda_p = -4\epsilon\sigma T^3}$$

Le changement de flux radiatif infrarouge est: $\delta R \approx \lambda_p\delta T$

$$T = 280\text{K} \;\; ; \; \lambda_p \approx \text{- } 5\ \text{Wm}^{-2}\text{K}^{-1} \;\; ; \; \delta T \approx 0.2\,(1-A)\delta I_s$$

$$T = 250\text{K} \;\; ; \; \lambda_p \approx \text{- } 3.5\ \text{Wm}^{-2}\text{K}^{-1} \;\; ; \; \delta T \approx 0.28\,(1-A)\delta I_s$$

Forcing and response to a solar absorption increase with a uniform temperature response



Réponse à une perturbation du flux solaire incident

Si l'albédo **dépend** de la température : $\frac{dA}{dT} \neq 0$

$\delta I_s \Rightarrow$

$$\epsilon\sigma(T + \delta T)^4 = \left(1 - (A + \frac{dA}{dT}\delta T)\right)(I_s + \delta I_s)$$

$$\epsilon\sigma\left(T^4 + 4T^3\delta T\right) \approx (1 - A)(I_s + \delta I_s) - \frac{dA}{dT}\delta T\, I_s + \epsilon(\delta^2)$$

$$(\lambda_p + \lambda_A)\,\delta T \approx -(1 - A)\delta I_s$$

avec $\lambda_p = -4\epsilon\sigma T^3$ et $\lambda_A = \frac{dA}{dT} I_s$

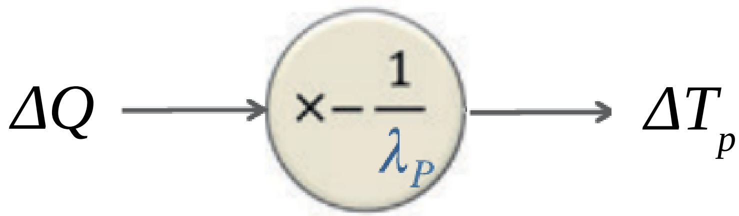
$$\delta T \approx \delta T_0 \frac{1}{1 - g}$$

avec $g = -\frac{\lambda_A}{\lambda_p}$ et $\delta T_0 \approx -\frac{(1 - A)\delta I_s}{\lambda_p}$

Réponse à une perturbation quelconque

Perturbation: flux ΔQ

réponse "de Planck" : $\Delta T_p = -\dfrac{\Delta Q}{\lambda_p}$

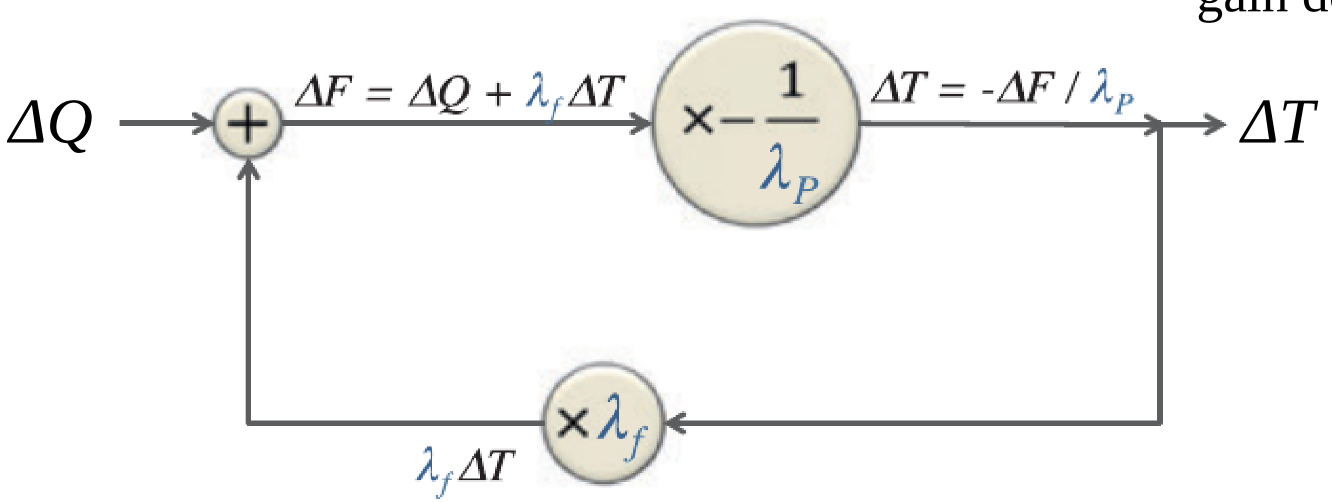


réponse du système complet :

$$\Delta T = -\frac{\Delta Q}{\lambda} \text{ avec } \lambda = \lambda_p + \lambda_f$$

$$= \frac{1}{1-g}\Delta T_p \quad \text{avec } g = -\frac{\lambda_f}{\lambda_p}$$

gain de rétroaction



Réponse à une perturbation quelconque

$$\Delta T_p = -\frac{\Delta Q}{\lambda_p} \qquad \Delta T = \frac{1}{1-g}\Delta T_p \qquad g = -\frac{\lambda_f}{\lambda_p}$$

Les rétroactions

- augmentent l'ampltitude de la réponse, par rapport à celle de Planck, si $\lambda_f \geq 0$, si le flux $\lambda_f \Delta T$ du fait des rétroactions augmente l'énergie reçue par la Terre pour $\Delta T \geq 0$

