Towards uncovering the origin of efficacy differences For different radiative forcings related to transport emissions

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Motivation

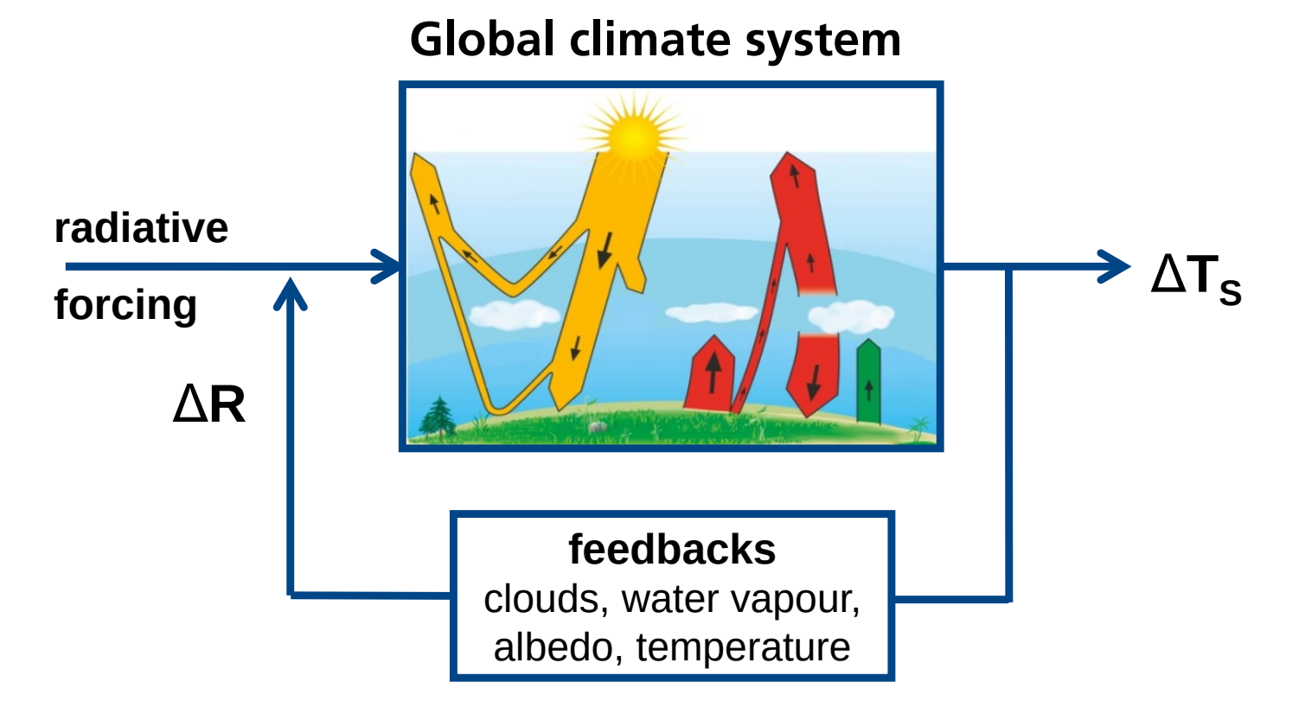
Climate sensitivity λ and efficacy r describe the global mean surface temperature response to a radiative forcing RF:

$$\Delta T_S = \lambda \cdot RF = \boldsymbol{r} \cdot \lambda_{CO_2} \cdot RF$$

Radiative forcings from perturbations of different kind or structure may give rise to distinctive radiative feedbacks, in turn leading to distinctive efficacies ($\boldsymbol{r}$).

This has been realized before, e.g., for some aviation forcings (Ponater et al., 2006), but understanding of the physical reasons has remained insufficient.

Feedback analysis could be useful to provide a physical explanation for different temperature responses and efficacies, by identifying the responsible climate feedbacks.



