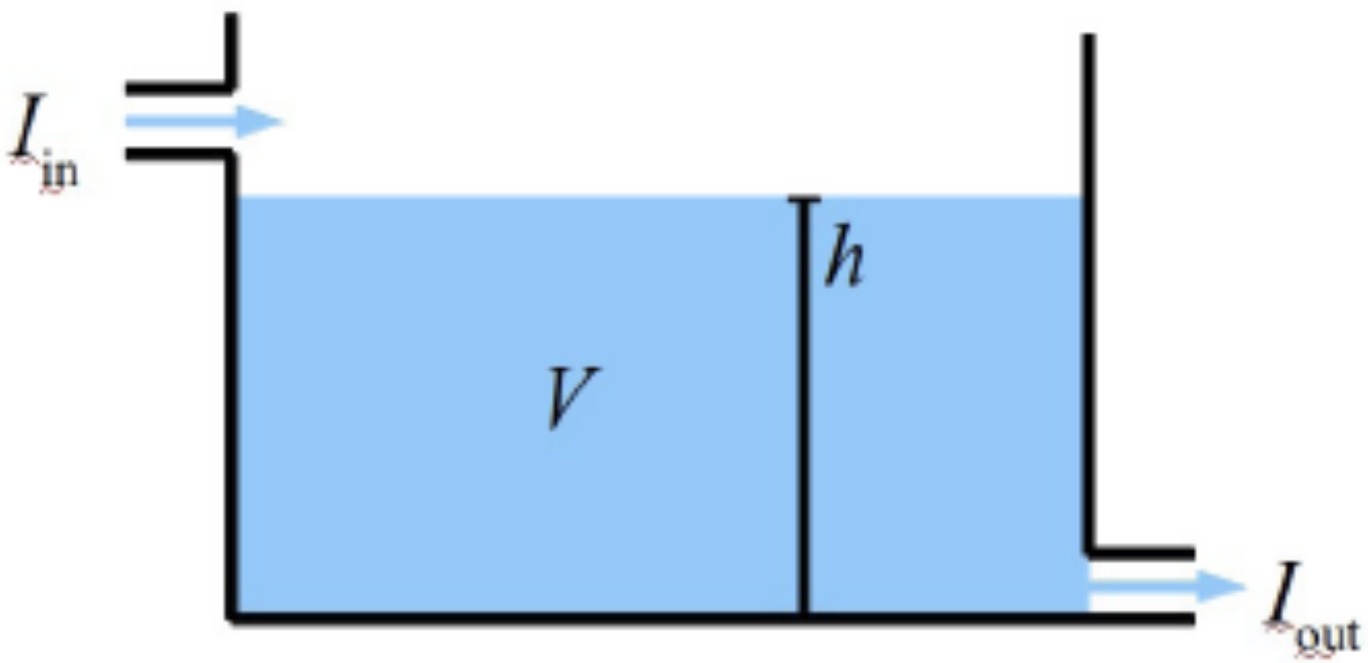
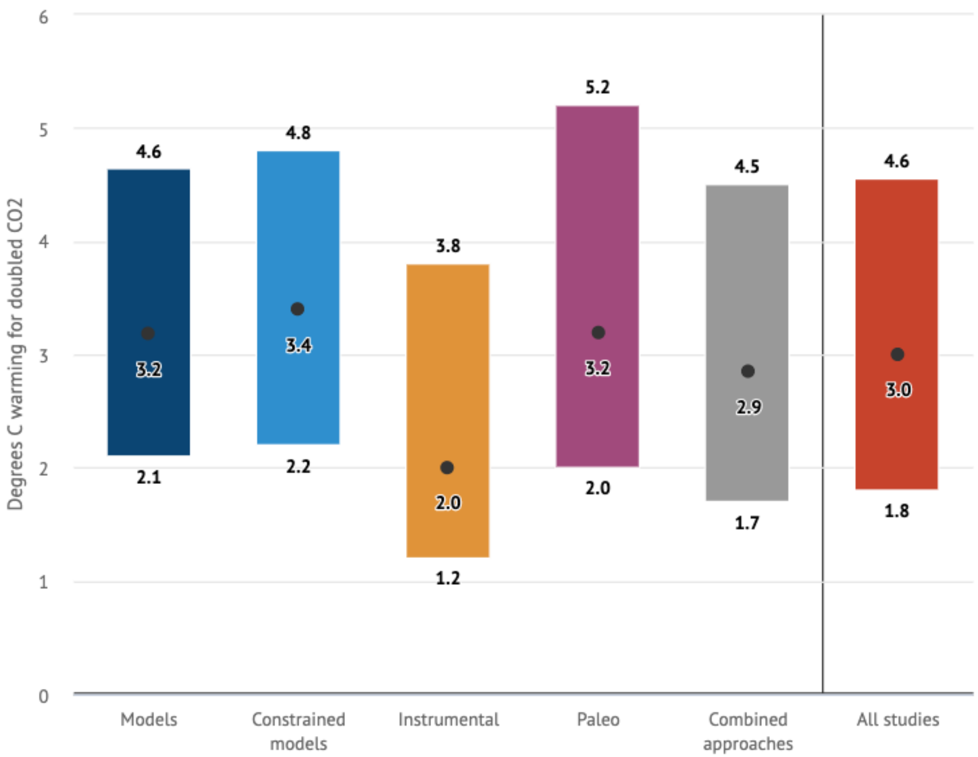
1. Feedback basics