- diminuent l'ampltitude de la réponse, par rapport à celle de Planck, si $\lambda_f \leq 0$, si le flux $\lambda_f \Delta T$ du fait des rétroactions diminue l'énergie reçue par la Terre pour $\Delta T \geq 0$

- rendent le système climatique instable si $g \geq 1$, c-à-d si $\lambda_f \geq -\lambda_p$, si le flux $\lambda_f \Delta T$ gagné par le système du fait des rétroactions est supérieur au flux $\lambda_p \Delta T$ perdu par "émission de Planck"

Climate feedbacks

On Earth, Planck parameter $\lambda_p \approx -3.2\ W.m^{-2}K^{-1}$

For a doubling of the CO_2 concentration, $\Delta Q \approx 3.7\ W.m^{-2}$, the temperature increases by ≈ 1.2 K, if nothing change except the temperature

But feedbacks exist:

- Snow and sea ice reflect solar radiation; if they decrease, more solar energy will be absorbed ⇒ positive feedback
- Water vapour is the main greenhouse gas; if it increases, the greenhouse effect will be enhanced ⇒ positive feedback
- Clouds reflect solar radiation and contribute to the greenhouse effect; if they change, the energy budget will be modified ⇒ positive or negative feedback

$$\Delta T_s^e = \frac{-\Delta Q_t}{\lambda}$$

$$\lambda = \lambda_P + \lambda_w + \lambda_L + \lambda_c + \lambda_\alpha$$

Planck	water vapor	lapse rate	clouds	surface albedo

How to compute feedbacks ?

Diagnostic of feedback parameters through the Kernel approach

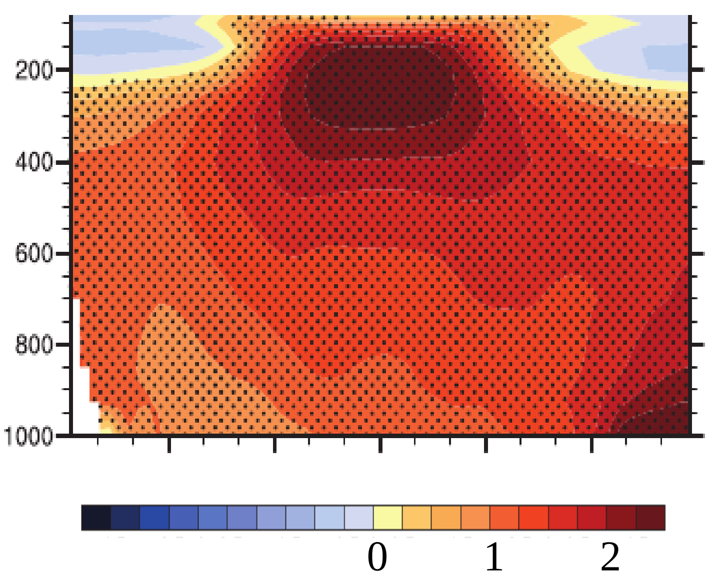
$$\lambda = \frac{\partial R}{\partial T_s} = \sum_x \frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s} = \lambda_P + \sum_{x \neq P} \lambda_x$$

radiative kernel computed by radiative codes ($\frac{\partial R}{\partial x}$)

response to surface temperature change ($\frac{\partial x}{\partial T_s}$)

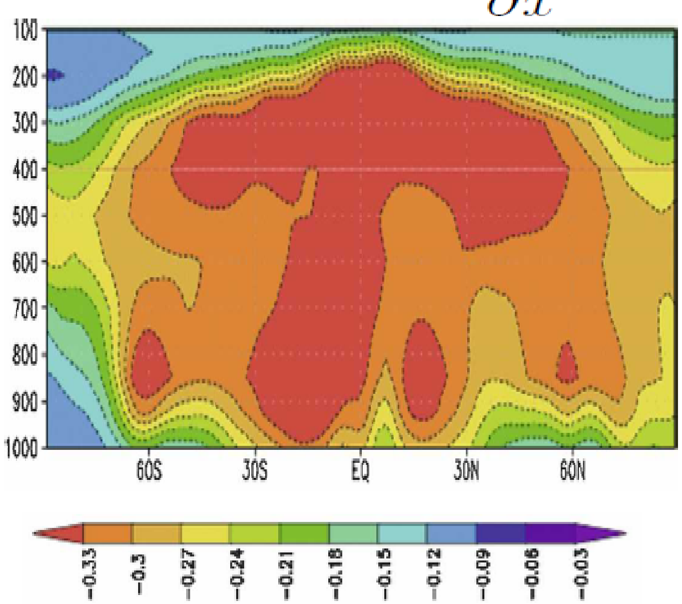
e.g. for *x* = *T* :

