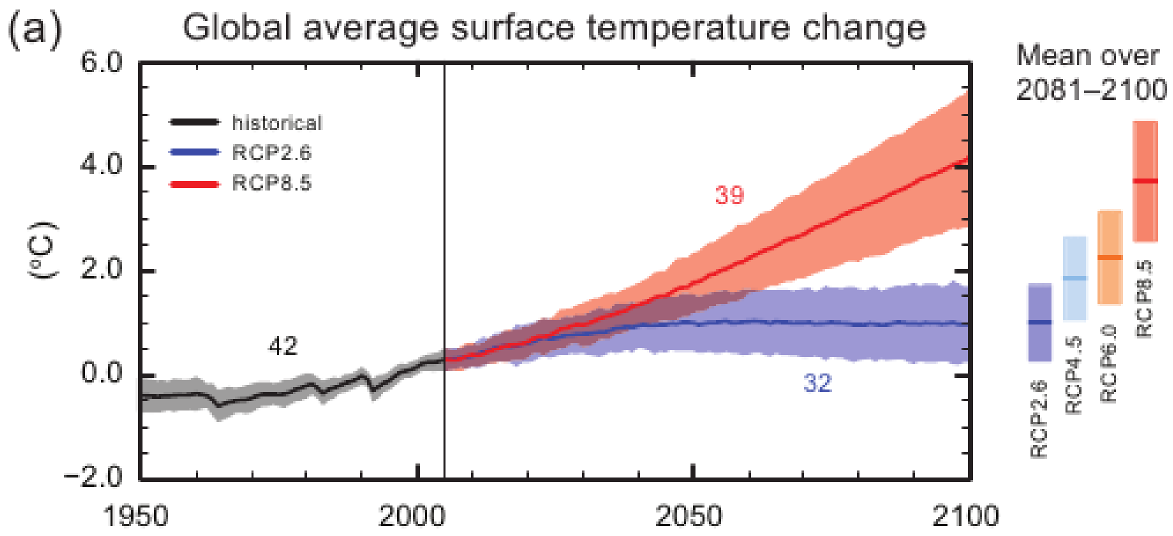
Climate Scenarios



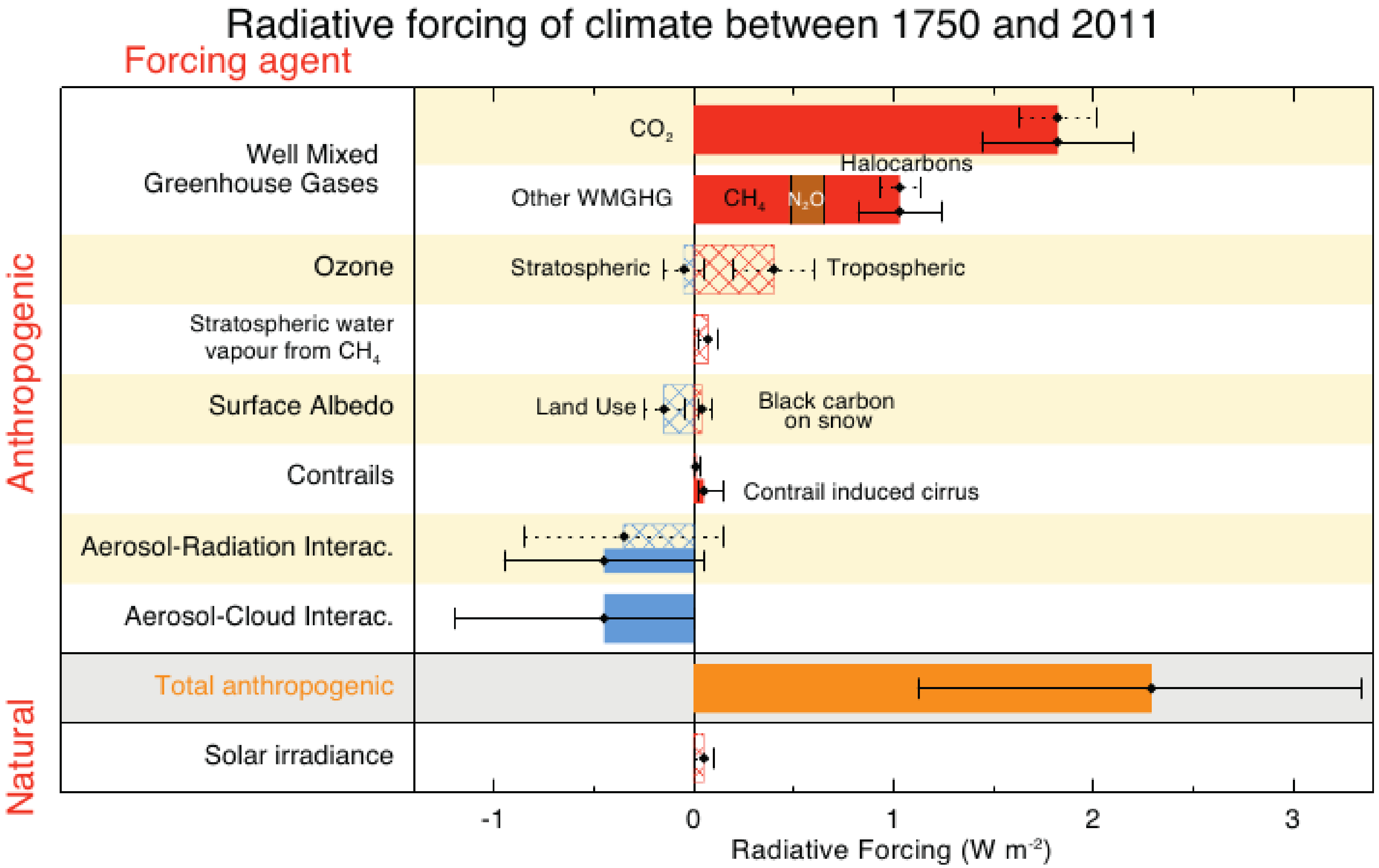
RCP: Representative Concentration Pathways

with xx Wm^{-2} applied total radiative forcing in 2100 relative to 1750

e.g. 2.6 Wm^{-2} for RCP2.6

IPCC AR5 (2013)

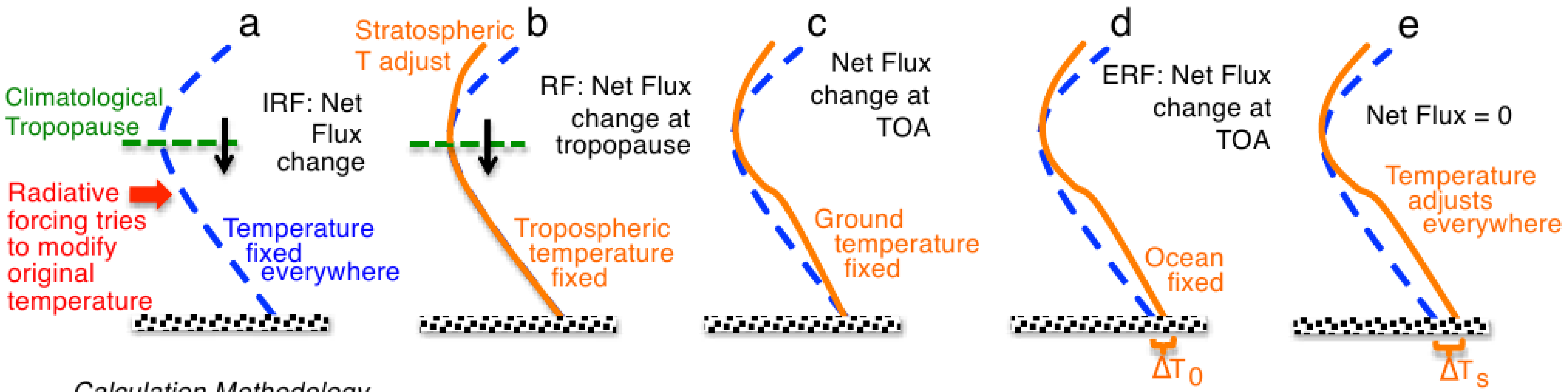
Forcing Agents



IPCC AR5 (2013)

