Clouds in a Changing Climate

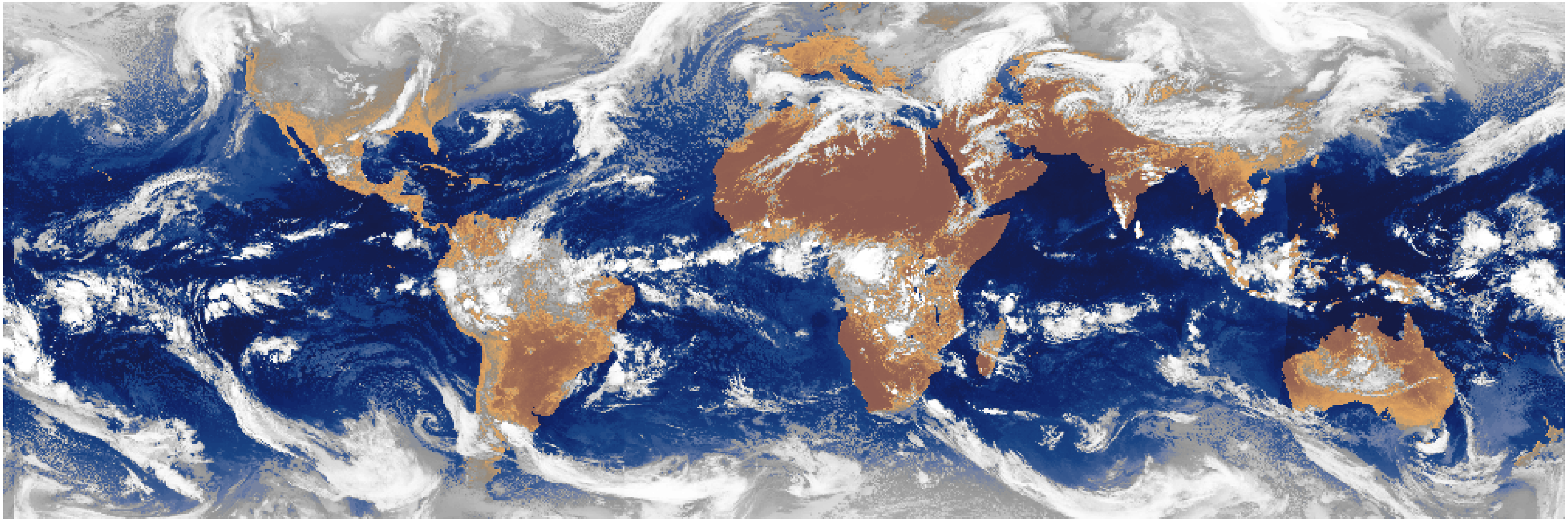
Sandrine Bony[1] & Bjorn Stevens[2]

1 : LMD/IPSL, Paris, France
2 : MPI, Hamburg, Germany

Lecture #1

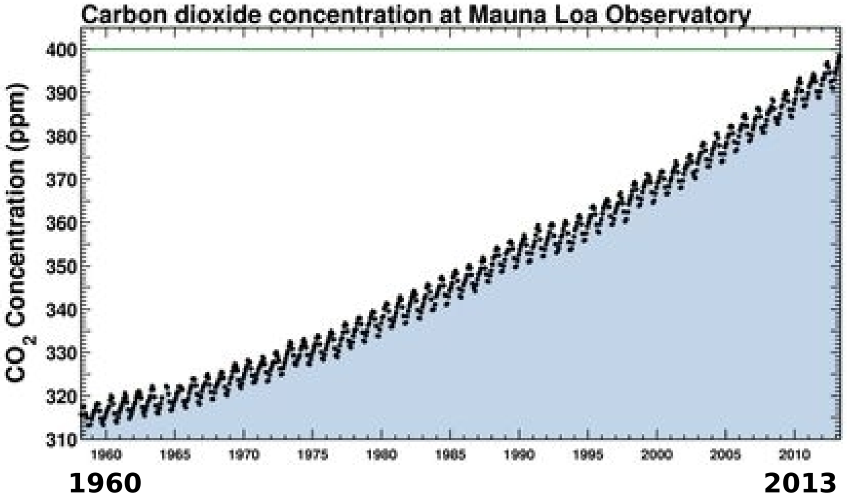
ÉCOLE DE PHYSIQUE
des HOUCHES

EUCLIPSE « Clouds in Climate » Summerschool
Les Houches, France, Jun 25 – Jul 5 2013



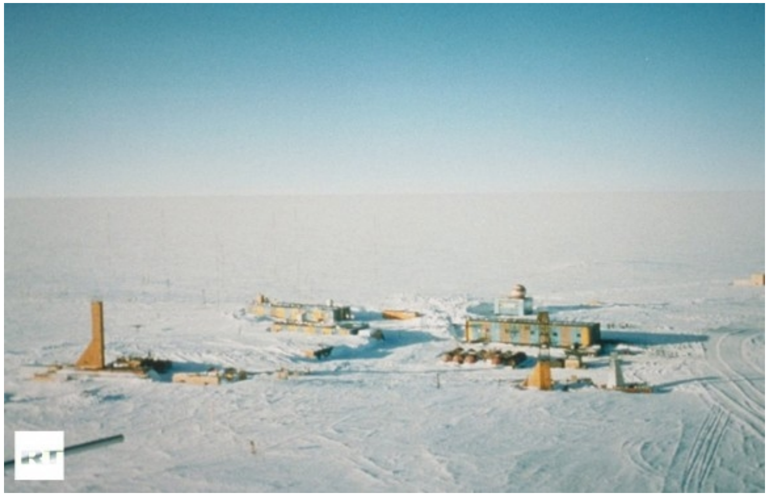
Humanity is running an unprecedented geophysical experiment

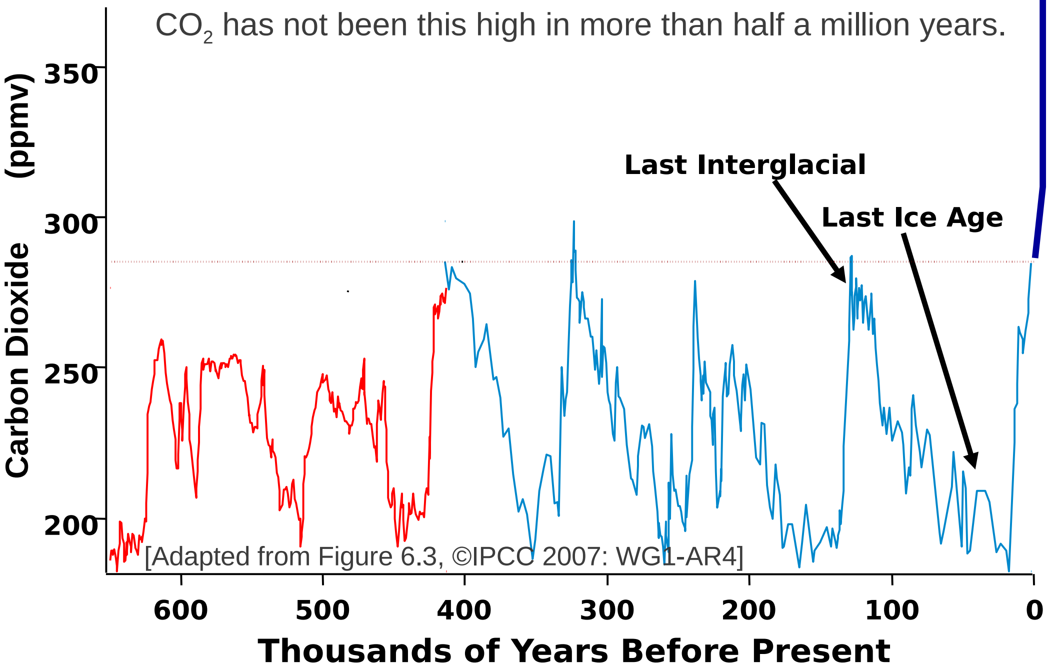
Mauna Loa



2013 : 400 ppm

Vostok

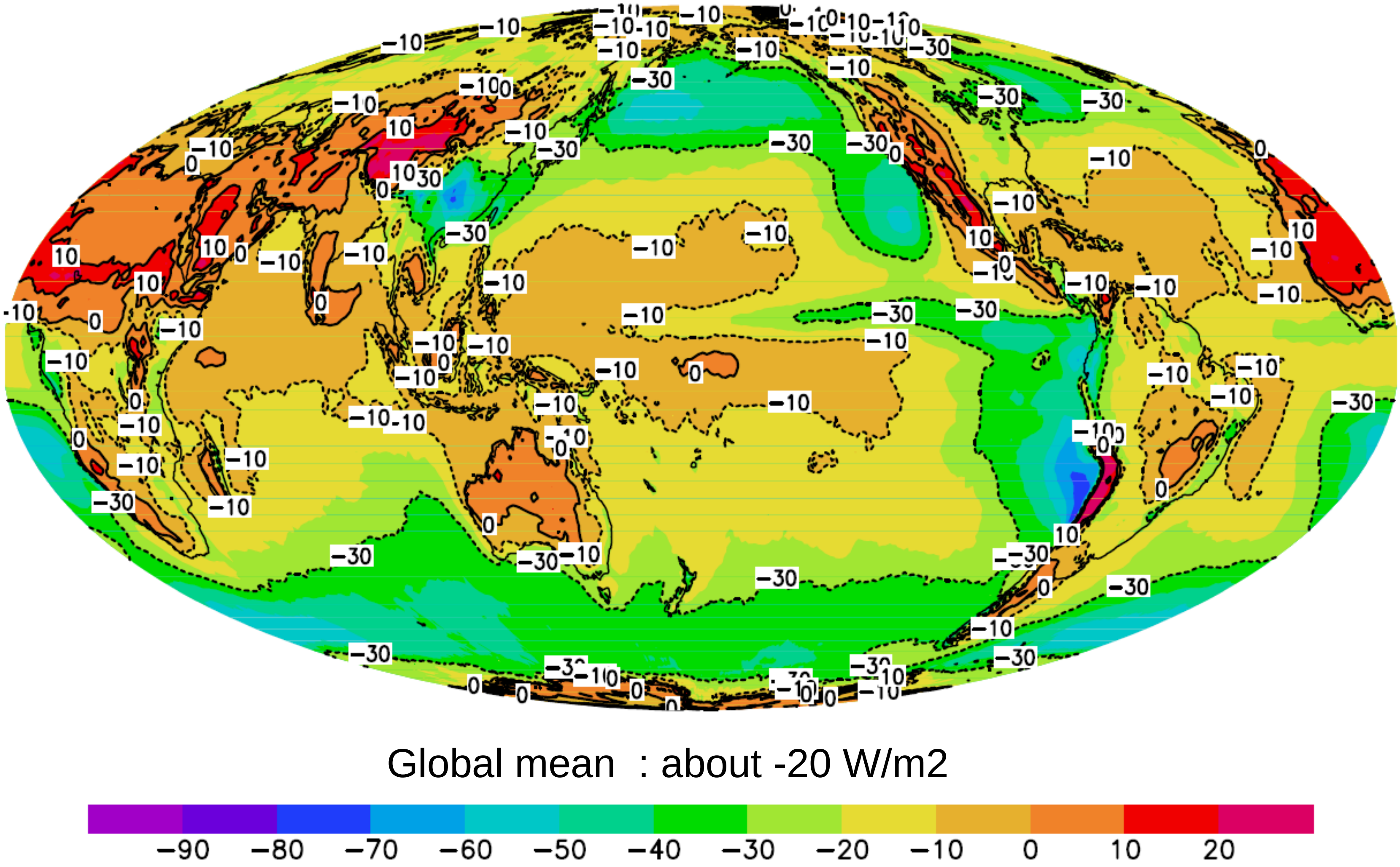




CO_2 has not been this high in more than half a million years.

[Adapted from Figure 6.3, ©IPCC 2007: WG1-AR4]

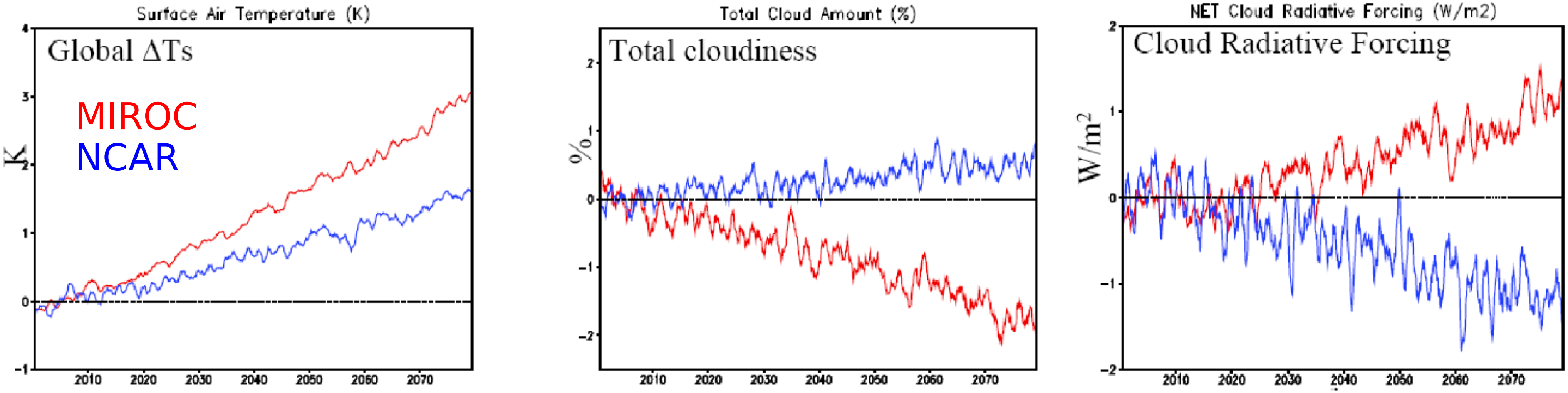
Cloud Radiative Effects in Present-Day Climate



Global mean : about -20 W/m2

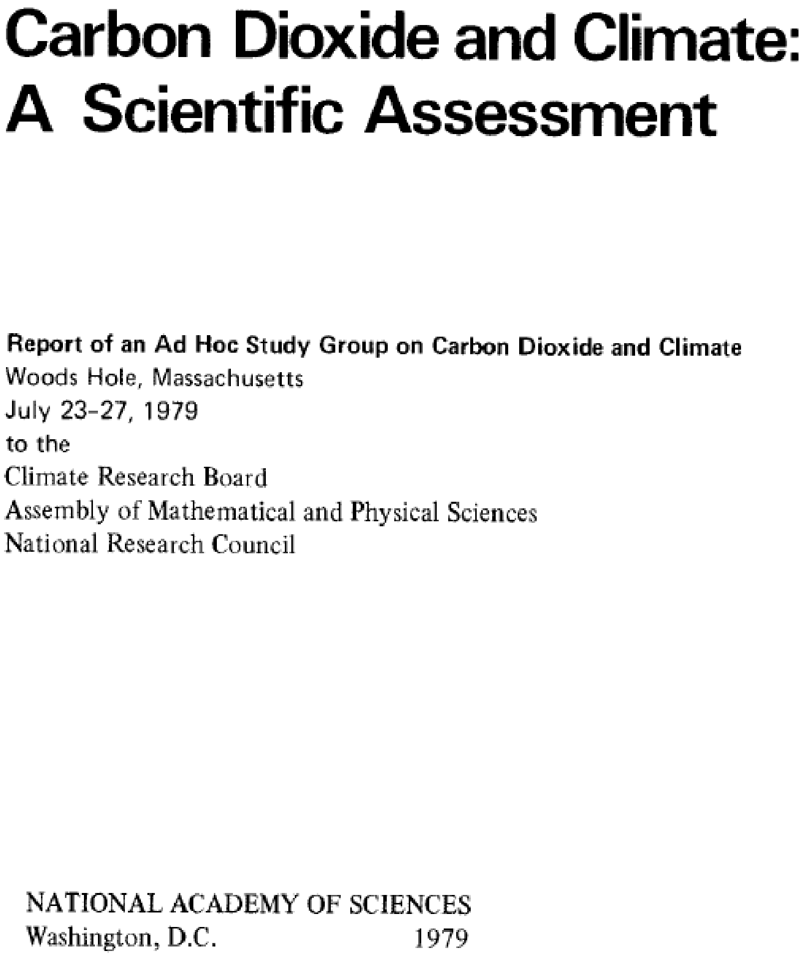
How will clouds respond to increased CO_2 : and how will that feed back on climate ?