Temperature change $\frac{\partial x}{\partial T_s}$



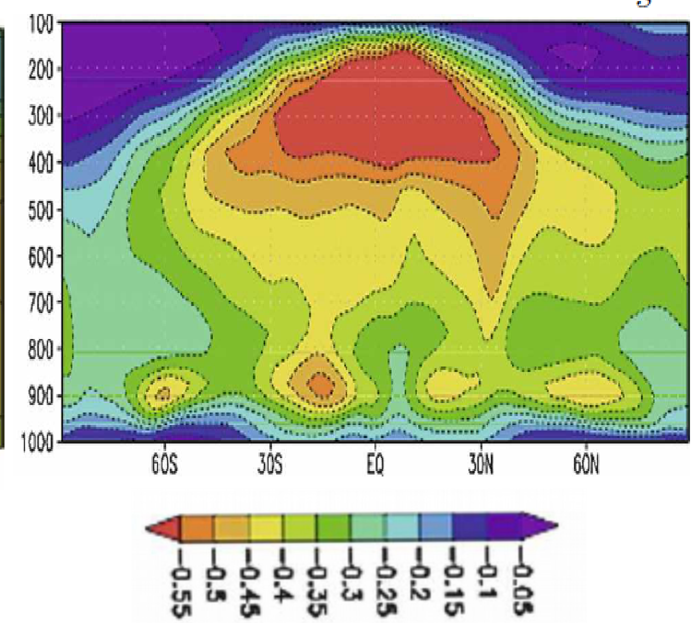
K/K (approximate)

Temperature kernel $\frac{\partial R}{\partial x}$



$W/m^2/K/(100hPa)$

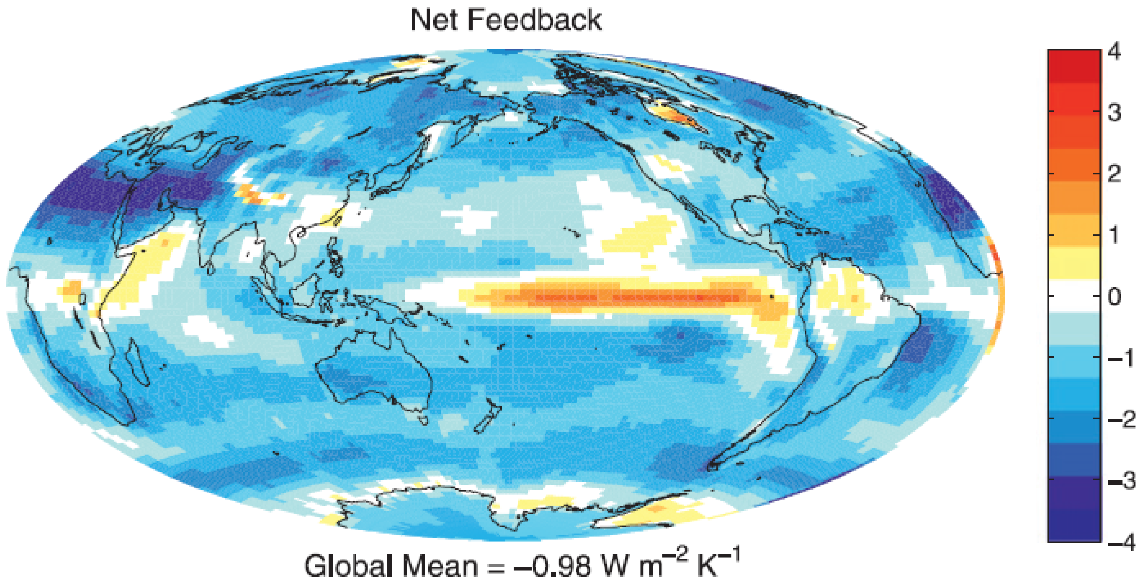
Temperature feedback parameter $\frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s}$