Comparison of forcing definitions

IPCC AR5 (2013), Chapter 8, following Hansen et al. (JGR,2005)



	Instantaneous RF	Stratospherically adjusted RF	Fixed Tsurf RF	Fixed SST RF = ERF (ΔT_0 = Land temp. change)	Equilibrium near surface temperature change = Climate Sensitivity
Calculation Methodology	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

Definitions

First principle concept:

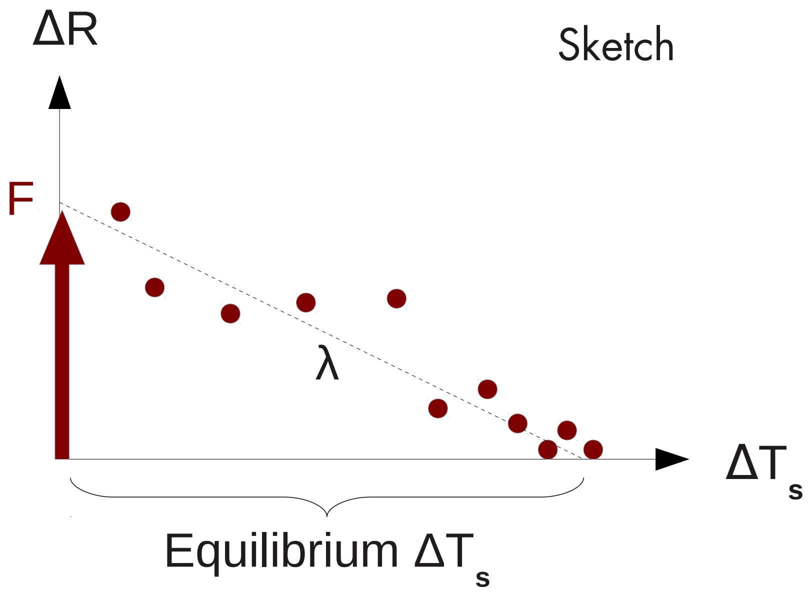
$$\Delta R = F + \lambda \Delta T_s$$

ΔR = change in net radiation at top of atmos.

F = radiative forcing (ΔR for $\Delta Ts = 0$)

λ = feedback parameter

ΔT_s = change in surface temperature



Radiative forcing (Wm^{-2}) is the instantanious change in TOA net radiative flux induced by a forcing agent, e.g. GhGs, Aerosols, Solar Irradiance, …

Radiative feedbacks ($Wm^{-2}K^{-1}$) show the adapting behaviour of the system in response to the forcing. They depend on the change in global (near) surface temperature and act slowly over longer timescales (decades).

Climate Sensitivity is the equilibrium change in global mean temperature in response to a doubling in CO2.

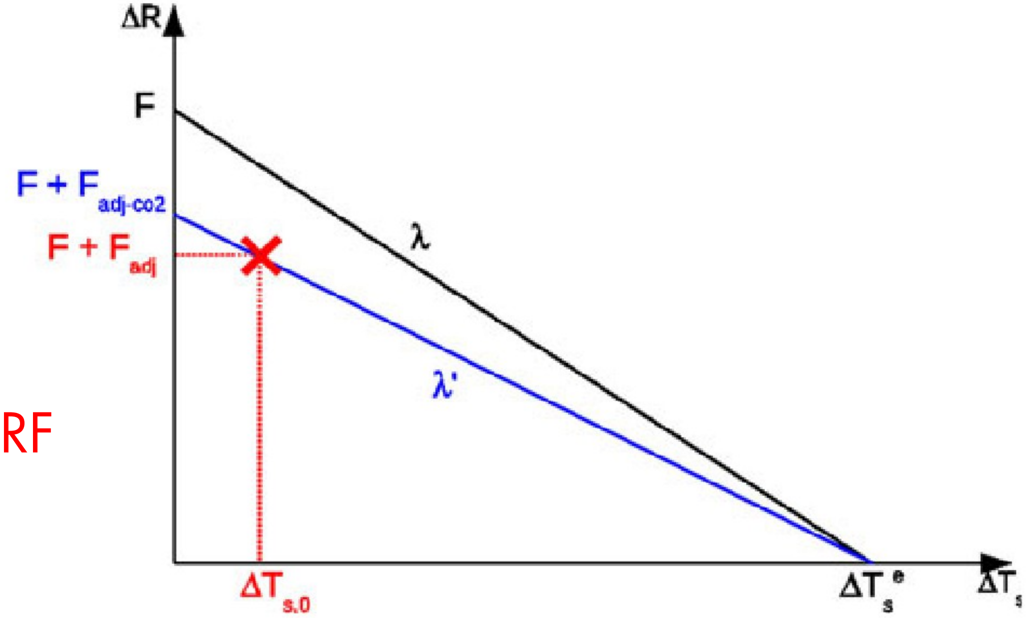
RF vs ERF

Vial et al. (ClimDyn.,2013)

Stratosphere adjusted RF

Stratosphere + Troposphere adjusted RF with fixed Tsurf

Stratosphere + Troposphere adjusted RF with fixed SST = ERF



➤ different forcing → different feedback

Experiments and their applications

- **abrupt forcing experiments (2x/4x/8x CO2):**
  → estimate of ERF, rapid adjustments, feebacks, climate sensitivity

- **transient forcing experiments (1% CO2 increase/year)**
  → estimate role of ocean heat uptake to feedback evolution

- **sstClim experiments (prescribed SSTs from CTRL simulation)**
  → allows no feedback estimation as SSTs are fixed
  → estimate relative relation of land and ocean warming,
  distuingish surface mediated from tropospherically adjusted responses

- **AMIP experiments (prescribed SSTs & Sea Ice from observations)**
  → similar to sstClim, but observationally constrained

- **Cess-type experiments (instead of forcing by CO2, uniformly increase of SSTs)**
  → estimating feedbacks without considering fast adjustments/forcing
  → after Cess et al.(JGR,1990)