Results from 2 different climate models (+ 1%CO2/yr)



Not a new story...

An Early Assessment of Long-Term Climate Change : The "Charney Report" (1979)



Carbon Dioxide and Climate: A Scientific Assessment

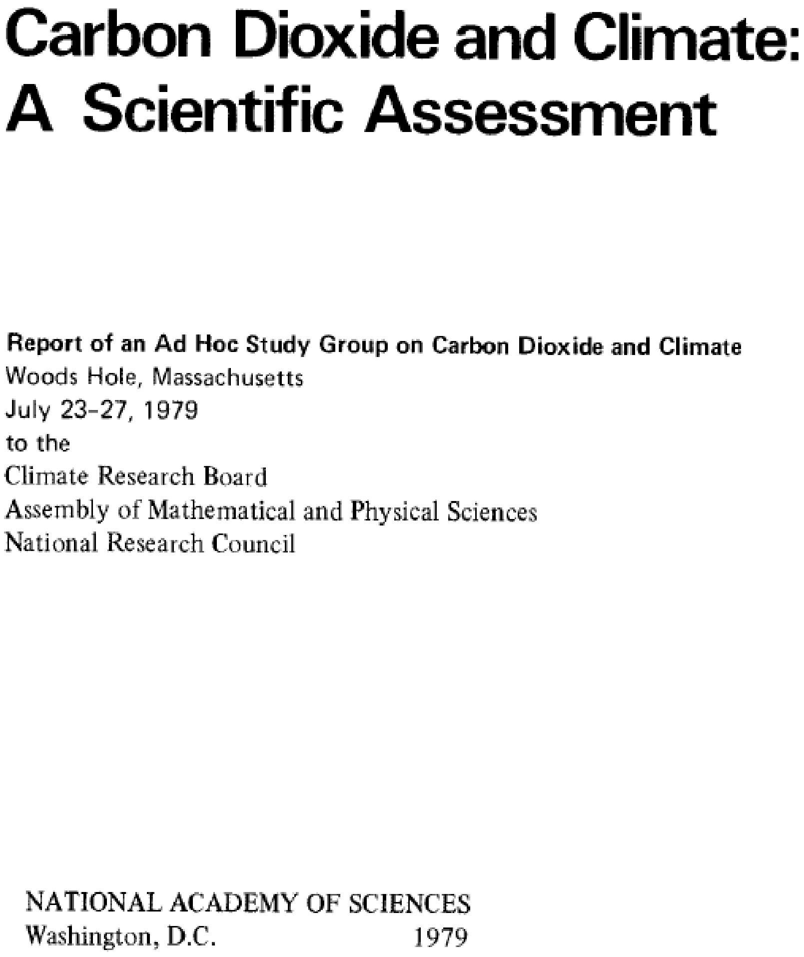
Report of an Ad Hoc Study Group on Carbon Dioxide and Climate
Woods Hole, Massachusetts
July 23–27, 1979
to the
Climate Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979

Jule Charney
(1917-1981)

Report available on Brian Medeiros' homepage
See also WCRP position paper Bony et al., (2013)

An Early Assessment of Long-Term Climate Change : The “Charney Report” (1979)



Carbon Dioxide and Climate: A Scientific Assessment

Report of an Ad Hoc Study Group on Carbon Dioxide and Climate
Woods Hole, Massachusetts
July 23-27, 1979
to the
Climate Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979

- Available material :
  - simple climate models (EBM, 1D..)
  - a few early general circulation models
  - very few global observations
- Amazingly prescient in its assessment :

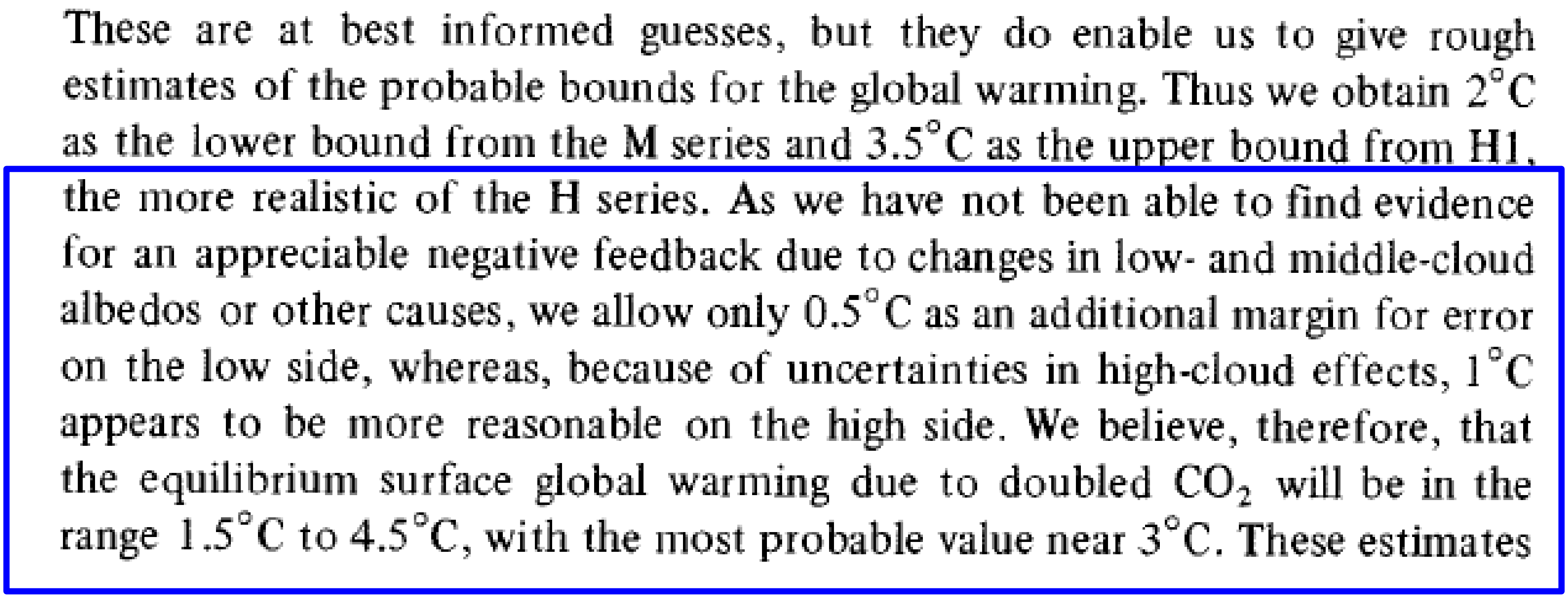
... of the effects of increased CO_2 on climate :

- timing of doubling of CO_2 concentration
- 2 x CO_2 radiative forcing : ~ 4 W/m^2
- pattern of surface warming (land/ocean, polar)
- water vapor and sea-ice feedback estimates
- climate sensitivity estimates :
  range : 1.5 – 4.5 K ; likely value : 3 K
- etc

... of key uncertainties, e.g. :

- role of the ocean in carbon and heat uptake
- regional precipitation changes
- cloud feedbacks

An Early Assessment of Long-Term Climate Change : The “Charney Report” (1979)



These are at best informed guesses, but they do enable us to give rough estimates of the probable bounds for the global warming. Thus we obtain 2°C as the lower bound from the M series and 3.5°C as the upper bound from H1, the more realistic of the H series. As we have not been able to find evidence for an appreciable negative feedback due to changes in low- and middle-cloud albedos or other causes, we allow only 0.5°C as an additional margin for error on the low side, whereas, because of uncertainties in high-cloud effects, 1°C appears to be more reasonable on the high side. We believe, therefore, that the equilibrium surface global warming due to doubled CO_2 will be in the range 1.5°C to 4.5°C, with the most probable value near 3°C. These estimates

Charney et al., 1979

The insights of the “Charney Report” were not an accident

They reflect the power of the scientific approach underlying the assessment :

*“In order to assess the climatic effects of increased CO2, we consider first
the primary physical processes that influence the climate system as a whole.”*

*“These processes are best studied in simple models
whose physical characteristics may readily be comprehended.”*

*“The understanding derived from these studies enables one better
to assess the performance of the 3D circulation models.“*

> *“ **Our confidence in our conclusion** that a doubling of CO2 will eventually result in significant temperature increases and other climate changes **is based on the fact that the results** of the radiative-convective and heat-balance model studies **can be understood in purely physical terms and are verified by the more complex GCMs.**”*

A lesson for us !

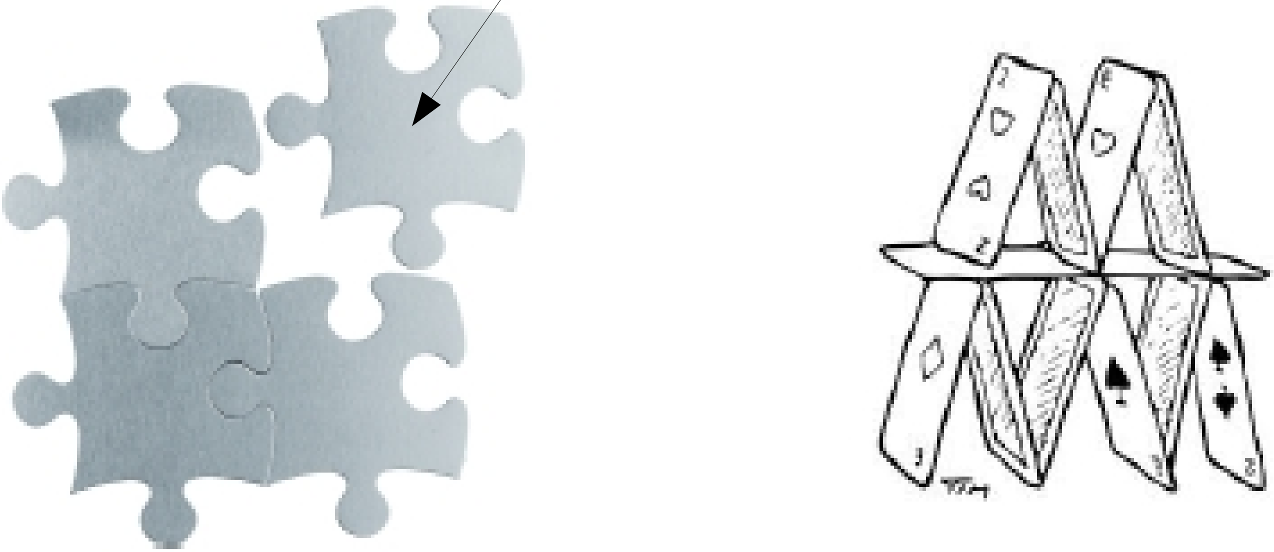
Long-standing characteristics of climate projections

Ambivalence of the results :

- some aspects are *uncertain*,
  i.e. not fully understood yet, differ amongst models

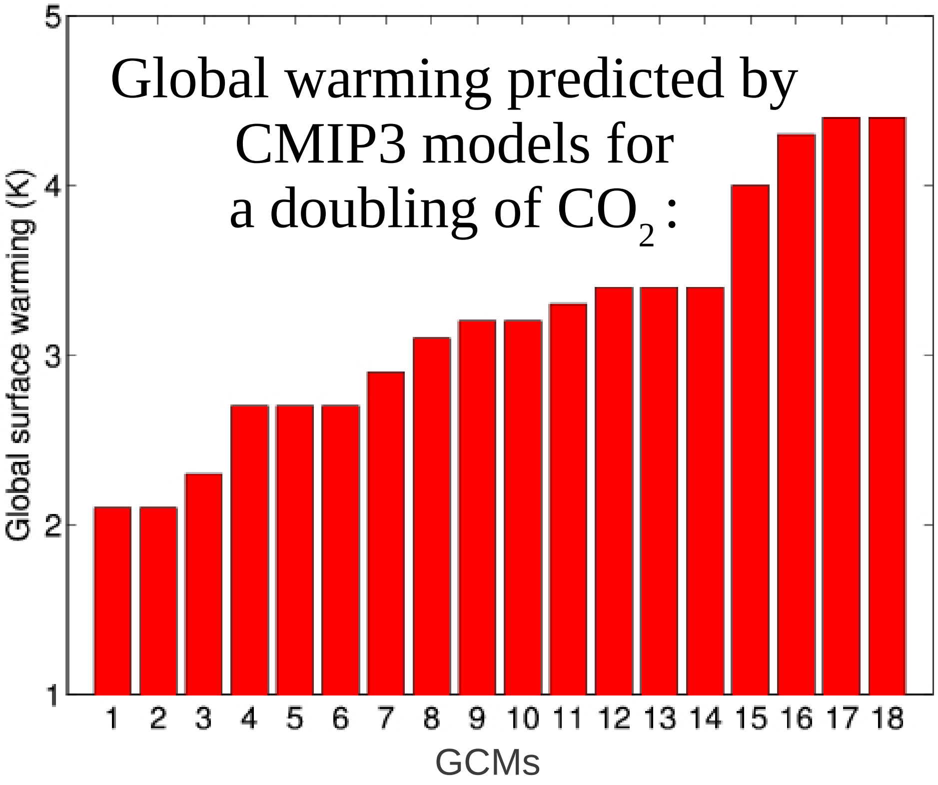
- other aspects are *robust*,
  i.e. physically understood, multiple lines of evidence (not only from GCMs!)

- both are not incompatible

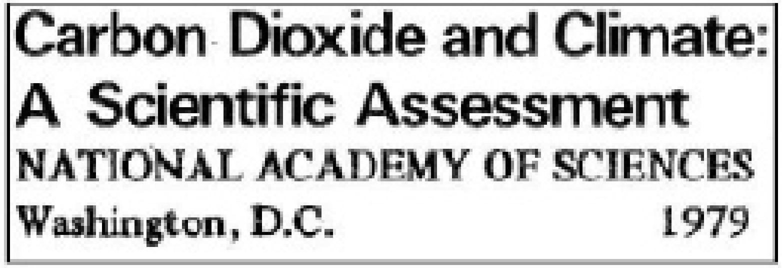


Physical understanding is what makes it possible to add pieces to the puzzle !