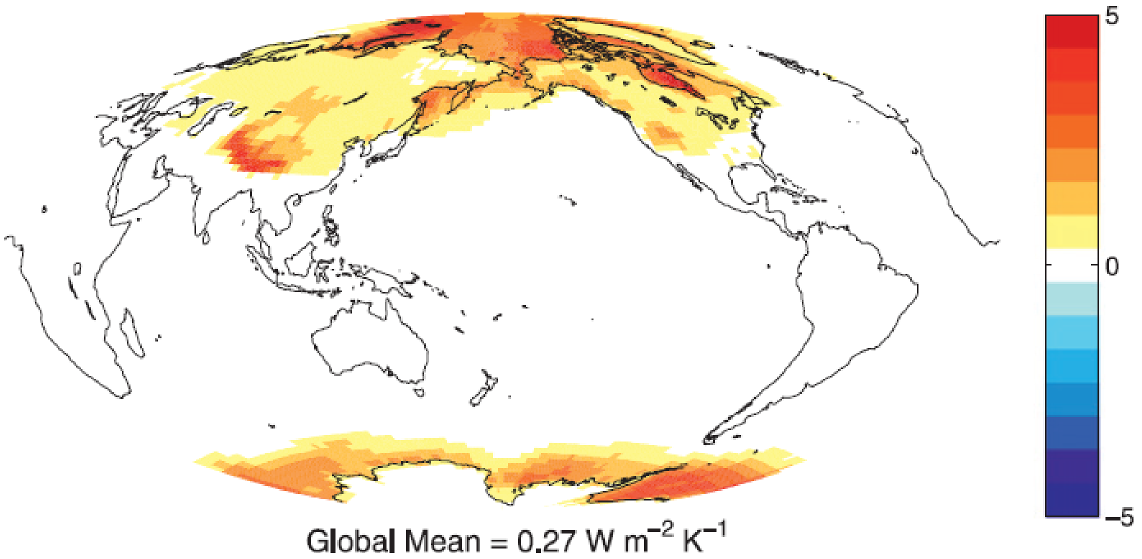
$W/m^2/K/(100hPa)$

Soden et al., J. Climate, 2008

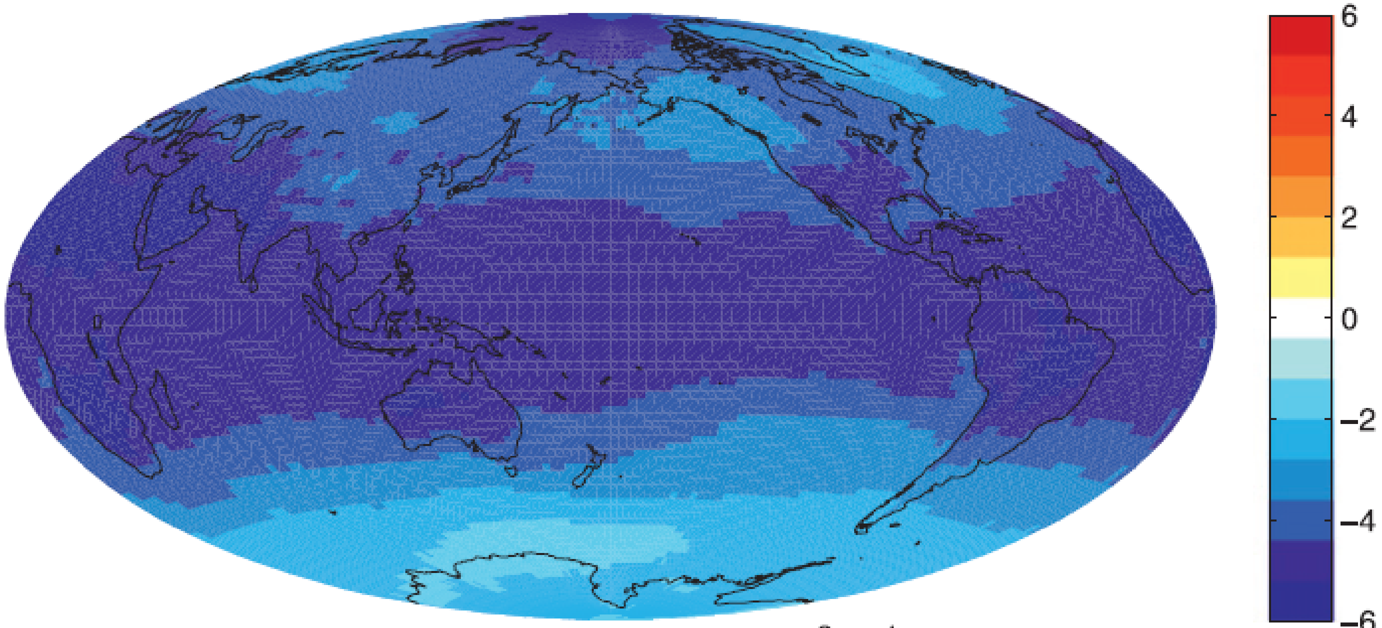
Climate feedback



Surface albedo feedback

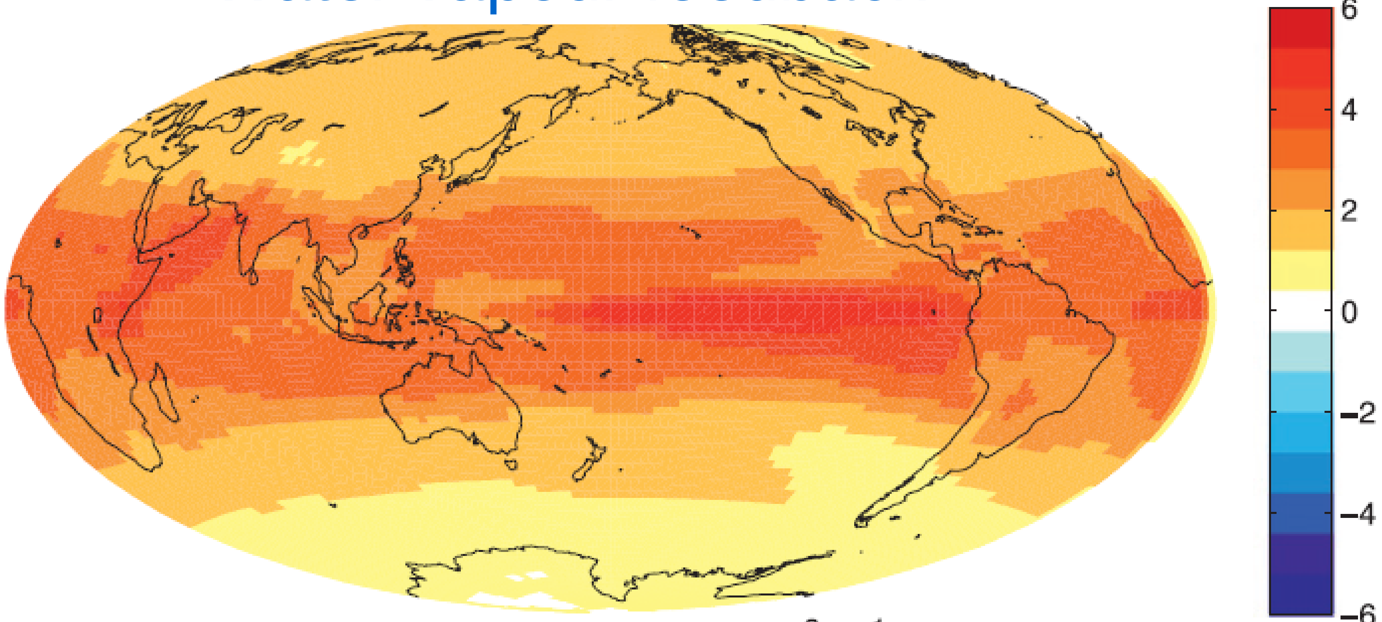


Temperature feedback



Global Mean = −4.02 W m^{-2} K^{-1}

Water vapour feedback



Global Mean = 2.16 W m^{-2} K^{-1}

