Project: **1205**

Project title: **SOCTOC – Effects of anthropogenic stratospheric ozone changes on climate sensitivity and tropospheric oxidation capacity**

Project lead: **Hauke Schmidt**
Contributors: Diego Jimenez de la Cuesta (MPI-M), Roland Ruhnke, Khompat Satitkovitchai (all KIT)

Report period: **01.01.2022 - 31.10.2022**

Introduction

The anthropogenic changes in the stratospheric ozone and the large-scale circulation influence the temperature and composition of the tropopause layer, especially the tropical tropopause layer (TTL). These effects on the TTL potentially alter the chemistry of other trace gases in the troposphere and modify the degree of surface warming in response to the changes in radiative forcing. Our project seeks to understand better the effect of these TTL changes on (a) the tropospheric oxidation capacity of methane, a potent greenhouse gas, and (b) the effect on the warming in response to a doubling of the atmospheric CO_2 concentration (climate sensitivity). To tackle these questions, we use a hierarchy of models, each one a tool for a specific purpose: from 1D-RCE, global climate, and climate-chemistry models.

Summary for part (a)

The oxidation capacity or self-cleaning in the troposphere is mainly controlled by the existence of the OH radical. The photolysis of ozone into O(1D) and the subsequent reaction with H2O is the primary OH production, which is thus tightly related to the local solar UV actinic flux and hence the overhead ozone column. Globally, the main destruction of OH occurs by the reaction with the greenhouse methane, which lifetime itself is controlled by the concentration of the OH radical. In order to improve our understanding of the effects of anthropogenic changes of stratospheric ozone on the oxidation of the greenhouse gas methane, we perform calculations within the ICON-ART framework and report results of long-term simulations with two model configurations concerning stratospheric ozone: a) without interactive ozone, and b) with linearized interactive ozone schemes. The simulations also include a simplified OH chemistry scheme and the CloudJ scheme for the calculation of photolysis rates. With this chemical configurations of ICON-ART two long-term simulations have been performed, one AMIP type simulation and one with increased temperatures in the troposphere by 4 K seen by the chemistry. This set of simulations allows to investigate whether the main influence of stratospheric ozone changes on tropospheric oxidation capacity and hence on the lifetime of CH4 is due to changes in the actinic UV flux reaching the troposphere or to tropospheric warming. Without and with interactive ozone simulations (AMIP-nofb and AMIP-fb) we analyse the changes in OH concentrations and find the important role for stratospheric ozone in how ozone influences OH (see Fig.1).

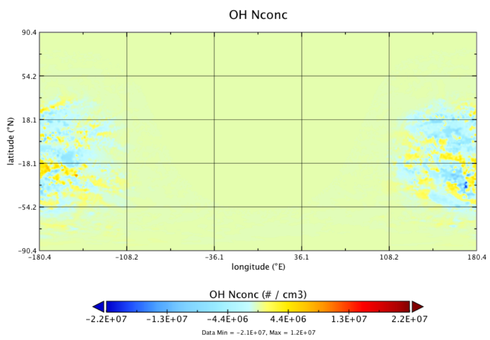


Figure 1: Map of OH concentration difference (one day in 1998) between AMIP-nofb and AMIP-fb at the lowest model level.

OH concentration in AMIP-nofb simulation is smaller with respect to the interactive one (AMIP-fb), which indicates that more ozone in the stratosphere leads to higher OH amounts at the lowest model level.

Besides that the stratospheric ozone also influences on global surface temperature (see Fig. 2), which results in temperature differences of about 3 Kw with warmer areas above e.g.Europe and colder regions (e.g. Australia).

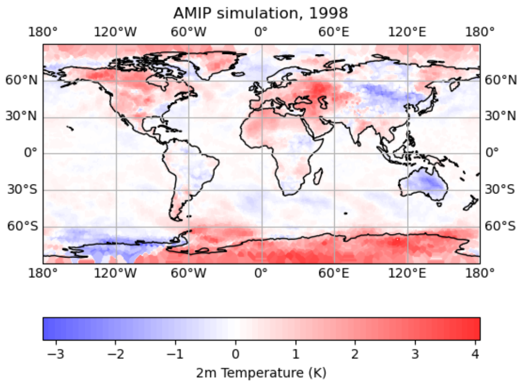


Figure 2: Temperature difference between AMIP-nofb and AMIP-fb at the surface for the year 1998.

Summary of previous findings for part (b)

The 1D-RCE "Konrad" results were the main inspiration for this year's experiments for question (b), as we reported in 2021. In those experiments, we analysed how the change in tropical stratospheric upwelling in response to tropical surface warming affected the tropical energy budget. Most global climate models of the CMIP5 and CMIP6 ensembles show an accelerated Brewer-Dobson circulation and, therefore, stronger tropical stratospheric upwelling. The main result of our upwelling change experiments is that increasing upwelling speeds lead to less tropical surface warming (lower tropical climate sensitivity), as shown in Figure 3.

