Analysis of Radiative Feedbacks in Model Simulations Including Interactive Chemistry

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Conceptual Framework

Radiative forcing, radiative feedback, climate sensitivity

The climate sensitivity parameter λ describes the global surface temperature response ΔT_S to a radiative forcing RF:

Non-CO_2 radiative forcings are said to have reduced or enhanced efficacy r, if the surface temperature response per unit radiative forcing (i.e, λ) is smaller or larger than the reference climate sensitivity parameter λ_{CO_2}.

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

Variations of the climate sensitivity (among different models, among different forcings, etc.) may be related to distinctive radiative feedbacks α_x.

$$\alpha_{phys} = \sum_x \alpha_x = -\frac{1}{\lambda}$$

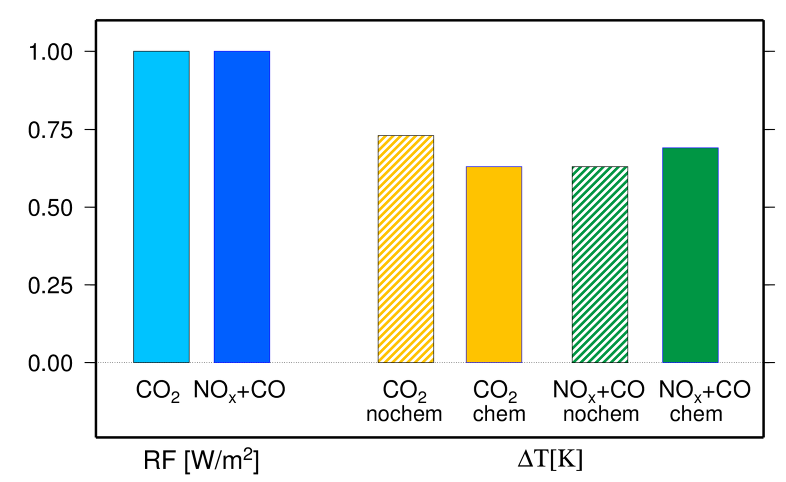
Classical climate models (AOGCMs) include a well defined set of physical feedback processes (x): Planck, water vapor, lapse rate, cloud, and surface albedo feedbacks.

Additional chemical feedback

Chemistry climate models (CCMs) include more feedbacks (y) than AOGCMs due to the presence of additional radiatively active tracers:

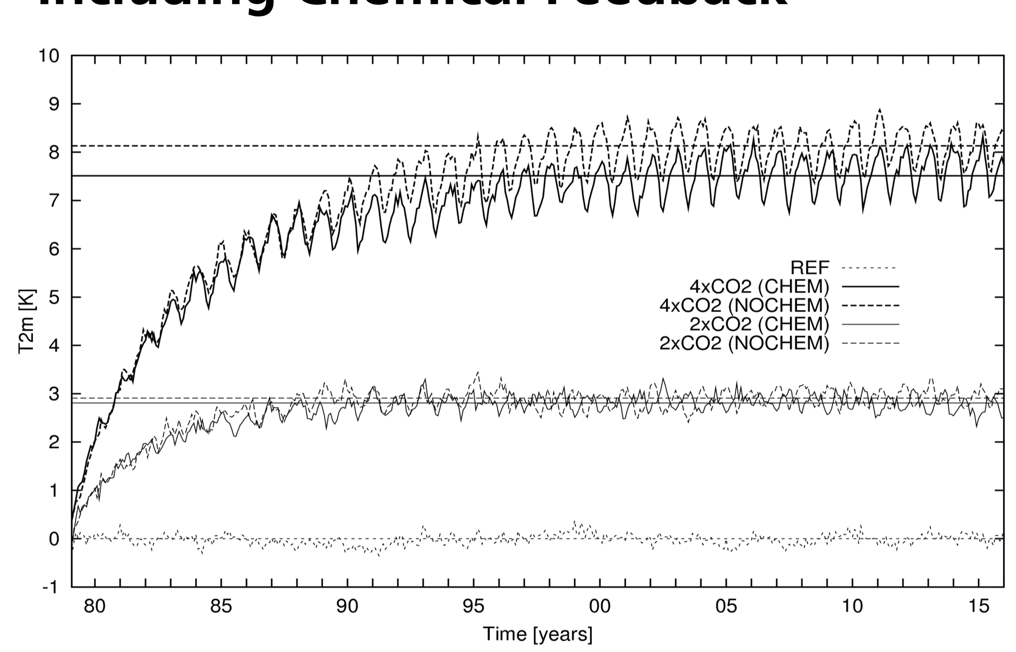
$$\alpha = \sum_y \alpha_y = \alpha_{phys} + \alpha_{chem}$$

