Ozone Radiative Feedback in Global Warming Simulations with CO_2 and non-CO_2 forcing

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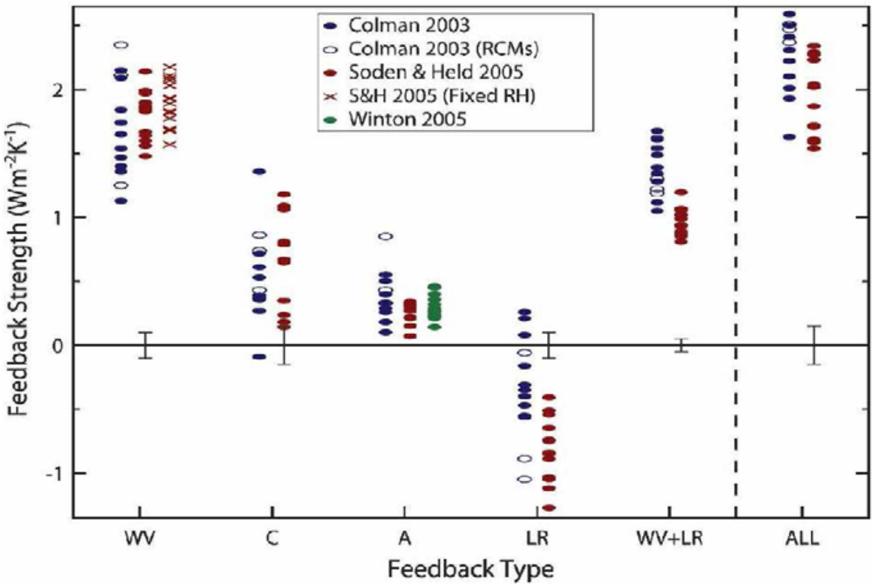
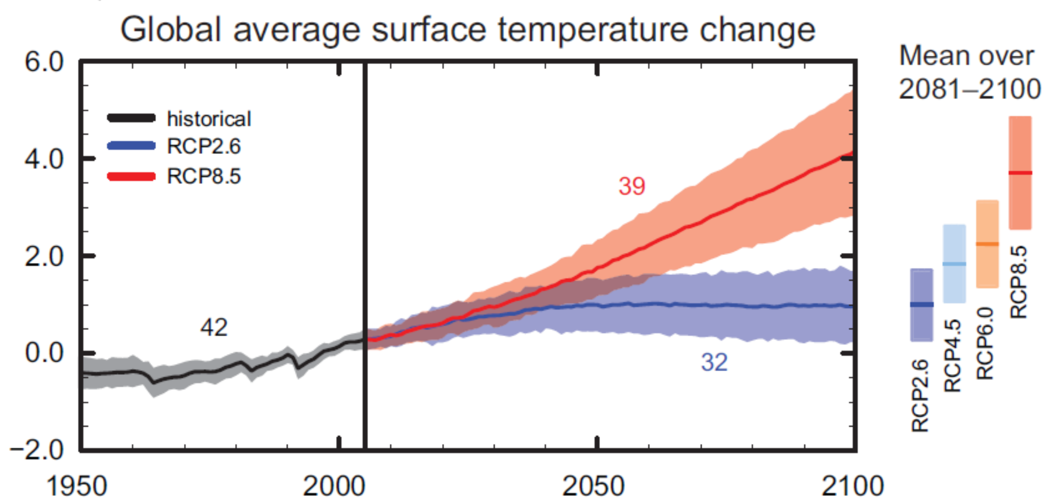
Feedbacks in climate model simulations



Analysis of feedbacks is a common exercise in climate research, because many physical feedbacks are known to differ between different climate models (e.g., Bony et al., 2006). This results in a model dependent climate sensitivity parameter (λ).

Hence, different climate models simulate a different temperature response development, even if the (radiative) forcing is the same (here: IPCC, 2013).



Radiative Forcing, Climate Response, Climate Sensitivity and Radiative Feedbacks

The climate sensitivity parameter λ links the global mean surface temperature response (ΔT_S) and the radiative forcing RF:

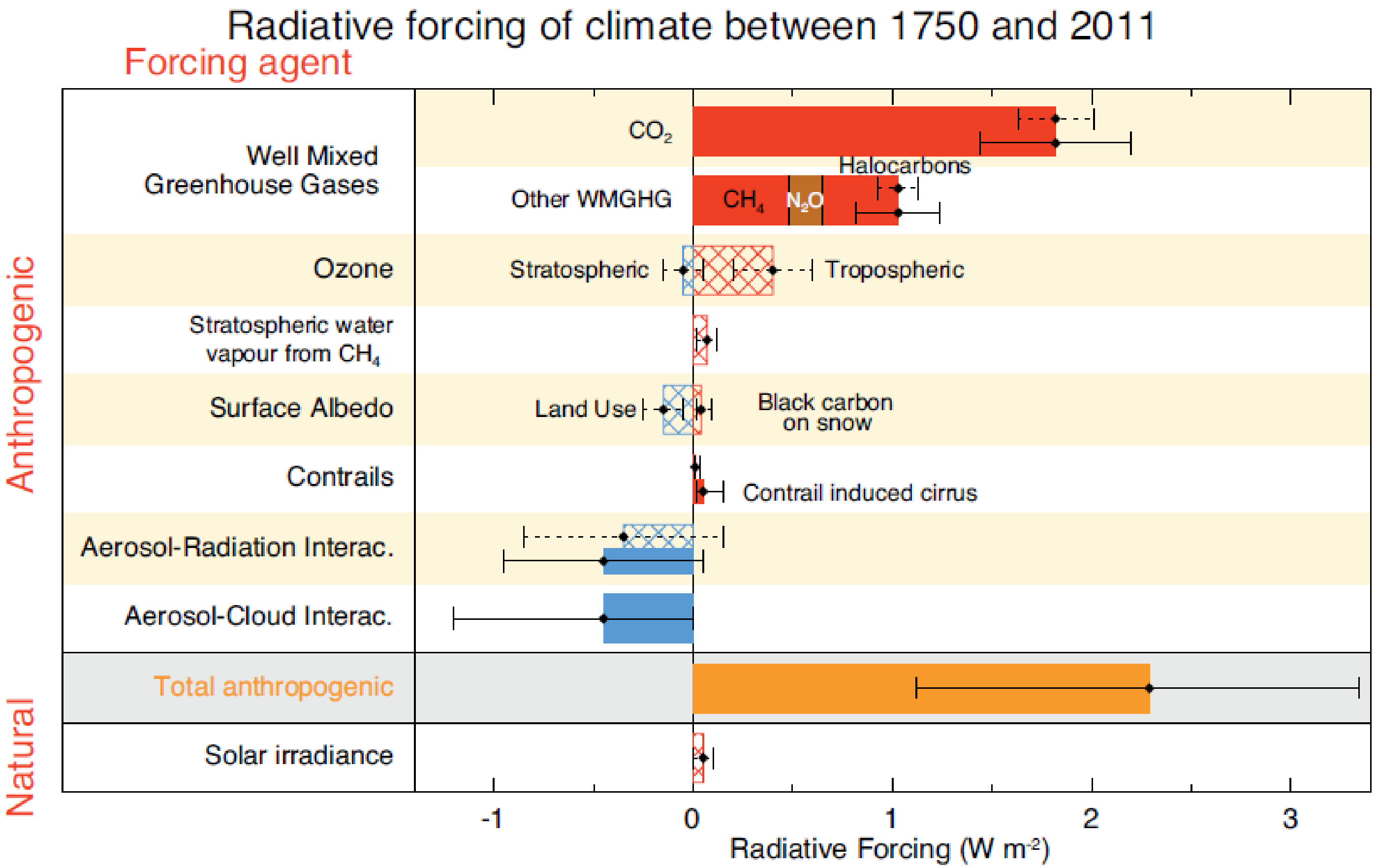
$$\Delta T_S = \lambda \cdot RF$$

λ crucially depends on the strengths of a number of the radiative feedbacks (α_x) acting in a given model and for a given forcing perturbation:

$$-\frac{1}{\lambda} = \alpha = \Sigma \alpha_x$$

As the feedbacks may be both model and perturbation dependent, so is the climate sensitivity parameter.