Feedbacks

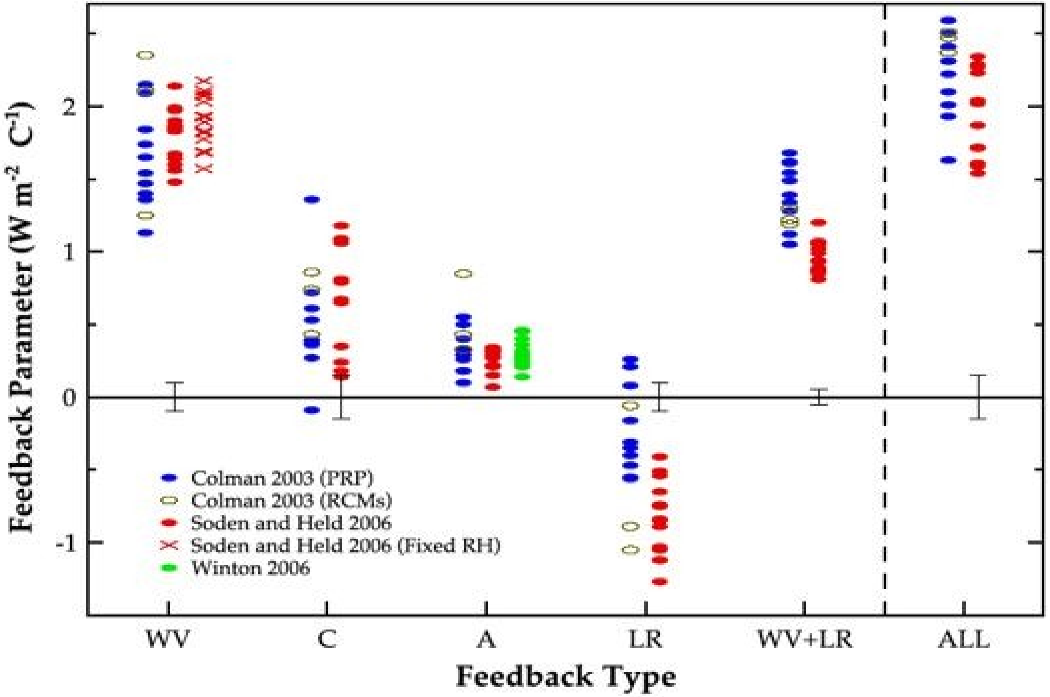
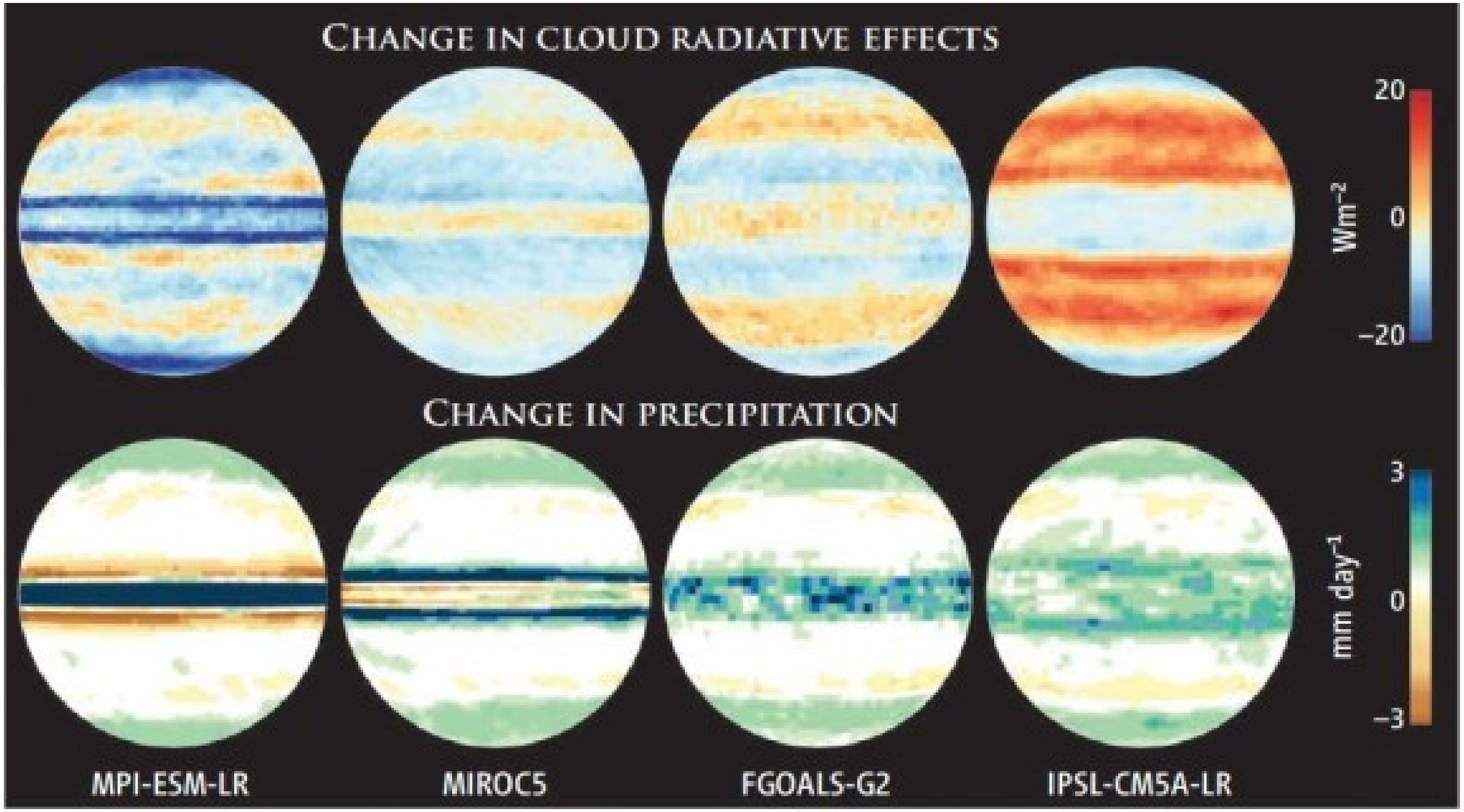


Figure 8.14. *Comparison of GCM climate feedback parameters for water vapour (WV), cloud (C), surface albedo (A), lapse rate (LR) and the combined water vapour plus lapse rate (WV + LR) in units of W m^{-2} °C^{-1}. 'ALL' represents the sum of all feedbacks. Results are taken from Colman (2003a; blue, black), Soden and Held (2006; red) and Winton (2006a; green). Closed blue and open black symbols from Colman (2003a) represent calculations determined using the partial radiative perturbation (PRP) and the radiative-convective method (RCM) approaches respectively. Crosses represent the water vapour feedback computed for each model from Soden and Held (2006) assuming no change in relative humidity. Vertical bars depict the estimated uncertainty in the calculation of the feedbacks from Soden and Held (2006).*

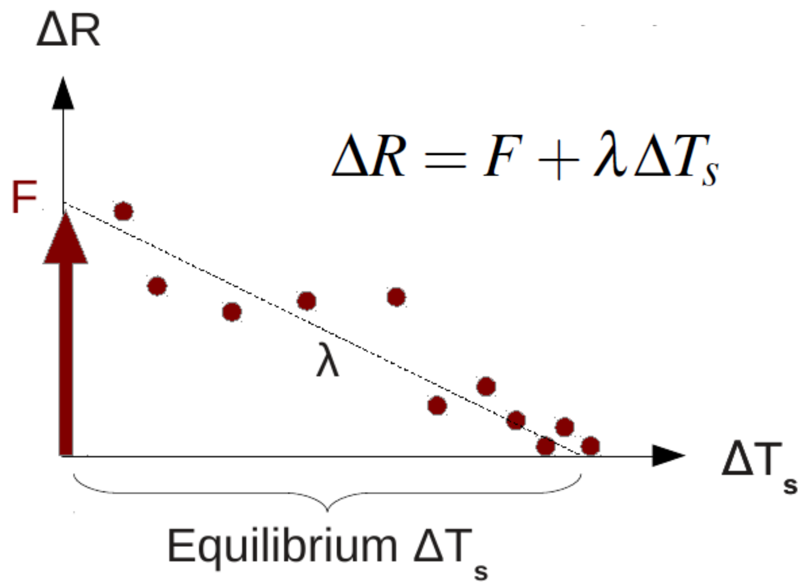
Clouds are the Achilles heels in climate modelling



Wide variation. The response patterns of clouds and precipitation to warming vary dramatically depending on the climate model, even in the simplest model configuration. Shown are changes in the radiative effects of clouds and in precipitation accompanying a uniform warming (4°C) predicted by four models from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) for a water planet with prescribed surface temperatures.

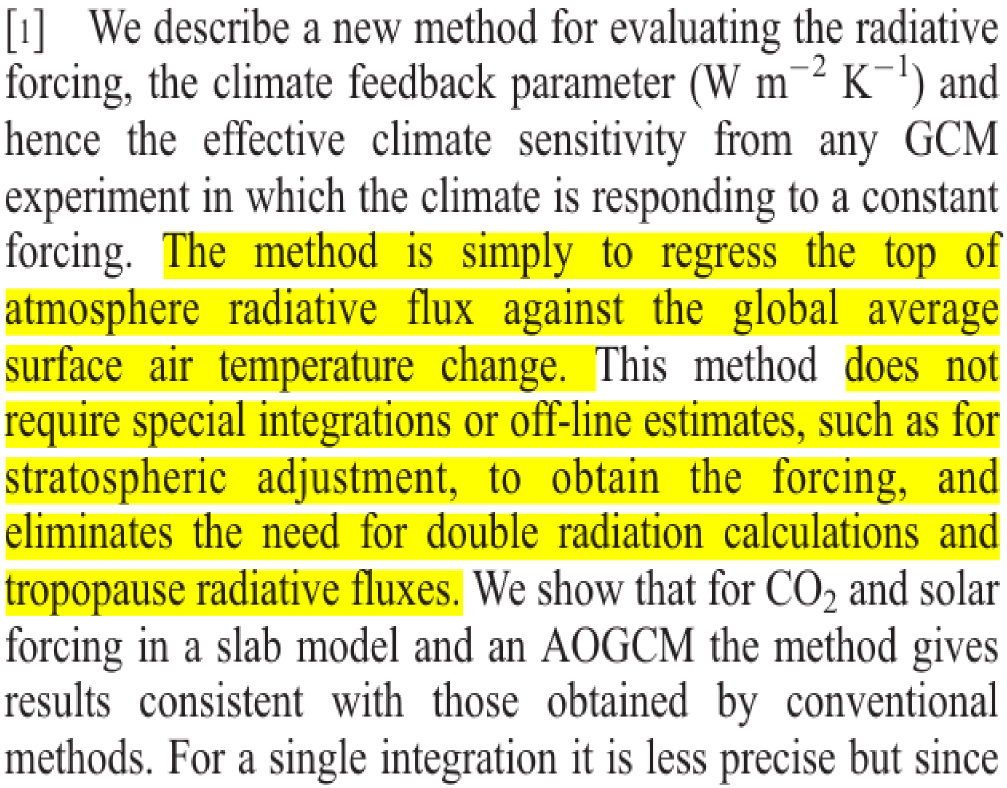
Figure: Stevens & Bony: What are climate models missing? (Science,2013)