Hence, CCMs can be expected to simulate a different climate sensitivity than an equivalent model with no chemical feedback α_{chem}.



The modifying impact of chemical feedbacks on the climate sensitivity can differ between different forcing mechanisms.

Reduced Climate Sensitivity in CO_2-driven Simulations Including Chemical Feedback



Model: EMAC

ECHAM5/MESSy Atmospheric Chemistry model

ECHAM5 : ECMWF/MPI-HAMburg model, version 5 (Roeckner et al., 2004)

MESSy: Modular Earth Submodel System (Jöckel et al., 2005)

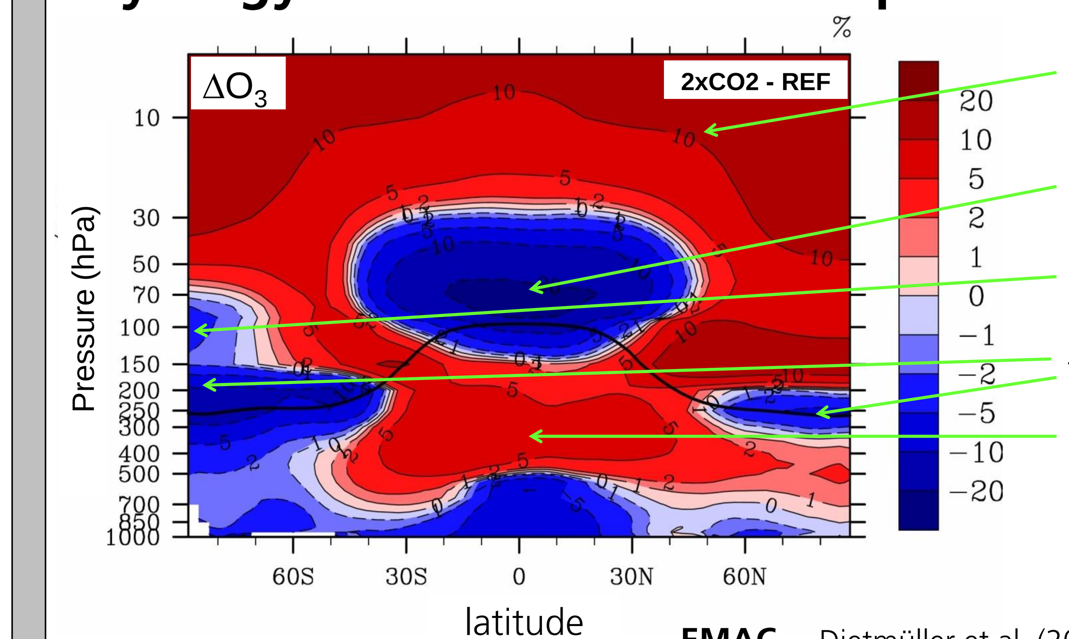
Simulation		RF Wm^{-2}	chemistry	Climate sensitivity λ K/(Wm⁻²) mean	[95% confi.]
Increase of CO_2 by 75 ppmv	+75CO2	1.06	no	0.73	[0.67; 0.79]
			yes	**0.63**	**[0.57; 0.68]**
Doubling of CO_2	2xCO2	4.13	no	0.70	[0.69; 0.72]
			yes	**0.68**	**[0.66; 0.69]**
Quadrupling of CO_2	4xCO2	8.93	no	0.91	[0.90;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

Simulations:

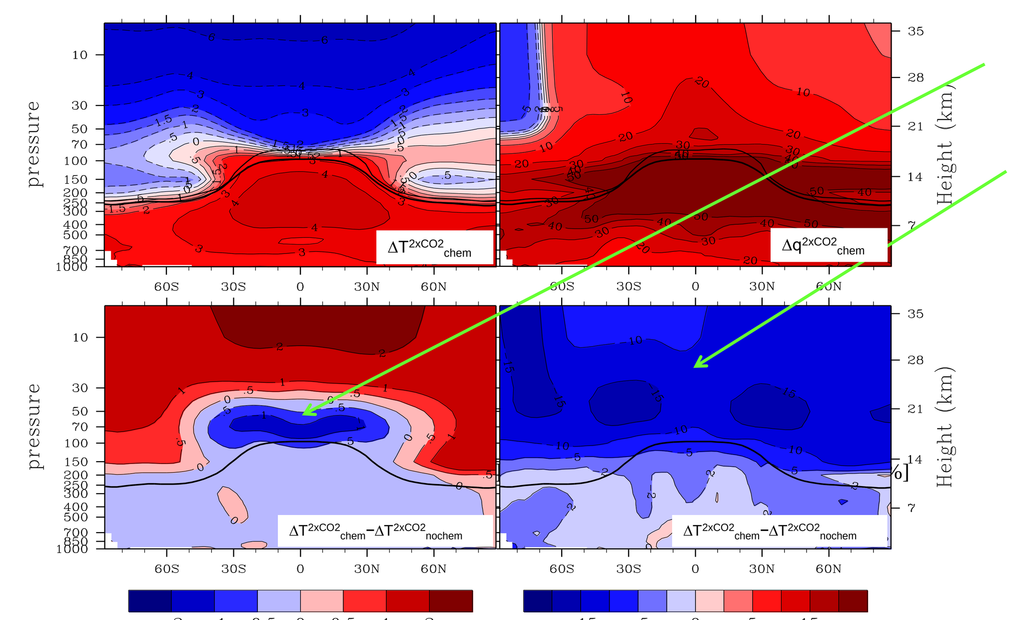
Dietmüller (2011)
Dietmüller et al. (2014)

Climate sensitivity changes are initiated by the feedback induced by interactive ozone.

Synergy of Ozone and Stratospheric Water Vapor Feedbacks



2xCO2
$\alpha_{O3} = -0.022\ Wm^{-2}K^{-1}$
4xCO2
$\alpha_{O3} = -0.015\ Wm^{-2}K^{-1}$



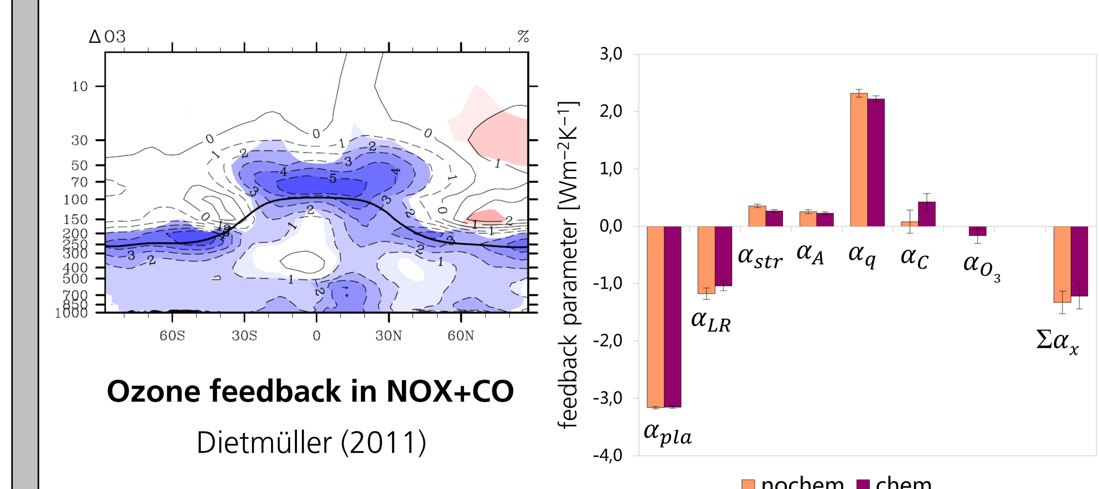
2xCO2
$\Delta\alpha_q = -0.027\ Wm^{-2}K^{-1}$
4xCO2
$\Delta\alpha_q = -0.047\ Wm^{-2}K^{-1}$