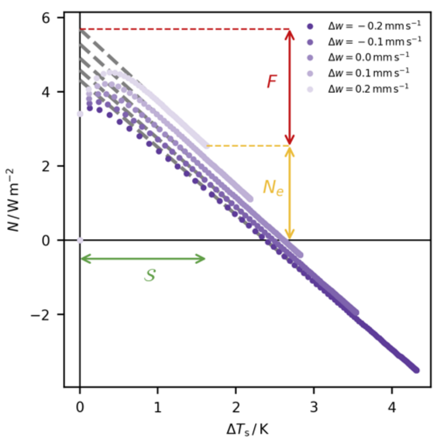


Figure 3: Changes in the tropical net radiative flux at the top of the atmosphere (N) versus surface temperature in "Konrad". In shades of violet, different changes in upwelling speed. The tropical energy export N_e increases, dampening the effective forcing F and reducing the equilibrium climate sensitivity S.

The reason is that part of the energy introduced by the change in forcing due to the CO_2 increase is exported to the extratropical regions, dampening the tropical effective radiative forcing or, equivalently, leading to a dynamical-radiative feedback mechanism. Adding interactive ozone to the experiment further enhanced the reduction in climate sensitivity by the normal atmospheric-composition radiative feedback (e.g. Dacie et al., 2019). Still, the effect of the stratospheric upwelling change dominates. Nonetheless, the global consequences of this increased tropical energy export are unclear.

Summary of present findings of part (b)

We hypothesized that such change in the tropical energy export in a full GCM would lead to extratropical stratospheric warming, stronger extratropical radiative feedback and, consequently, a reduced global climate sensitivity.

Tropical energy export in CMIP5 and CMIP6 ensembles

First, we investigated if CMIP models showed a similar change in tropical energy export. We found that such change also occurs in these models, following a similar relationship as in “Konrad” (Fig. 4).

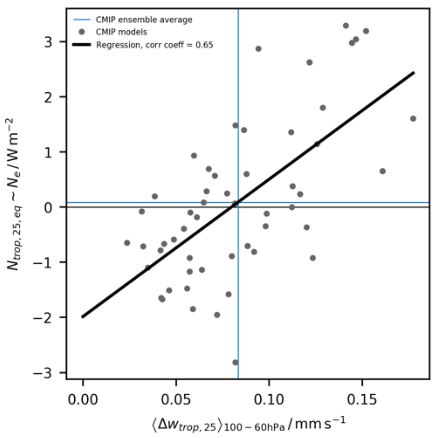


Figure 4: Change in the tropical net radiative flux at the top of the atmosphere at equilibrium ($N_{trop,25,eq}$) versus change in the tropical upwelling between 100 and 60 hectopascals in CMIP models. There is more export of energy with increasing tropical upwelling.

We have already presented these results with the “Konrad” ones at conferences and submitted them in an article under the first review round (Jiménez-de-la-Cuesta & Schmidt, 2022).

Because of these findings, we performed the nudged circulation experiments with MPI-ESM 1.2 to test the consequences for the extratropical radiative feedback mechanisms and the global climate sensitivity.

Effects of the nudged circulation on surface climate in MPI-ESM 1.2

Using the existing spectral nudging infrastructure in MPI-ESM 1.2, we performed experiments following the abrupt-4xCO2 protocol but with the dynamics nudged to the pre-industrial control (pi-Control) state. By nudging the dynamics, the model will presumably have the same tropical upwelling and energy export as in the pi-Control experiment. Consequently, we can test if the extratropical feedback mechanisms weaken, increasing global climate sensitivity. We chose 50 years of a pi-Control experiment and rerun these years for storing 6-hourly output.

In the nudged abrupt-4xCO2 experiments, we used the stored 6-hourly divergence and vorticity fields to nudge the dynamics with different strengths. We only nudge dynamics from ~300 hPa to ~7 hPa. Depending on the nudging time scale, the nudging data is combined with the calculated dynamical state in a different proportion, leading to diverse nudging strengths. We tested combinations of nudging time scales for vorticity and divergence. Thus, we obtained from increases in the tropical upwelling (weak nudging) to almost no change (strong nudging), as shown in Figure 5.