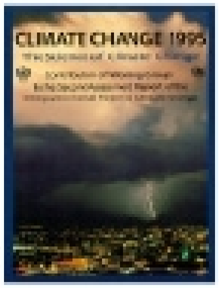
Since the Charney Report, clouds have always been recognized as a key source of uncertainty for climate sensitivity


Global warming predicted by CMIP3 models for a doubling of CO_2:

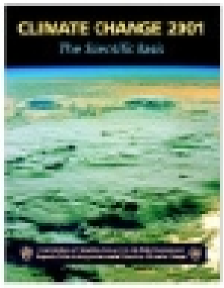
Randall et al., IPCC 2007


Carbon Dioxide and Climate:
A Scientific Assessment
NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979

1990



1995



2001

2007

AR5

2013

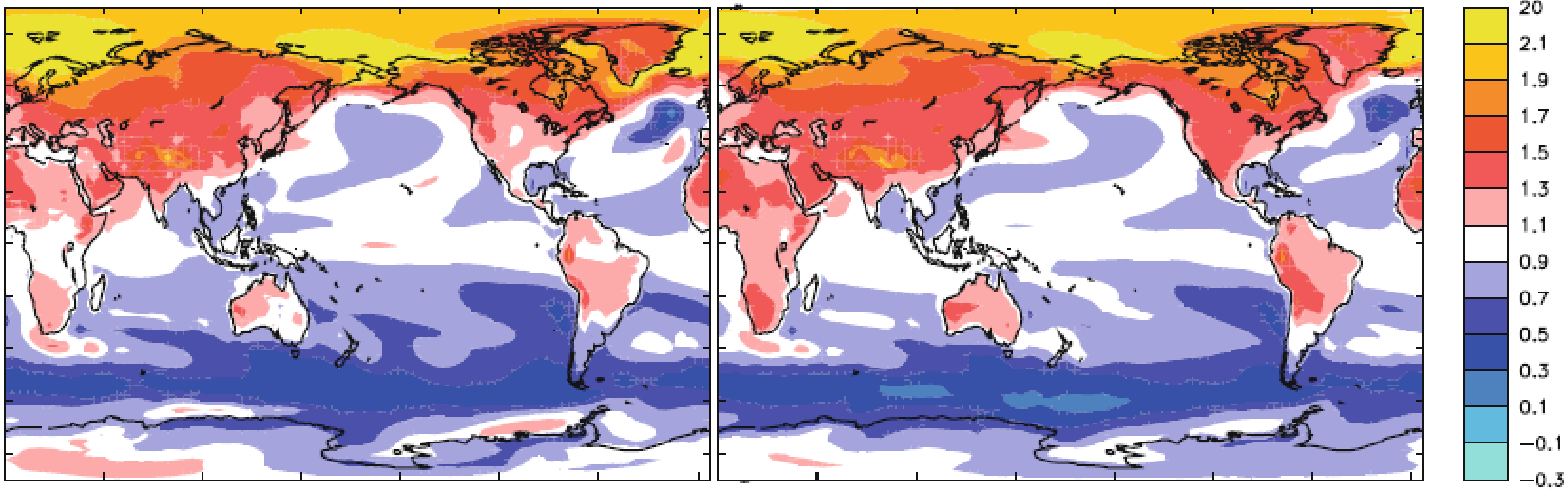
Why do we care so much about global ΔT ?

- For many models, as a first approximation :

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

- **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

Clouds in a Changing Climate

I. Conceptual frameworks

- How can we formalize the link between clouds and climate sensitivity ?
- How does increased CO2 affect clouds ?
- How can we apply conceptual frameworks to observations or GCM results ?

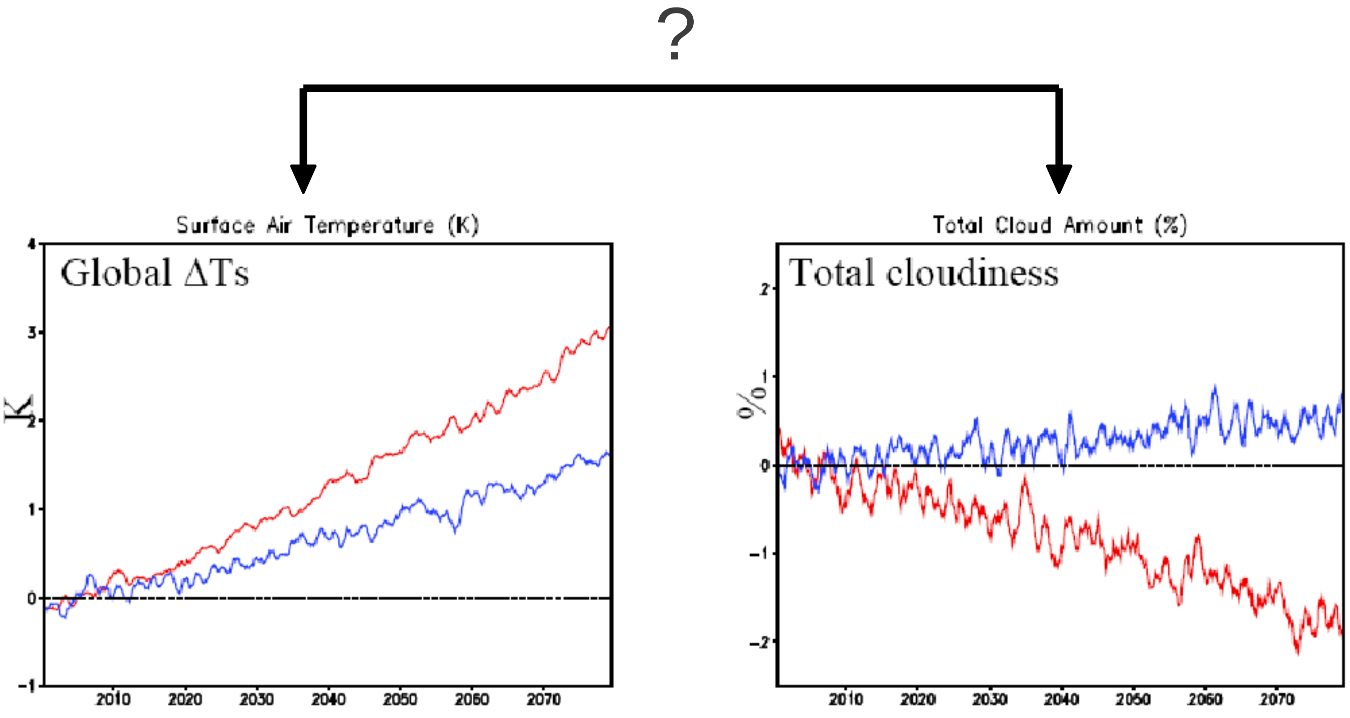
II. Cloud feedback processes

- What are the underlying processes ?
- Are some of these processes robust ? Why ?
- Where do cloud feedback uncertainties come from ?

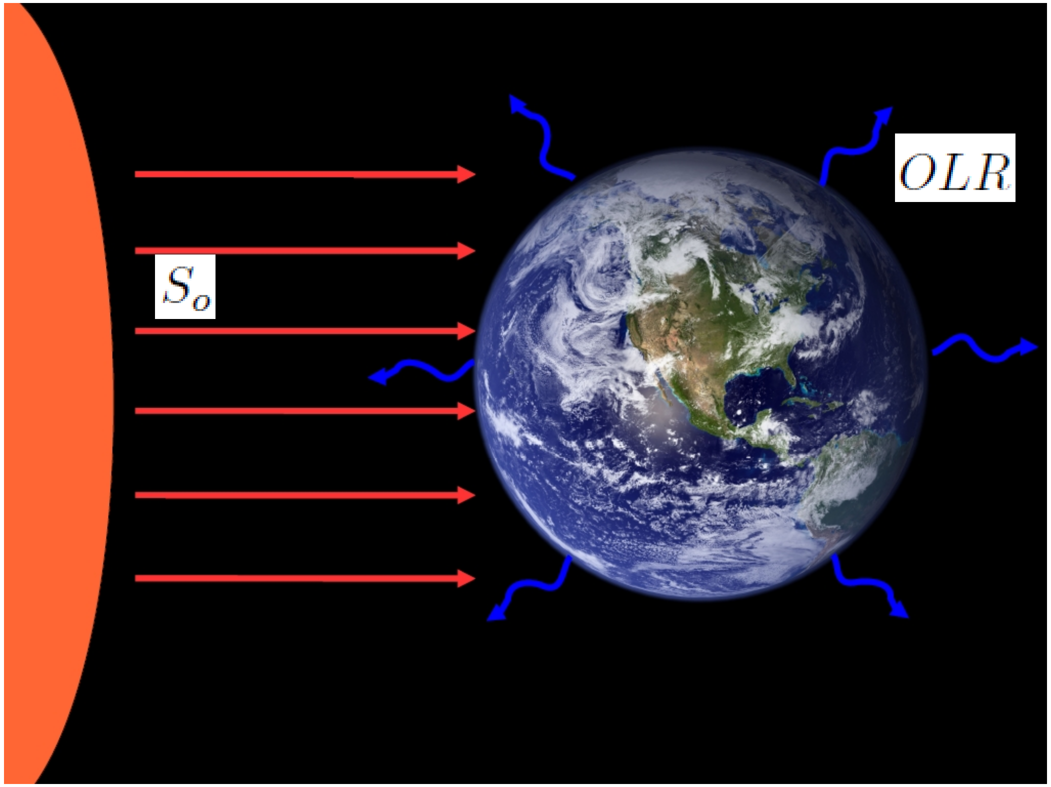
III. Precipitation projections

- How does global precipitation respond to increased CO2 ?
- How does regional precipitation respond to increased CO2 ?
- Interactions between cloud-radiative effects, circulation and precipitation

How to formalize the link between clouds and climate sensitivity ?



Global Energy Balance Analysis



$$R = \frac{S_o}{4}(1-\alpha) - OLR \qquad OLR = \sigma T_e^4$$

$$\text{At equilibrium,}\ R = 0$$

The dependence of OLR on temperature constitutes the main basic restoring force towards Earth's energy balance

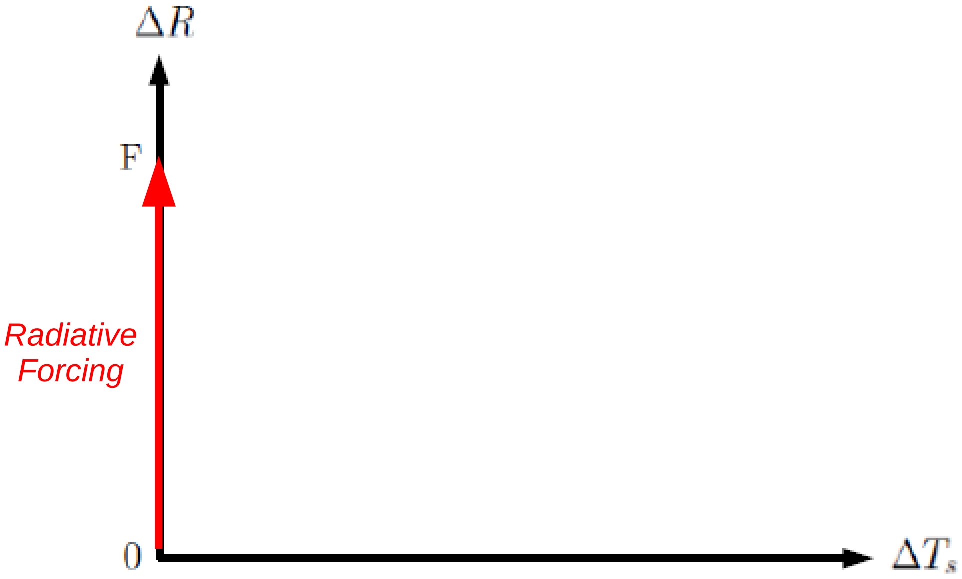
$$R = \frac{S_o}{4}(1-\alpha) - OLR$$

Let's assume that : $R = \frac{S_o}{4}(1-\alpha) - \gamma(co_2, wv, cld, lr, ...)\,.\,\sigma\, T_s^4$

$$R = \frac{S_o}{4}(1-\alpha) - OLR$$

Let's assume that : $R = \frac{S_o}{4}(1-\alpha) - \gamma(co_2, wv, cld, lr, ...) \, . \, \sigma \, T_s^4$

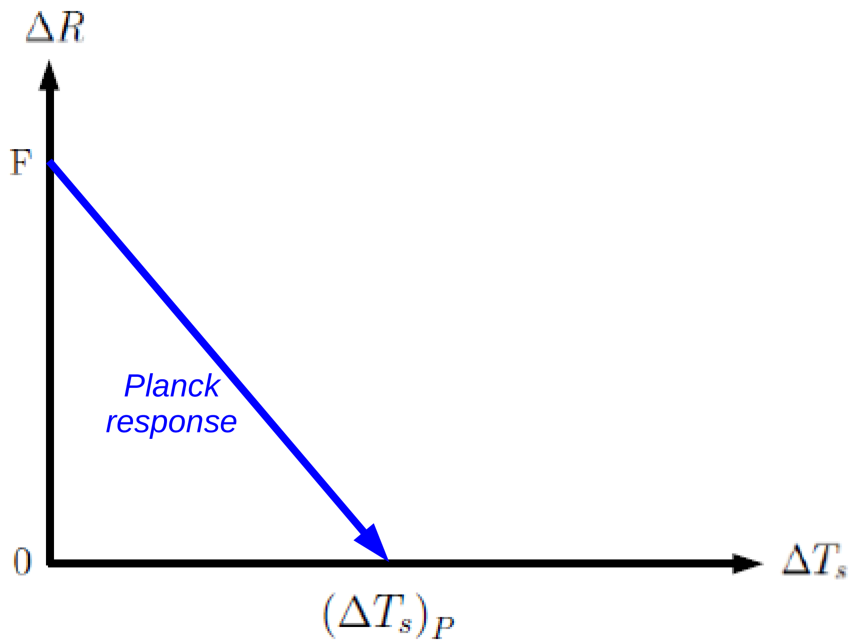
- If S_o or CO_2 abruptly increases → $\Delta R > 0$



$$R = \frac{S_o}{4}(1-\alpha) - OLR$$

Let's assume that : $R = \frac{S_o}{4}(1-\alpha) - \gamma(co_2, wv, cld, lr, \ldots)\,.\,\sigma\,T_s^4$