Radiative Forcing



Radiative forcing and climate response

$$\Delta T_S = \lambda \cdot RF$$

Radiative forcing: Fundamental metric to quantitatively assess and inter-compare various contributions to total climate change (here: IPCC, 2013 [AR5])

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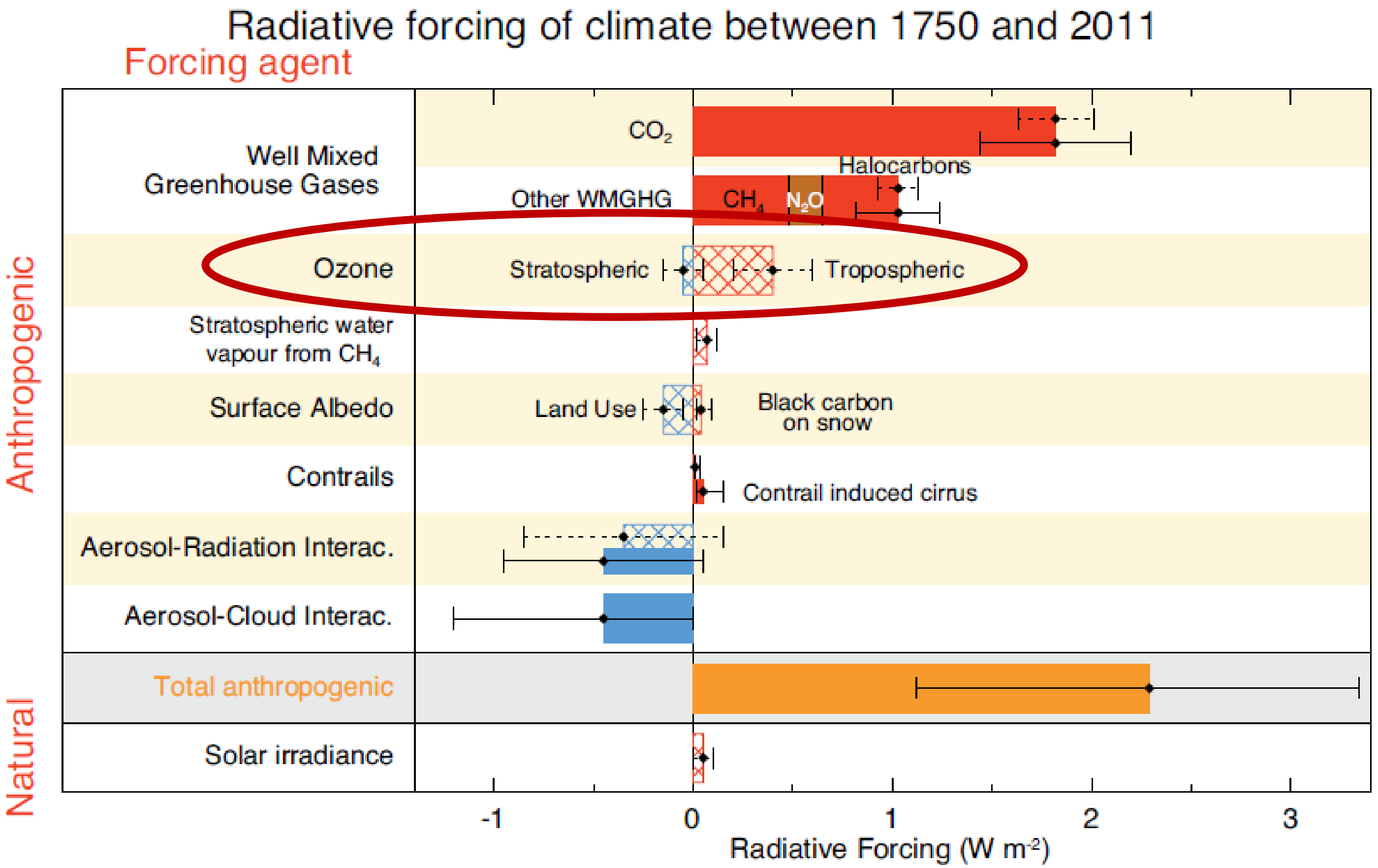
Radiative Forcing



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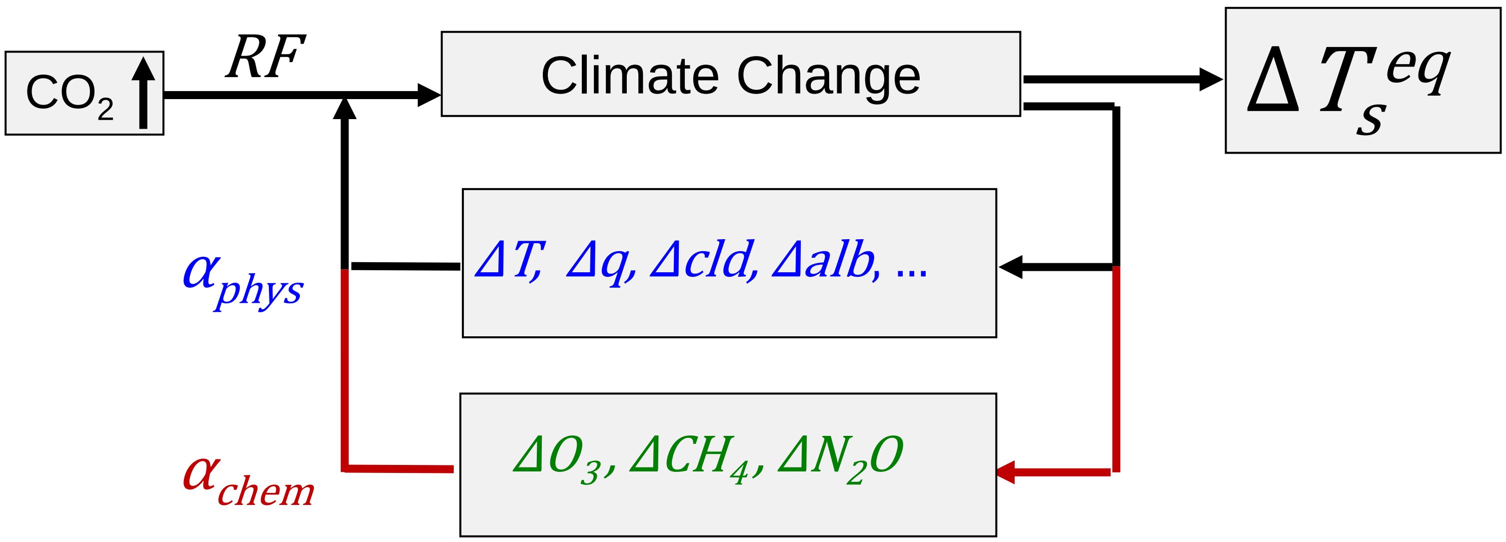
Radiative Forcing and Radiative Feedbacks

Example: CO_2–driven climate change



$$\alpha = \sum_x \alpha_x = \alpha_{pla} + \alpha_q + \alpha_{LR} + \alpha_{alb} + \alpha_{cld} + \ldots$$

$$\ldots + \alpha_{O3} + \alpha_{CH4} + \alpha_{N2O} + \alpha_{FCKW} + \alpha_{Aero} \ldots$$