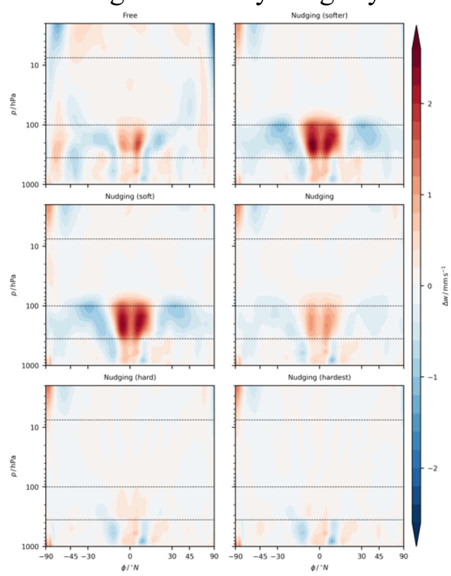
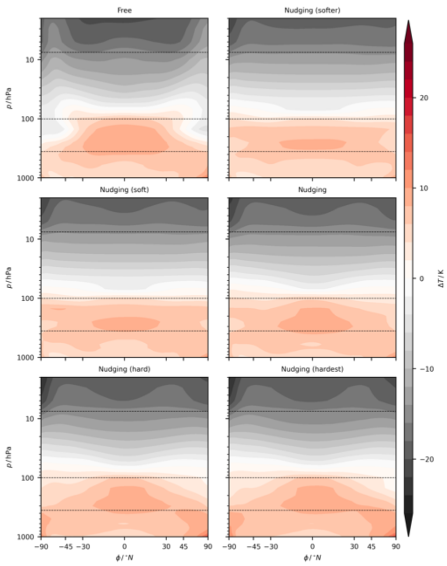


Figure 5: Zonal average of the change in upward motion in the nudged abrupt-4xCO2. Changes in relation to the pi-Control case. Dashed horizontal lines mark the ~300 hPa, 100 hPa and ~7 hPa levels. The stronger the nudging, the weaker the tropical upwelling change and the less extratropical downwelling.

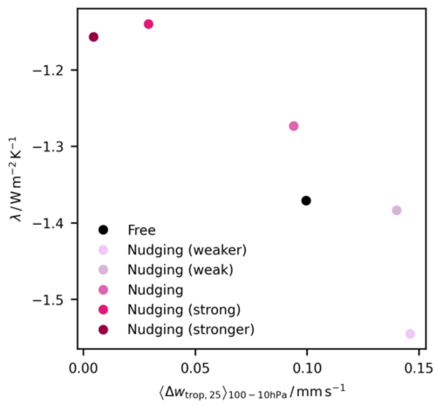
Figure 6: Zonal average of the change in temperature in the nudged abrupt-4xCO2. Changes in relation to the pi-Control case. Dashed horizontal lines mark the ~300 hPa, 100 hPa and ~7 hPa levels. The stronger the nudging, the stronger the meridional temperature gradient. However, the free and the nudging experiments are not directly comparable.



With decreasing tropical upwelling change, extratropical downwelling also decreases. Therefore, the extratropical upper troposphere and lower stratosphere warm less (Figure 6). Consequently, the extratropical net radiative feedback weakens as the region emits less outgoing longwave radiation, weakening the global net radiative feedback and leading to a higher climate sensitivity (Figure 7).

Although the nudging process has only affected the dynamics, Figure 6 shows that we cannot directly compare the free abrupt-4xCO2 to the nudging cases, as the structure of the warming is not the same as the free case, even in the medium nudging scenario, that has approximately the same tropical upwelling strength (Figure 5, right column, second row). Given that we are nudging vorticity and divergence, the temperature should adjust to the thermal wind relation. Perhaps, other variables, such as cloud water and ice, can have a role in this adjustment.

Figure 7: Global net feedback parameter versus the change in the tropical upwelling between 100 and 10 hectopascals in abrupt-4xCO2 experiments. The net feedback is less negative as the tropical upwelling change is reduced



Thus, as stated in the new computing time proposal, we would like to make more simulations to understand better how the nudging changes the meridional energy transport and test different nudging regions and strengths.

References

Dacie, Sally and Kluft, Lukas and Schmidt, Hauke and Stevens, Bjorn and Buehler, Stefan A. and Nowack, Peer J. and Dietmüller, Simone and Abraham, N. Luke and Birner, Thomas: "A 1D RCE Study of Factors Affecting the Tropical Tropopause Layer and Surface Climate" *Journal of Climate, 32(20), 6769 – 6782* DOI: 10.1175/JCLI-D-18-0778.1, 2019.

Jiménez-de-la-Cuesta, Diego and Schmidt, Hauke: "Tropical stratospheric upwelling impacts the tropical equilibrium climate sensitivity by reducing the effective forcing" *ESSOAR repository (under review at Journal of Climate)* DOI: 10.1002/essoar.10512195.1, 2022.

Satitkovitchai, K. and Ruhnke, R.: Investigations of the effects of anthropogenic stratospheric ozone on tropospheric OH, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-7764, https://doi.org/10.5194/egusphere-egu22-7764, 2022.