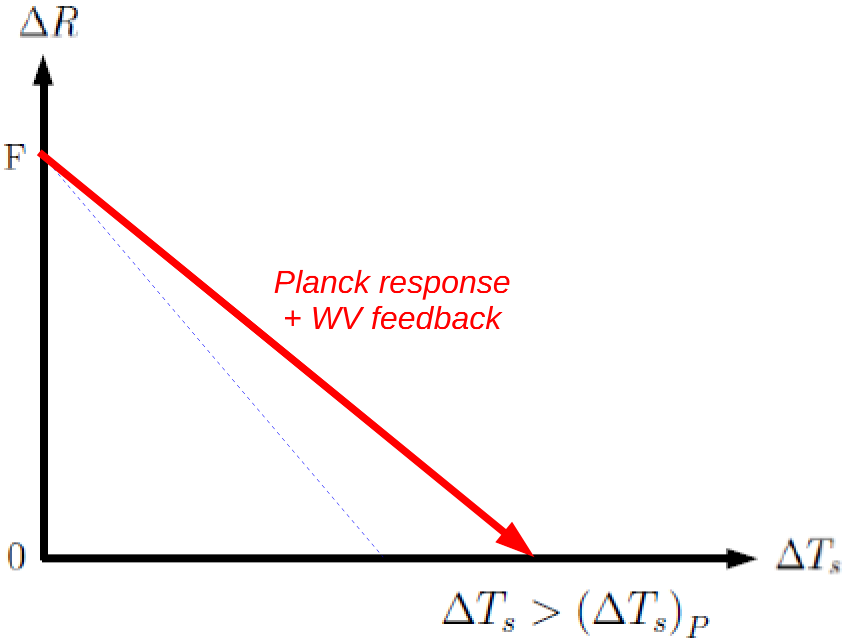
- If S_o or CO_2 abruptly increases $\rightarrow$ $\Delta R > 0$
- Let's assume that only T_s responds to the perturbation : $\partial R/\partial T_s = -4\,\gamma\,\sigma\,T_s^3$ $\rightarrow$ $\Delta R = 0$ reached for $\Delta T_s = (\Delta T_s)_P$.



$$R = \frac{S_o}{4}(1-\alpha) - OLR$$

Let's assume that : $R = \frac{S_o}{4}(1-\alpha) - \gamma(co_2, wv, cld, lr, ...)\,.\,\sigma\, T_s^4$

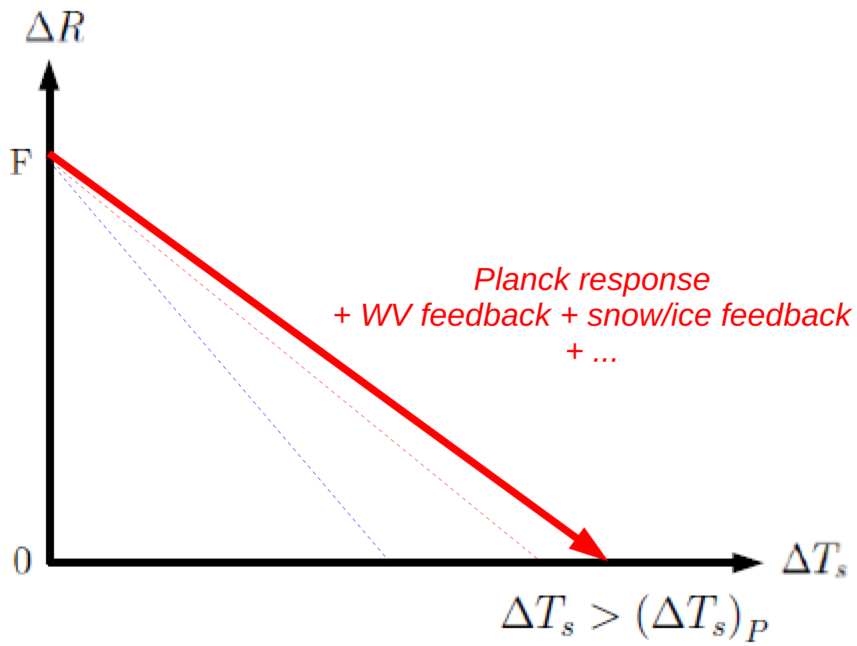
- If S_o or CO_2 abruptly increases $\rightarrow\ \Delta R > 0$
- Let's assume that only T_s responds to the perturbation : $\partial R/\partial T_s = -4\,\gamma\,\sigma\, T_s^3\ \rightarrow\ \Delta R = 0$ reached for $\Delta T_s = (\Delta T_s)_P$.
- Let's assume now that wv increases as T_s increases... $\rightarrow\ \Delta T_s > (\Delta T_s)_P$



$$R = \frac{S_o}{4}(1-\alpha) - OLR$$

Let's assume that : $R = \frac{S_o}{4}(1-\alpha) - \gamma(co_2, wv, cld, lr, ...)\,.\,\sigma\,T_s^4$

- If S_o or CO_2 abruptly increases $\rightarrow\ \Delta R > 0$
- Let's assume that only T_s responds to the perturbation : $\partial R/\partial T_s = -4\,\gamma\,\sigma\,T_s^3\ \rightarrow \Delta R = 0$ reached for $\Delta T_s = (\Delta T_s)_P$.
- Let's assume now that wv increases as T_s increases...
  $\rightarrow \Delta T_s > (\Delta T_s)_P$
  ...and that α_{ice} decreases as T_s increases... etc



Classical Framework

Let's assume that $R = R(\varphi, T_s)$
where φ is an external perturbation (ΔS_o, $\Delta \mathrm{CO_2}$, etc).

$$\Delta R = \left(\frac{\partial R}{\partial \varphi}\right)_{T_s} \Delta\varphi + \left(\frac{\partial R}{\partial T_s}\right)_{\varphi} \Delta T_s$$

$$\boxed{\Delta R = F + \lambda\,\Delta T_s}$$

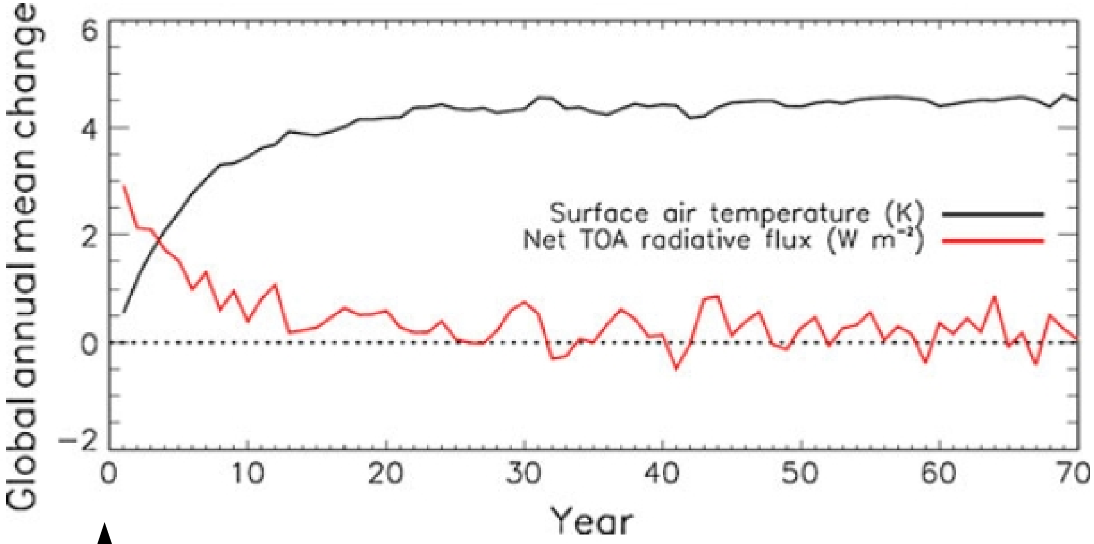
with

- ΔR: net heat flux transitory stored within the system (heat uptake)
- $F = \left(\frac{\partial R}{\partial \varphi}\right)_{T_s} \Delta\varphi$: radiative forcing ($\mathrm{W/m^2}$)
- $\lambda = \left(\frac{\partial R}{\partial T_s}\right)_{\varphi}$: feedback parameter ($\mathrm{W/m^2/K}$)

$$\Delta R = 0 \longrightarrow \Delta T_s^{eq} = -\frac{F}{\lambda}$$

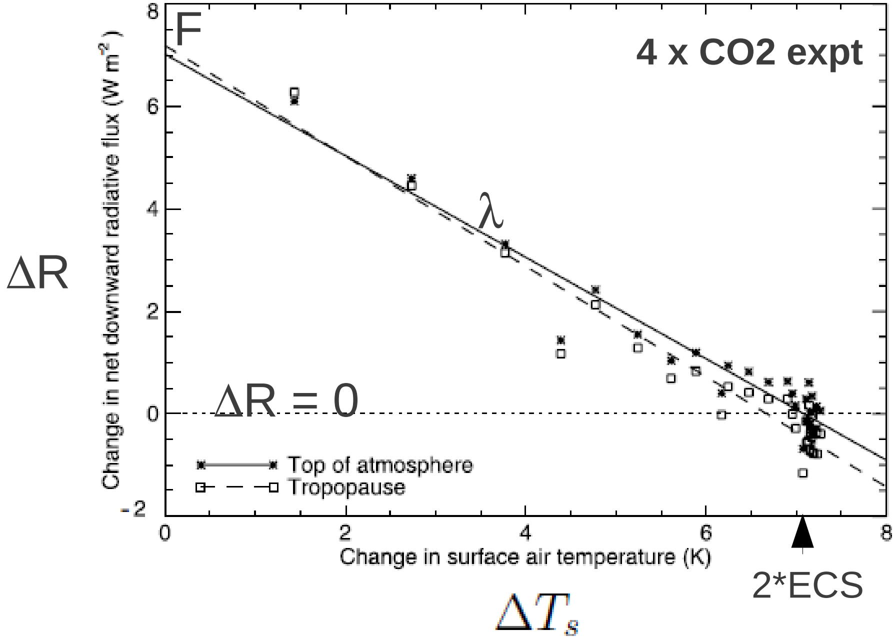
For a doubling of CO2, this quantity is named Equilibrium Climate Sensitivity (ECS)

Model estimates of climate sensitivity



Abrupt CO2 increase

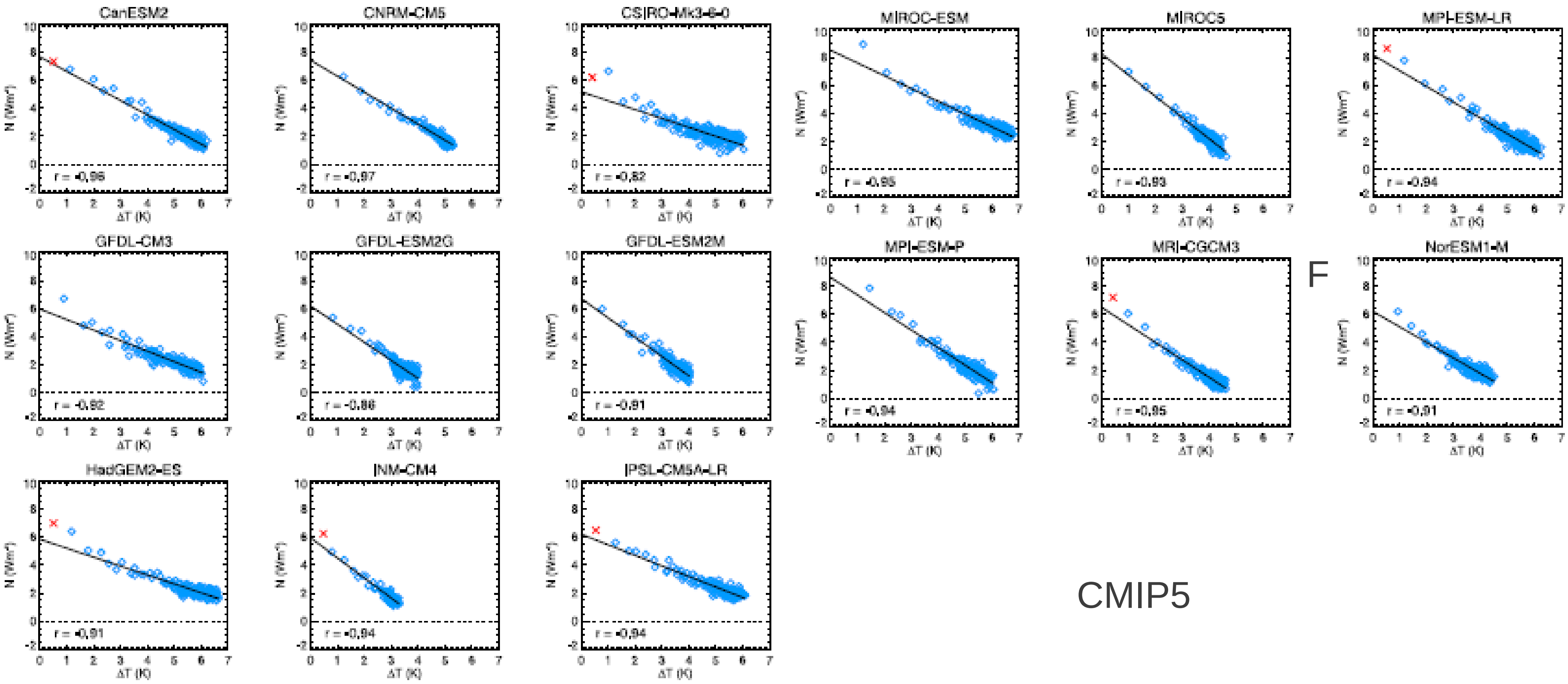
« Gregory plot »