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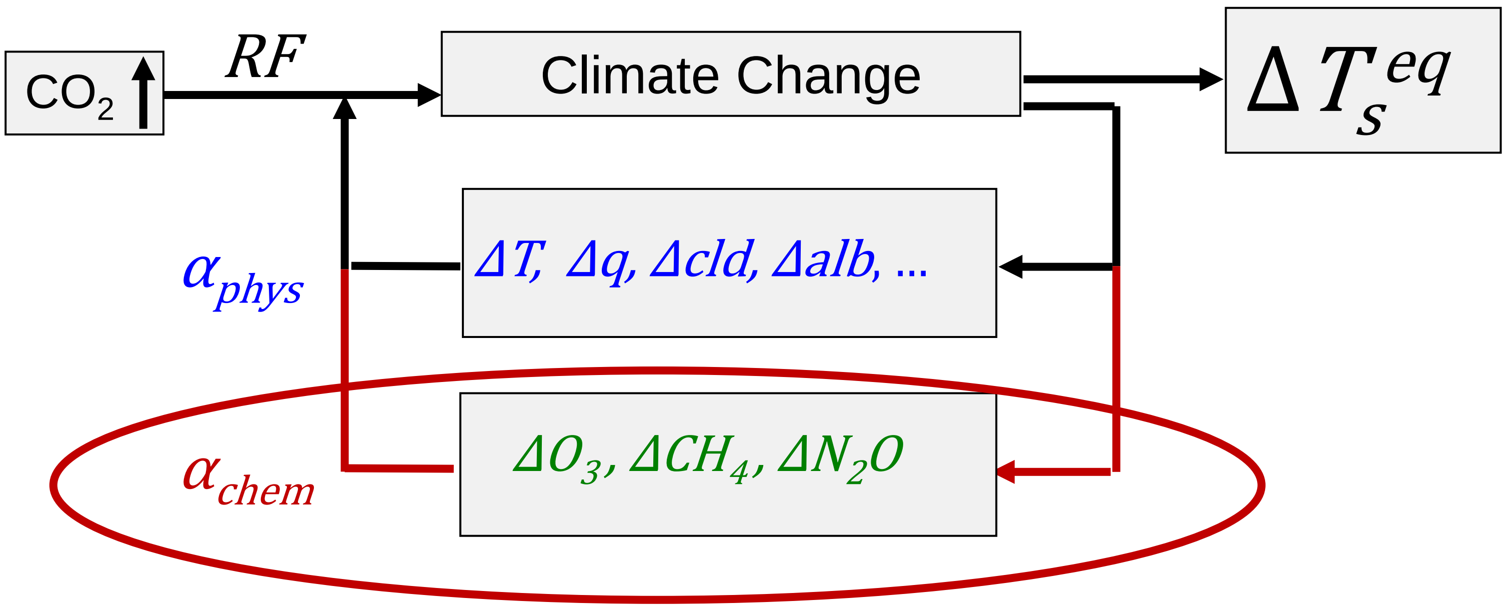

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ECHAM5/Messy Atmospheric Chemistry (EMAC)

ECHAM = ECMWF-model, version HAMburg

General circulation model

Reference: Roeckner et al. , MPI-Report No.349

MESSy = Modular Earth Submodel System

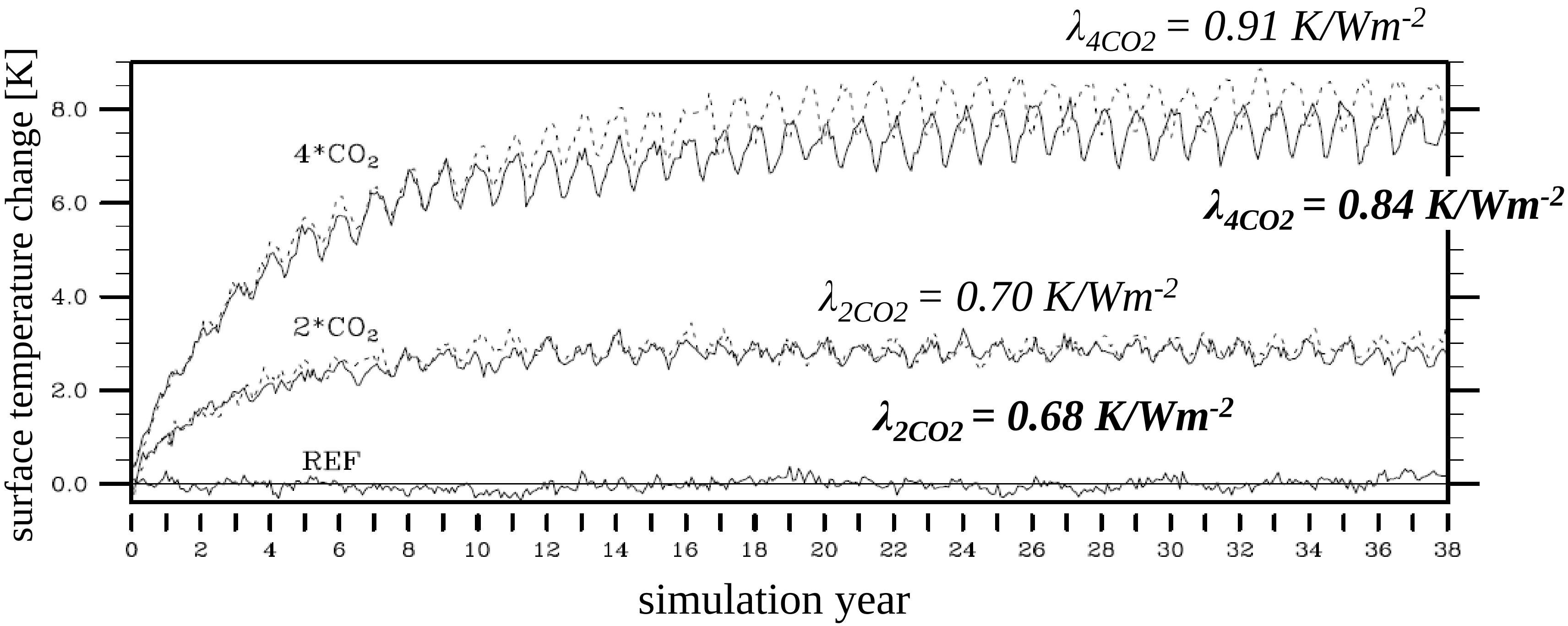
Reference: Jöckel et al., 2005 (*Atmos. Chem. Phys.*)

- an interface with infrastructure to couple 'processes' (submodels) to a GCM (base model)
- a set of processes coded as switchable submodels
- an appropriate coding standard

Different Feedbacks = Different Climate Sensitivity

Example: Additional feedbacks with interactive chemistry

CO_2-driven equilibrium climate simulations (Dietmüller et al., 2014)



Different Feedbacks = Different Climate Sensitivity

Example: Additional feedbacks with interactive chemistry

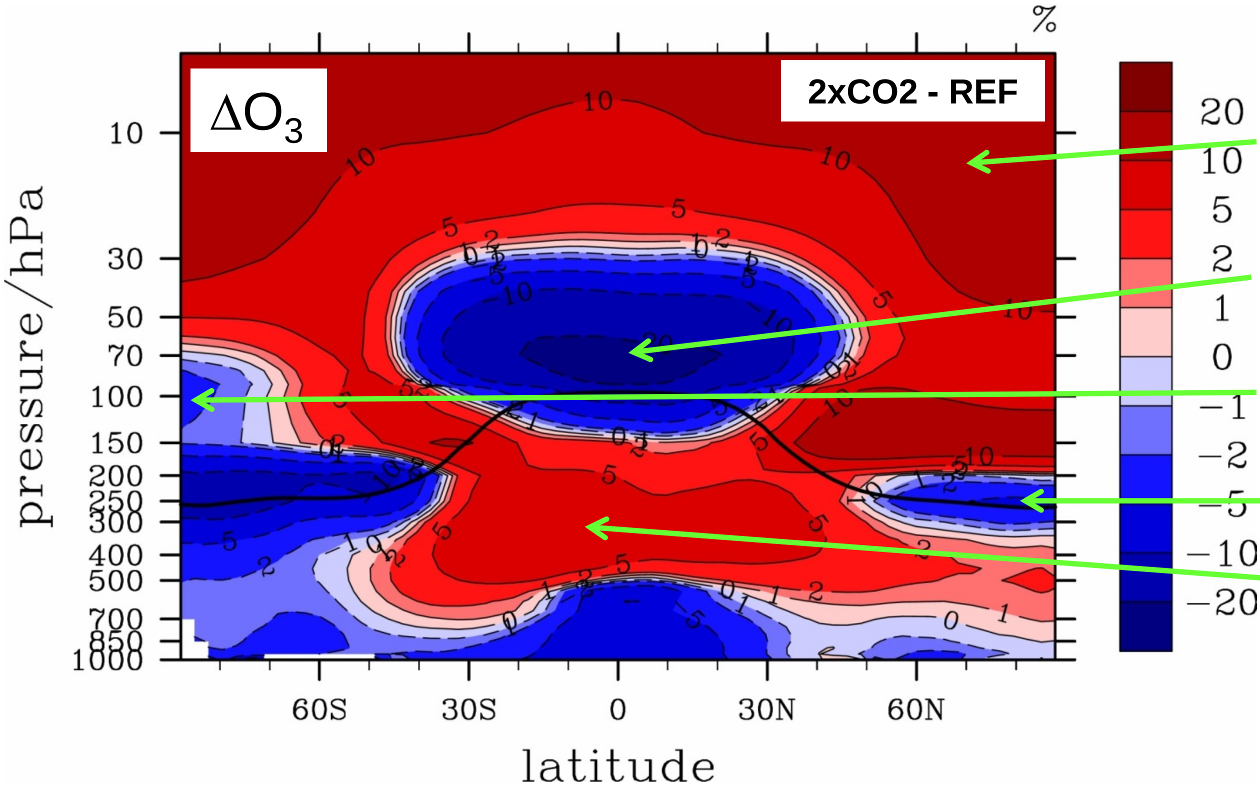
CO_2-driven equilibrium climate simulations (Dietmüller et al., 2014)