Global climate system

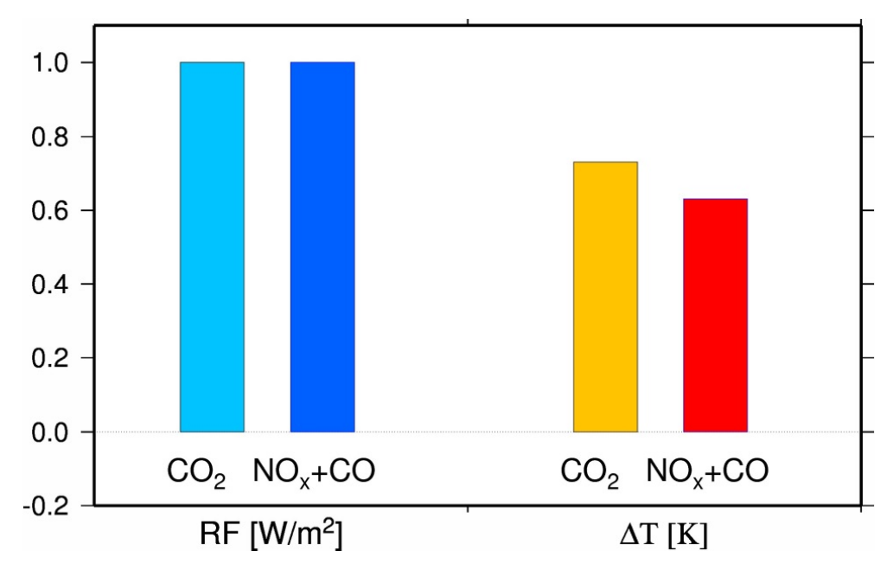
radiative forcing

ΔR

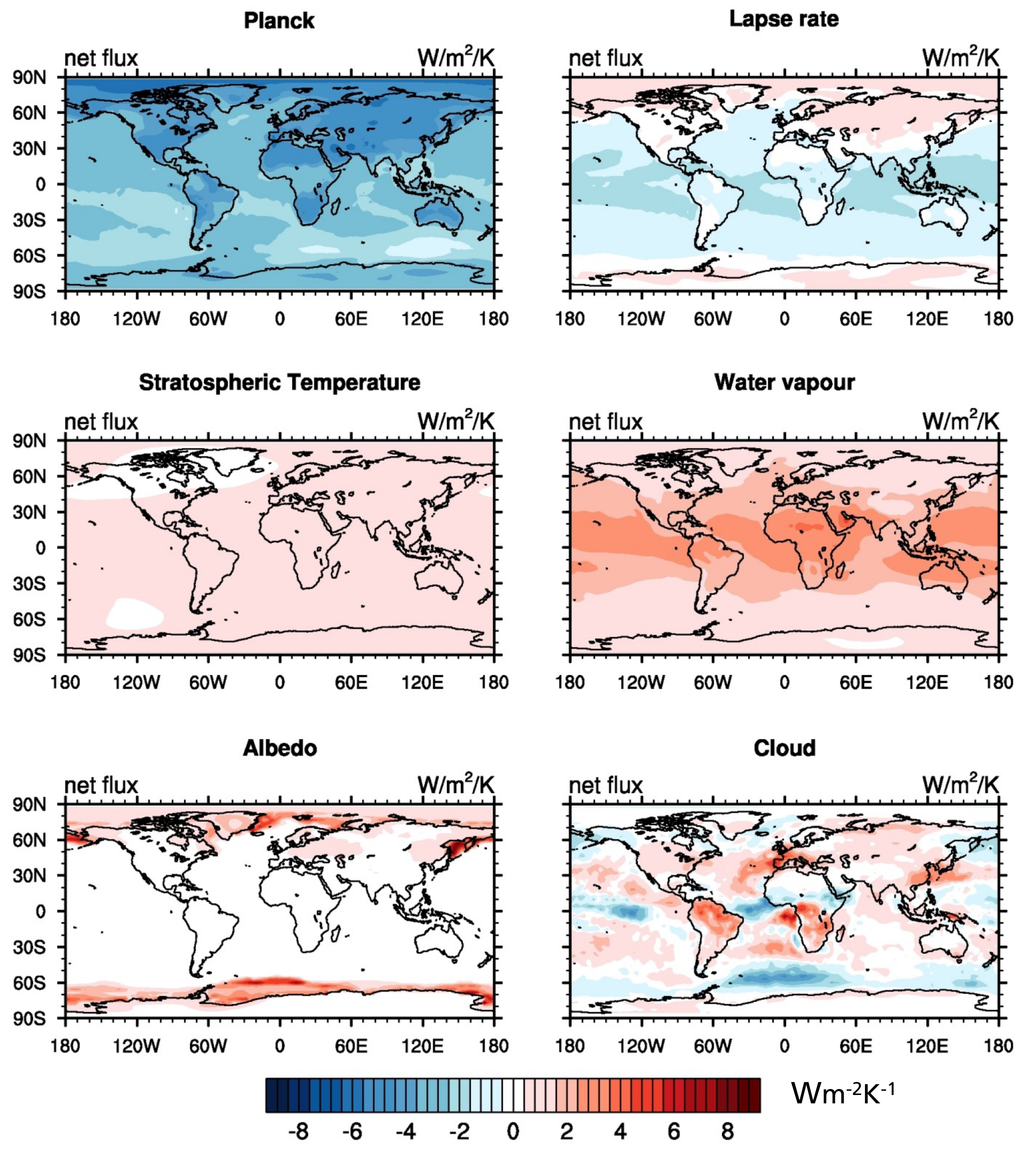
ΔT_S

feedbacks
clouds, water vapour, albedo, temperature

Example:
O_3 (from NO_x/CO surface emissons) has a reduced efficacy



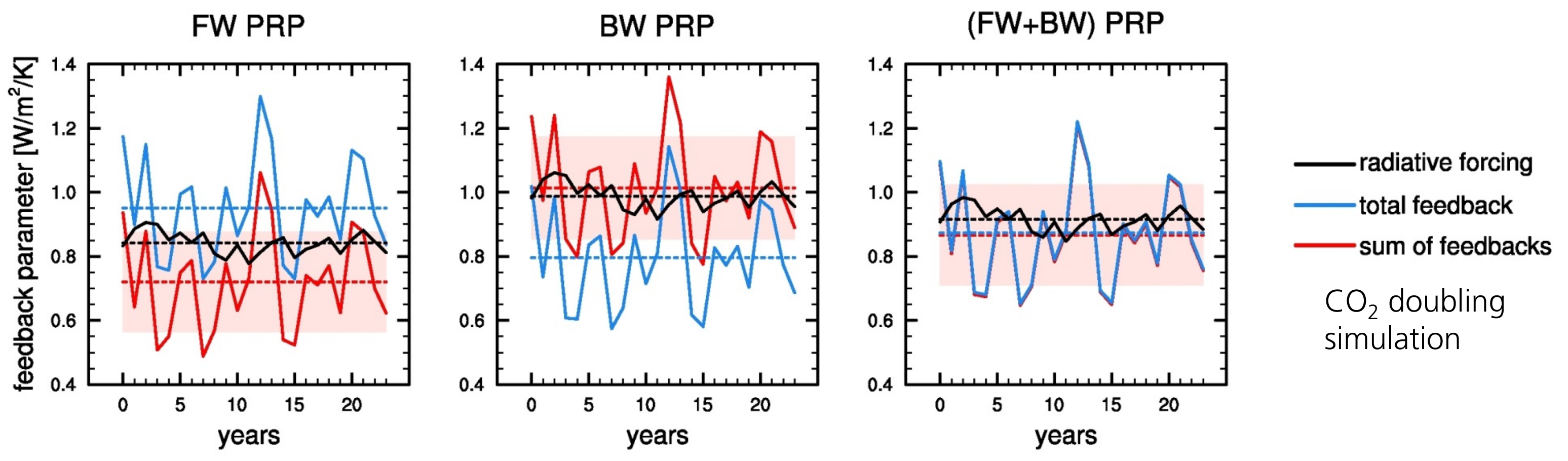
Global distribution of climate feedbacks for a CO_2 doubling simulation (RF = 4.13 W/m², ΔT_S = 2.91 K)



Global mean feedbacks:

- Temperature feedback split up:
  - Planck feedback α_{pla}: - 3.10 $Wm^{-2}K^{-1}$
  - Lapse rate feedback α_{LR}: - 0.86 $Wm^{-2}K^{-1}$
  - Stratospheric temperature feedback α_{str}: + 0.56 $Wm^{-2}K^{-1}$
- Water vapour feedback α_q: + 2.01 $Wm^{-2}K^{-1}$
- Surface albedo feedback α_A: + 0.23 $Wm^{-2}K^{-1}$
- Cloud feedback α_C: + 0.29 $Wm^{-2}K^{-1}$

Recommendations for successful feedback analysis



CO_2 doubling simulation

- Statistical uncertainty of feedbacks may be large, especially for small forcings
  ➔ perturbation should be sufficiently large to extract the signal from high background noise
- Combination of forward (FW) and backward (BW) PRP feedback calculation guarantees
  ➔ reproduction of the near-zero radiation balance at top of the atmosphere
  ➔ separability of the feedbacks (sufficiently small residuum)

Can feedback analysis be used to understand efficacy differences between radiative forcings?