Gregory et al., J. Climate, 2004

Model estimates of climate sensitivity

Reponse to an abrupt CO2 increase

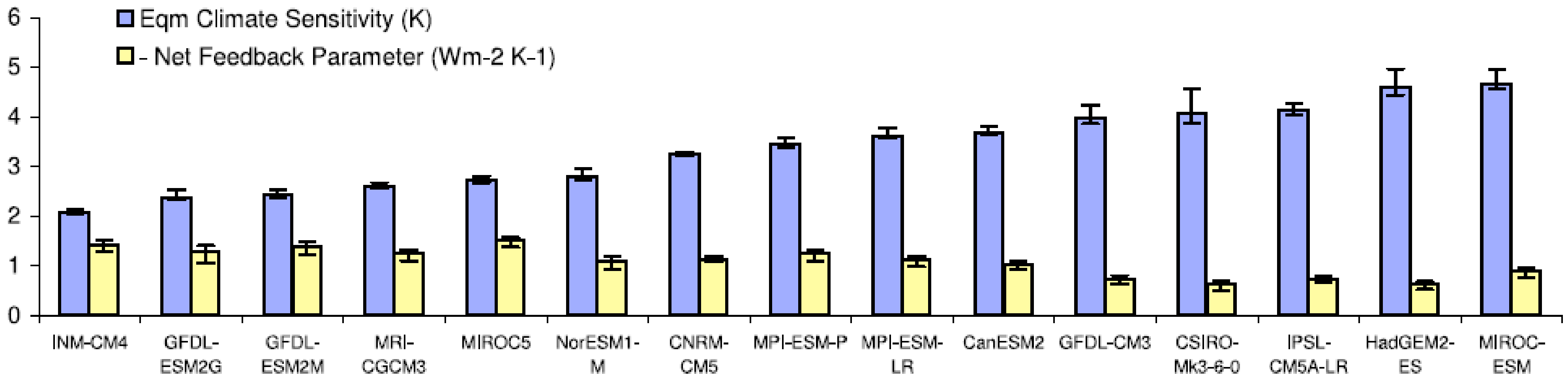


F

CMIP5

Andrews et al., GRL, 2012

Model estimates of climate sensitivity



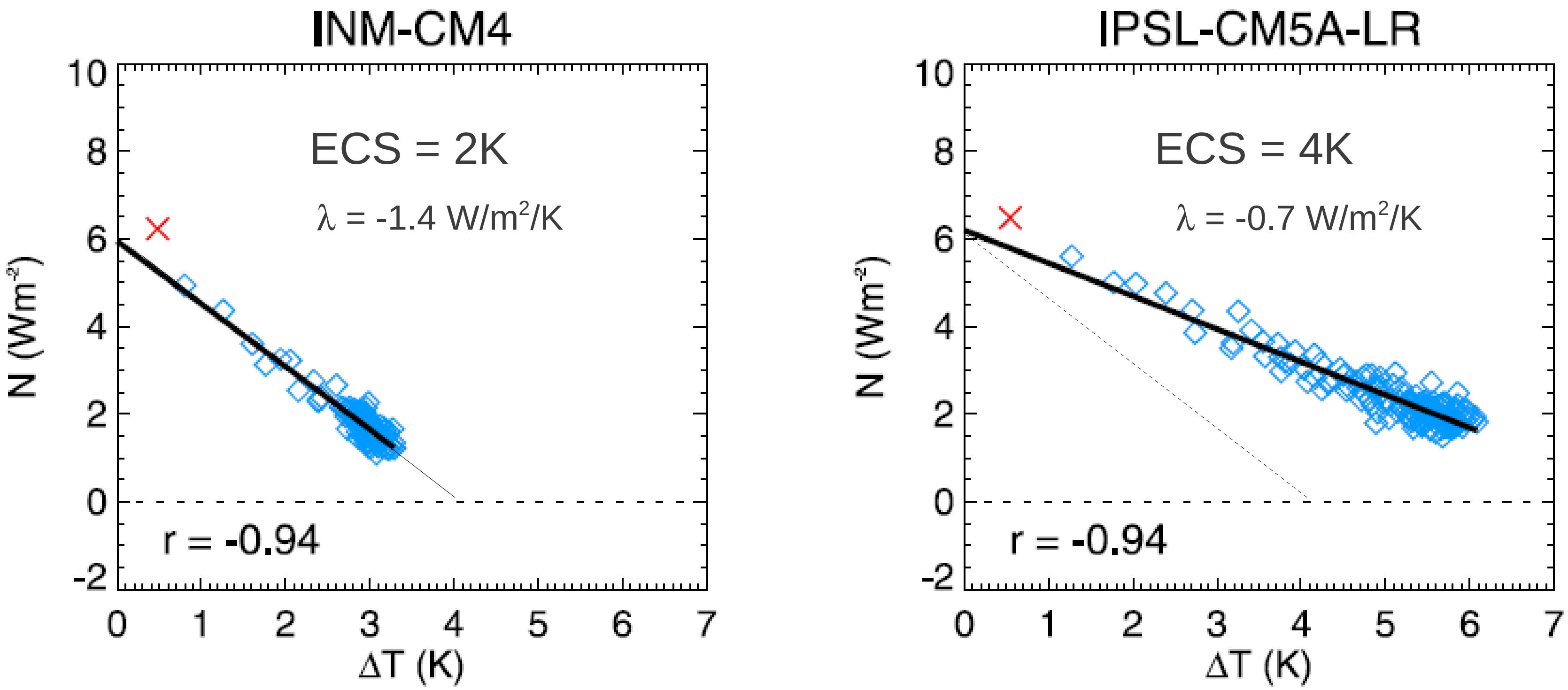
ECS range from CMIP5 models : 2 – 4.5 K

Spread primarily due to the feedback parameter

Andrews et al., GRL, 2012

Two « extreme » models

Abrupt 4xCO2 experiment



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

Andrews et al., GRL, 2012

From feedback parameters to climate sensitivity

At equilibrium :

$$\Delta T_s = \frac{1}{1+\sum\limits_{x\neq P}\frac{\lambda_x}{\lambda_P}}\,(\Delta T_s)_P \ \text{ with } \ (\Delta T_s)_P = -\frac{F}{\lambda_P}$$

exercise :
derive it

$$\boxed{\Delta T_s = (\Delta T_s)_P + \sum_{x\neq P}\Delta T_{s,x} \qquad \text{with } \Delta T_{s,x} = -\frac{\lambda_x}{\lambda_P}\,(\Delta T_s)_P}$$

Plank response

Influence of each feedback x
on climate sensitivity

From feedback parameters to climate sensitivity

At equilibrium :

$$\Delta T_s = \frac{1}{1+\sum\limits_{x\neq P}\frac{\lambda_x}{\lambda_P}}\,(\Delta T_s)_P \quad \text{with} \quad (\Delta T_s)_P = -\frac{F}{\lambda_P}$$

exercise :
derive it

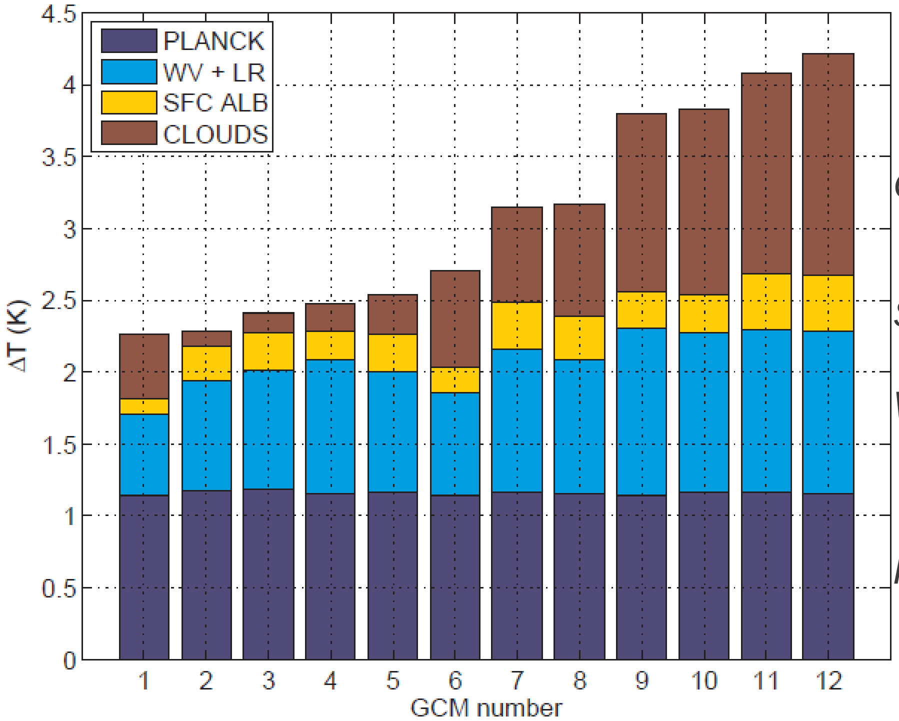
$$\boxed{\Delta T_s = (\Delta T_s)_P + \sum_{x\neq P} \Delta T_{s,x} \qquad \text{with } \Delta T_{s,x} = -\frac{\lambda_x}{\lambda_P}\,(\Delta T_s)_P}$$

Plank response

Influence of each feedback x
on climate sensitivity

Helps interpret inter-model differences in climate sensitivity :

ΔT



Cloud feedback

Surface albedo feedback

Water vapor + lapse rate feedbacks

Planck response

Dufresne & Bony, J. Clim., 2008

How to diagnose feedback parameters ?

several methods..

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 a radiation code)

response to climate change

Diagnostic of feedback parameters through the Kernel approach

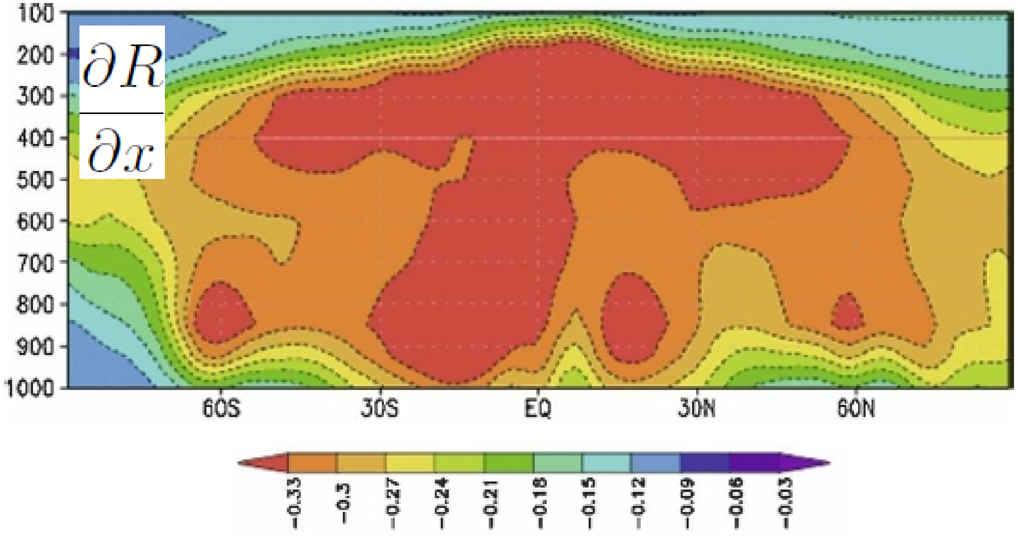
$$\lambda = \frac{\partial R}{\partial T_s} = \sum_x \frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s} = \lambda_P + \sum_{x \neq P} \lambda_x$$

radiative kernel
(computed by a radiation code)

response to climate change

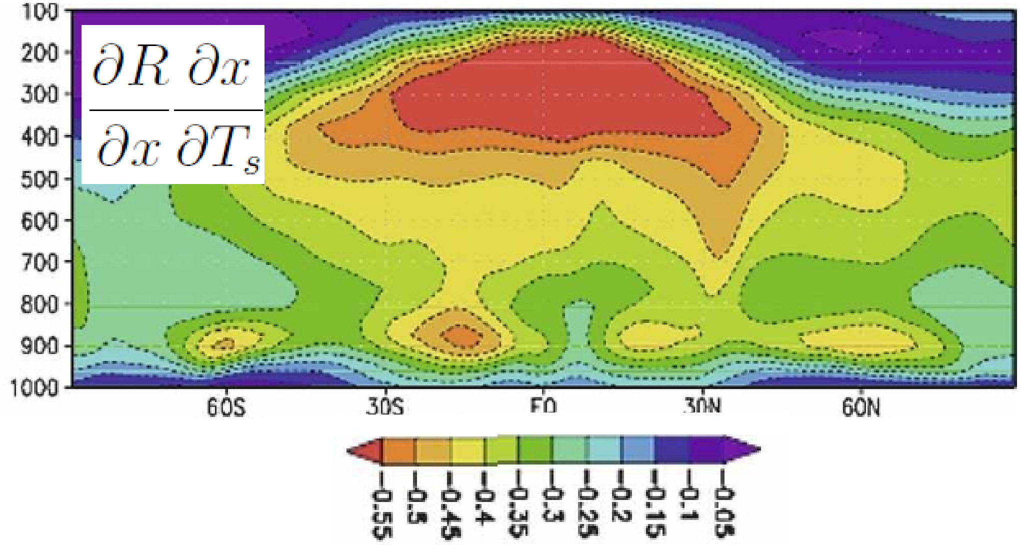
e.g. for x = T :

Temperature kernel



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

Temperature feedback parameter



λ_T = vertical integral (W/m^2/K)

Soden et al., J. Climate, 2008

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 a radiation code)

response to climate change

e.g. for x = ISCCP cloud types

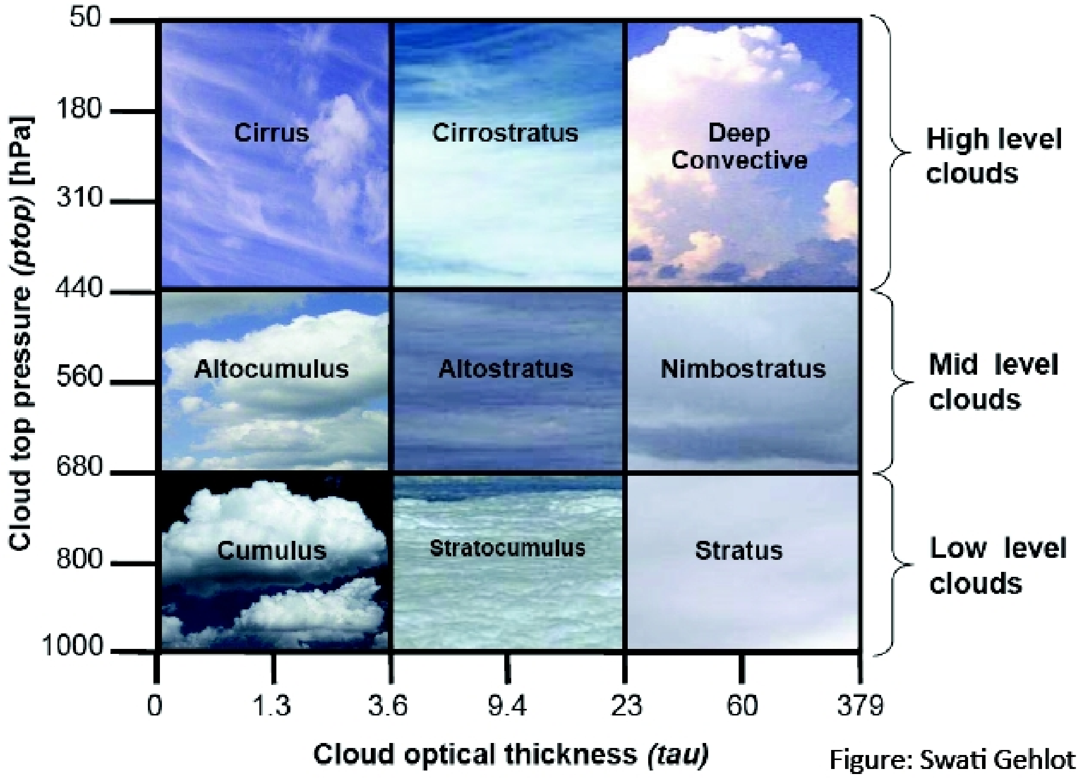


Figure: Swati Gehlot

Diagnostic of feedback parameters through the Kernel approach

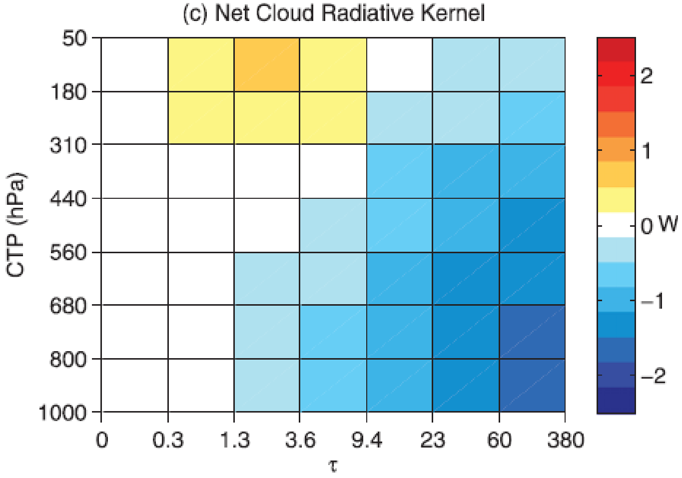
$$\lambda = \frac{\partial R}{\partial T_s} = \sum_x \frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s} = \lambda_P + \sum_{x \neq P} \lambda_x$$

radiative kernel
(computed by a radiation code)

response to climate change

e.g. for x = ISCCP cloud types

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



Zelinka et al., J. Climate, 2012

Diagnostic of feedback parameters through the Kernel approach

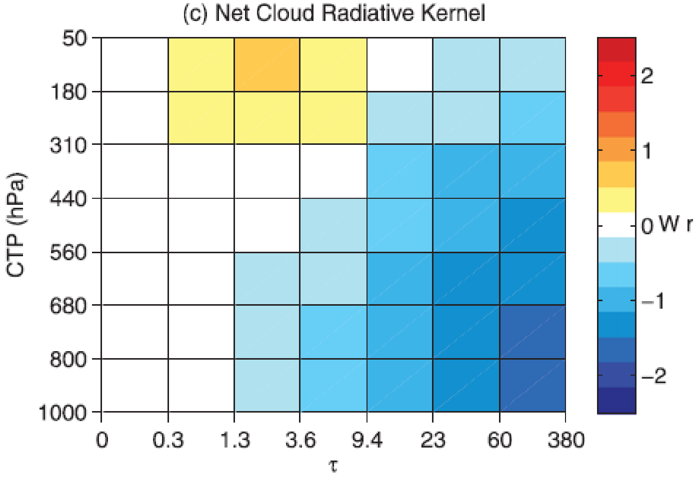
$$\lambda = \frac{\partial R}{\partial T_s} = \sum_x \frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s} = \lambda_P + \sum_{x\neq P}\lambda_x$$

radiative kernel
(computed by a radiation code)