λ = 0.91 K/Wm^{-2}

Simulation		RF Wm^{-2}	chemistry	Climate sensitivity λ (K/Wm^{-2}) mean	[95% confi.]
75 ppmv CO_2 increase	+75CO2	1.06	no	0.73	[0.67; 0.79]
			yes	**0.63**	**[0.57; 0.68]**
Doubling of CO_2	2xCO2	4.13	no	0.70	[0.69; 0.72]
			yes	**0.68**	**[0.66; 0.69]**
Quadrupling of CO_2	4xCO2	8.93	no	0.91	[0.90; 0.92]
			yes	**0.84**	**[0.83; 0.85]**

simulation year

Negative ozone feedback in CO_2-driven simulations



slower ozone destruction

Enhanced tropical upwelling as troposphere warms

more PSCs in colder stratosphere

Tropopause lifting

modified NO_y background (e.g., lightning NO_x production)

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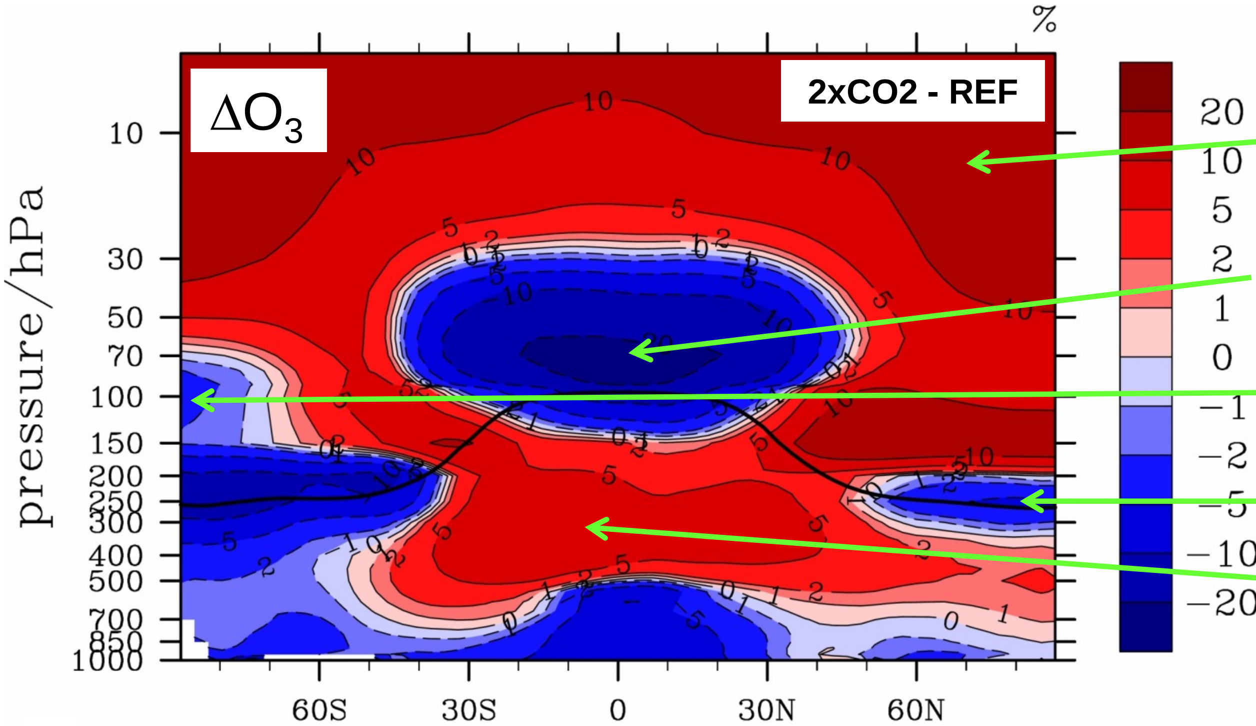
Negative ozone feedback in CO_2-driven simulations



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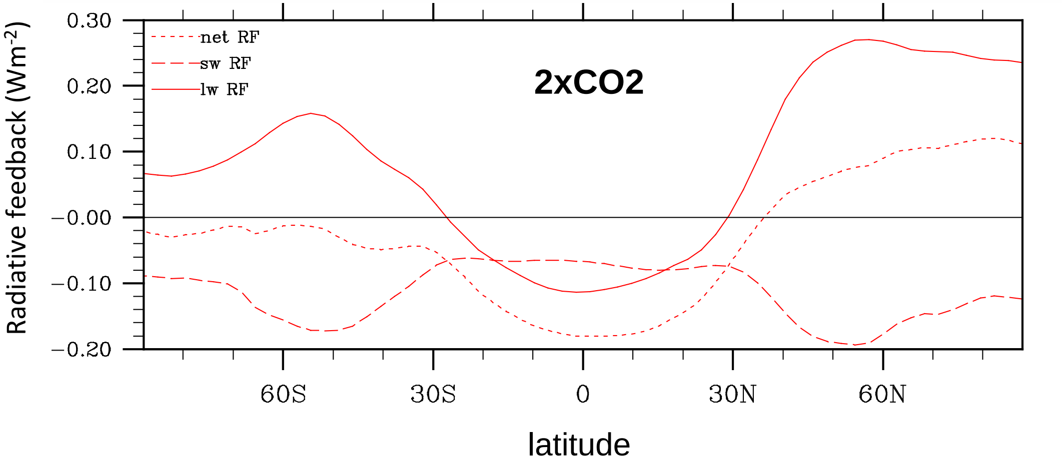
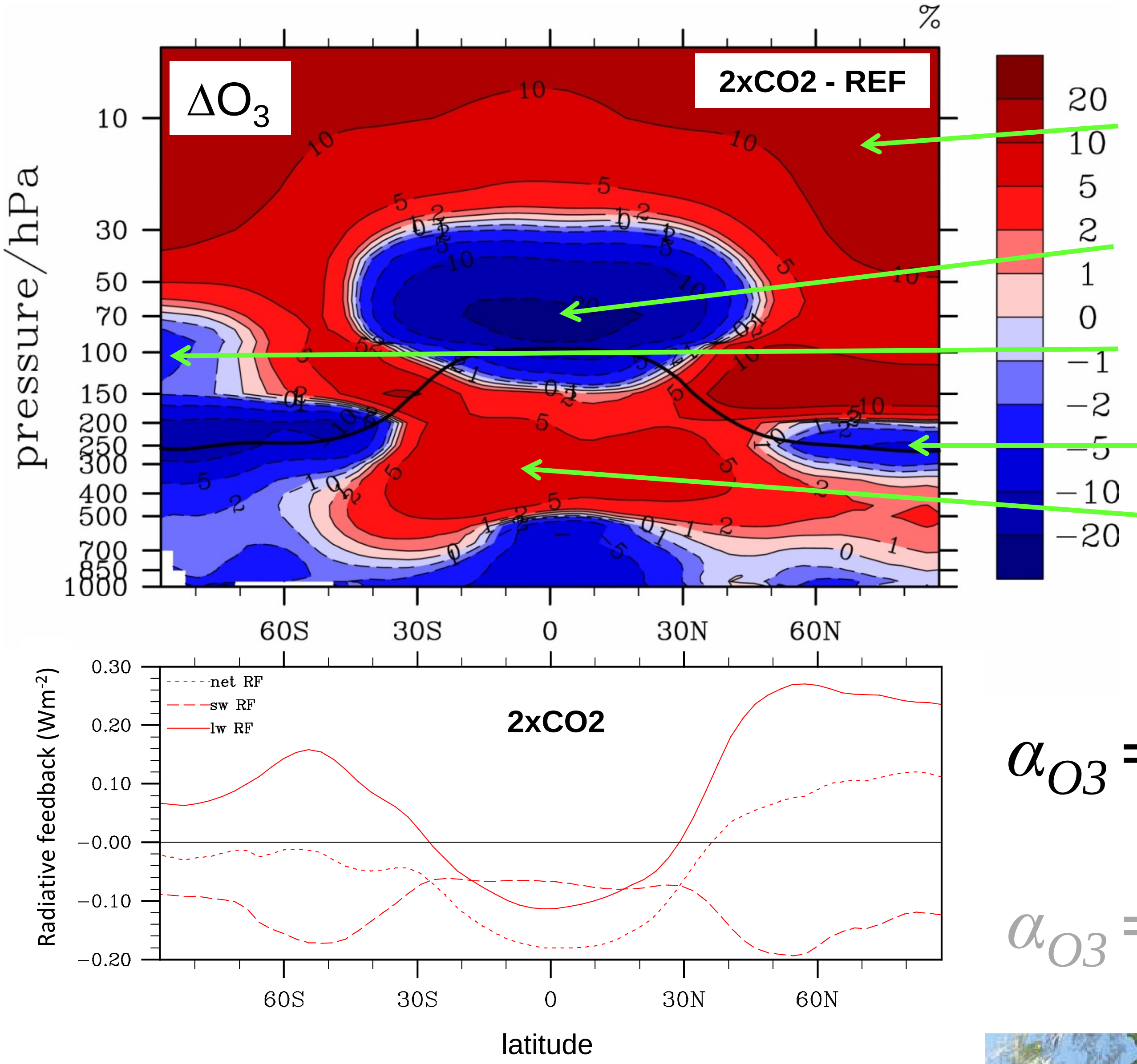