Interactive chemistry in CO_2-driven climate change simulations

- introduces an additional negative radiative feedback from stratospheric ozone.
- may lead to a substantial reduction of the stratospheric water vapor radiative feedback (with considerable inter-model dependency)
- may significantly reduce the climate sensitivity (in **EMAC** by 3.4%: 2xCO2, or by 8.4%: 4xCO2), in comparison to a model setup with prescribed ozone.

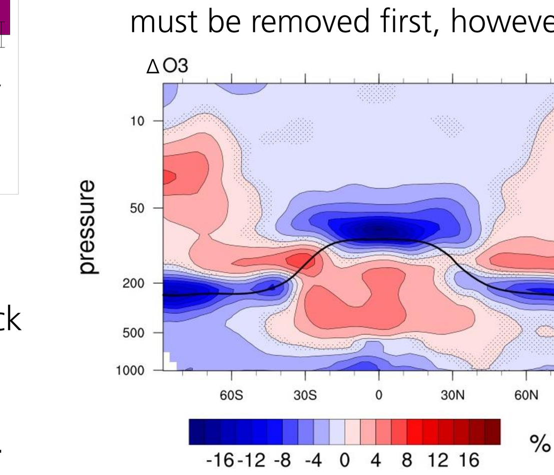
Ozone Feedback under Non-CO_2 Radiative Forcings

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	no	NOX+CO	1.22	0.63	[0.55; 0.67]	0.86
ΔO_3 from enhanced NO_x+CO	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



If enhanced NO_x and CO surface emission induce the climate change, ozone acts both as radiative forcing *and* feedback. The ozone feedback pattern is similar as in the CO_2 case, but the effect on the climate sensitivity parameter is less straightforward and a complete feedback analysis (Rieger et al., 2017) is needed to understand the overall impact.

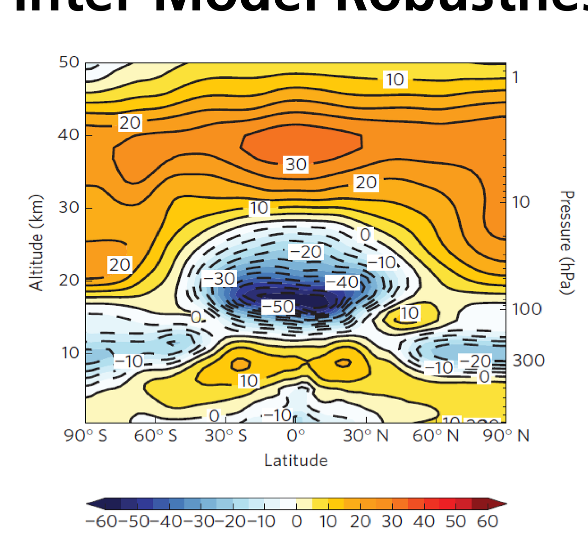
If the climate warming originates from (5x) CH_4 forcing, the **ozone feedback** pattern again comes out similar (see below). Rapid ozone adjustments to the CH_4 increase (Winterstein et al., 2019) must be removed first, however.