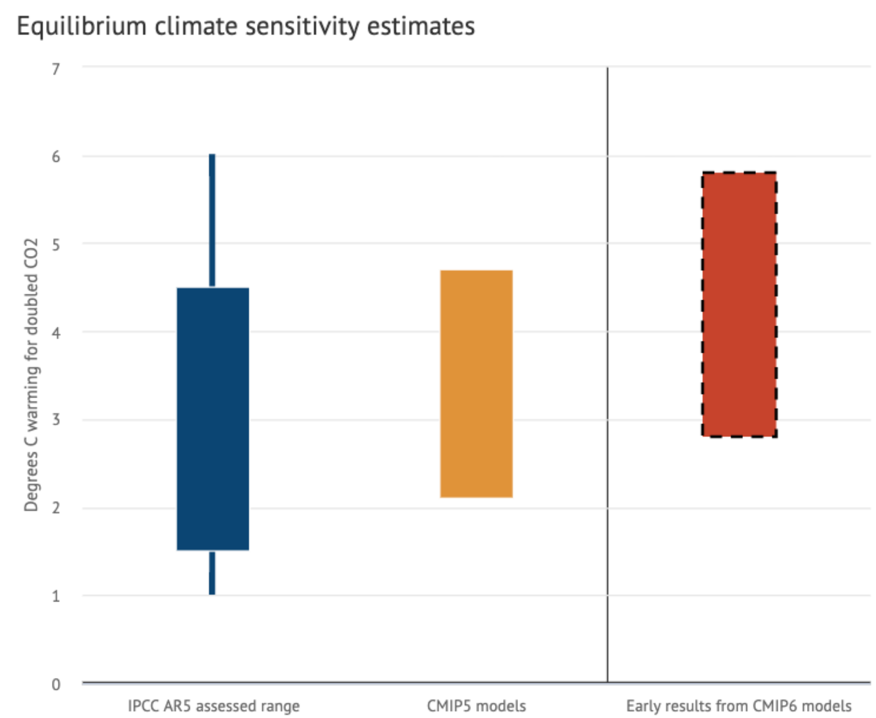


New GCM versions are running hotter

model estimates of the equilibrium climate sensitivity are increasing

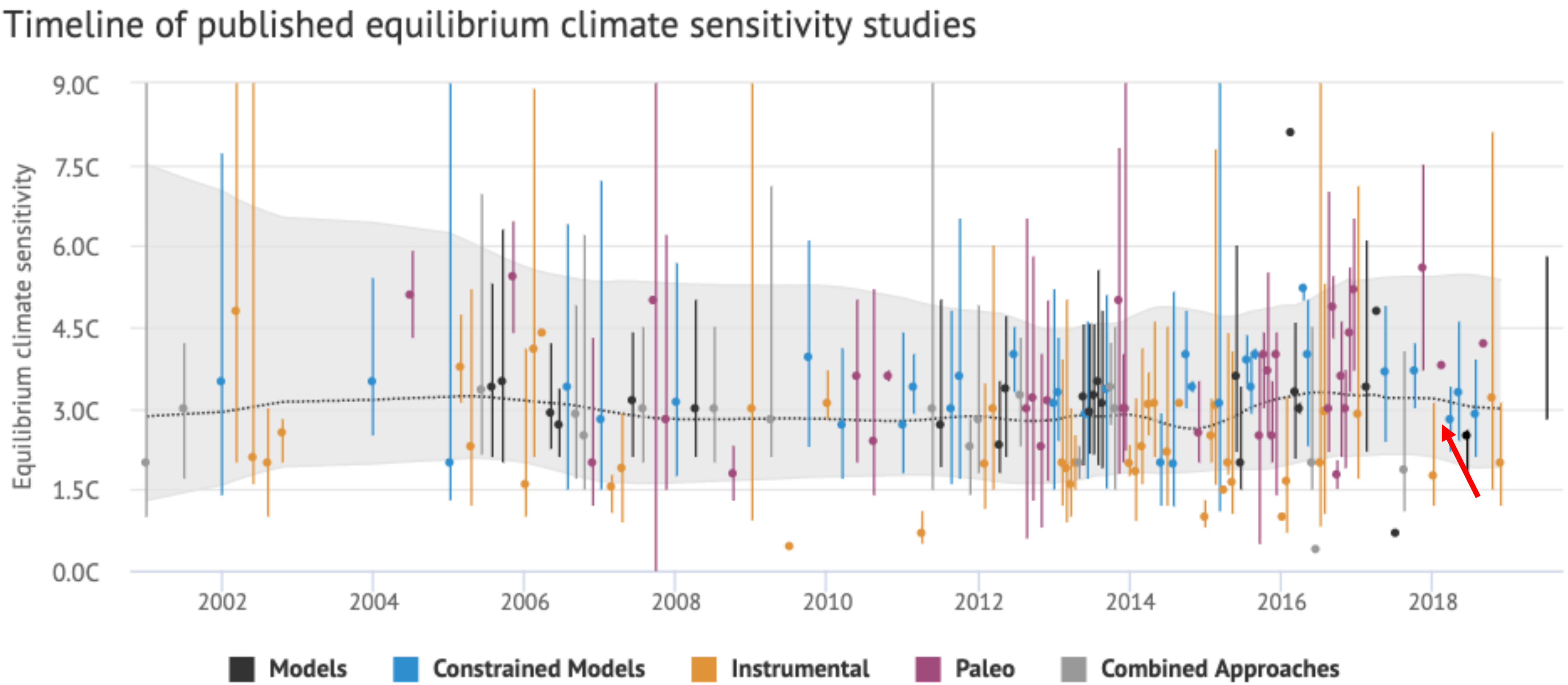


[Hausfather, 2018, Carbonbriefs]()



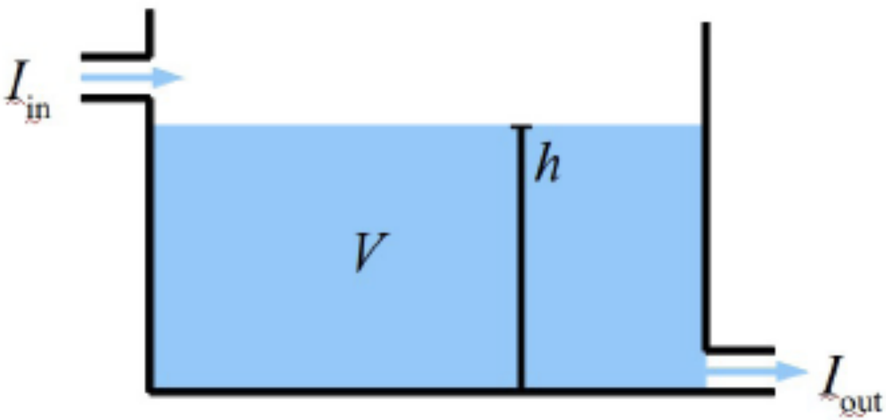
[Belcher et al., UK Met office, March 2019]()

This breaks a long, stable streak



Belcher et al., UK Met office, March 2019

Feedback math



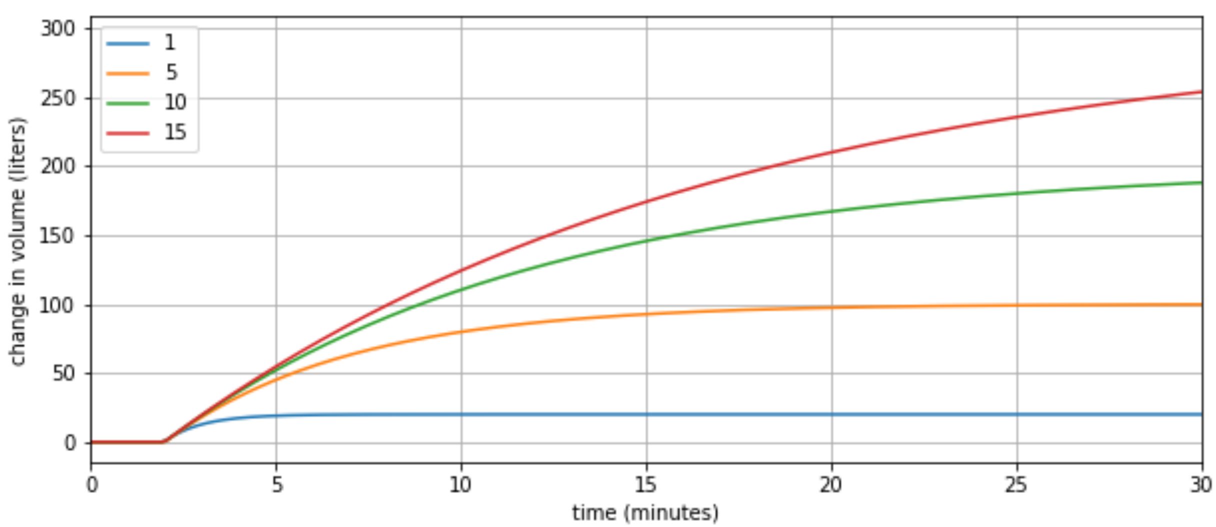
Strong negative feedback = big outflow pipe=big k