Water vapor + lapse rate feedbacks

RH ≈ constant
Clausius Clapeyron

increase of WV

increase of greenhouse effect

decrease of OLR

positive feedback

theory

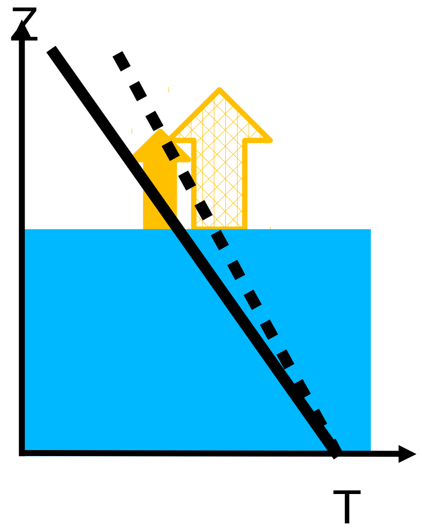
decrease of moist adiabatic lapse rate

decrease of lapse rate

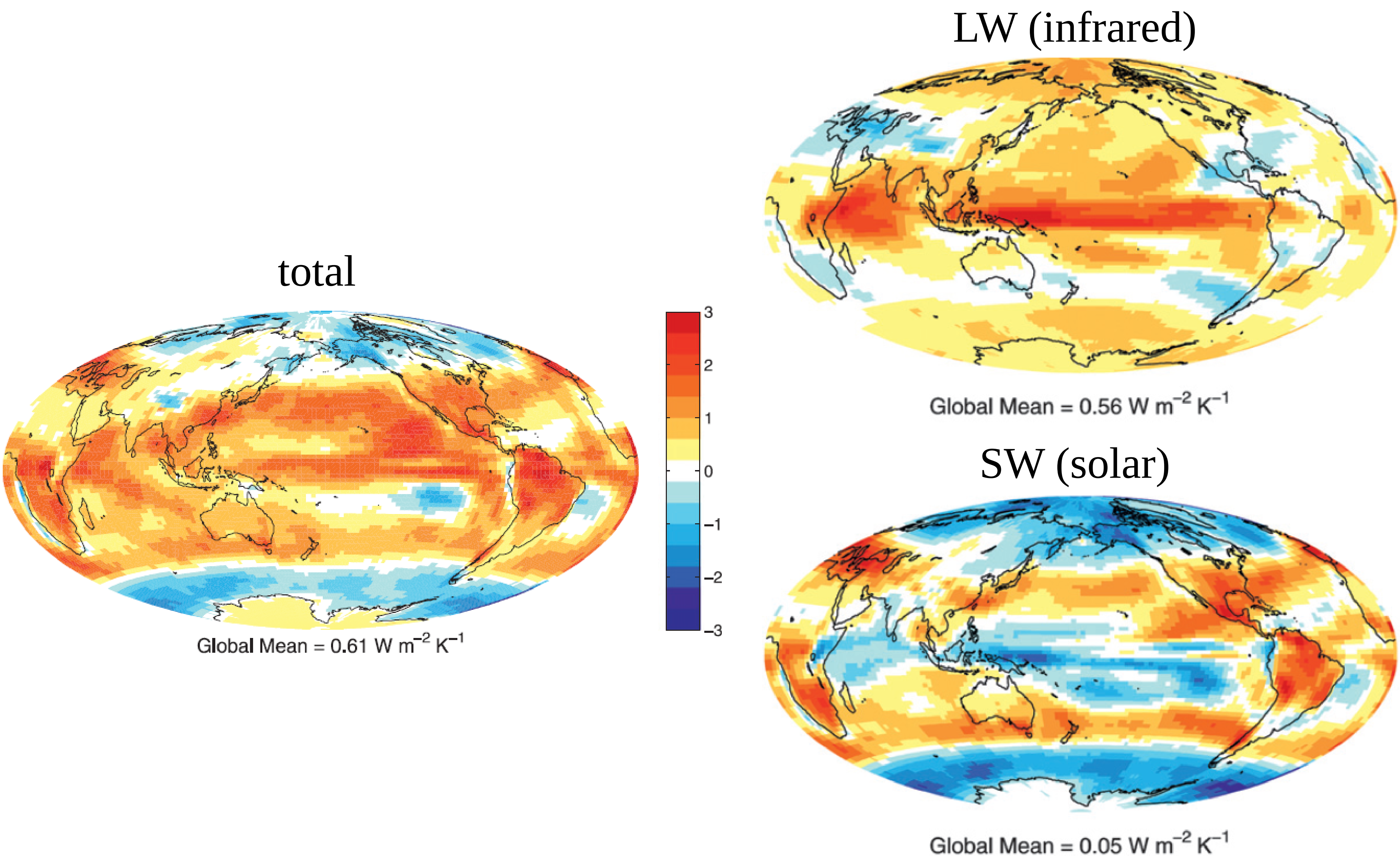
increase of OLR

negative feedback

