Ozone Radiative Feedback in Global Warming Simulations with CO$_2$ and non-CO$_2$ forcing

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Wissen für Morgen
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 ($\lambda$).

Hence, different climate models simulate a different temperature response development, even if the (radiative) forcing is the same (here: IPCC, 2013).
The climate sensitivity parameter $\lambda$ links the global mean surface temperature response ($\Delta T_S$) and the radiative forcing $RF$:

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

$\lambda$ crucially depends on the strengths of a number of the radiative feedbacks ($\alpha_x$) 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: Fundamental metric to quantitatively assess and inter-compare various contributions to total climate change (here: IPCC, 2013 [AR5])

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

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\[ \Delta T_S = \lambda \cdot RF \]
Radiative Forcing and Radiative Feedbacks

Example: CO₂–driven climate change

\[ RF \xrightarrow{\text{CO}_2} \text{Climate Change} \xrightarrow{\Delta T, \Delta q, \Delta cld, \Delta alb, \ldots} \Delta T_s^{eq} \]

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

\[ \ldots + \alpha_{O_3} + \alpha_{CH_4} + \alpha_{N_2O} + \alpha_{FCKW} + \alpha_{Aero} \ldots \]
Radiative Forcing and Radiative Feedbacks

Example: CO₂–driven climate change

\[ RF \]

\[ \Delta T, \Delta q, \Delta cld, \Delta alb, \ldots \]

\[ \Delta O_3, \Delta CH_4, \Delta N_2O \]

\[ \alpha = \sum \alpha_x = \alpha_{pla} + \alpha_q + \alpha_{LR} + \alpha_{alb} + \alpha_{cld} + \ldots + \alpha_{O_3} + \alpha_{CH_4} + \alpha_{N_2O} + \alpha_{FCKW} + \alpha_{Aero} \ldots \]
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)

\[
\begin{align*}
\lambda_{4\text{CO}_2} &= 0.91 \text{ K/Wm}^{-2} \\
\lambda_{2\text{CO}_2} &= 0.70 \text{ K/Wm}^{-2} \\
\lambda_{\text{REF}} &= 0.68 \text{ K/Wm}^{-2}
\end{align*}
\]
Different Feedbacks = Different Climate Sensitivity

Example: Additional feedbacks with interactive chemistry CO$_2$-driven equilibrium climate simulations (Dietmüller et al., 2014)

<table>
<thead>
<tr>
<th>Simulation</th>
<th>RF Wm$^{-2}$</th>
<th>chemistry</th>
<th>Climate sensitivity $\lambda$ (K/Wm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 ppmv CO$_2$ increase</td>
<td>+75CO$_2$</td>
<td>1.06</td>
<td>no 0.73 [0.67; 0.79]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>yes 0.63 [0.57; 0.68]</td>
</tr>
<tr>
<td>Doubling of CO$_2$</td>
<td>2xCO$_2$</td>
<td>4.13</td>
<td>no 0.70 [0.69; 0.72]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>yes 0.68 [0.66; 0.69]</td>
</tr>
<tr>
<td>Quadrupling of CO$_2$</td>
<td>4xCO$_2$</td>
<td>8.93</td>
<td>no 0.91 [0.90; 0.92]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>yes 0.84 [0.83; 0.85]</td>
</tr>
</tbody>
</table>
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$_x$ background (e.g., lightning NO$_x$ production)
Negative ozone feedback in CO$_2$-driven simulations

\[ \Delta O_3 = -0.022 \text{ Wm}^{-2}\text{K}^{-1} \]

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\[ \alpha_{O3} = -0.022 \text{ Wm}^{-2}\text{K}^{-1} \]
Negative ozone feedback in CO$_2$-driven simulations

$\Delta O_3 = 2xCO_2 - REF$

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- Modified NO$_y$ background (e.g., lightning NO$_x$ production)

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

$\downarrow 4xCO_2$

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

(Dietmüller et al. 2014)
Ozone feedback reduces stratospheric water vapour feedback

Δα_q = −0.027 Wm⁻²K⁻¹

(Dietmüller et al. 2014)

4xCO2

Δα_q = −0.047 Wm⁻²K⁻¹

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 3.4% (2xCO2) and 8.4% (4xCO2) in comparison to an equivalent model setup with prescribed ozone.
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 3.4% (2xCO$_2$) and 8.4% (4xCO$_2$) in comparison to an equivalent model setup with prescribed ozone.

Robustness

EMAC/MLO results qualitatively confirmed by 2 similar model setups in 4xCO$_2$ simulations (Muthers et al., 2014, Nowack et al., 2015), but the latter paper finds 20% climate sensitivity reduction in HADGEM3/AO.
Chemical feedback in non-\(\text{CO}_2\)-driven simulations

- Ozone feedback in 2\(\times\)\(\text{CO}_2\)\text{chem}
- Ozone feedback in 1.2\(\times\)\(\text{CO}_2\)\text{chem}
- Ozone forcing in NOX+CO
- Ozone feedback in NOX+CO\text{chem}
Chemical feedback in non-CO$_2$-driven simulations

$\alpha_{O3} = -0.17$ Wm$^{-2}$K$^{-1}$
## Climate feedbacks and sensitivity for non-CO$_2$ forcing

<table>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>[0.57; 0.68]</td>
</tr>
<tr>
<td>O$_3$ change (through more NO$_x$/CO surface emissions)</td>
<td>1.22</td>
<td>no</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>yes</td>
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**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 (???)
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 ...
\[ \lambda = -\frac{1}{\alpha} \]
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/m².

• 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).
\[(r_i \cdot RF_{adj}) = RF_{e_{ij}}\]

Questions?