$$\frac{dV}{dt} = I_{in} - I_{out} = I_{in} - kV$$

$$\frac{d\Delta V}{dt} = \Delta I_{in} - \frac{\Delta V}{\lambda}$$

$$\Delta V_{final} = \lambda \Delta I_{in}$$

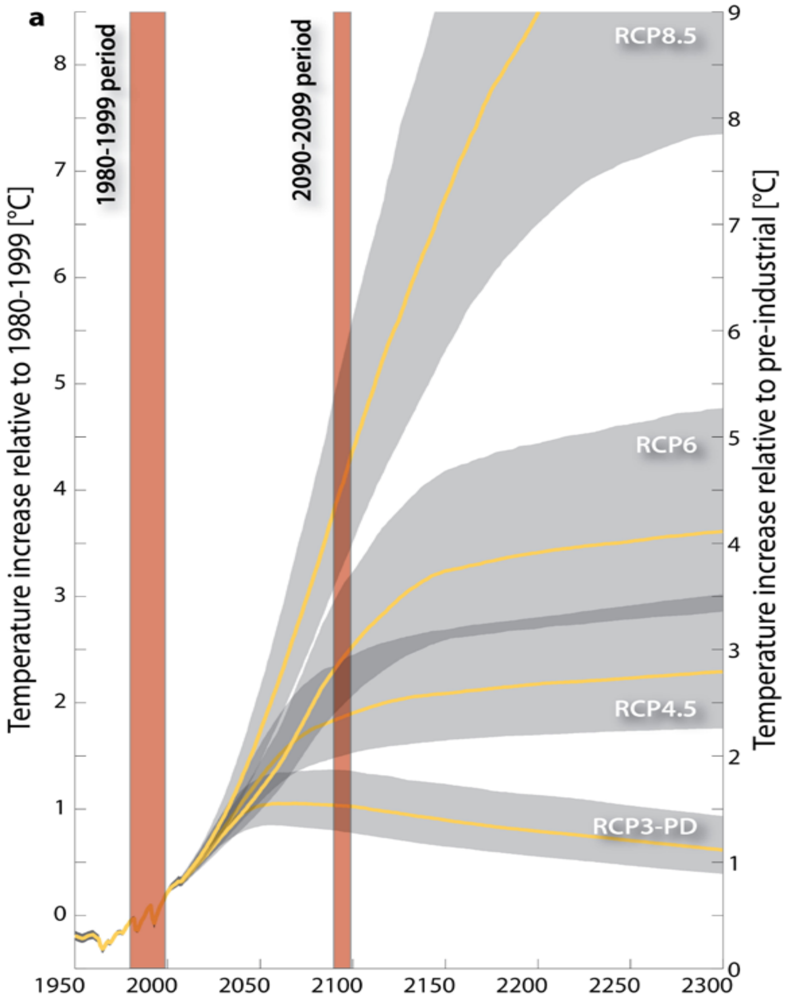
$$\Delta V(t) = \lambda \Delta I_{in} \left(1 - e^{-t/\lambda}\right)$$



As λ=1/k gets larger
Pipe gets smaller
Time constant increases
Equilibrium volume goes up

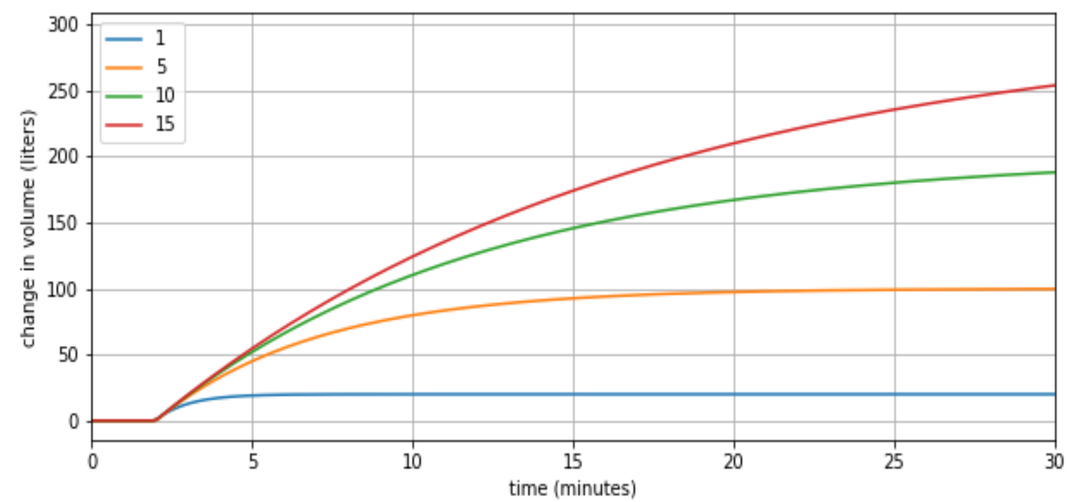
Note the similarity with CMIP 5
fully coupled atmos/ocean GCMs

CMIP5 models



AR5 chapter 11

Our bathtub



Feedback math

Write Climate Energy Budget as:

$$d\Delta E / dt = \Delta F + \Delta R \text{ with } \Delta R = f\,\Delta T$$

$$d\Delta E / dt = \Delta F + f\,\Delta T$$

1. An external change ΔF to the climate forcing

2. Climate system responds with a change ΔR to the surface radiative flux

Compare with the Climate Sensitivity

$$\frac{\Delta E}{dt} = \Delta F - \frac{\Delta T}{\lambda}$$

Therefore, the feedback factor is related to the climate sensitivity:

$$f = -1/\lambda$$

To a good approximation the total feedback is the sum of individual feedback factors, each representing a climate process:

$$\frac{d\Delta E}{dt} = \Delta F + (f_{PL} + f_{WV} + f_{LR} + \ldots)\Delta T = \Delta F + \left(\sum f_n\right)\Delta T$$

Feedback math

Can write feedback factor as $$f = \sum_n f_n = \Delta R / \Delta T$$

$$\Delta R = f \Delta T$$

In climate modelling, we attempt to estimate each feedback factor f_n for a given feedback mechanism '*n*' according to:

$$f_n = \frac{\Delta R_n}{\Delta T} = \left(\frac{\Delta R_n}{\Delta climate_n} \right) \left(\frac{\Delta climate_n}{\Delta T} \right)$$

where n=Planck, clouds, sea-ice, water vapor, etc.