positive feedback



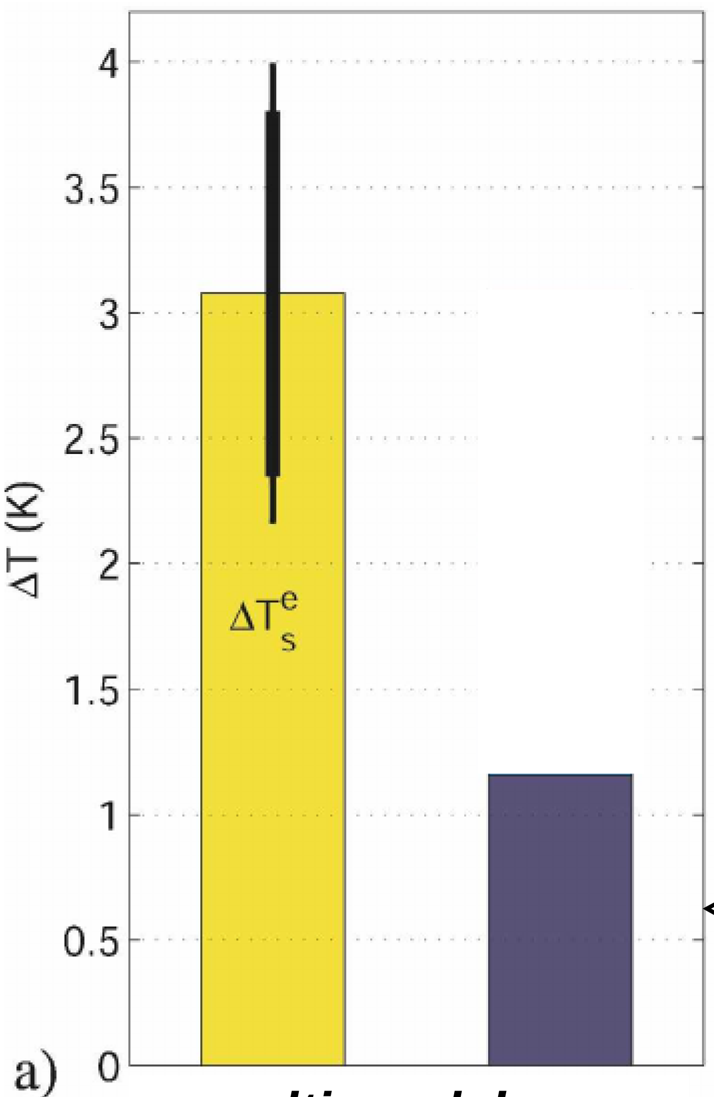
Cloud feedback



[Zelinka et al., 2012]

From feedback parameters to climate sensitivity

Equilibrium temperature response to a CO_2 doubling



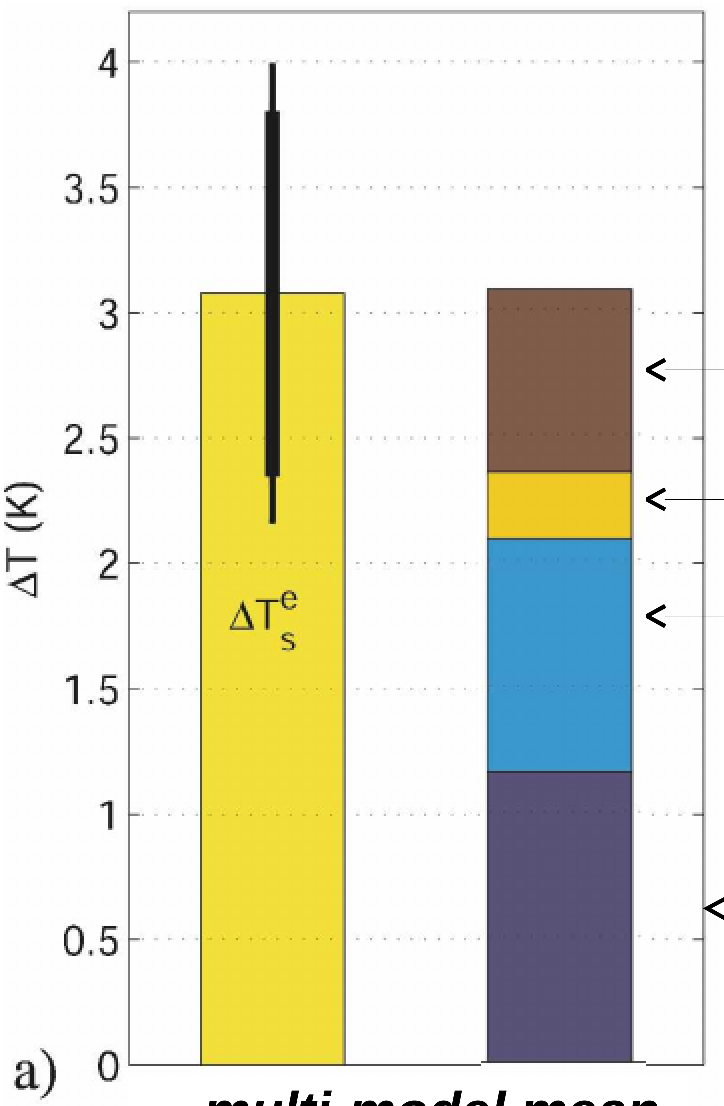
multi-model mean

Direct response to the forcing
Planck response

(Dufresne & Bony, 2008)