- Significant feedback changes may be identified in a carefully chosen PRP analysis framework.
  ➔ All feedbacks are potential candidates to significantly modify the feedback balance and to cause a distinctive efficacy of a given perturbation.
- Larger forcing gives a better signal to noise ratio and facilitates the analysis, but feedbacks and climate sensitivity can also change significantly with increasing forcing.
  ➔ Scaling forcings may be misleading when searching for physical reasons for efficacy differences.
- Feedbacks may be separable but are nevertheless interactive
  ➔ An extended model framework involving new feedbacks may lead to substantial changes of the whole feedback balance and, thus, may yield different efficacy estimates.

"Partial Radiative Perturbation" (PRP)-method

Under the assumption of linearity and separability of radiative effects, each variable is substituted, one by one, from a climate change simulation, whereas all other variables are taken from a control simulation (forward calculation). By means of an offline radiation tool, the net radiation flux changes at top of the atmosphere ΔR_x are calculated.

➔ feedback parameter $\alpha = \sum_x \alpha_x = \sum_x \frac{\Delta R_x}{\Delta T_S}$ $\quad x = q, C, A, T, \ldots$

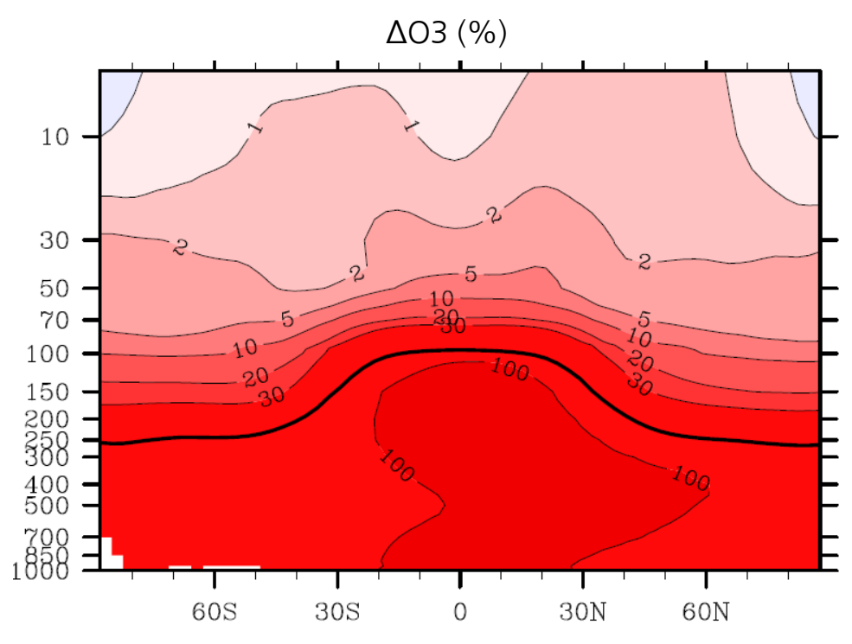
The sum of feedbacks counteracts the radiative forcing to restore the radiative equilibrium at top of the atmosphere:

$$\alpha = \sum_x \alpha_x = -\frac{RF}{\Delta T_S} = -\frac{1}{\lambda}$$

Feedbacks under a variety of forcings

Climate sensitivity and efficacy may vary under

- different type of radiative forcing
- different strength of radiative forcing
- spatial structure of the perturbation/forcing
- amongst different models