ΔR_n is called the "radiative response" due to feedback n

In the case of sea-ice, it is negative (more negative upward radiation) when sea ice fraction increases, and positive (less reflection) when sea ice fraction decreases.

Individual feedback factors

Water Vapour FdBk: $$f_{wv} = \left(\frac{\Delta R}{\Delta H_2O}\right)\left(\frac{\Delta H_2O}{\Delta T}\right)$$ (Positive/Amplifying)

(Positive +) (Positive +)

Albedo Feedback: $$f_{ice} = \left(\frac{\Delta R}{\Delta ice}\right)\left(\frac{\Delta ice}{\Delta T}\right)$$ (Positive/Amplifying)

(Negative -) (Negative -)

Lapse Rate FdBk: $$f_{LR} = \left(\frac{\Delta R}{\Delta \Gamma}\right)\left(\frac{\Delta \Gamma}{\Delta T}\right)$$ (Negative/Stabilizing)

(Negative -) (Positive +)

Cloud Feedback: $$f_{clouds} = \left(\frac{\Delta R}{\Delta clouds}\right)\left(\frac{\Delta clouds}{\Delta T}\right)$$ (± depends on the altitude of the cloud)

Tip: Think of fraction like a derivative and treat it independently

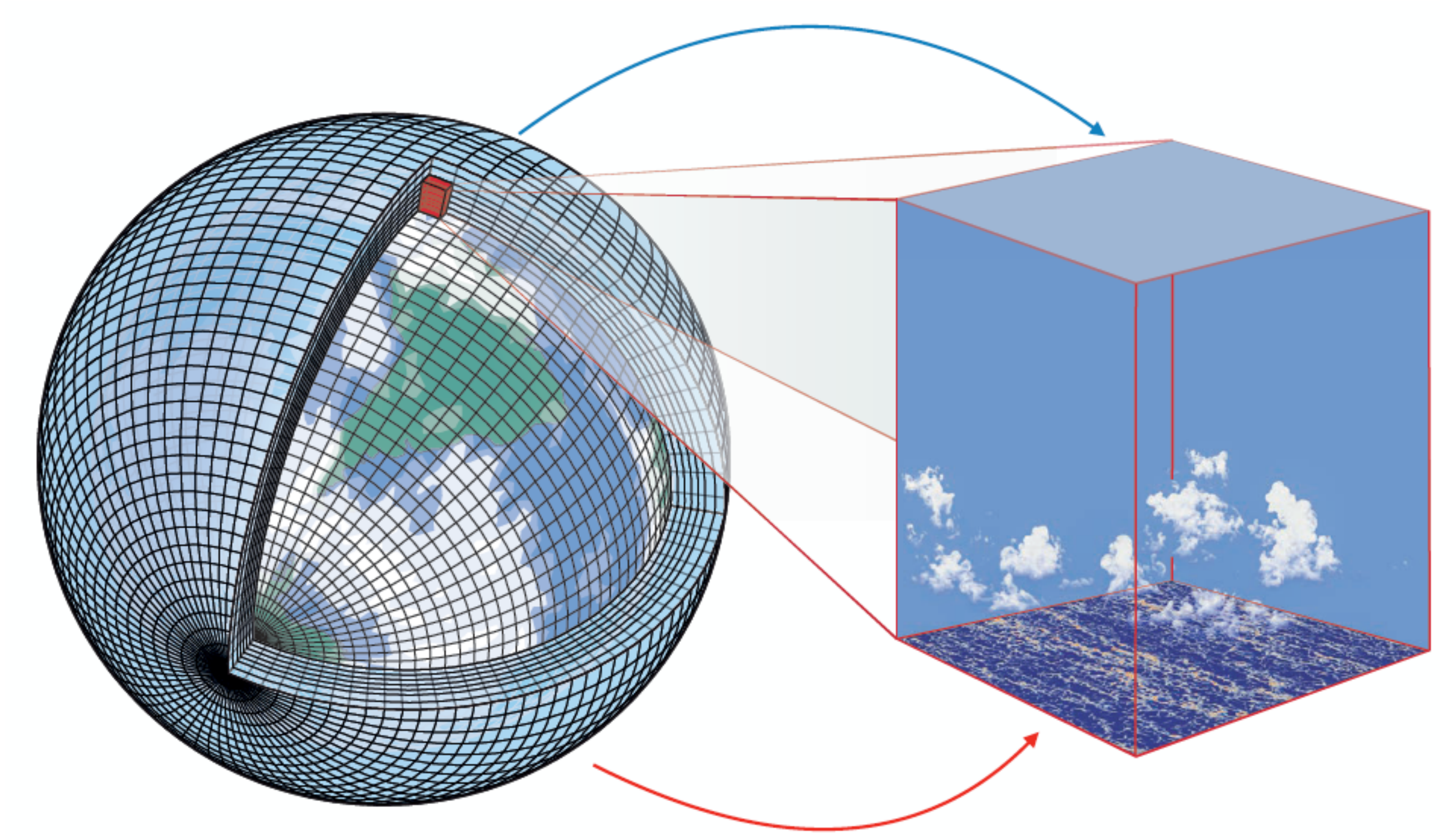
1. Summary

$$f_{ice} = \left(\frac{\Delta R}{\Delta ice}\right)\left(\frac{\Delta ice}{\Delta T}\right)$$

- Finding the paired derivatives in terms like f_{ice}
  is a better use of computer time that
  running “black box” projections for a range of forcings