$$\alpha_{O3} = -0.022\ \mathrm{Wm^{-2}K^{-1}}$$

Negative ozone feedback in CO_2-driven simulations



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modified NO_y background (e.g., lightning NO_x production)

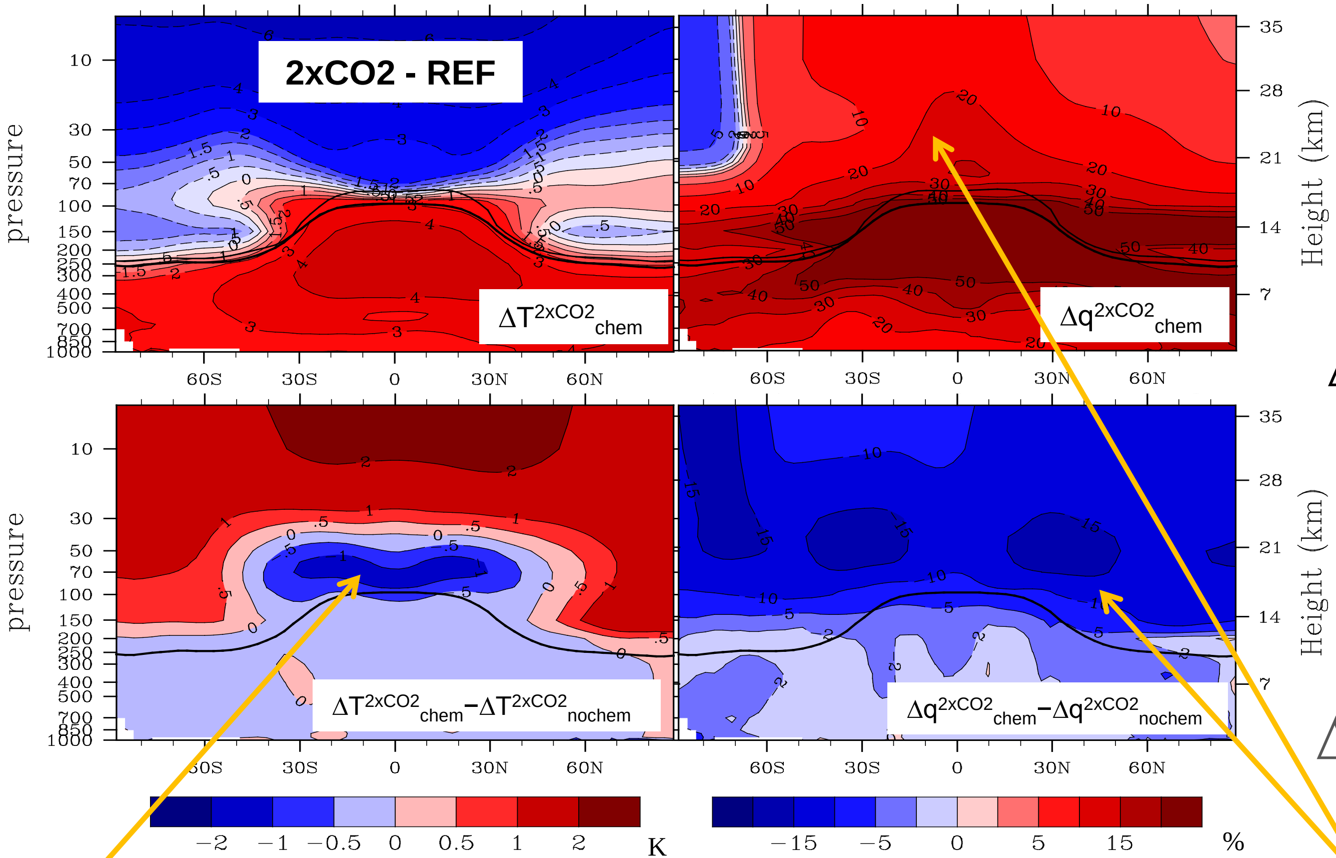
$$\alpha_{O3} = -0.022\ \mathrm{Wm^{-2}K^{-1}}$$

↓ 4xCO2

$$\alpha_{O3} = -0.015\ \mathrm{Wm^{-2}K^{-1}}$$

(Dietmüller et al.. 2014)

Ozone feedback reduces stratospheric water vapour feedback



$\Delta\alpha_q = -0.027\ \mathrm{Wm^{-2}K^{-1}}$

4xCO2

$\Delta\alpha_q = -0.047\ \mathrm{Wm^{-2}K^{-1}}$

(Dietmüller et al.. 2014)

Ozone feedback leads to reduced heating at the tropical cold point tropopause.

Stratospheric water vapor increase and its radiative feedback is small than without interactive chemistry.

Additional negative feedbacks reduce climate sensitivity

Taking into account interactive chemistry in CO_2-driven climate change simulations (Dietmüller et al.. 2014)

- introduces an additional negative feedback from stratospheric ozone.
- leads to a reduction of the stratospheric water vapour feedback by between 15% and 20%.
- reduces the climate sensitivity by <u>3.4%</u> (2xCO2) and <u>8.4%</u> (4xCO2) in comparison to an equivalent model setup with prescribed ozone.