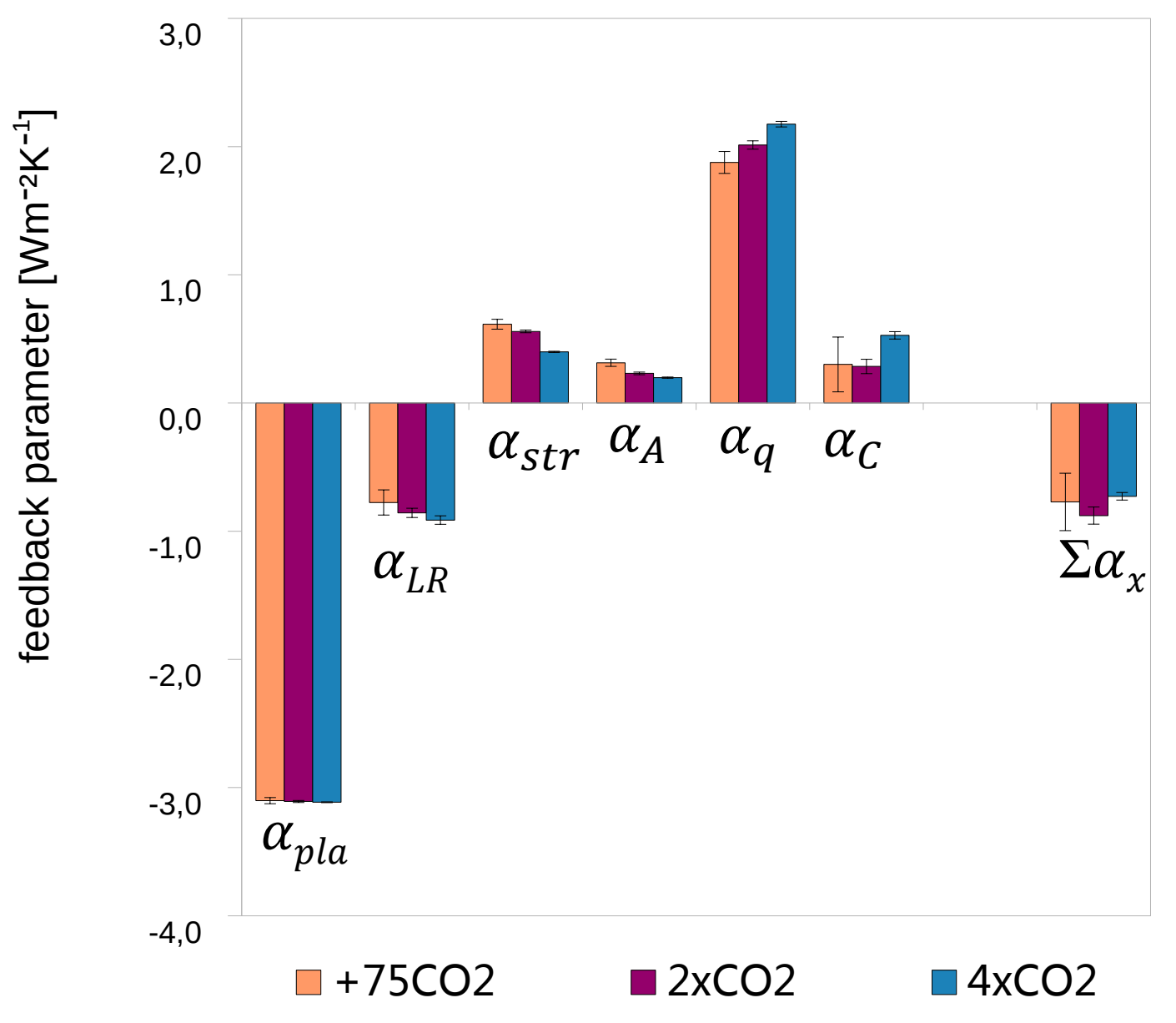


Ozone change due to enhanced NO_X/CO emissions

Simulation experiment with EMAC	Inter-active chemistry		Radiative forcing Wm^{-2}	Climate sensitivity λ K/Wm^{-2}	[95% confi.]	Efficacy r
ΔO_3 from enhanced NO_X+CO (v.s.)	no	NOX+CO	1.22	0.63	[0.55; 0.67]	0.86
ΔO_3 from enhanced NO_X+CO (v.s.)	yes	NOX+CO_chem	1.22	0.69	[0.65; 0.73]	0.95
Increase of CO_2 by 75 ppmv	no	+75CO2	1.06	0.73	[0.67; 0.79]	1
Doubling of CO_2	no	2xCO2	4.13	0.70	[0.69; 0.72]	0.96
Quadrupling of CO_2	no	4xCO2	8.93	0.91	[0.90; 0.92]	1.25