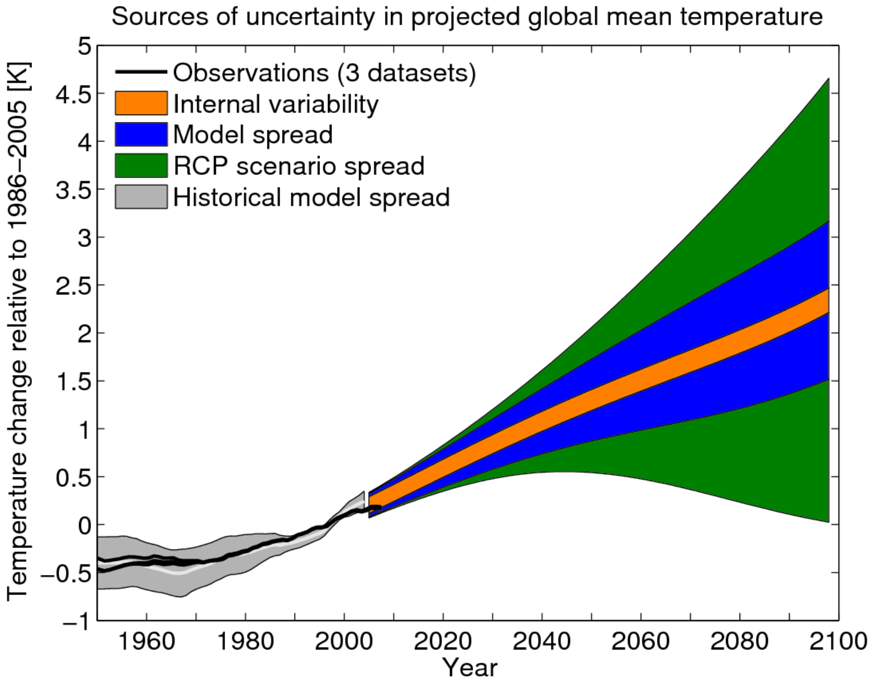
- The first term is called the “radiative kernel” and can be calculated offline using the models radiation code, or a single kernel can be shared between models
- The second term requires the full GCM, it is the derivative that accounts for all the feedbacks