Take Home Message

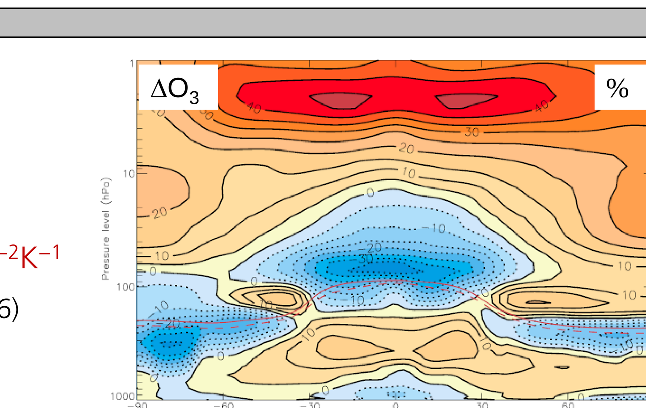
- A robust ozone concentration response develops in chemistry-climate models under CO_2–driven climate change, inducing a negative radiative feedback.
- The respective impact on climate sensitivity is quite model-dependent, however.
- The negative ozone feedback is dominated by an ozone decrease in the lowermost tropical stratosphere, which originates from enhanced tropical upwelling.
- Ozone feedback and stratospheric water vapor feedback are strongly coupled.
- Some key features of the ozone feedback pattern also occur, if a forcing other than from CO_2 drives the climate change, but …
- … ozone rapid adjustments may differ substantially for different forcings.

Inter-Model Robustness (4xCO2)

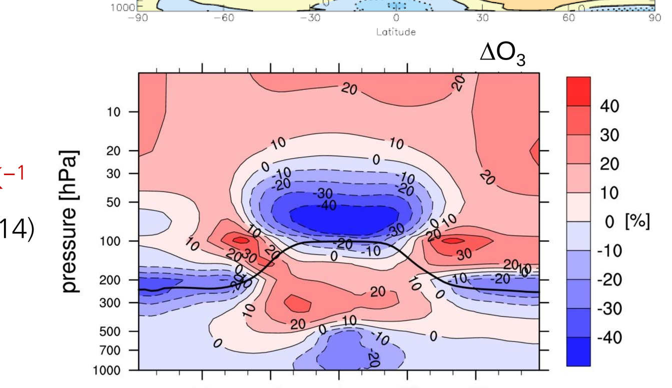


HADGEM2
Nowack et al. (2015)
$\alpha_{O3} \sim -0.13\ Wm^{-2}K^{-1}$
Δλ ~ −20%

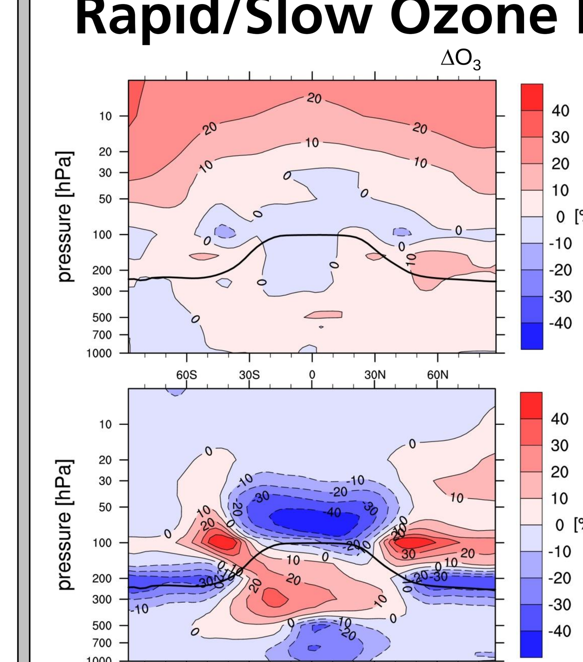
WACCM
$\alpha_{O3} \sim -0.011\ Wm^{-2}K^{-1}$
Marsh et al. (2016)
Δλ ~ −1%



EMAC
$\alpha_{O3} \sim -0.015\ Wm^{-2}K^{-1}$
Dietmüller et al. (2014)
Δλ ~ −8%



Rapid/Slow Ozone Feedback (4xCO2)



The main part of the ozone feedback pattern develops slowly, on the time-scale of the SST change (bottom panel).

However, above ~30 hPa, rapid adjustment to the stratospheric cooling caused by the CO_2 increase dominates.

This may result in radiative impact contributions of different sign.

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