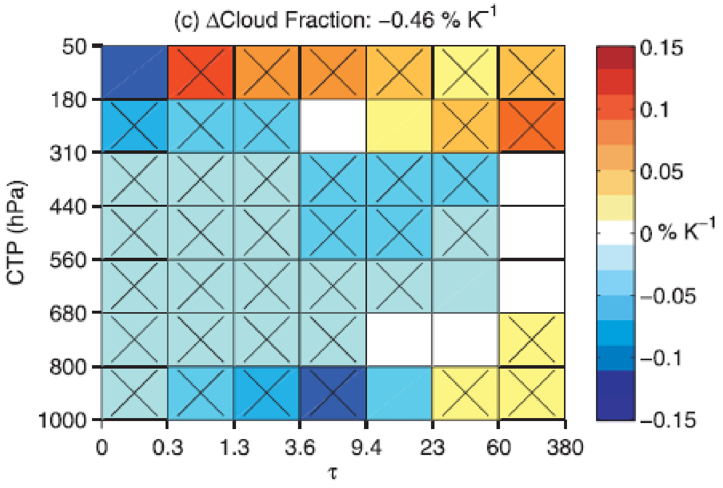
response to climate change

e.g. for x = ISCCP cloud types

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


(c) Net Cloud Radiative Kernel

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


(c) ΔCloud Fraction: −0.46 % K^{-1}

Zelinka et al., J. Climate, 2012

Diagnostic of feedback parameters through the Kernel approach

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

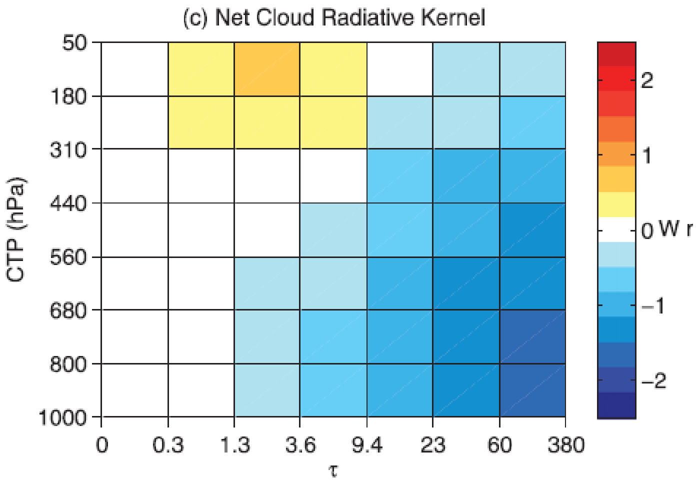
radiative kernel
(computed by a radiation code)

response to climate change

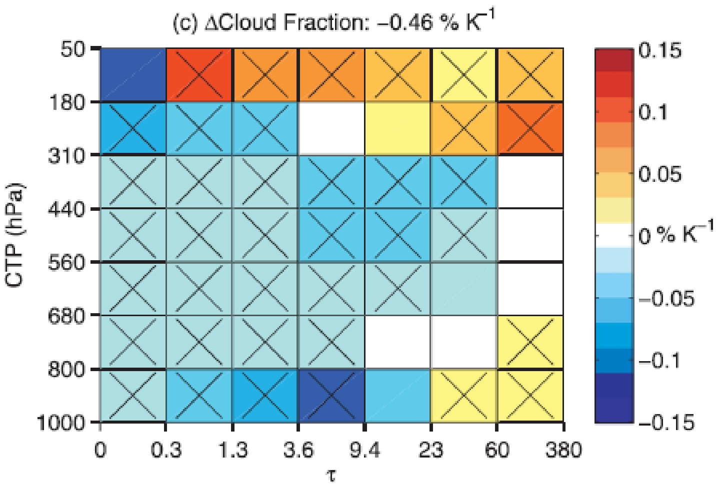
e.g. for x = ISCCP cloud types

λ_C = vertical integral = +0.6 W/m^2/K

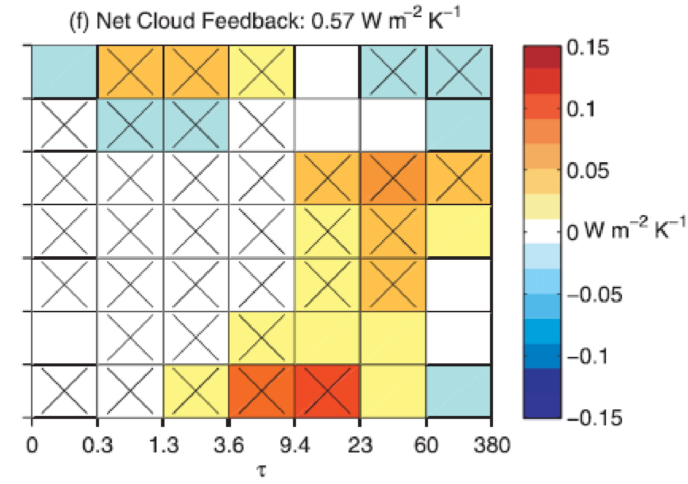
$$\frac{\partial R}{\partial x}$$


(c) Net Cloud Radiative Kernel

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


(c) ΔCloud Fraction: −0.46 % K^{-1}

$$\frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s}$$

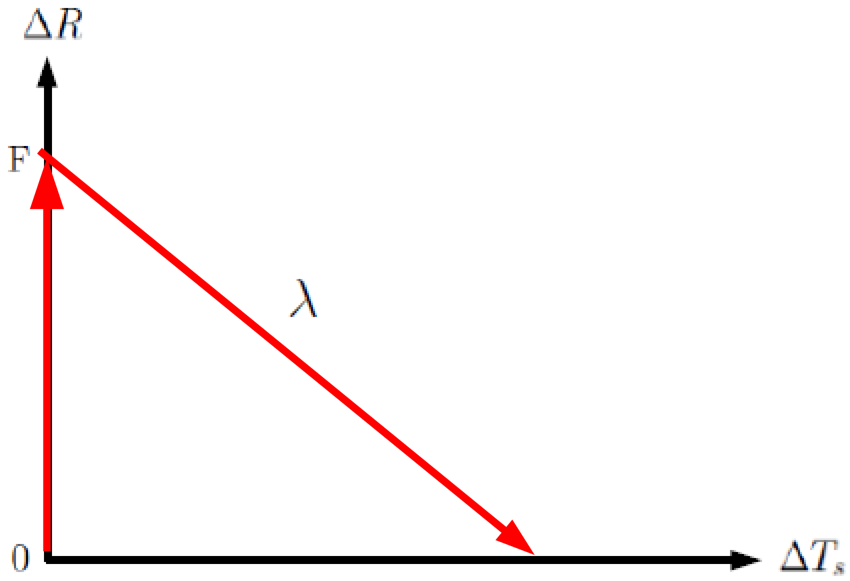

(f) Net Cloud Feedback: 0.57 W m^{-2} K^{-1}

Zelinka et al., J. Climate, 2012

But wait !

So far, we have assumed that the global climate response to increased CO2 was associated with Ts changes

Instantaneous
radiative change
due to increased CO2



$$\Delta R = F + \lambda \, \Delta T_s$$

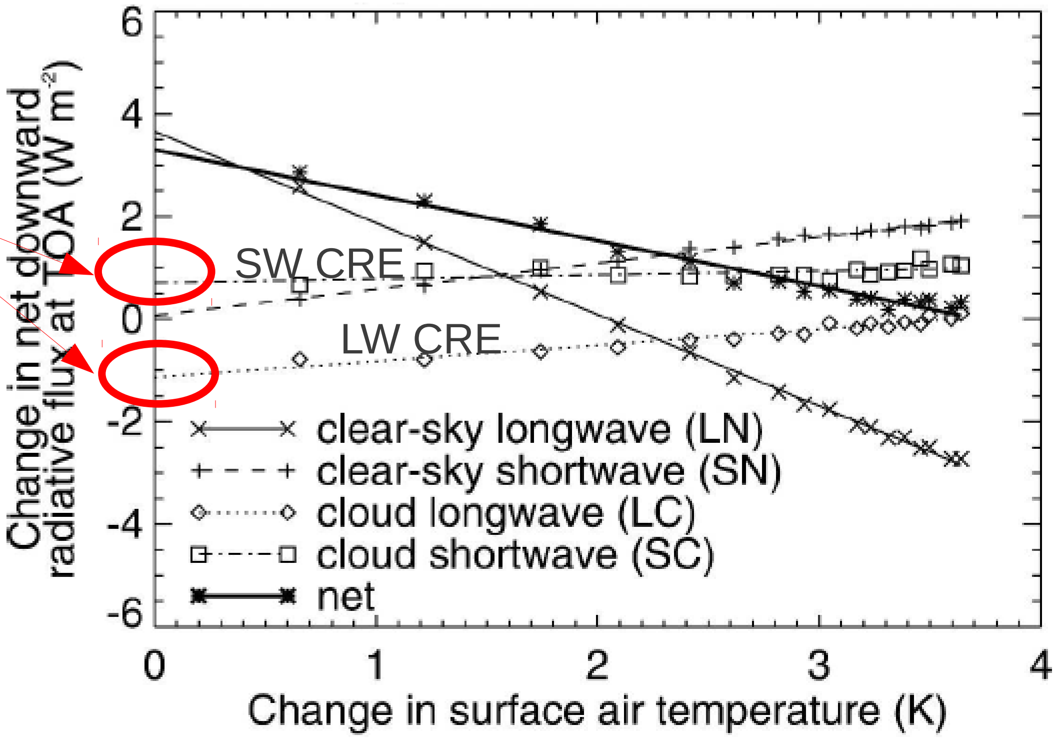
$$F = \left(\frac{\partial R}{\partial \varphi}\right)_{T_s} \Delta\varphi$$

$$\lambda = \left(\frac{\partial R}{\partial T_s}\right)_{\varphi}$$

How true is it ?

Regression of cloud-radiative effects upon Ts changes

Intercepts ≠ 0



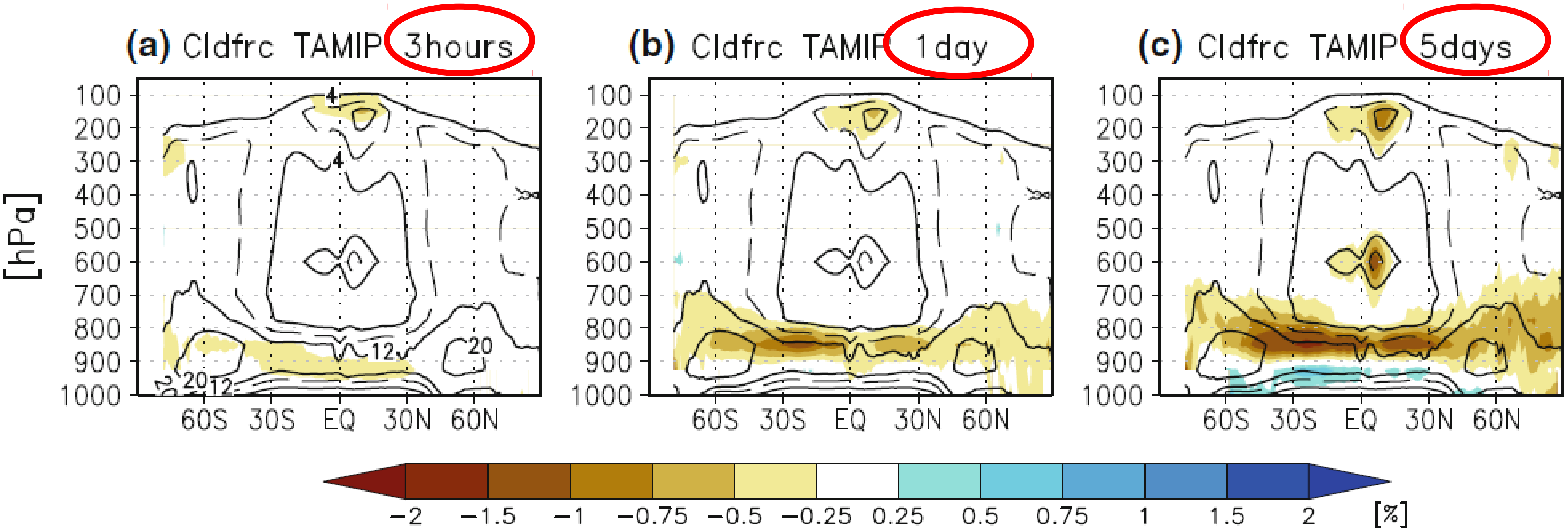
Significant cloud response to increased CO2 even in the absence of Ts change !