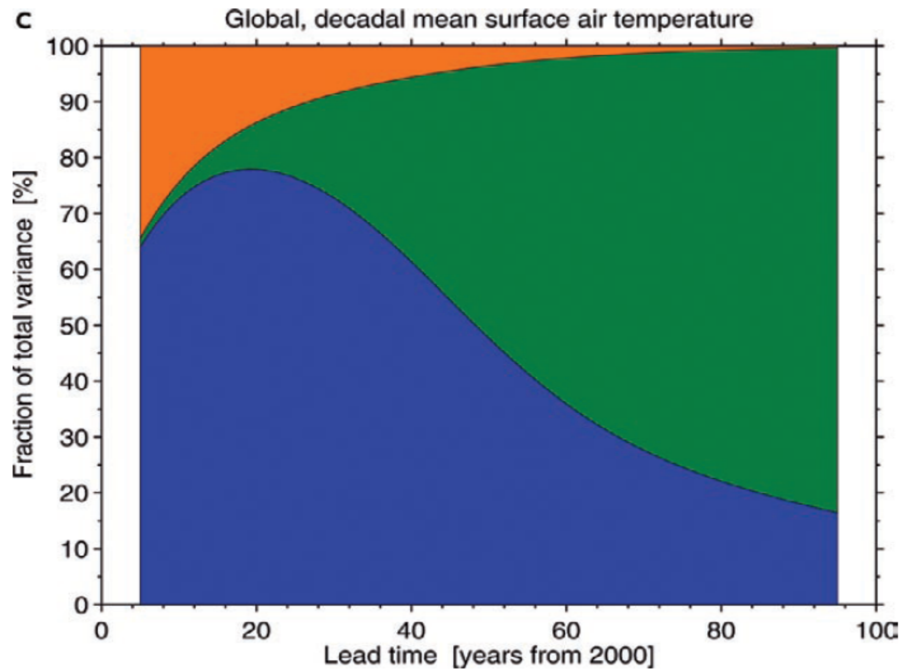
2. Estimating feedback



Schneider et al., 2018

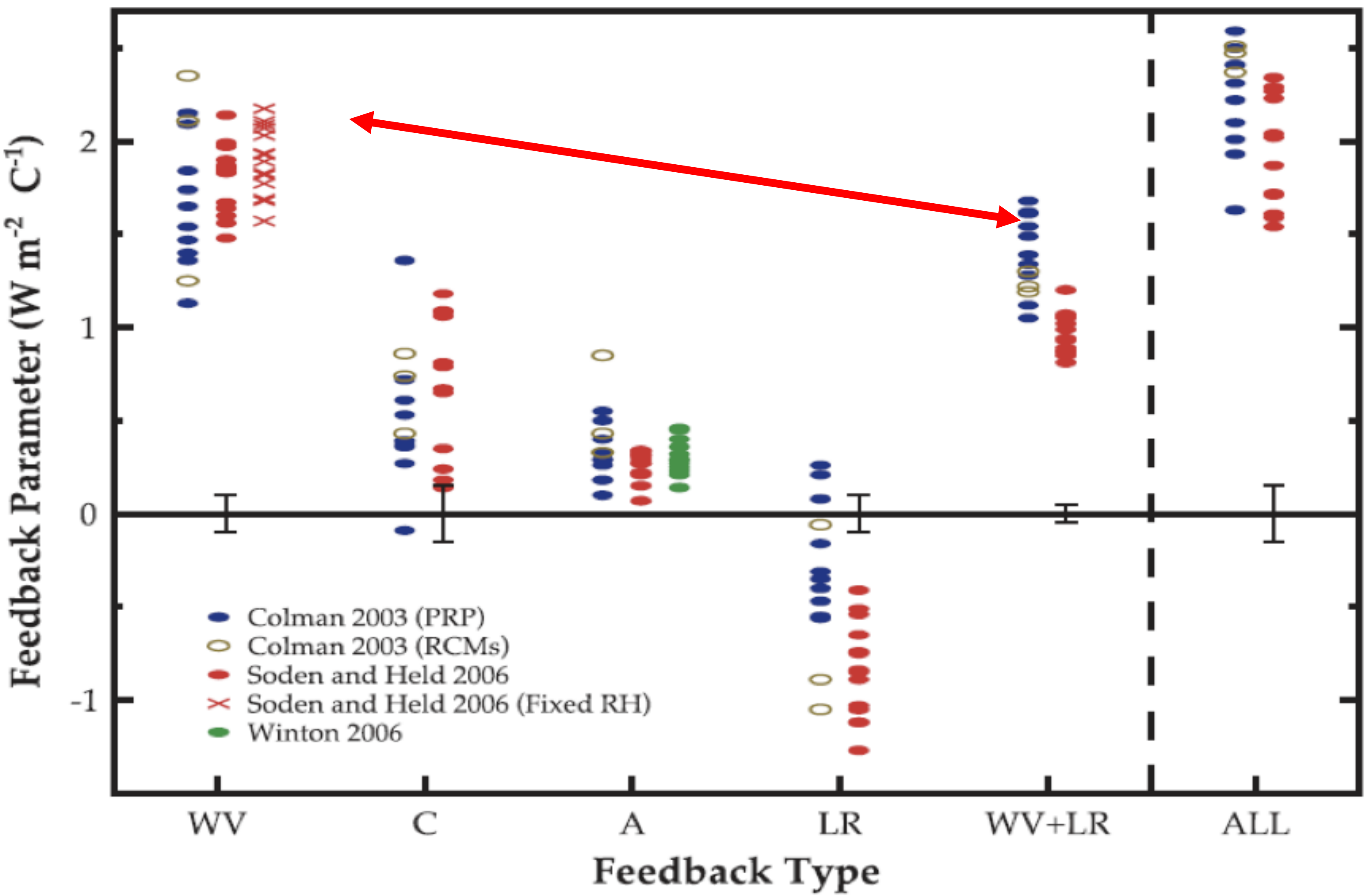
Caveat: policy dominates physics





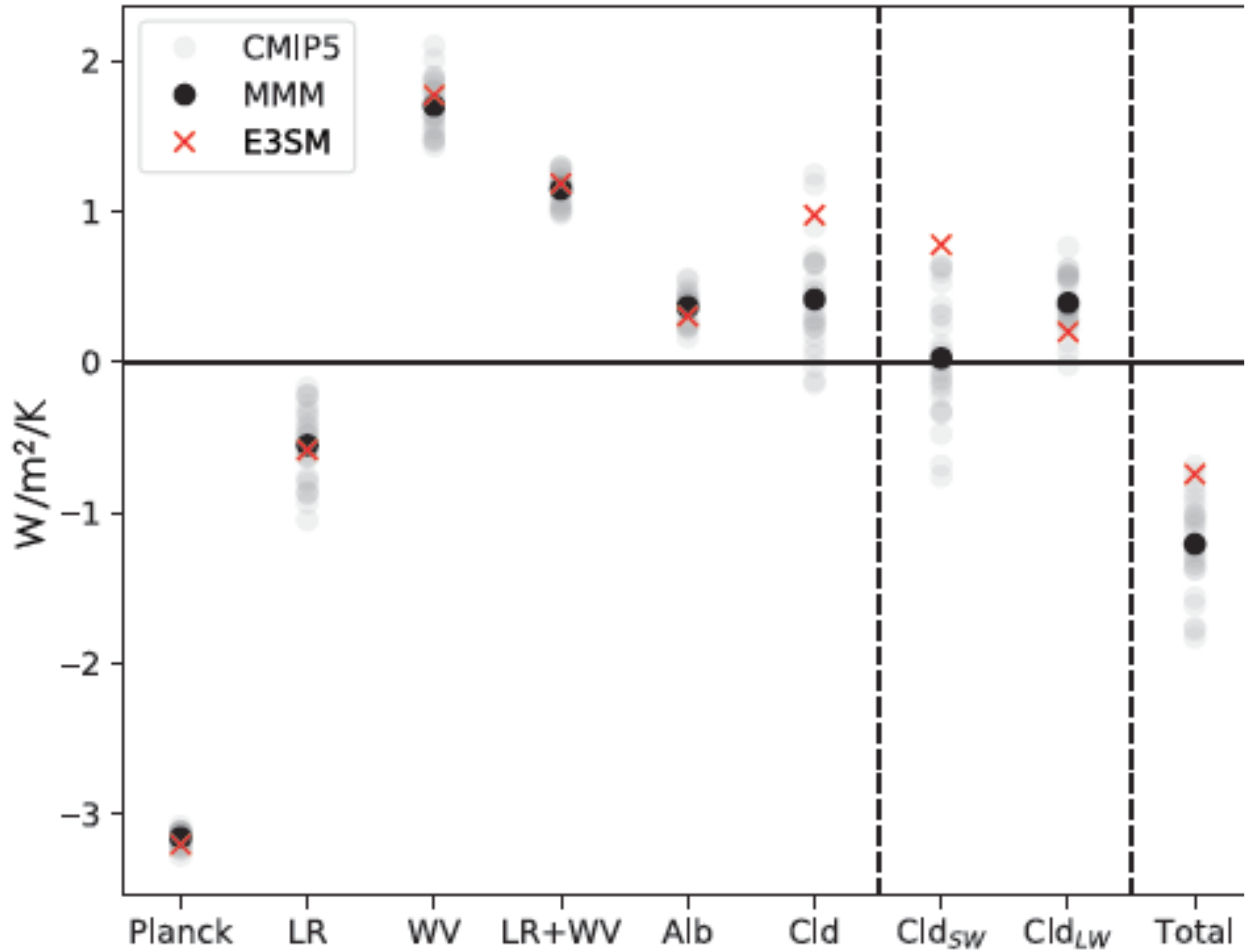
