Climate Variability in the Stratosphere during the 20th Century

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Introduction

The stratosphere is subject to a large dynamical variability, including the interannual-to-decadal scale. Climate forcings such as solar variability, volcanic eruptions, and variability patterns like ENSO can affect stratospheric climate and ozone to a large degree. Through dynamical and radiative mechanisms and its coupling to the troposphere, the stratosphere plays an important role in affecting Earth's climate. Conversely, tropospheric climate variability can affect stratospheric chemical and dynamical variability. Therefore it is highly interesting to investigate the mechanisms leading to stratospheric variability and to understand the processes modulating them. This requires model-based studies by means of a middle atmosphere chemistry-climate model (CCM) over several decades.

Most CCM studies cover the past 30 years (satellite period), focussing on anthropogenic influences (emissions of greenhouse gases and ozone depleting substances) and volcanic eruptions (El Chichon and Mt. Pinatubo). Only a few CCM studies go back to 1950s. However to represent the full natural variability in the stratosphere, model studies over several decades are needed. Also, much larger variations occurred before 1950 than in the past 50 years (El Niño 1941, volcanic eruption of Krakatoa 1883).

Here we present first results of 20th century runs (9 ensemble members) with the CCM SOCOL, applied in transient mode.

Experimental Setup

- CCM SOCOL[1,2]: Combination of middle atmosphere version of ECHAM4 coupled to the chemistry-transport model MEZON
- T30 resolution; 39 vertical levels from surface up to 0.01 hPa
- Transient simulation from 1901-1999[4] with 9 Ensemble Members
- Spin-up with offline CTM over 10 years and one year with coupled simulation

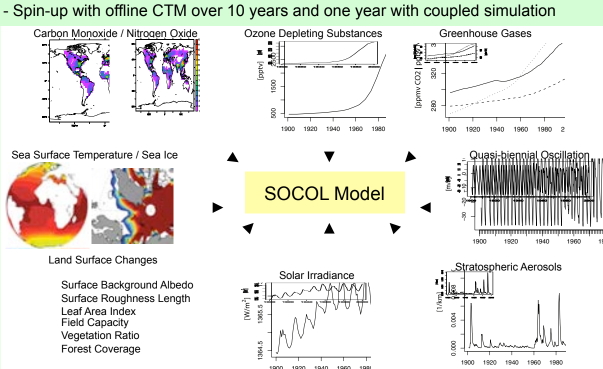
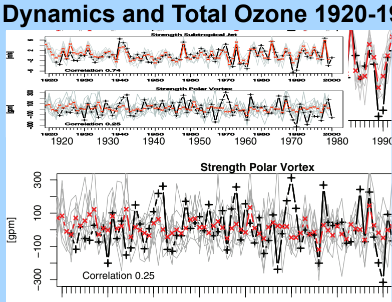


Figure 1: Schematic representation of the external forcing structure applied for the different SOCOL – runs.

Dynamics and Total Ozone 1920-1999



- Correlation ensemble mean and reconstructed index for subtropical jet high; Interannual variability related to tropical SST and ENSO
- Year-to-year variability of polar vortex not captured by SOCOL, but observations lie within ensemble spread; not predictable
- Both modeled indices fully consistent with reconstructions

Figure 2: Strength of subtropical jet (maximum of zonal mean wind at 200hPa in the NH) and polar vortex (Difference between 100hPa GPH 75-90N and 40-55N) with respect to a climatology of 1961-1990. Displayed are the individual ensemble members (gray lines), ensemble mean (red) and statistically reconstructed time series (black).

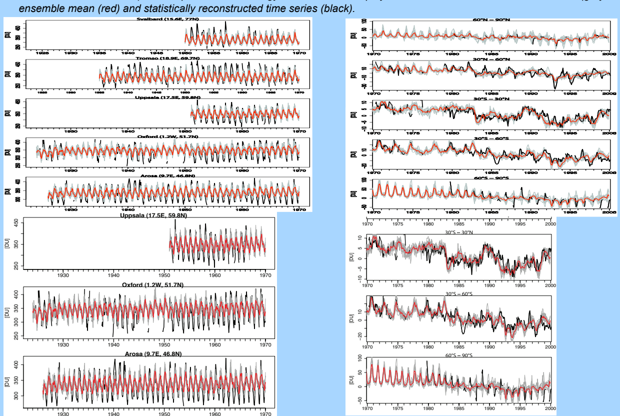


Figure 3: Total Ozone at different locations in the Northern Hemisphere (left) and area averaged (right) for the SOCOL simulations compared against satellite as well as ground-based observations (black).