From feedback parameters to climate sensitivity

Equilibrium temperature response to a CO_2 doubling



multi-model mean

Climate feedbacks: Indirect response to the forcing

- clouds
- snow and ice (surface albedo)
- water vapor

Direct response to the forcing

- Planck response

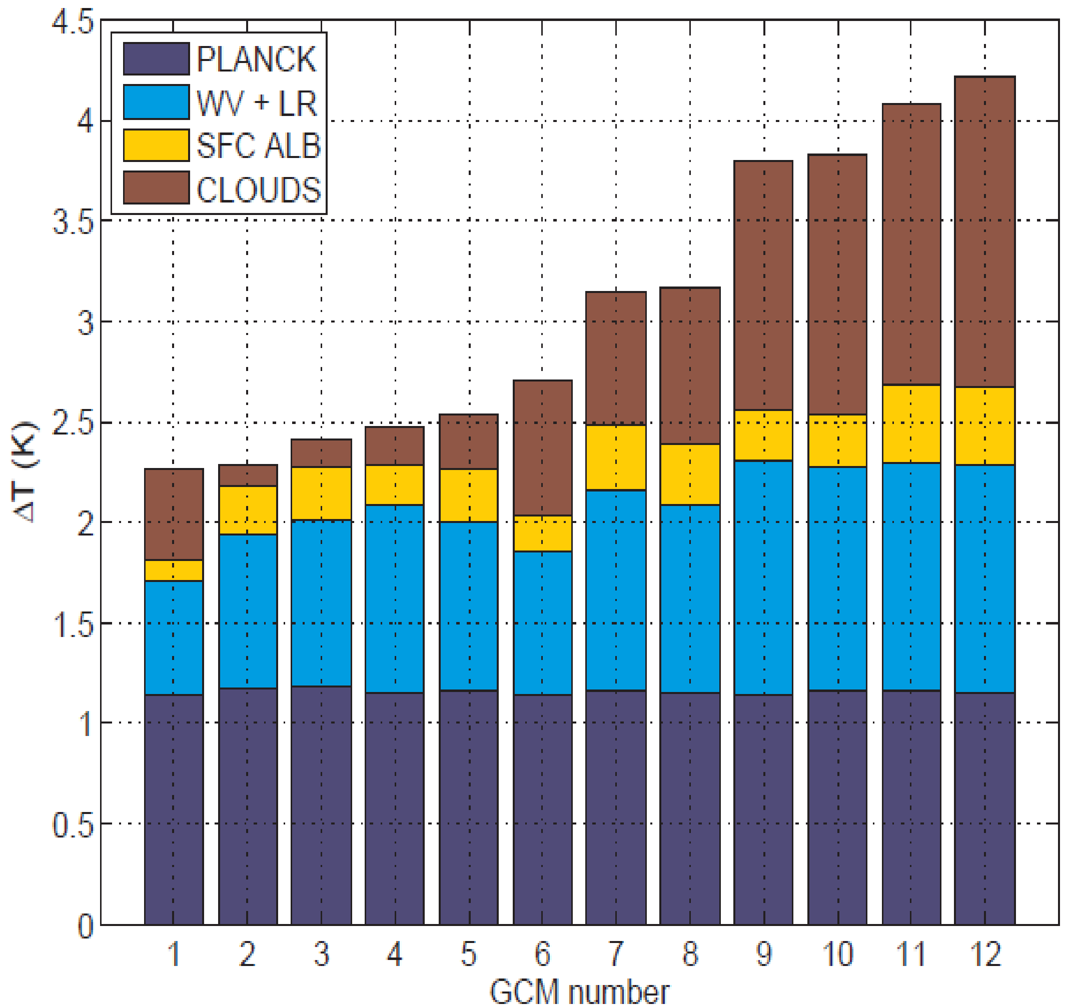
(Dufresne & Bony, 2008)

From feedback parameters to climate sensitivity

Equilibrium temperature response to a CO_2 doubling

Origine of inter-model differences in climate sensitivity :