IPCC AR5 Figure 11.8

Feedbacks from models ca 2005
(for comparison remember f_{planck}= -4 Wm^{-2} K^{-1})



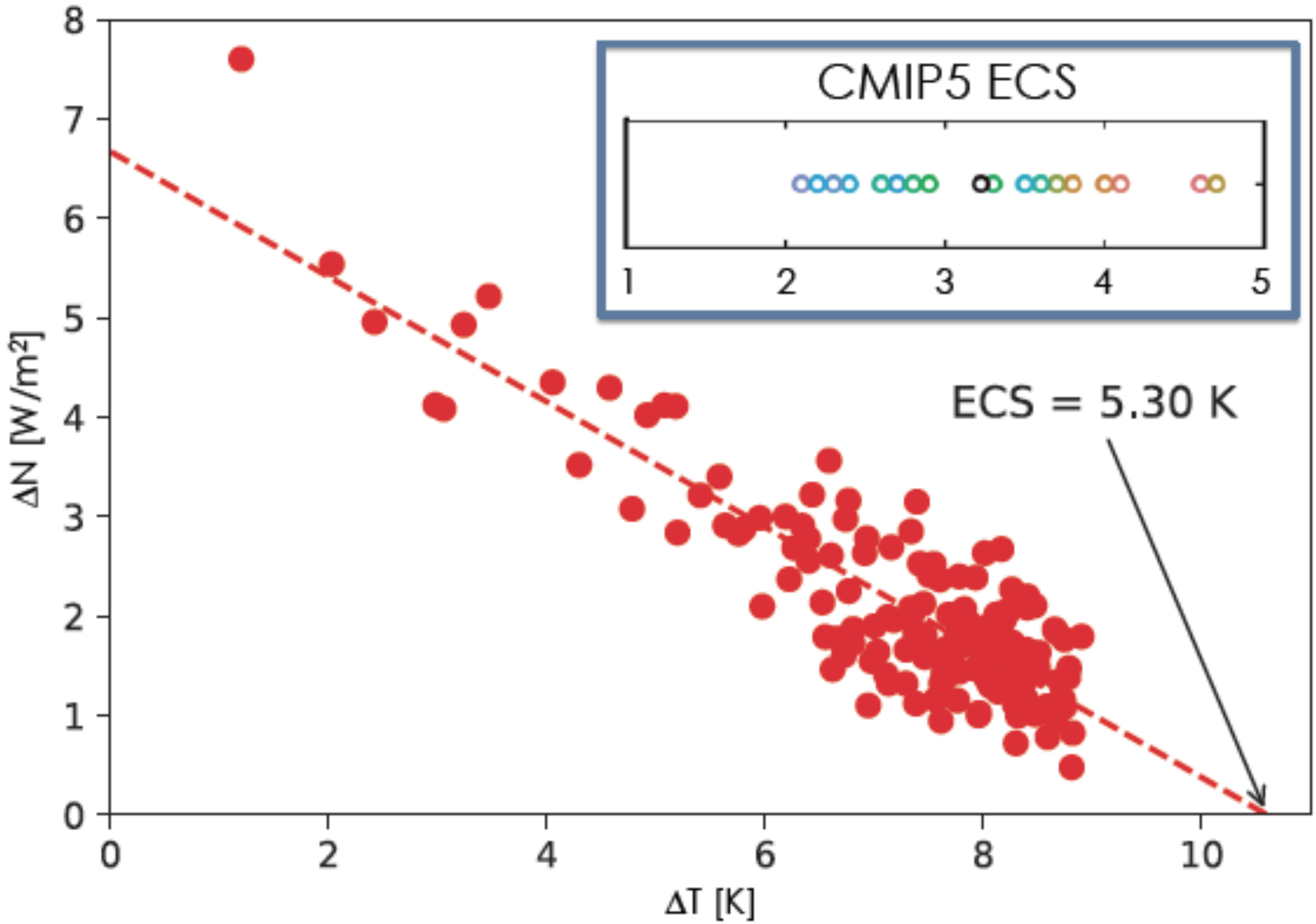
wv=water vapor, c=clouds, a=ice albedo, lr=lapse rate, wv+lr=combined wv and lr