- Model well able to capture long-term development in total ozone, but seasonal cycle underestimated.
- Internal model variability highest in North Polar region reflecting different perturbations of the polar vortex
- Good agreement found for interannual variability (especially in Tropics and Mid-Latitudes)

Solar Signal / Stratospheric Aerosols

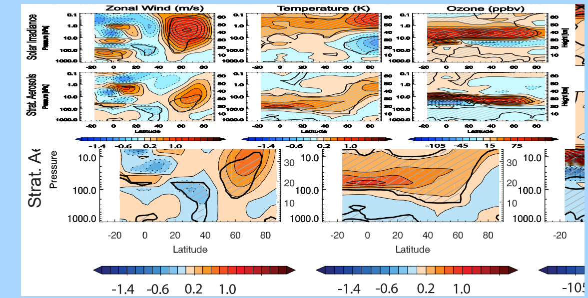


Figure 4: Multiple Regression Coefficients (with respect to one standard deviation in the explanatory variable) upon solar irradiance (top) and stratospheric aerosols (below) over the time-period 1901-1999.

- Solar signal: intensification of the polar vortex system and weakening of the subtropical jet; stronger Arctic zonal winds lead to cooling in the Arctic stratosphere
- Ozone increased over the whole upper stratosphere with a maximum at around 25°N => heating of the upper stratosphere
- With elevated stratospheric aerosol loading ozone increases due to reduction of the NOx ozone destruction cycle.
- Differential heating observed in the lower stratosphere with a maximum at the equator
- Zonal wind response upon stratospheric aerosols qualitatively similar to solar signal

Stratospheric ENSO imprint El Niño (1941) - La Niña (1976)

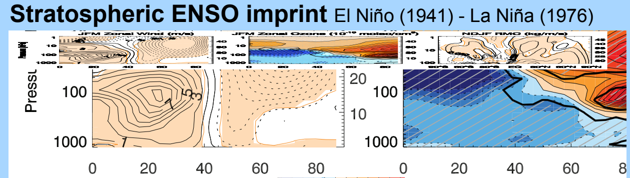


Figure 5: Model response upon ENSO out of time-slice simulations. Shown are the winter differences (JFM) between El Niño (1941) and La Niña (1976). Orange shading and hatched areas mark statistical significance (t-test, p-value < 0.05).

- The ENSO imprint out of time slice simulations[3] reveals significant weakening of the polar vortex and an intensification of the subtropical jet. Signal in zonal wind reaching down to the troposphere
- Residual meridional circulation increased over the whole northern hemisphere => intensified ozone transport from equatorial stratosphere towards northern latitudes

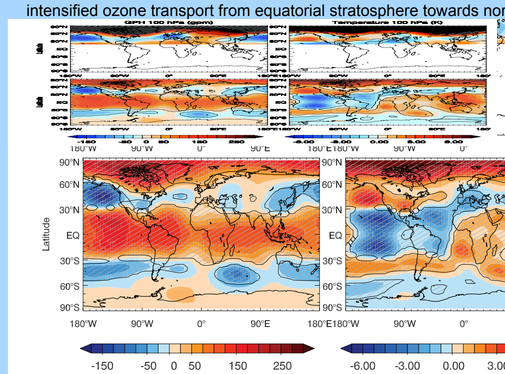


Figure 6: Differences in GPH (left) and temperature (right) at 100 hPa for reconstructed upper-level fields (top) and model (below). Hatched areas mark statistical significance (t-test, p-value < 0.05).

- Modeled GPH increased over (sub-) tropical and the Arctic stratosphere in line with reconstructions; In mid-latitudes wave structure (negative anomaly centre over Central Europe) less well reproduced.
- Together with a weakening of the zonal flow, temperature in the Arctic stratosphere much enhanced; negative anomaly band stretching from equatorial Pacific towards Europe and Central Asia in both, model and reconstructions.

Conclusions

Simulations with the CCM SOCOL perform rather well compared to observations and reconstructed indices. The model is in very good agreement for ozone and dynamics in the (sub-) tropical belt, where a strong ENSO response is reproduced. The internal variability is dependent on the analyzed region and can be a dominating source of variability (e.g. North Polar region). In these regions the benefit of large ensemble member sizes is most evident.

The solar cycle and elevated stratospheric aerosols contribute to an intensification of the polar vortex, while ENSO is weakening the northern zonal flow. The decelerated zonal winds during El Niños are caused by enhanced wave-mean flow interaction, thereby increasing the residual meridional circulation and the equator-to-pole transport of ozone.

References

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