ΔT



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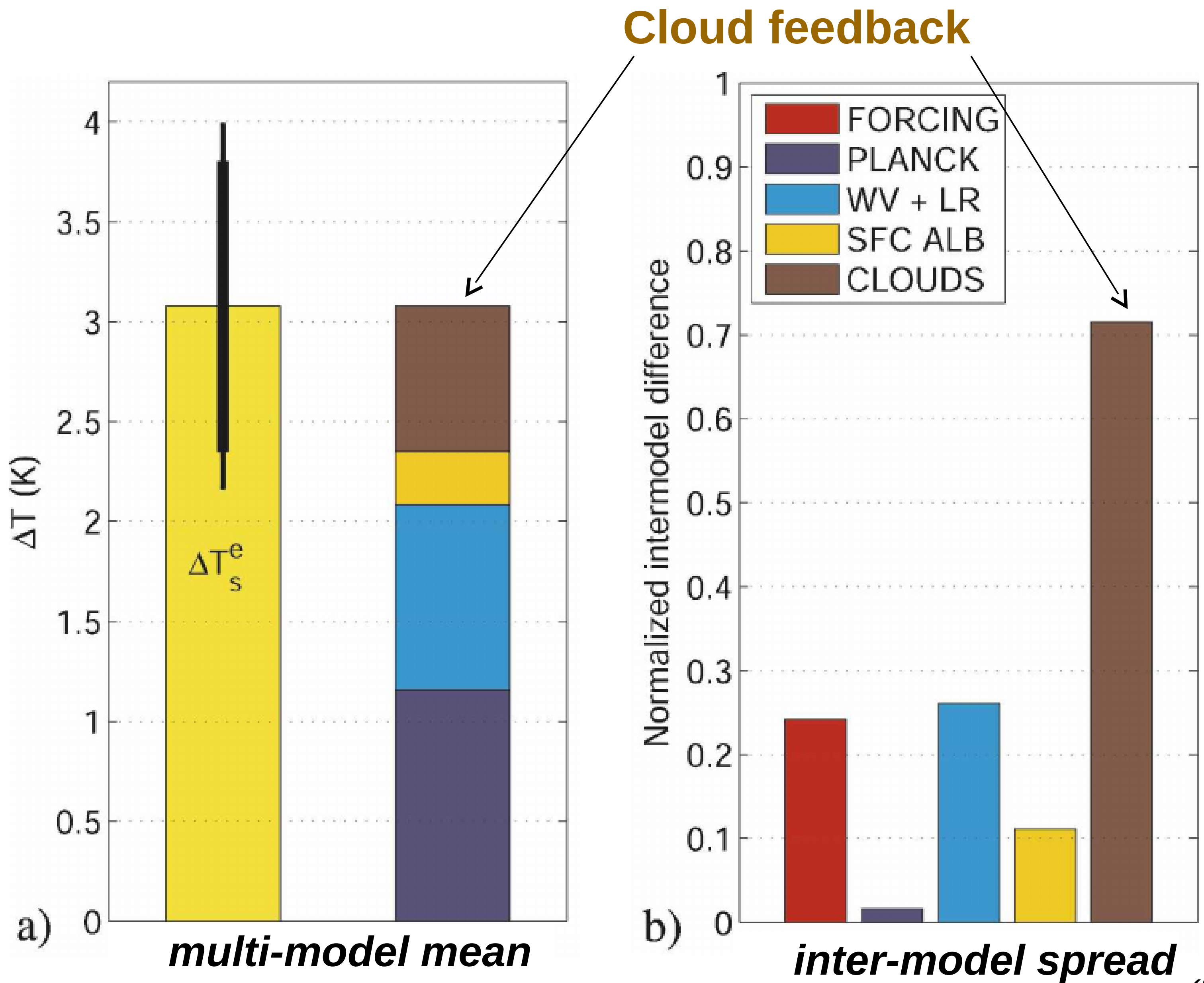


(Dufresne & Bony, 2008)

Why do we care so much about global ΔT ?

- For many models, as a first approximation :

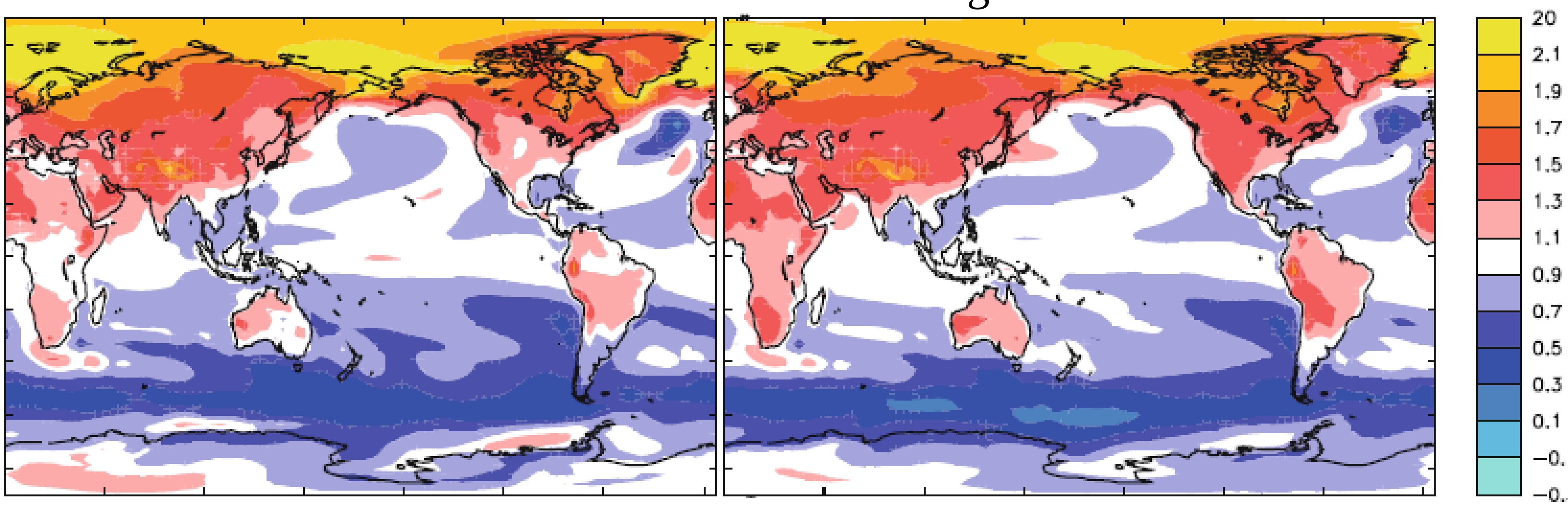
$$\Delta X(\text{space,time}) = \text{global } \Delta T(\text{time}) \times \text{pattern}(\text{space})$$

- **Global ΔT : a scaling factor for many global and regional climate responses**
- Maybe it works in the real world too (at least to some extent)

Change in temperature normalized by global ΔT (K/K)

RCP 2.6 (ΔT = 2K)
low GHG scenario

RCP 8.5 (ΔT = 6K)
high GHG scenario

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