Feedbacks from models ca 2018



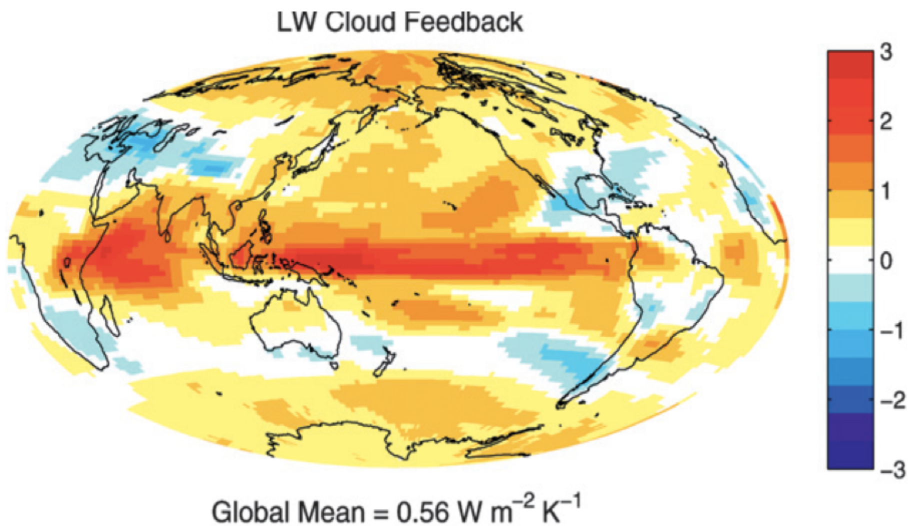
Zelinka et al. 2018

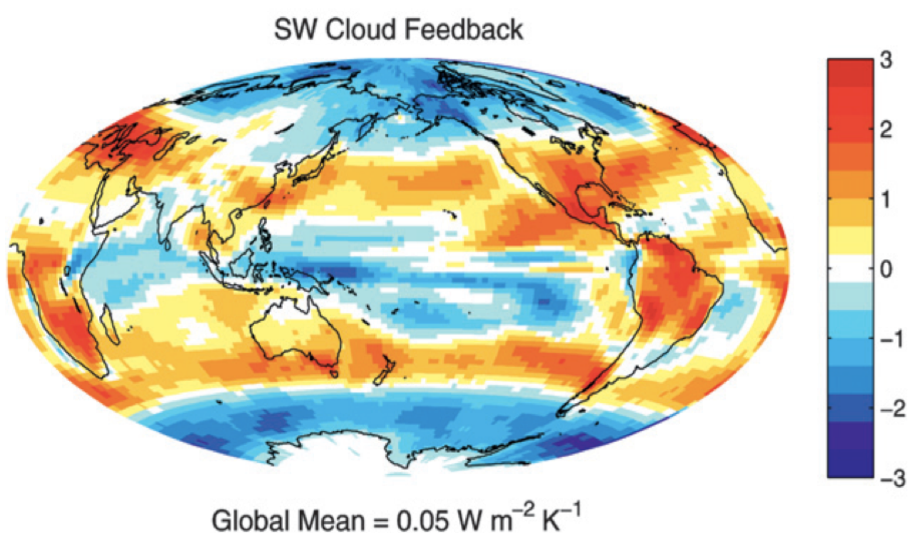
A Gregory plot for sensitivity



Zelinka et al. 2018

Spatial feedbacks with radiative kernels





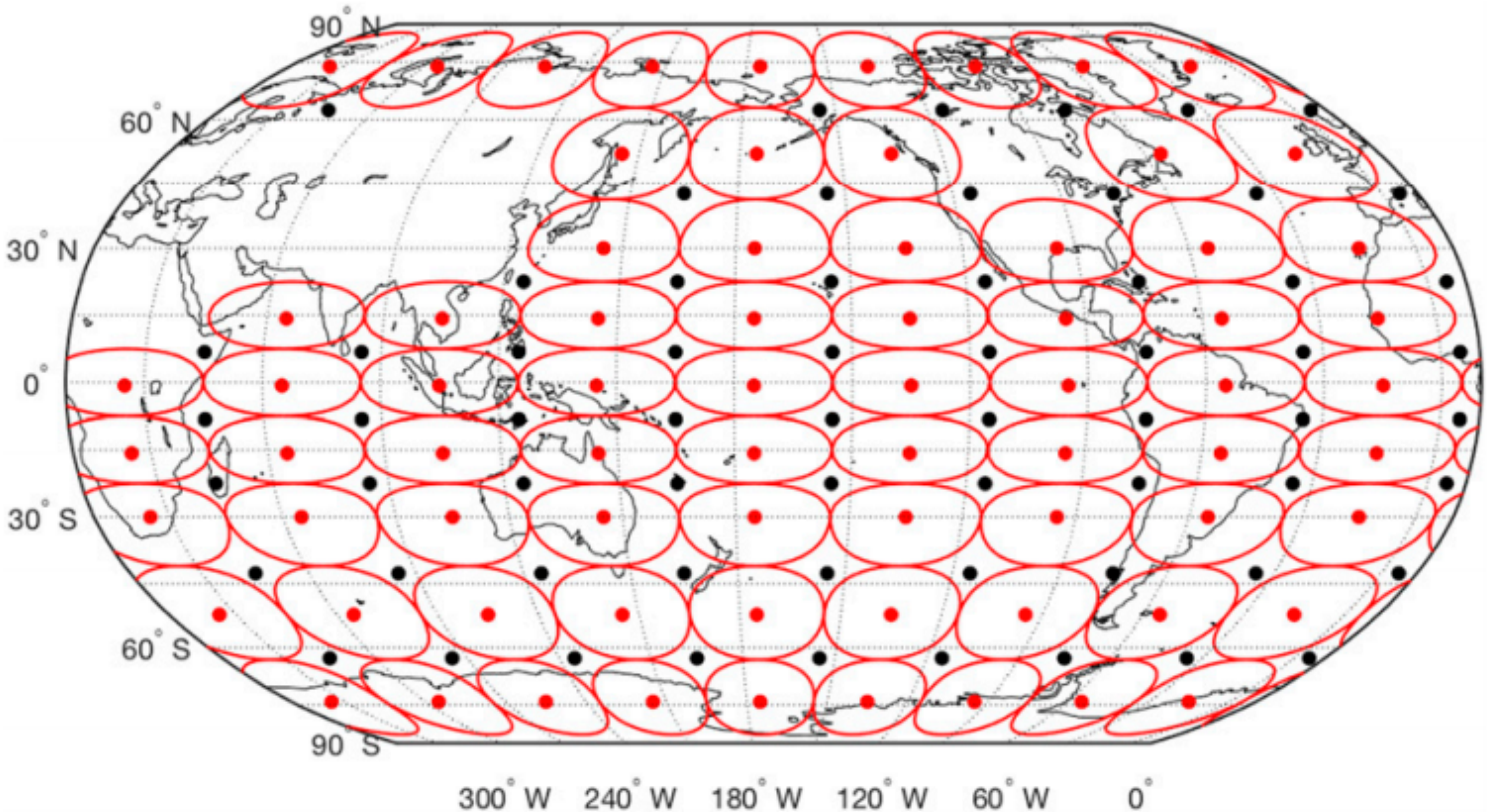
Zelinka et al., 2013

- Run a climate model
- Increase sea surface temperatures by 2K
- Measure changes to ΔR due to clouds

$$f_x = \frac{\Delta R}{\Delta T} = \left(\frac{\Delta R}{\Delta climate}\right)\left(\frac{\Delta climate}{\Delta T}\right)$$

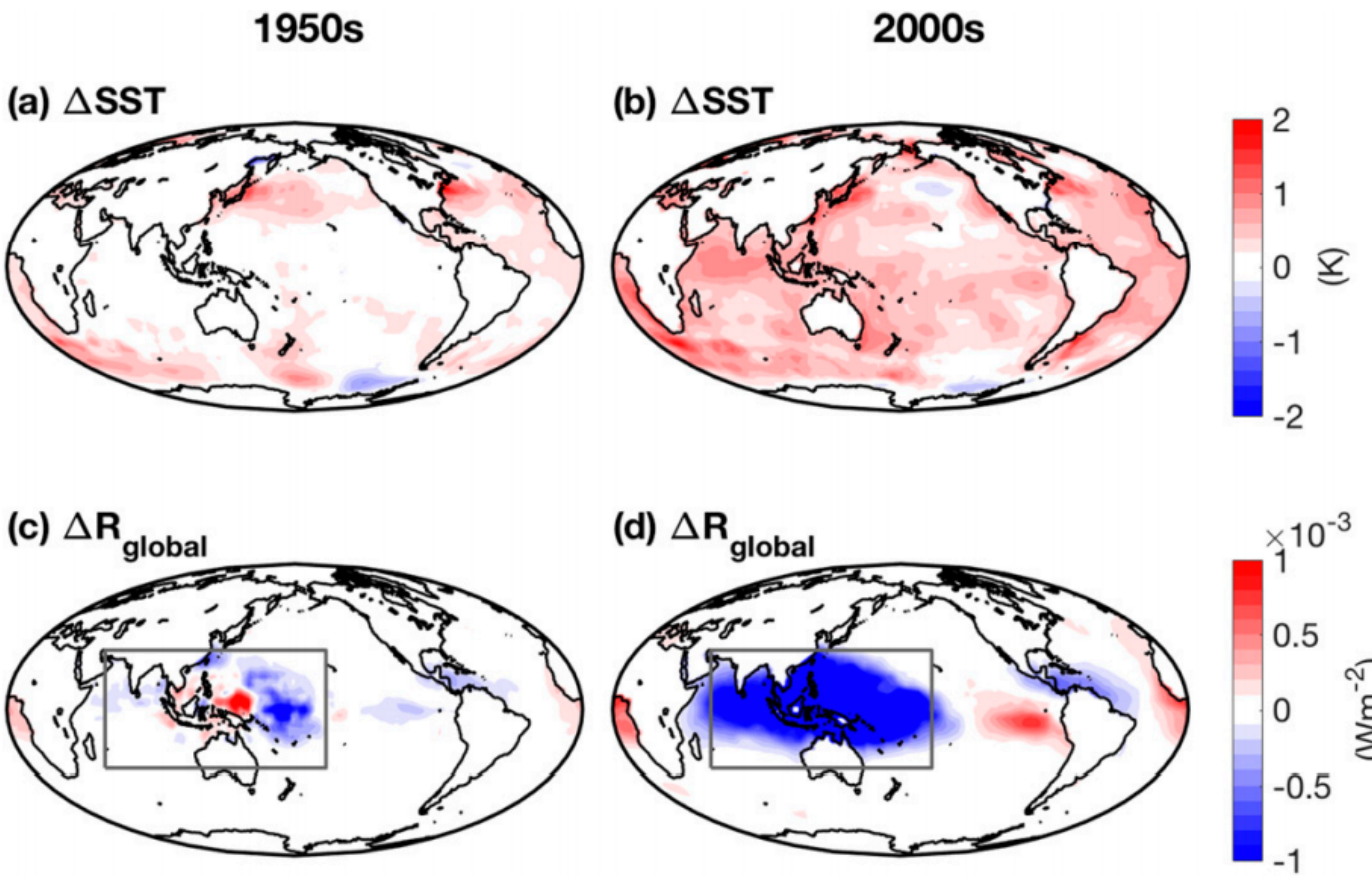
Note the long and shortwave feedbacks approximately cancel for deep convection in the tropics

Next level: Green's functions



Y Dong, C Proistosescu, KC Armour, DS Battisti, 2019

Temperature perturbations in the western Pacific warmpool dominate the radiative response (negative ΔR is heating)



3. Summary

- Long and shortwave cloud feedback estimates differ significantly between models
- Many groups are working on analyses of the physical mechanisms behind the feedback, using a variety of techniques (radiative kernels, patterned SST, Green’s functions, high frequency output at specific locations, aquaplanet runs, cloud condensate tendency runs, etc.