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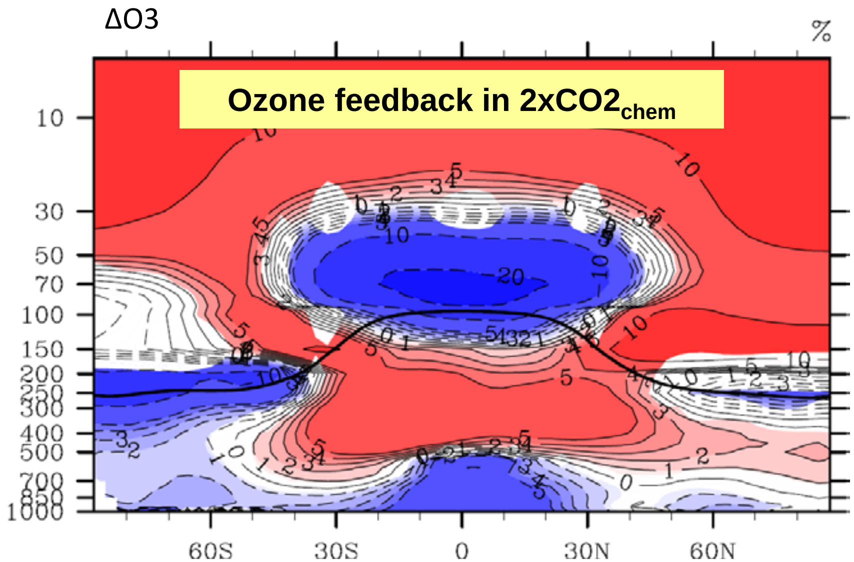
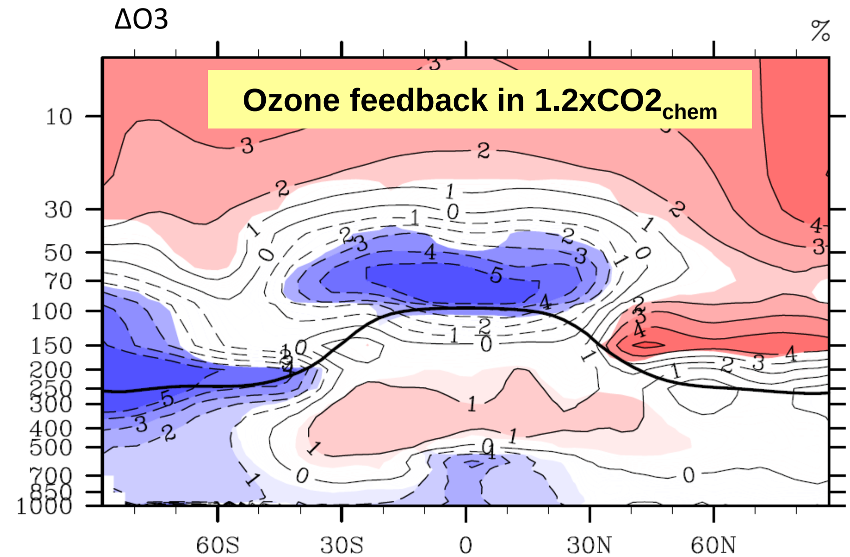
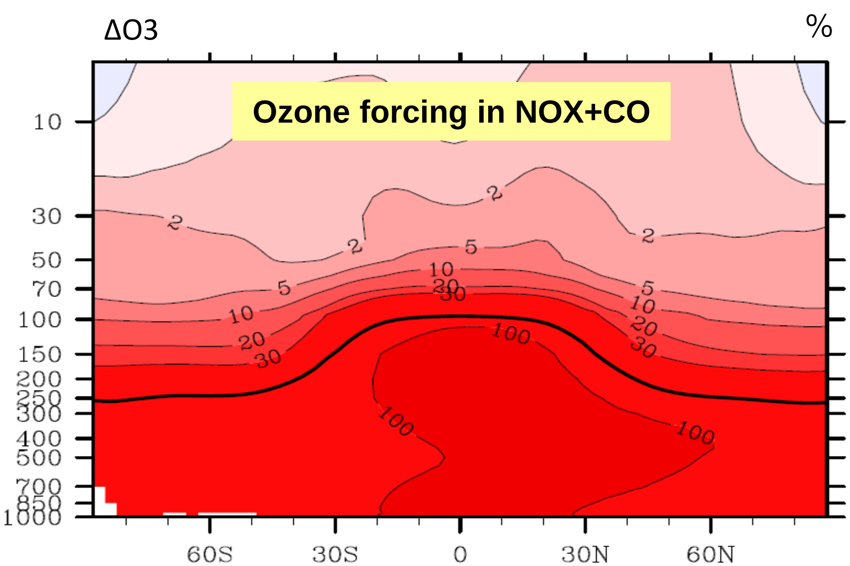
Robustness

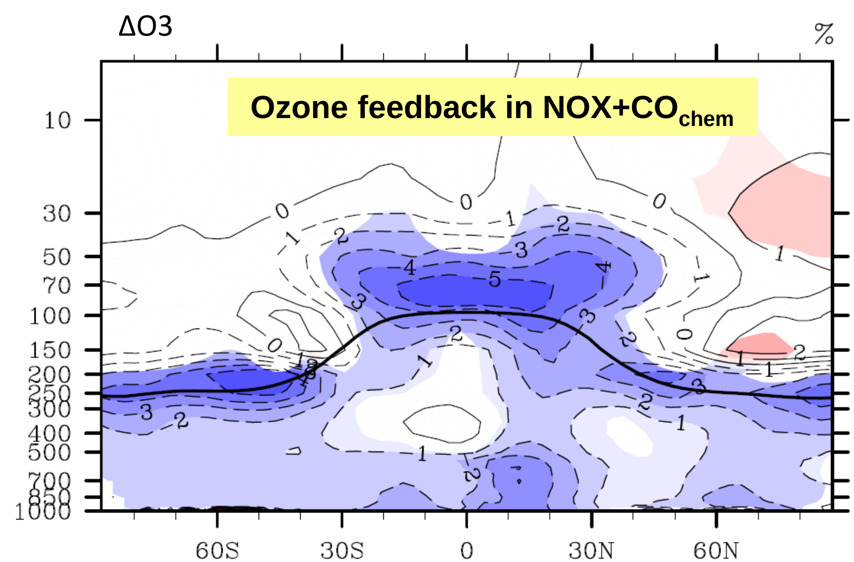
EMAC/MLO results qualitatively confirmed by 2 similar model setups in 4xCO2 simulations (Muthers et al., 2014, Nowack et al., 2015), but the latter paper finds <u>20%</u> climate sensitivity reduction in HADGEM3/AO.