Gregory Method



Forcing F = y-intercept (ΔTs = 0)
Feedback = regression slope ΔR/ΔTs
Eff. Climate Sensitivity = x-intercept (ΔR = 0)

Gregory et al. (GRL,2004)



[1] We describe a new method for evaluating the radiative forcing, the climate feedback parameter (W m^{-2} K^{-1}) and hence the effective climate sensitivity from any GCM experiment in which the climate is responding to a constant forcing. The method is simply to regress the top of atmosphere radiative flux against the global average surface air temperature change. This method does not require special integrations or off-line estimates, such as for stratospheric adjustment, to obtain the forcing, and eliminates the need for double radiation calculations and tropopause radiative fluxes. We show that for CO_2 and solar forcing in a slab model and an AOGCM the method gives results consistent with those obtained by conventional methods. For a single integration it is less precise but since

Gregory Method

Assumptions:

- Linearity in radiative response

Method:

- Simple regression analysis

Advantages:

- Very easy application
- Does not require special integrations/offline computations
- No double radiative transfer calculations
- By choosing between tropopause/TOA radiation imbalance, stratospheric adjustment can be excluded/included
- No new equilibrium model state necessary

Disadvantages:

- No clear separation of individual forcings/feedbacks possible
- Only computation of SW/ LW/ NET & Allsky/ Clearsky radiation fluxes
- Cloud feedback can only be estimated from ΔCRE
- Only applicable for simulations with abrupt forcing

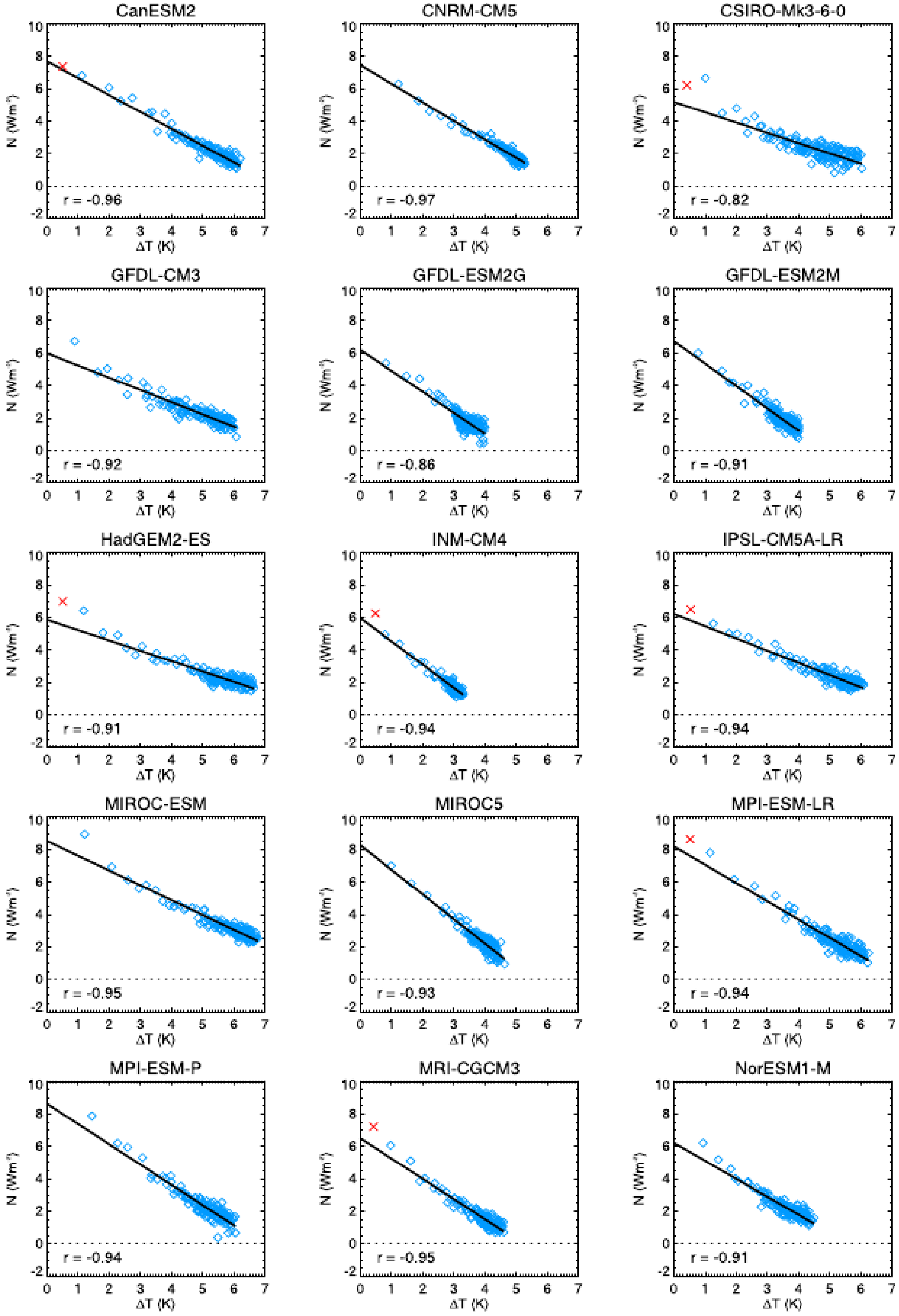
Application Example: Gregory Method

Andrews et al. (GRL, 2012):
Comparison of forcing, feedback & climate sensitivity in CMIP5 models

→ first application of Gregory analysis to an ensemble of AOGCMs

→ abrupt 4xCO2 experiment

→ deviations from linear behaviour arising from SW cloud radiative effects over the ocean, validated by fixed SST experiments (red cross in plots)



Figures: Andrews et al. (GRL,2012)

Partial Radiative Perturbation Method (PRP)

Assumptions:

- Linearity in radiative response
- Separability of feedbacks

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

$$\longrightarrow \quad \Delta R \approx \Delta R_{CO_2} + \Delta R_T + \Delta R_W + \Delta R_C + \Delta R_A \qquad (1)$$

$$\frac{dR}{dT_s} = \lambda \approx \sum_x \lambda_x, \quad \lambda_x = \frac{\partial R}{\partial X}\frac{dX}{dT_s} \qquad (2)$$

??

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$$\frac{dR}{dT_s} = \lambda \approx \sum_x \lambda_x, \quad \lambda_x = \frac{\partial R}{\partial X}\frac{dX}{dT_s} \quad ?? \qquad (2)$$

PRP Method (forward)

Take X from perturbation (state B) and substitute it in the instantaneous flux computation of the unperturbed simulation (state A)

→

$$\delta_w \overline{R} = \overline{R(w_B, T_A, c_A, a_A)} - \overline{R(w_A, T_A, c_A, a_A)}$$

(1) →

$$\delta \overline{R} = \delta_w \overline{R} + \delta_T \overline{R} + \delta_c \overline{R} + \delta_a \overline{R} = -G$$

Direct radiative forcing

(2) →

$$\lambda_X = -\frac{\delta_X \overline{R}}{\delta X}\frac{\delta X}{\delta T_s}$$

based on Wetherald & Manabe (J.Atmos.Sc.,1988)

Corrected PRP

Colman & Mc Avaney (JGR, 1997):

Bias in PRP (forward) due to assumption of temporally decorrelated fields!