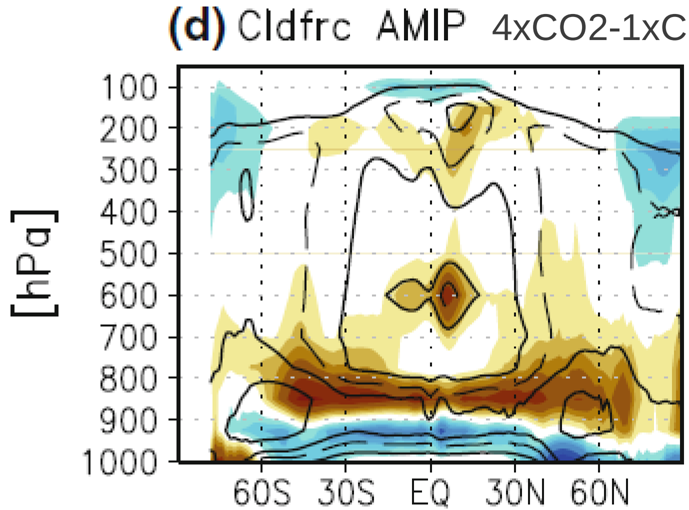
Tropospheric adjustments to CO2

Gregory and Webb, J. Climate, 2008

Clouds respond to CO_2 even in the absence of T_s changes
...and the response is fast !

After an abrupt quadrupling of CO2 (SST fixed):



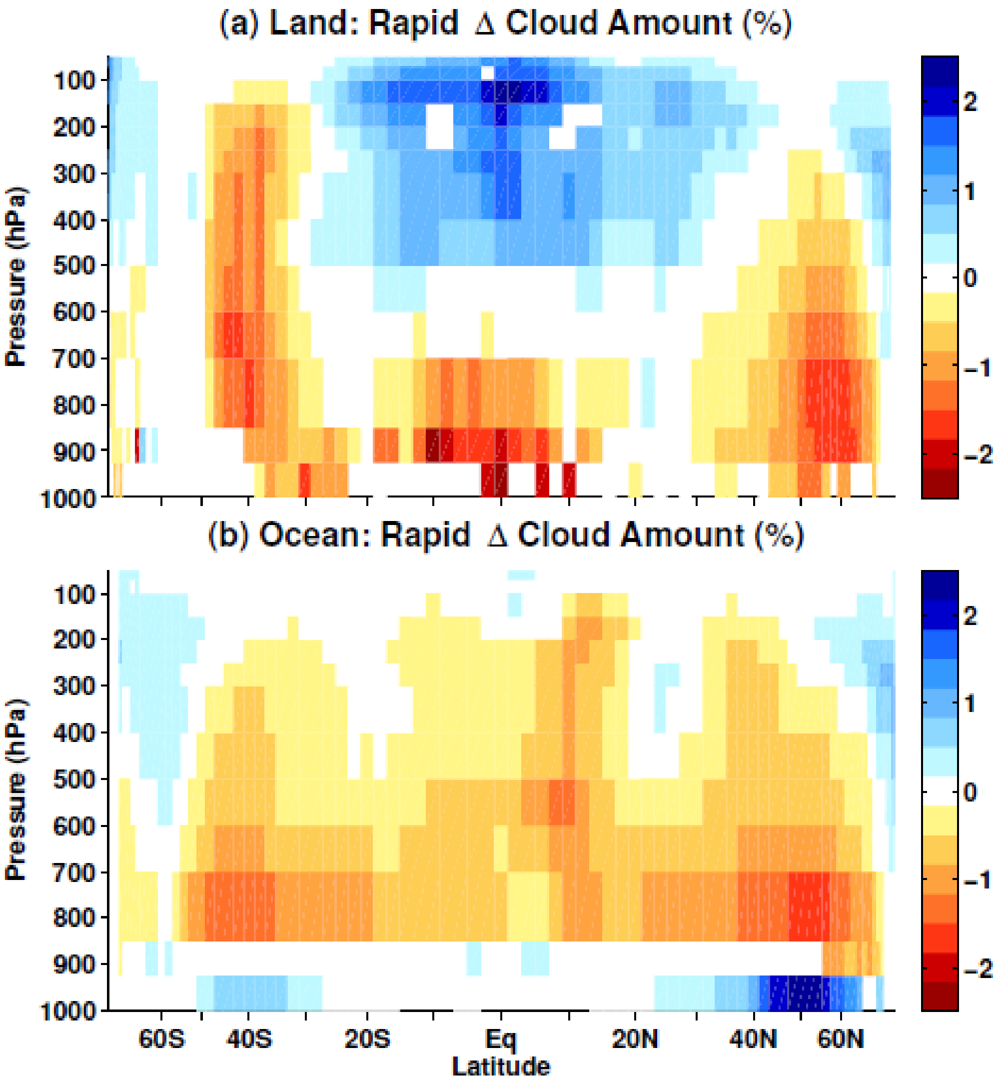


cf Youichi Kamae's poster

Kamae & Watanabe, Clim. Dyn, 2012

Clouds respond to CO_2 even in the absence of T_s changes

(4xCO2 experiments with fixed SSTs)



Zelinka et al., J. Climate, 2013

Underlying physical processes ?

Increased CO_2 reduces the radiative cooling of the troposphere,
and thus radiatively warms the troposphere, leading to :

- PBL shoaling (cf Youichi Kamae's poster)

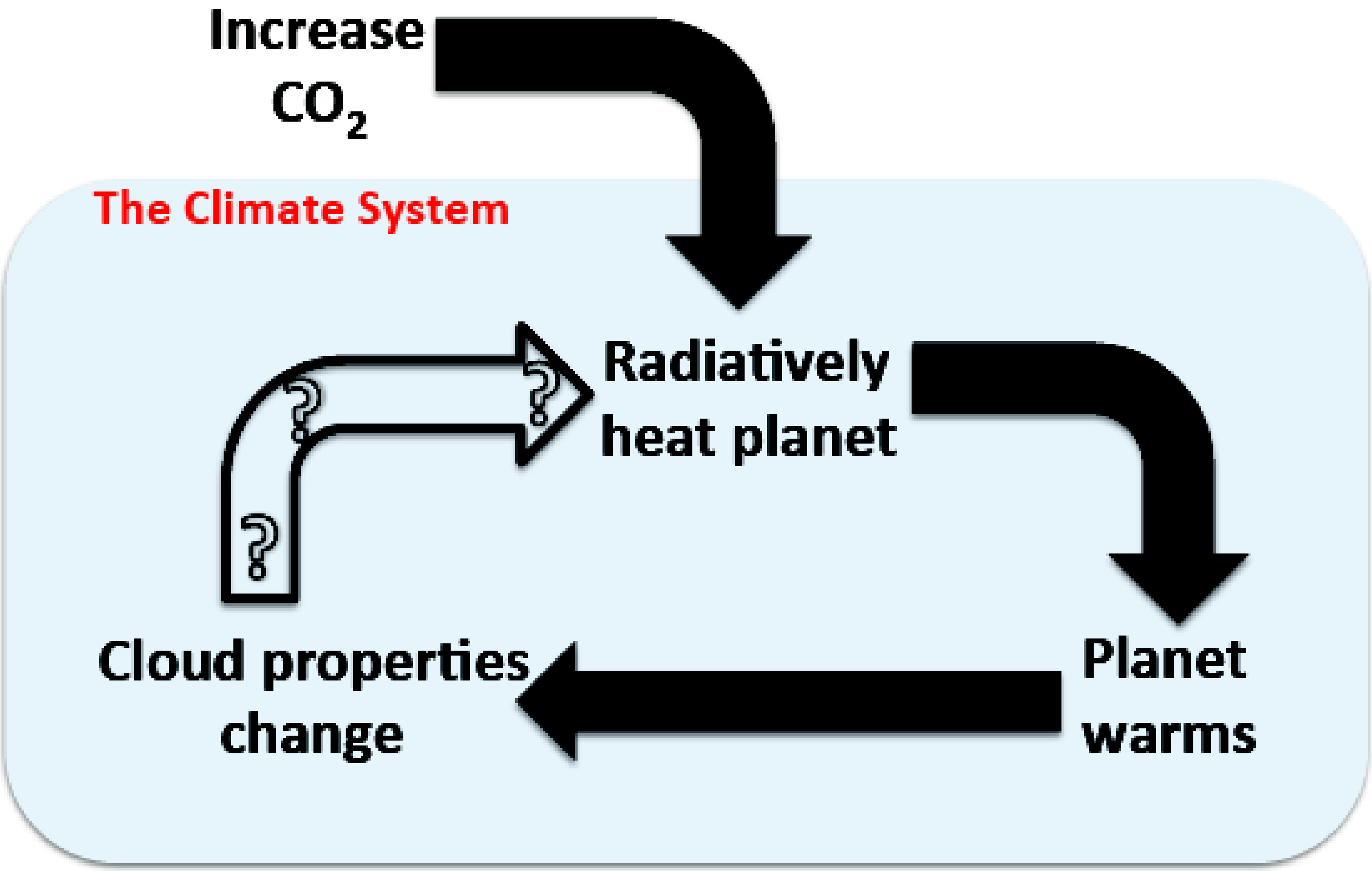
  CO2 radiative forcing induces a low-tropospheric warming, RH and stability changes

- 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, Clim. Dyn, 2012
Bony et al., NGS, 2013

How does CO2 affect clouds ?



Increase CO_2

The Climate System

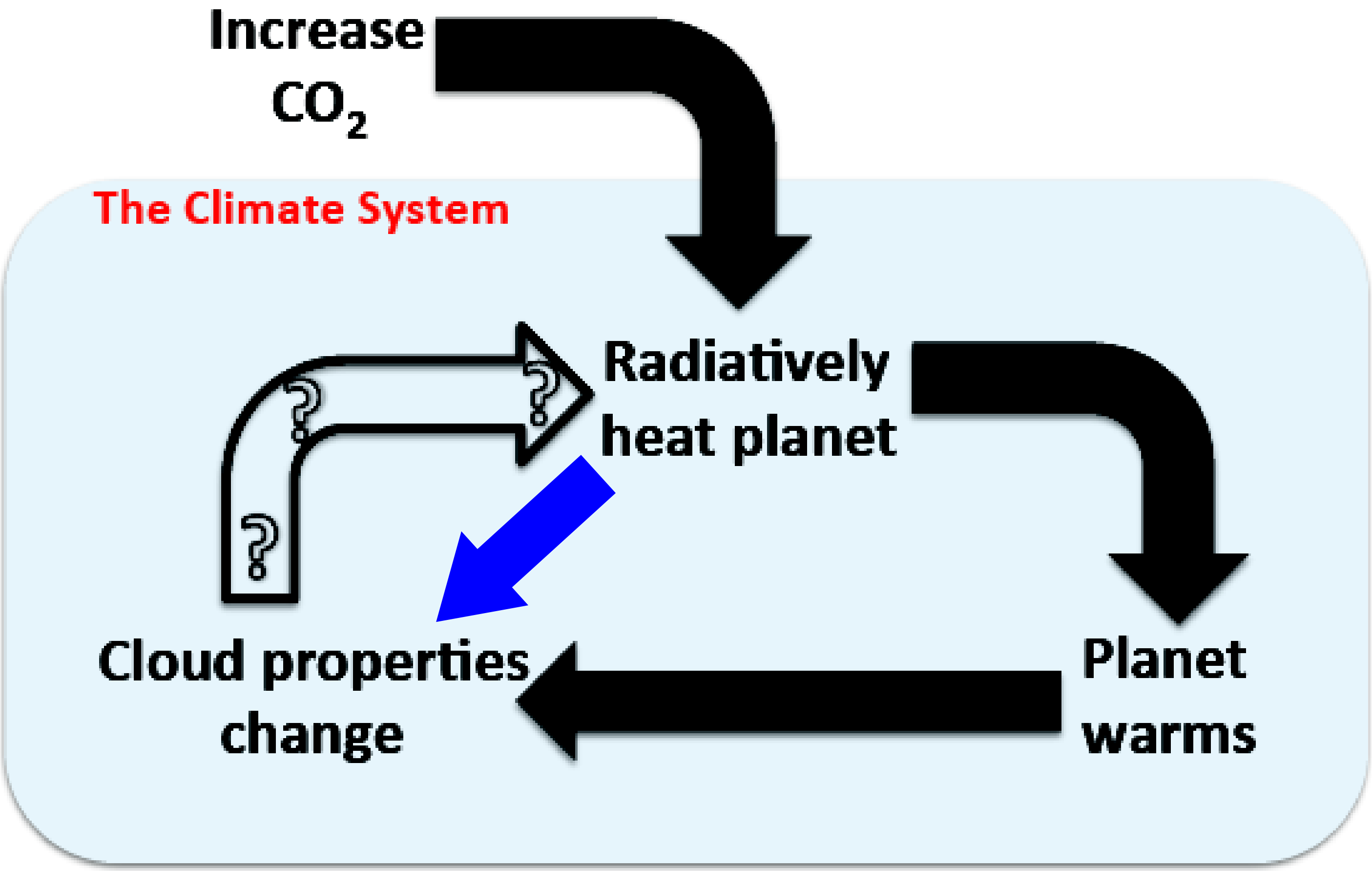
Radiatively heat planet

Planet warms

Cloud properties change

after Mark Zelinka (2013)

How does CO2 affect clouds ?



Two components :

Tropospheric adjustments + temperature-mediated responses

after Mark Zelinka (2013)

Important limitation of the classical framework

Part of the climate response to CO2 is not mediated by surface temperature changes.

What implications ?