Chemical feedback in non-CO_2-driven simulations

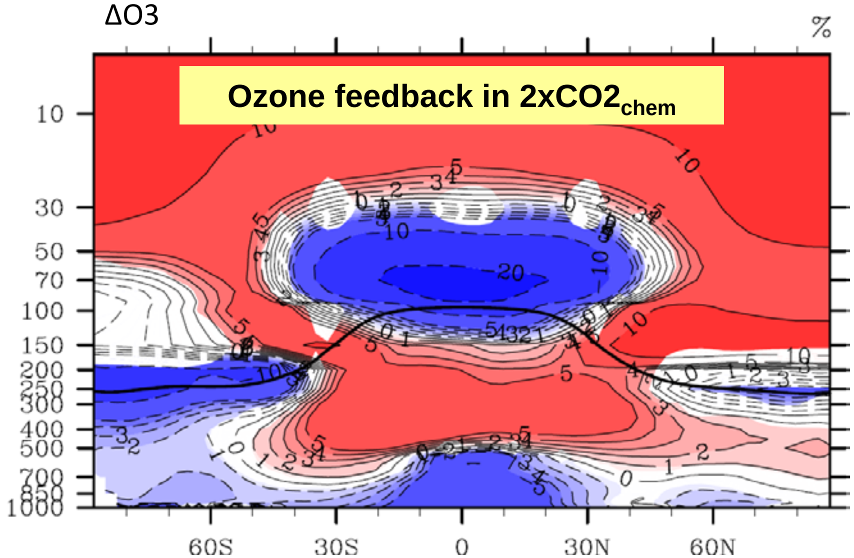


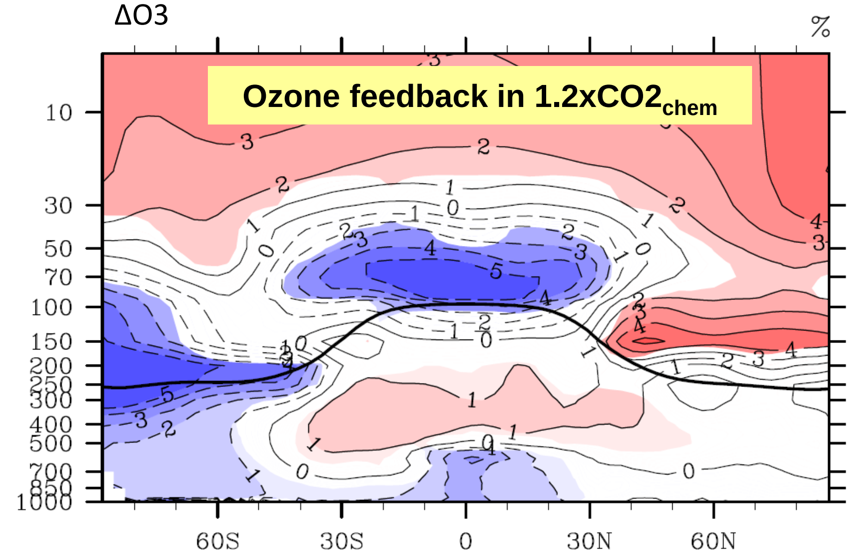


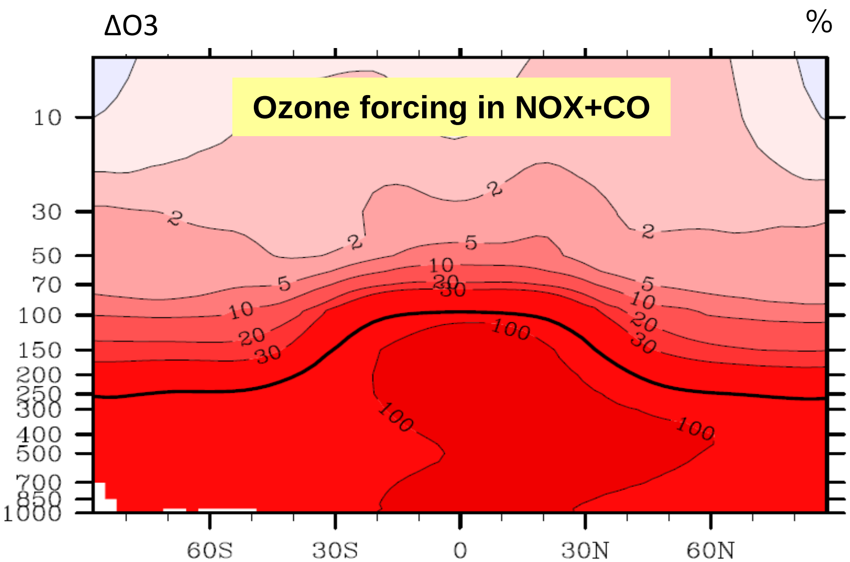


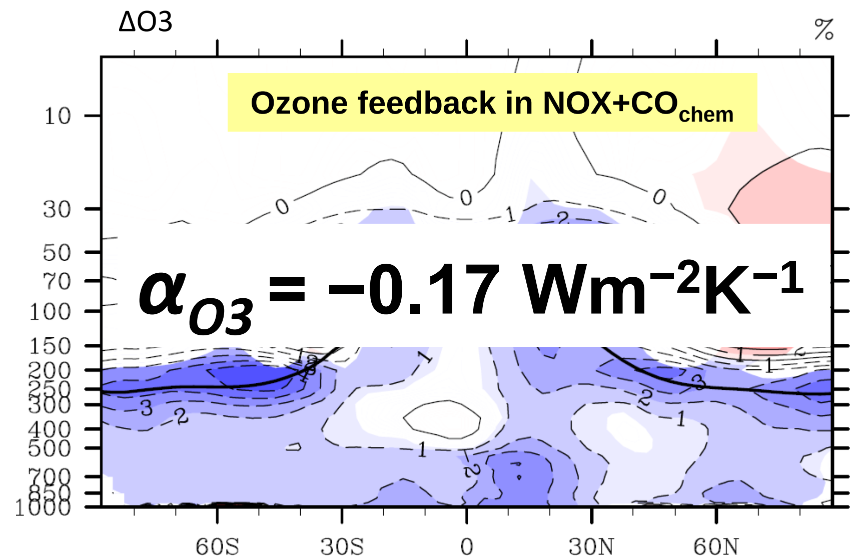


Chemical feedback in non-CO_2-driven simulations









Climate feedbacks and sensitivity for non-CO_2 forcing

simulation	RF Wm^{-2}	chemistry	Climate sensitivity λ K/(Wm^{-2}) mean	[95% conf.int.]
CO_2 increase (75 ppmv)	1.06	no	0.73	[0.67; 0.79]
		yes	**0.63**	**[0.57; 0.68]**
O_3 change (through more NO_x/CO surface emissions)	1.22	no	0.63	[0.57; 0.69]
		yes	**0.69**	**[0.65; 0.73]**

interactive chemistry with RF(CO_2):
reduced climate sensitivity due to negative ozone radiative feedback (!)

interactive chemistry with RF(O_3):
enhanced climate sensitivity despite negative ozone radiative feedback (???)

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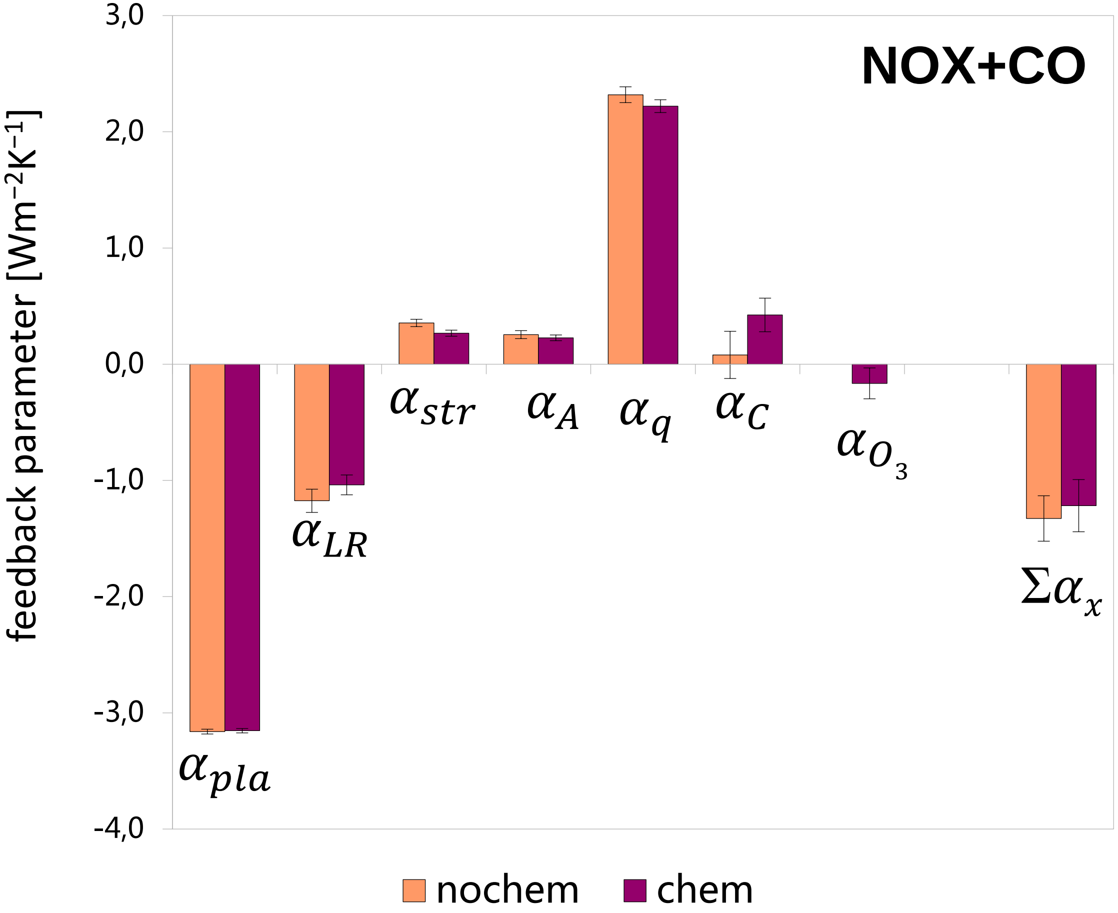
Complete feedback analysis

$$\lambda = -\frac{1}{\alpha}$$



In the ozone-driven simulations (via NOX+CO) the damping influence of negative ozone radiative feedback on climate sensitivity is masked; it is (over-)compensated by an enhanced (positive) cloud radiative feedback.