→ partly overcome this problem by symmetrizing forward & backward PRP
→ backward PRP: Substitute from unperturbed (state B) into perturbed simulation (state A) (opposite from forward PRP)

→ **2-sided PRP**:

$$\frac{1}{2}\left[\,\overline{R(w_B, c_A)} - \overline{R(w_A, c_A)} + \overline{R(w_B, c_B)} - \overline{R(w_A, c_B)}\,\right].$$

Summary: PRP

Assumptions:

- Linearity in radiative response
- Separability of feedbacks

Method:

- Systematically replacing relevant feedback parameters between unperturbed and perturbed simulations (2-sided)

Advantages:

- Radiative partial derivatives are calculated directly
- Clean separation of unperturbed flux and flux response from perturbation

Disadvantages:

- Isolated offline radiative transfer computations needed
- Computationally expensive
  - Requires several experiments to distuingish forcings from feedbacks
  - Simulations need to run to new equilibrium

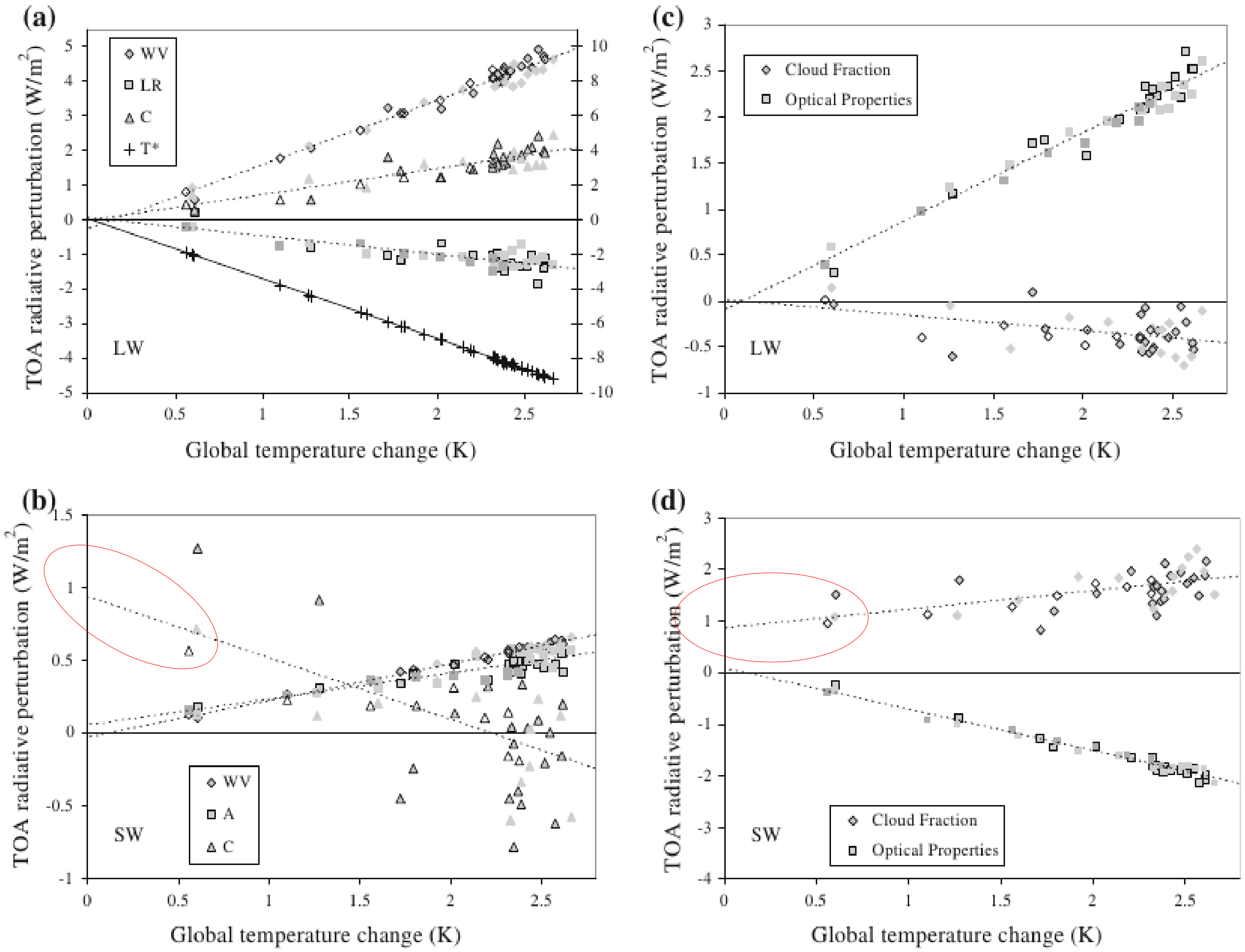
Application Examples: Combined PRP-Gregory

Colman and McAvaney et al. (ClimDyn, 2011):
Tropospheric rapid adjustments and climate feedbacks

→ 2xCO2 & (scaled) 4xCO2 experiments

→ rapid adjustment to CO2 forcing confined to cloud fraction changes (not cloud optical properties) affecting SW radiation

$$\delta R_{\tilde{C}} \approx \delta R_{\tilde{C}_F} + \delta R_{\tilde{C}_O}$$



Figures: Colman & McAvaney (ClimDyn,2011)

Kernel Technique

Assumptions:

- Linearity in radiative response
- Separability of feedbacks

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

$$\Rightarrow \quad \Delta R \approx \Delta R_{CO_2} + \Delta R_T + \Delta R_W + \Delta R_C + \Delta R_A \qquad (1)$$

$$\frac{dR}{dT_s} = \lambda \approx \sum_x \lambda_x, \quad \lambda_x = \frac{\partial R}{\partial X}\frac{dX}{dT_s} \quad ?? \qquad (2)$$

Kernel Technique

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- Linearity in radiative response
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$$\Delta R = F + \lambda \Delta T_s$$

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$$\frac{dR}{dT_s} = \lambda \approx \sum_x \lambda_x, \quad \boxed{\lambda_x = \frac{\partial R}{\partial X}\frac{dX}{dT_s}} \;\; ?? \qquad (2)$$

Kernel Method

Perturb the mean climate by predefined small increment

→ $$\Delta R_T = R(T_a + \delta \overline{T}, W_a, C_a, A_a) - R(T_a, W_a, C_a, A_a)$$

$$\Delta R_T \approx \frac{\partial R}{\partial T}(T_a, W_a, C_a, A_a)\,\delta T = \boxed{K_T}\,\delta T$$

Radiative Kernel

(1) → $$\Delta R \approx \sum_x \Delta R_x \approx \sum_x K_x \delta X$$

(2) → $$\lambda_x = K_x \frac{\delta X}{\delta dT_s}$$

based on Soden et al. (J.Clim.,2008)