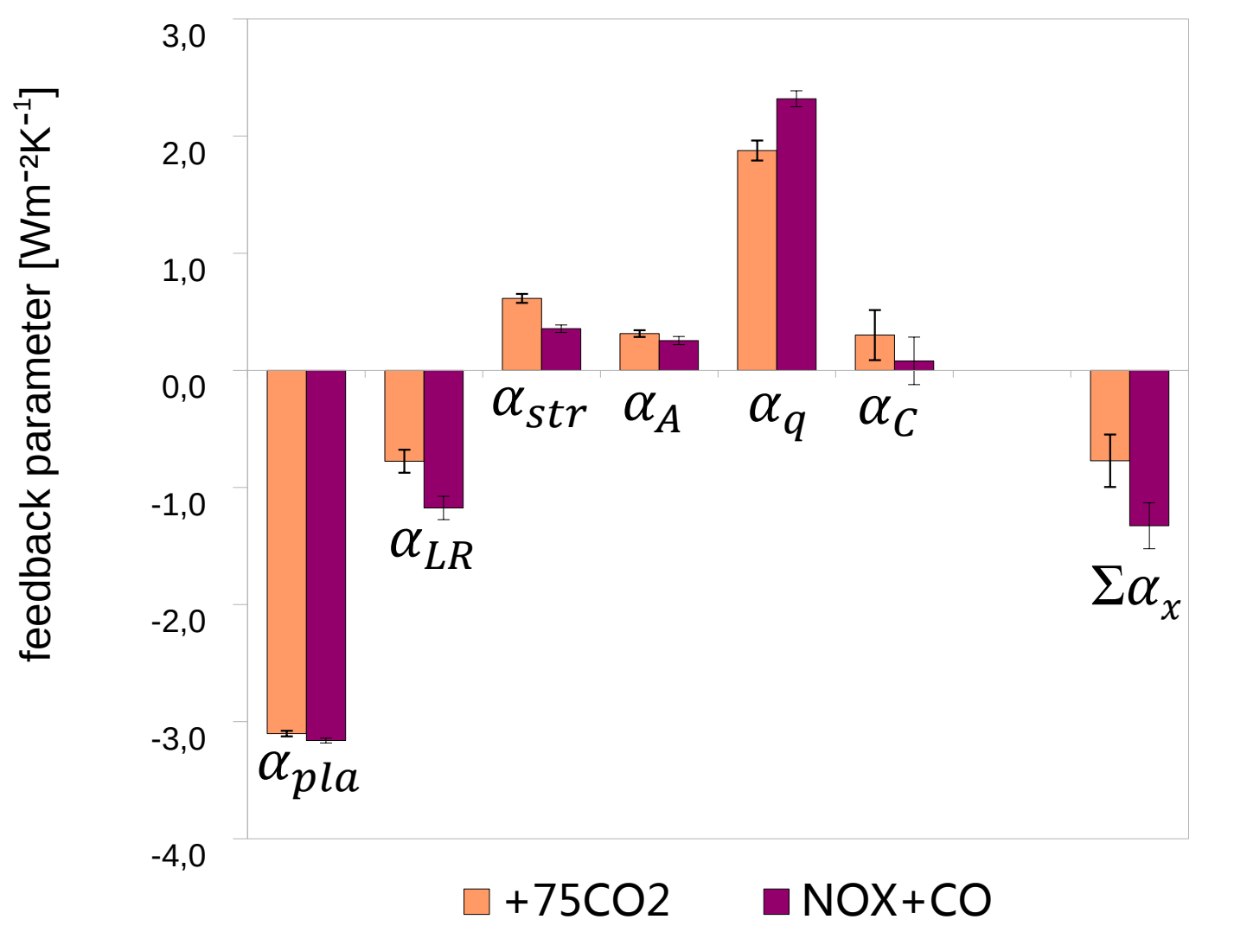
EMAC global model simulations (Dietmüller, 2011; Dietmüller et al, 2014)