Need to revisit the forcing / feedback framework

Revised Framework

let's assume that $R = R(\varphi, T_s, X)$ $\quad X = X(\varphi, T_s)$

$$\Delta R = \left[\left(\frac{\partial R}{\partial \varphi}\right)_{T_s,X} + \left(\frac{\partial R}{\partial X}\right)_{\varphi,T_s}\frac{\partial X}{\partial \varphi}\right]\Delta\varphi + \left[\left(\frac{\partial R}{\partial T_s}\right)_{\varphi,X} + \left(\frac{\partial R}{\partial X}\right)_{\varphi,T_s}\frac{\partial X}{\partial T_s}\right]\Delta T_s$$

instantaneous radiative change + *fast adjustments to φ*

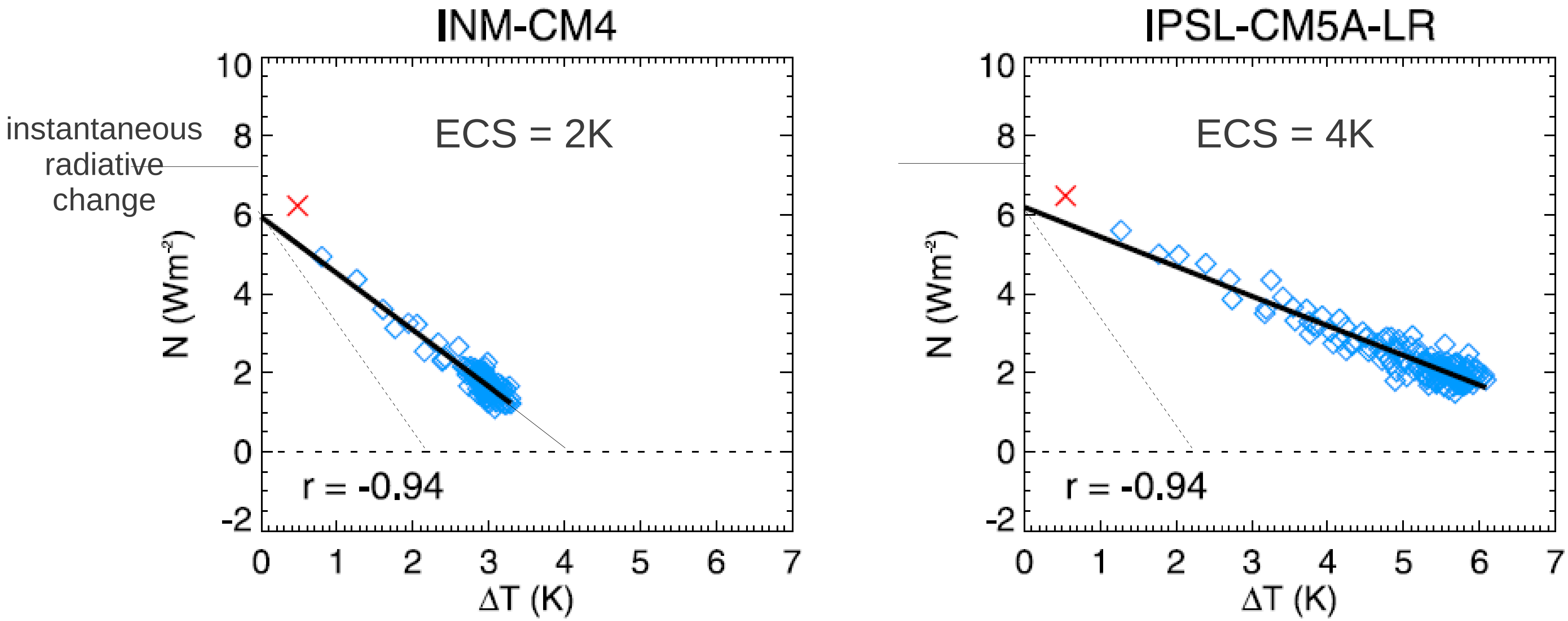
Planck response + *radiative feedbacks*

radiative forcing
(named « effective radiative forcing » in AR5)

climate response

CMIP5 models

Abrupt 4xCO2 experiment



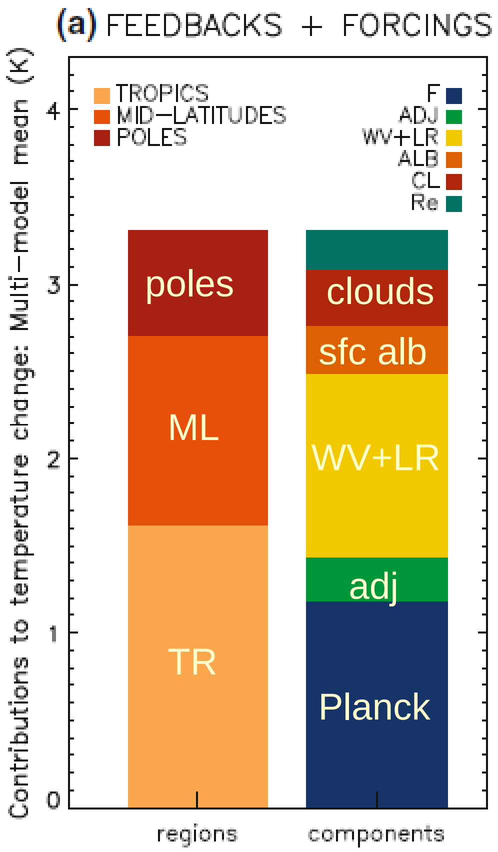
x 4xCO2 AGCM experiment with fixed-SST (30 year average)

(Andrews et al., GRL, 2012)

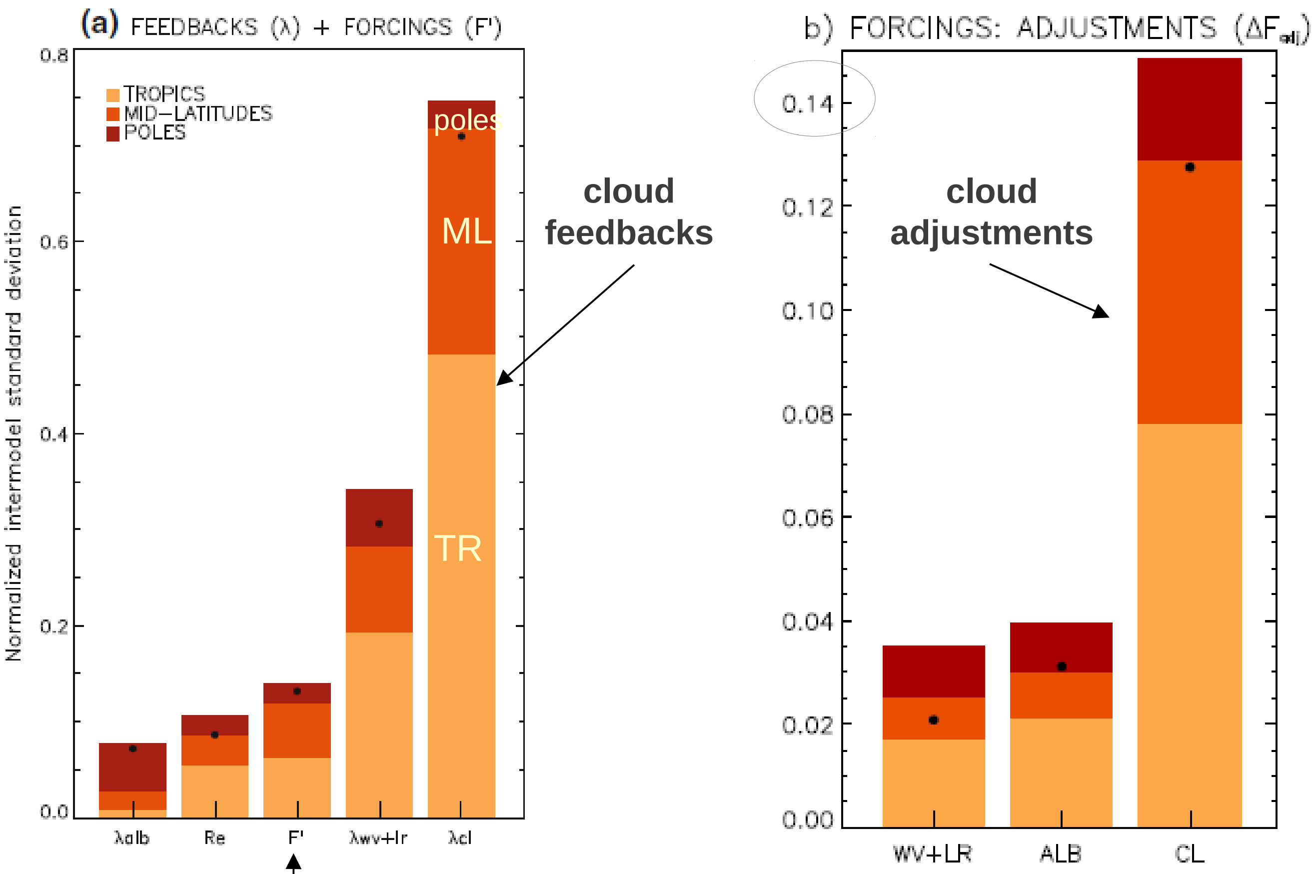
Application to CMIP5 models

Decomposition of CMIP5 climate sensitivity estimates

Multi-Model Mean



Inter-Model Spread



cloud feedbacks

cloud adjustments

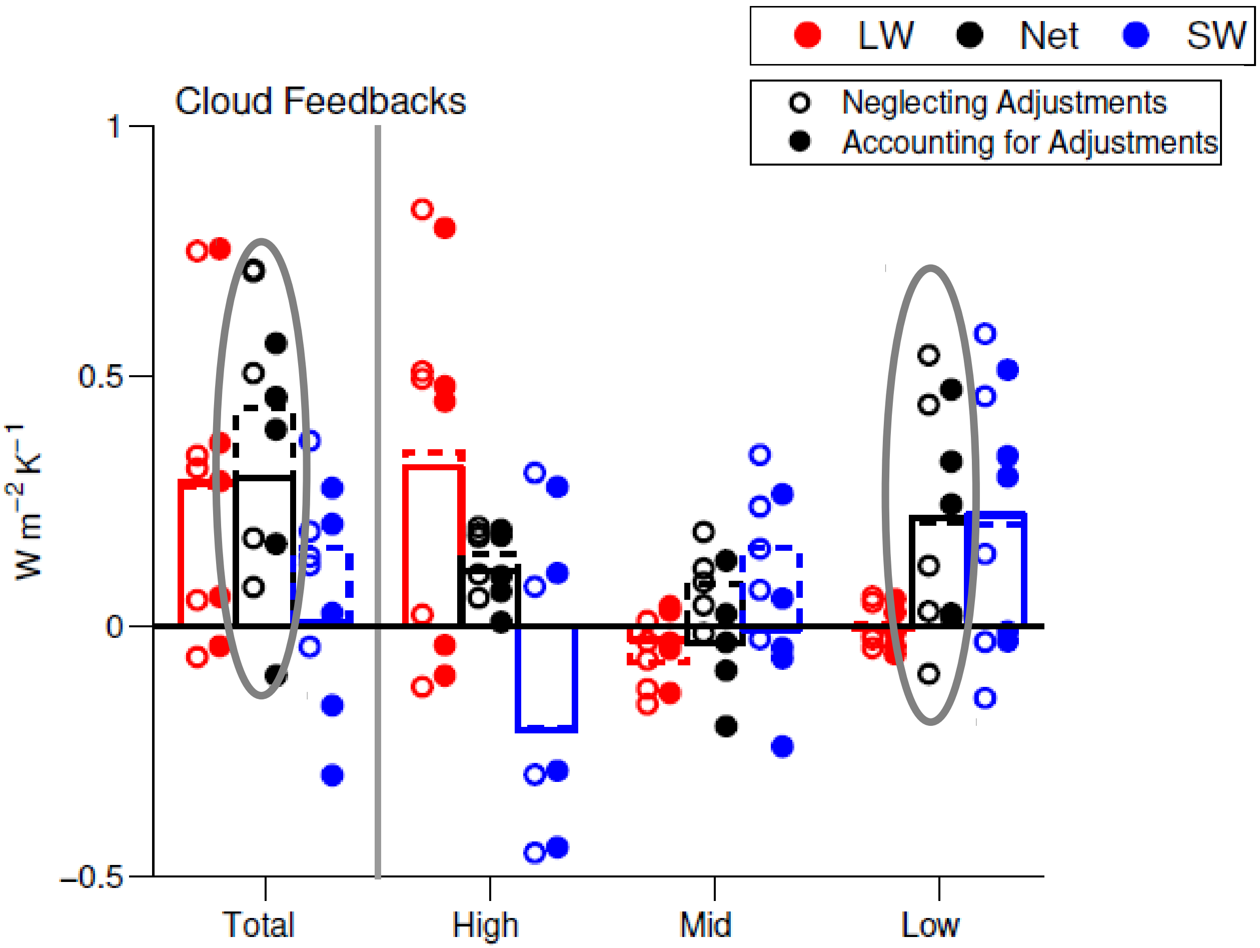
(adjusted) radiative forcing

Cloud feedbacks still constitute a leading source of uncertainty.

Vial et al., Clim. Dyn., 2013

How do the different cloud types contribute to global cloud feebdacks ?

CMIP5 Cloud Feedbacks



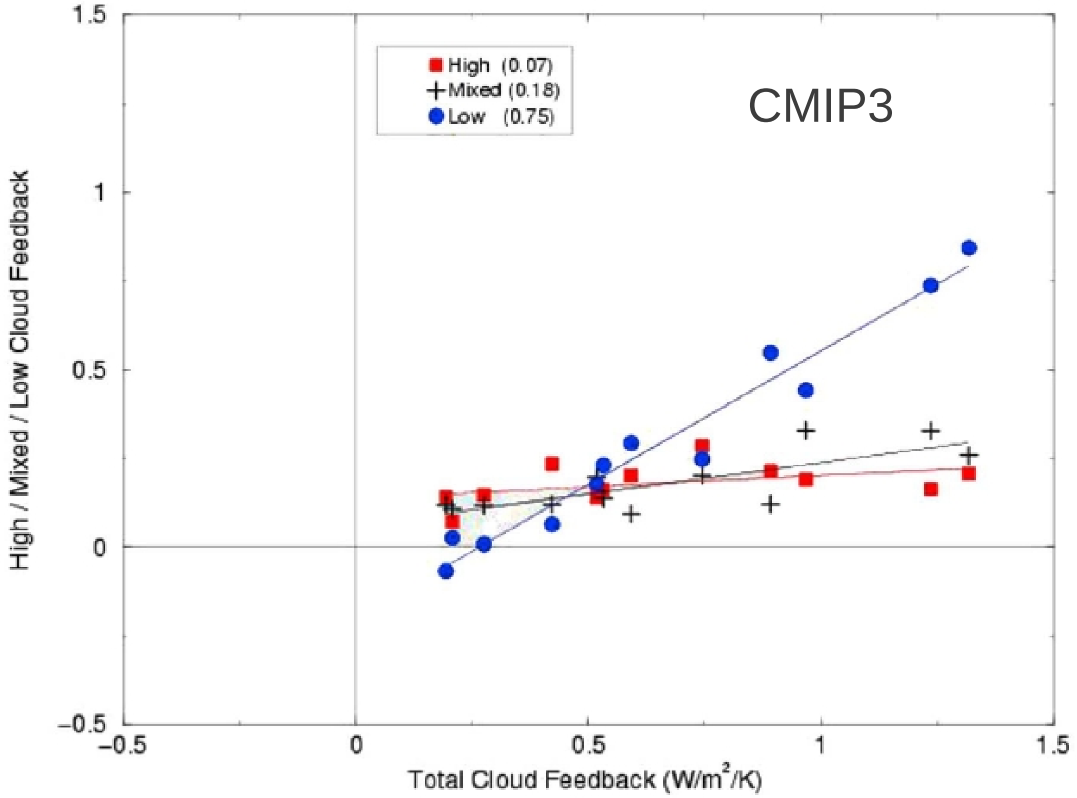
- Positive cloud feedback primarily arises from low-level and high-level cloud feedbacks

- Spread primarily arises from low-level cloud feedbacks

Zelinka et al., J. Climate, 2013

Low-cloud feedbacks dominate the spread of model cloud feedbacks

High/Mid/Low
cloud feedback



spread
low-cloud feedback

spread
high-cloud feedback

Total cloud feedback (W/m2/K)

Soden and Vecchi, GRL, 2008
also Bony and Dufresne, GRL, 2005
Webb et al., Clim. Dyn., 2006

Summary

- Our assessment of future climate change primarily relies on physical understanding
- Global energy balance analysis provides a useful framework to formalize the link between external radiative perturbations, clouds and climate sensitivity
- Two components in the clouds response to increased CO2 ; fast adjustments + feedbacks
- Adjustments and feedbacks may be diagnosed and decomposed in many different ways
- Most models produce a positive cloud feedback, but with a large spread in magnitude ; (Low) cloud feedbacks constitute the primary source of climate sensitivity uncertainty

Next :

Physical processes underlying cloud feedbacks