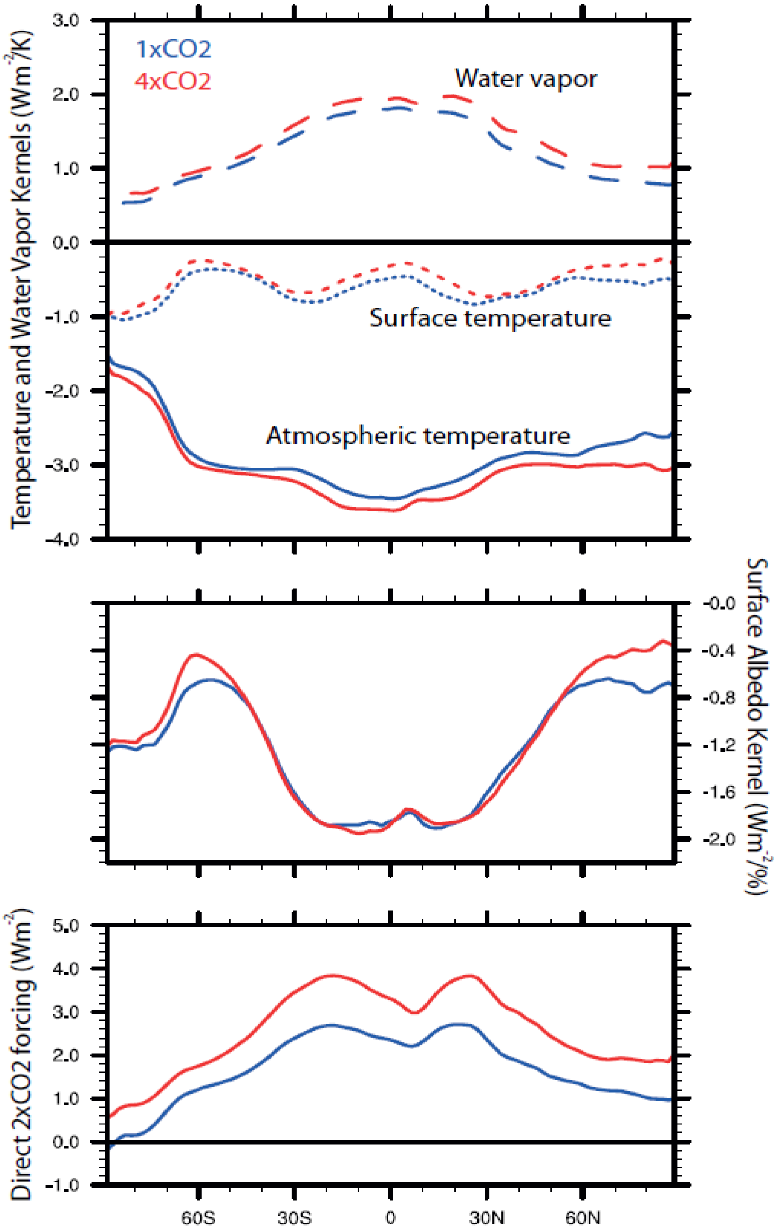
The Kernels

In total, **5 Kernels** are calculated & applied as monthly averages:

- 2D CO_2 Kernel $\mathbf{K}_{\mathbf{CO2}}$: Differential radiative response at TOA of doubling CO2 concentration, used for direct CO2 forcing estimates
- 2D Surface Albedo Kernel $\mathbf{K}_{\mathbf{A}}$: Differential radiative response at TOA of increasing the albedo by 1%
- 2D Surface Temp. Kernel $\mathbf{K}_{\mathbf{Ts}}$: Differential radiative response at TOA of increasing the surface temperature by 1K
- 3D Air Temp. Kernel $\mathbf{K}_{\mathbf{Ta}}$: Differential radiative response at TOA of increasing the air temperature by 1K, level by level
- 3D WV Kernel $\mathbf{K}_{\mathbf{W}}$: Differential radiative response at TOA of increasing specific water vapor by an amount corresponding to 1K-warming (using Clausius Clapeyron relation), level by level

Vertical Intergration of 3D Kernels gives differential radiative response at TOA for entire atmosphere!

The Kernels

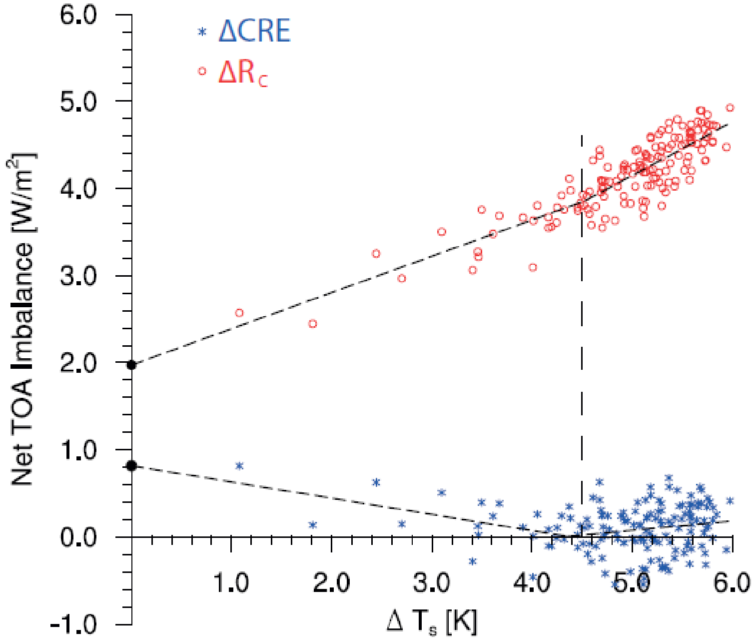


$$CRE = (R^{SW} - R^{SW}_{clr}) + (R^{LW} - R^{LW}_{clr})$$

$$\Delta CRE = CRE_{prt} - CRE_{ctrl}$$

Environmental correction for the cloud feedback (following Soden et al. (J.Clim.,2008))

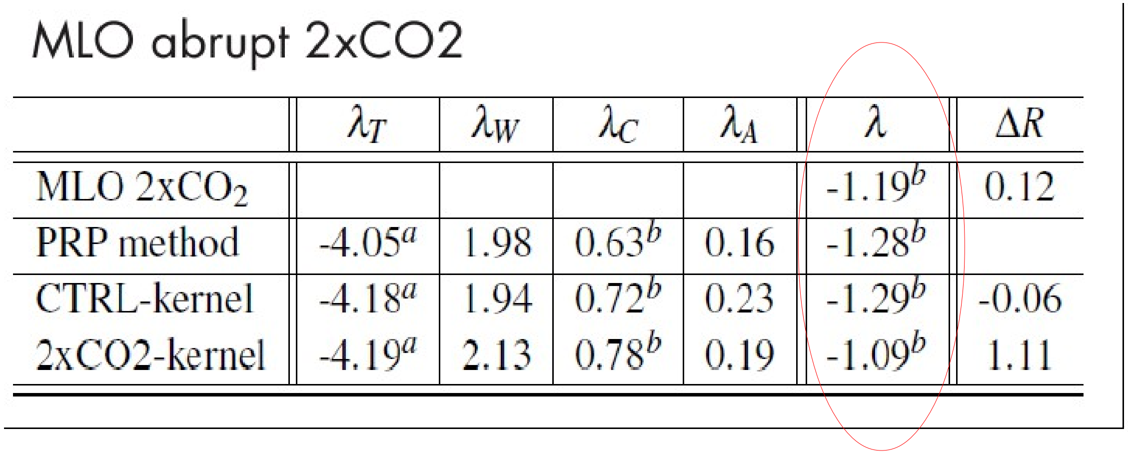
$$\boxed{\Delta R_C \approx \Delta \mathrm{CRE} - \sum_x (K_x - K_x^{clr}) \cdot \Delta X}$$



Figures: Block & Mauritsen (JAMES,2013)