Different strength of radiative forcing



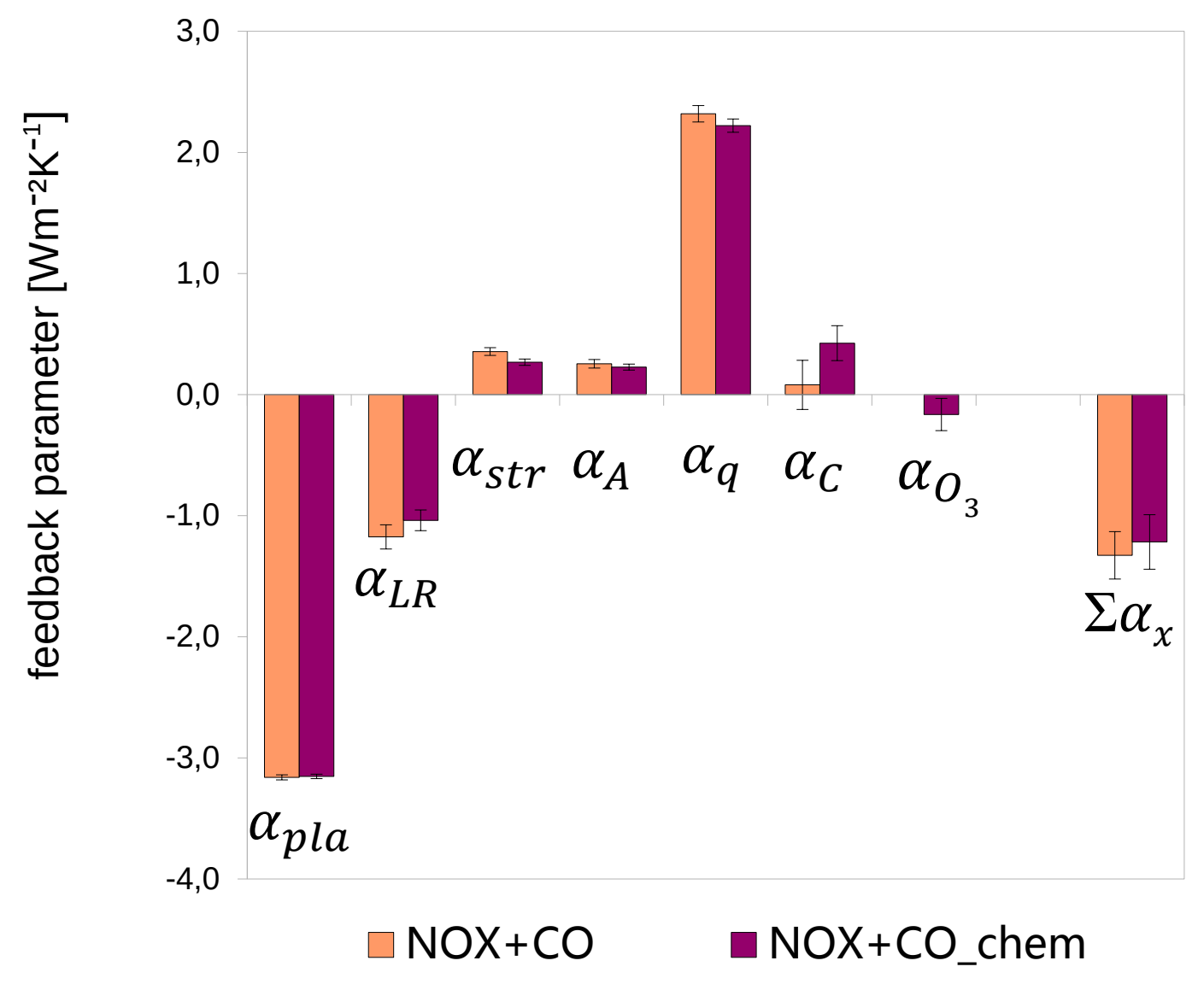
- 2xCO2 and 4xCO2 simulations show statistically significant differences.
  ➔ Contributions from water vapour, stratospheric temperature, and cloud feedbacks are responsible for the climate sensitivity variation.
- No significant distinction of the feedback sum for +75CO2 simulation (from 2xCO2) is possible as the statistical noise level (inter-annual variability) is too high.
  ➔ Possibility to identify feedback processes responsible for climate sensitivity variation becomes limited for small forcings.

Different type of radiative forcing



- NOX+CO and +75CO2 (without interactive chemistry) show a significant difference of the feedback sum, consistent with smaller efficacy for the NOX+CO forcing.
  ➔ Various feedback changes contribute to a distinctive NOX+CO efficacy; enhanced positive α_q is compensated by enhanced negative α_{LR}; less positive α_{str} and α_{str} seem to shift the feedback balance to smaller climate sensitivity for NOX+CO.

Advanced model (interactive chemistry)



- Additional feedbacks occur in a model setup with interactive atmospheric chemistry. Despite a additional negative ozone feedback (α_{O_3}), the sum of feedbacks becomes less negative, leading to enhanced climate sensitivity.
  ➔ α_C reacts markedly to the changes in α_{str} and the negative α_{O_3} and, hence, appears to be responsible for the impact reversion compared to the primary chemical feedback (α_{O_3}).

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