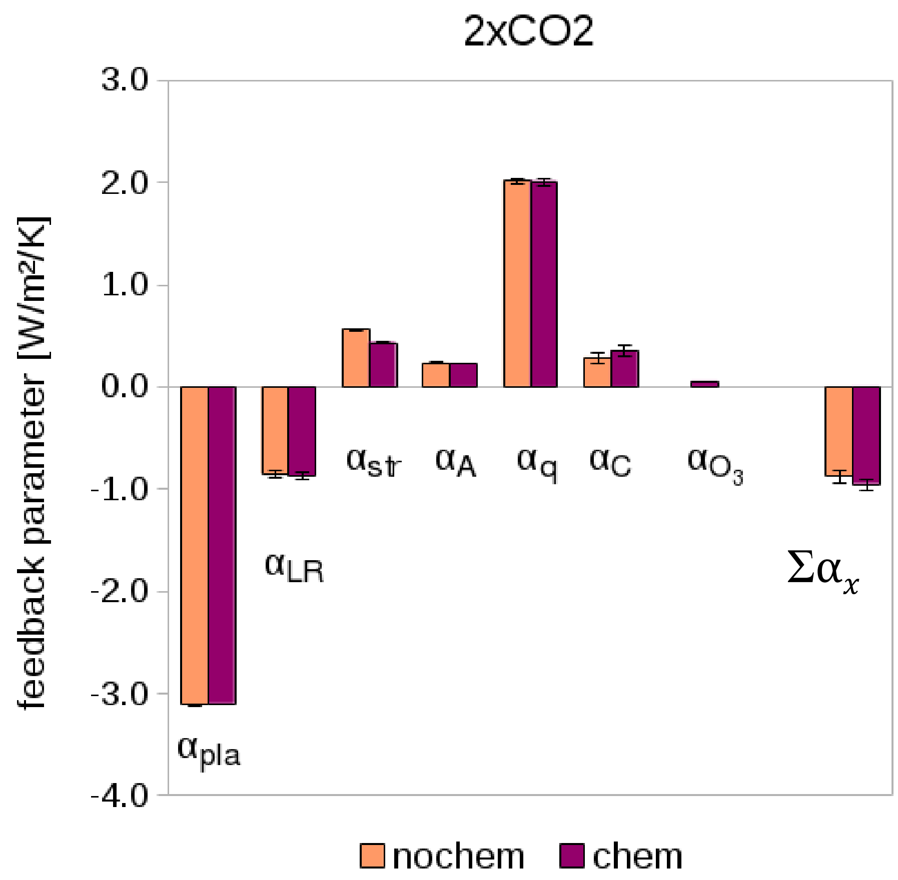
Complete Feedback Analysis

All ready for routine use ?

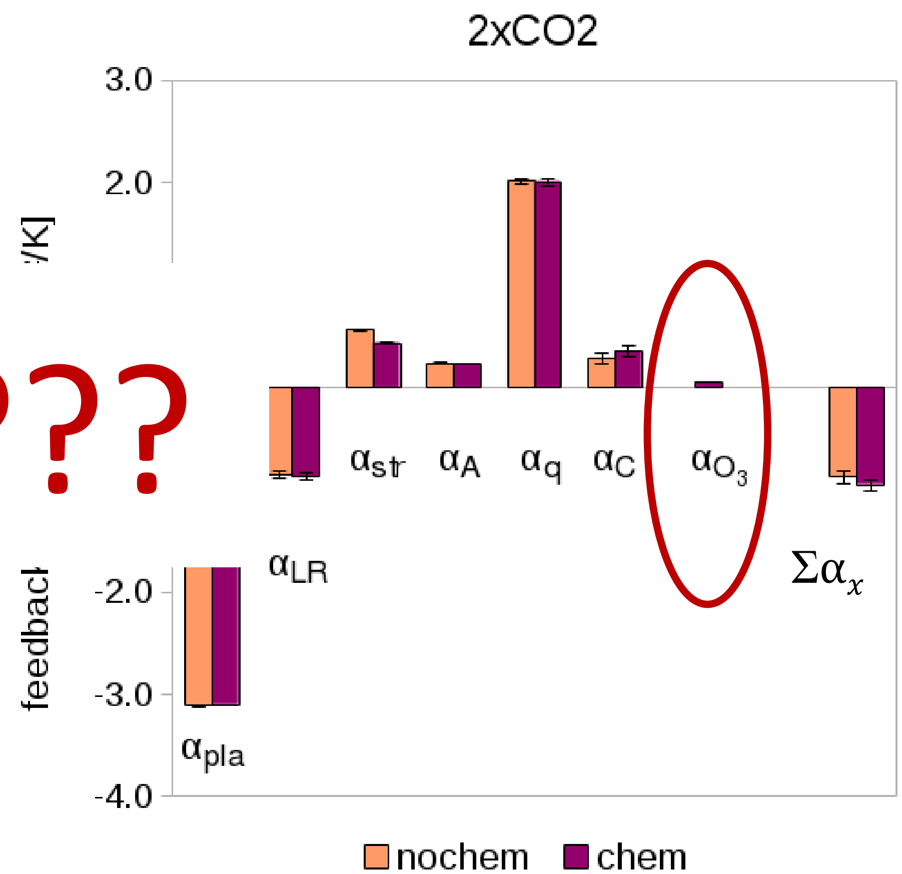
Not quite …

Feedback Analysis − Method Optimisation

$$\lambda = -\frac{1}{\alpha}$$



Feedback Analysis – Method Optimisation



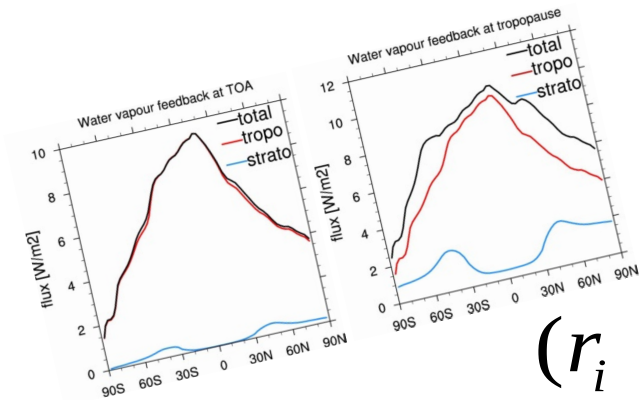
OOPS ???

With conventional methodology of feedback analysis (instantaneous ToA flux changes, without stratospheric temperature adjustment!) some known drawbacks of the forcing/feedback definition do pop up again!

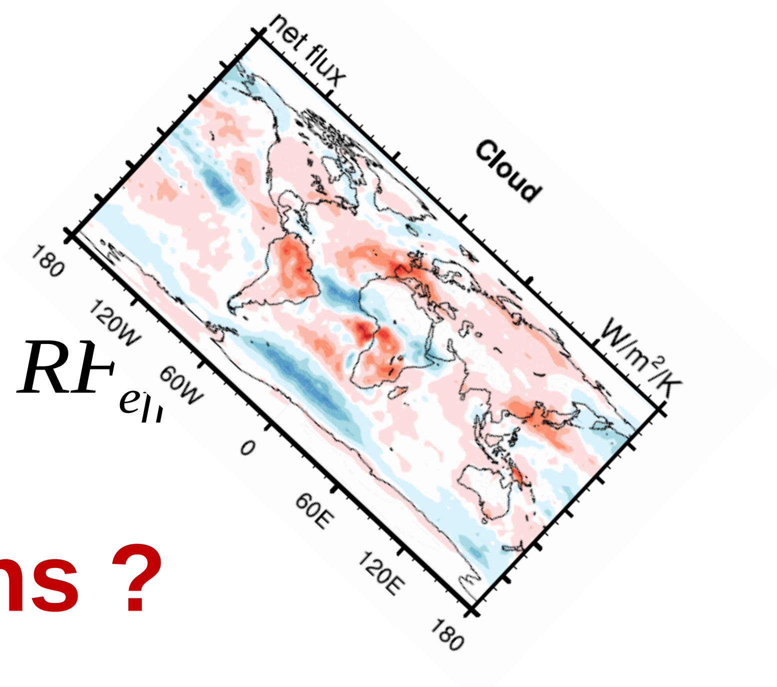
Radiative feedback analysis including ozone

Conclusions and Outlook

- Consistent explanation of climate sensitivity variations by feedback variations (incl. chemistry) is possible, on principle.
- An appropriate methodology allows to identify statistically significant feedback changes down to a radiative forcing magnitude of about 1 W/m^2.
- Further method optimisation is desirable to reconcile the common way of feedback analysis (instantaneous flux changes at ToA) with physically more reasonable variables (flux changes at the tropopause, or including stratospheric temperate adjustment).



$$(r_i \cdot RF_{adj}) = RF_{e}$$



Questions ?