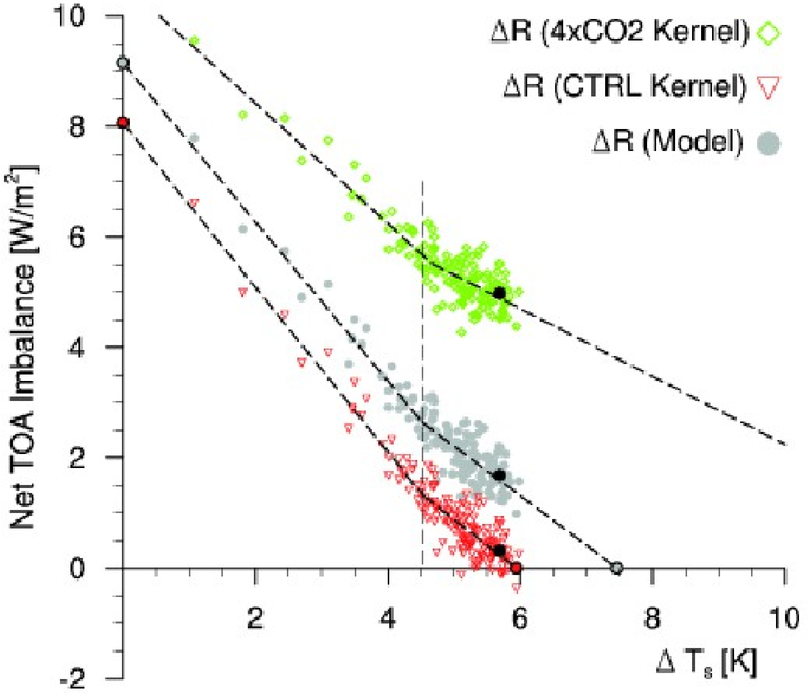
Accuracy of Kernel Technique

MLO abrupt 2xCO2

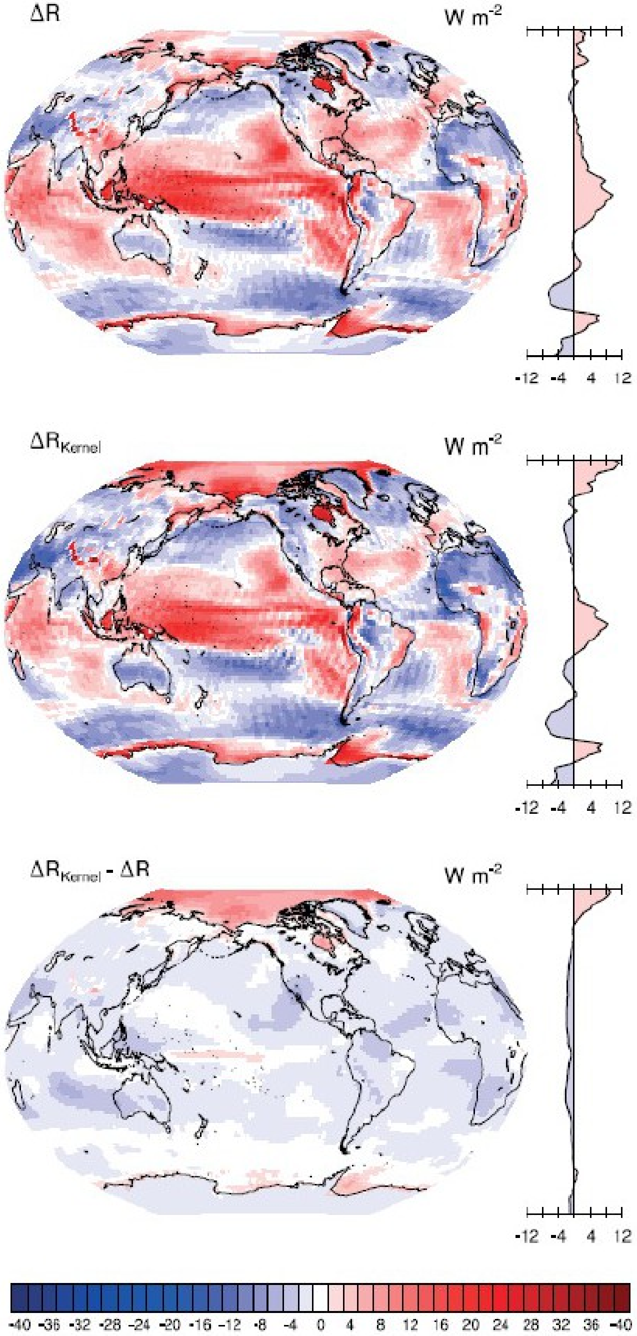


	λ_T	λ_W	λ_C	λ_A	λ	ΔR
MLO $2xCO_2$					-1.19[b]	0.12
PRP method	-4.05[a]	1.98	0.63[b]	0.16	-1.28[b]	
CTRL-kernel	-4.18[a]	1.94	0.72[b]	0.23	-1.29[b]	-0.06
2xCO2-kernel	-4.19[a]	2.13	0.78[b]	0.19	-1.09[b]	1.11

MPI-ESM-LR abrupt 4xCO2



Best estimate:
CTRL-state
kernels



Figures & Tables: Block & Mauritsen (JAMES,2013)

Summary: Kernel Technique

Assumptions:

- Linearity in radiative response
- Separability of feedbacks

Method:

- Perturb mean climate by small predefined increment
- Fluxes estimated from linearization of radiative transfer calculations
- Radiative kernel = differential radiative response

Advantages:

- Computationally efficient
- Once kernels are computed no offline radiation computations necessary
- Clean separation of unperturbed flux and flux response from perturbation

Disadvantages:

- Radiative kernels are state-dependent
- Hence, application only for small perturbations
- No cloud kernel
  → other estimation necessary

Application Examples: Kernel Method

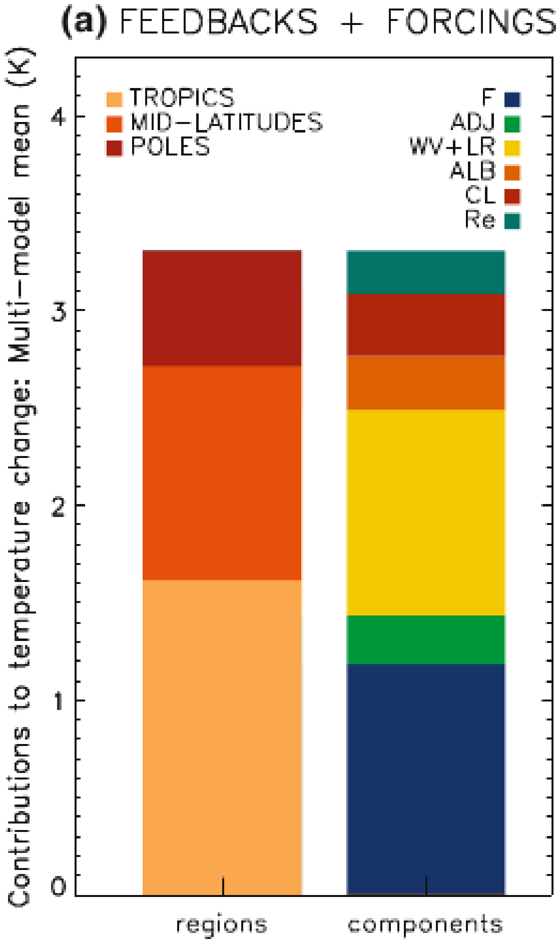
Vial et al. (ClimDyn, 2013):
Intermodel spread in CMIP5
climate sensitivity

→ adjusted forcing:
sstClim4xCO2 - sstClim

→ feedbacks:
abrupt4xCO2 - sstClim4xCO2

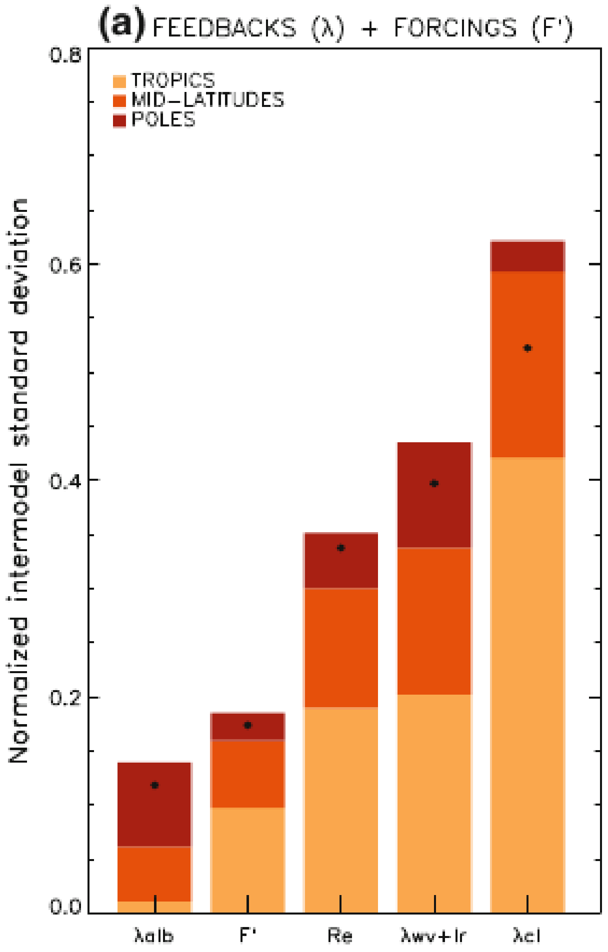
→ feedbacks contribute more to climate sensitivity than forcings+adjustments

→ spread in CMIP5 from tropical cloud feedbacks



Proportional to area of latitudinal belt

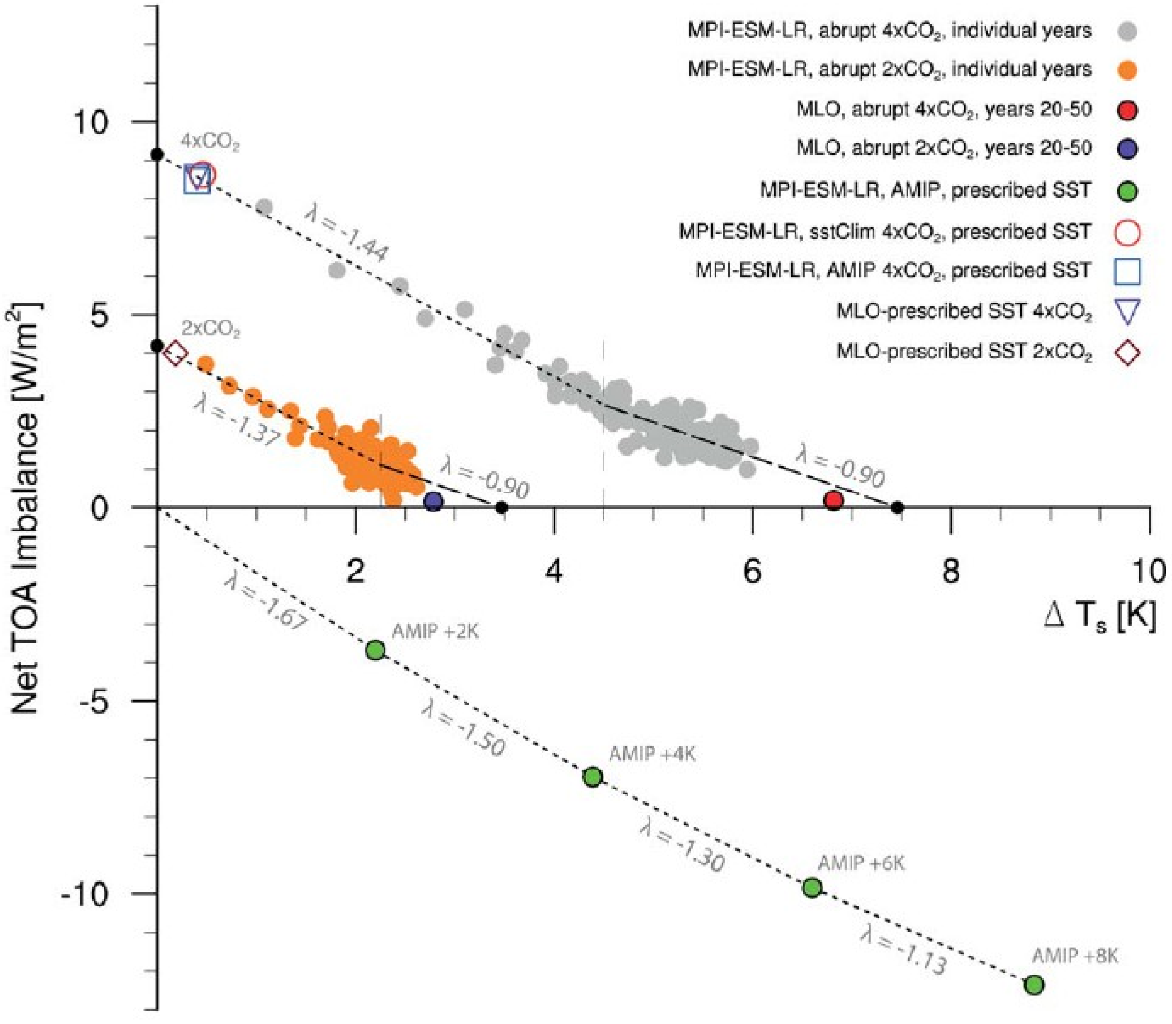
Not proportional to area extent



Figures: Vial et al. (ClimDyn,2013)

Application Examples: Combined Kernel-Gregory

Block and Mauritsen et al. (JAMES, 2013):
Forcings & Feedbacks in MPI-ESM



→ abrupt 2x/4xCO2 & prescribed SST experiments

→ non-linear radiative relaxation

- consistent weakening of total feedback factor with warming climate
- feedback factor could be considered function of climate state
- all feedbacks might contribute to shift in climate sensitivity

Figures: Block & Mauritsen (JAMES,2013)

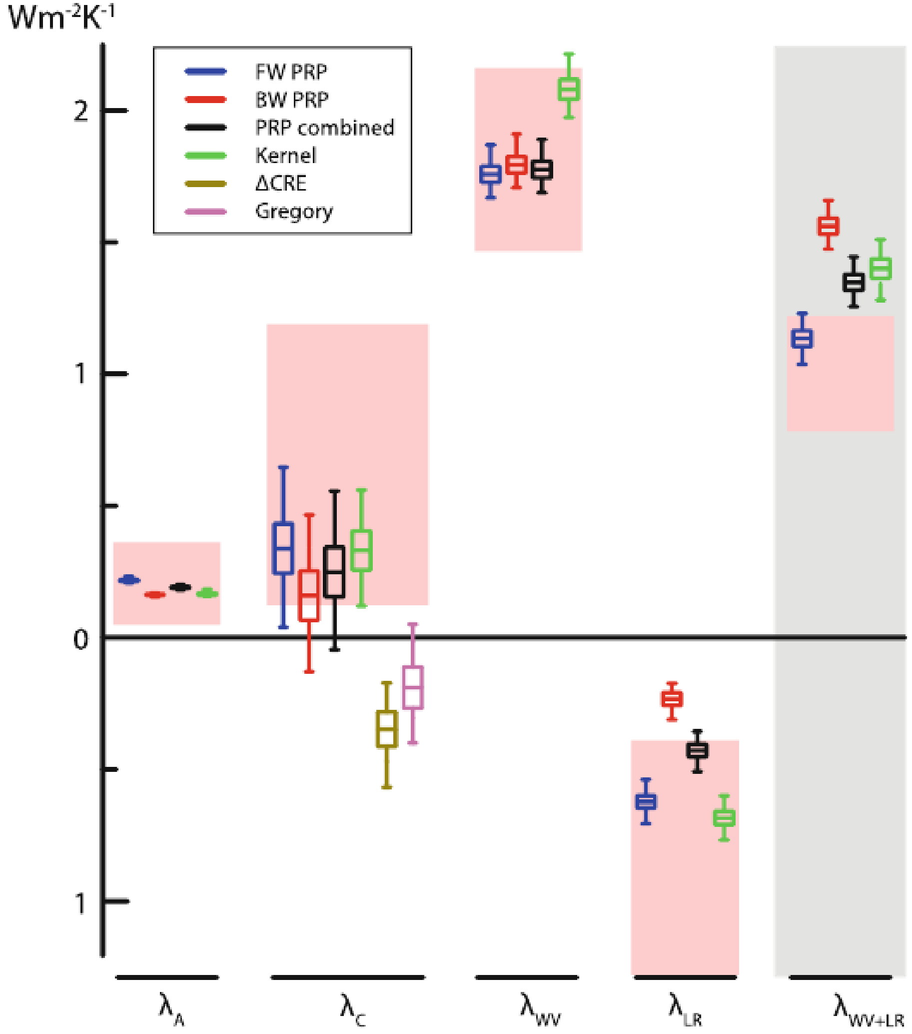
Intercomparison

Klocke et al. (ClimDyn, 2013):
Assessment of different metrics for analysing physical climate feedbacks

→ 2xCO2 experiment with Echam5, compared to CMIP3 range (pink boxes)

→ Residual terms for both PRP & Kernel are appreciably different from zero

→ Sampling errors, assumptions in the feedback diagnostic methodologies and specifics of how those methodologies are applied can lead to inconsistencies



Figures: Klocke et al. (ClimDyn,2013)

Summary Lecture

- Definitions: forcing, feedback and climate sensitivity
- Derivation of forcing-response relationship from perturbation analysis in radiative balance equation
- Climate feedbacks and fast adjustment processes
- Computational methods, differences and applications