CCMI-2022 Ref-D1 stratospheric ozone profiles: trends, natural variability and comparison to observations and CCMI-1 Ref-C2

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Introduction

Stratospheric ozone and its evolution in time have been the subject of global concern and scientific research already since the mid 1970's (e.g., WMO, 2014; 2018 and references therein), resulting to the adoption and implementation of the 1987 Montreal protocol (and amendments), with the concentration of ODS in the atmosphere declining since the late 1990s. In response, global ozone is no longer declining and has remained almost stable since about 1996 [Godin-Beekman et al., 2022; Weber et al., 2022; WMO, 2018). Stratospheric ozone levels have stabilized, with statistically significant increases in the upper stratosphere (around 2hPa), however with reported continuous decline in lower stratosphere (Ball et all., 2018). A comprehensive investigation is given in the Report by the "Long-term Ozone Trends and Uncertainties in the Stratosphere" initiative (LOTUS), a SPARC Project (http://www.sparc-climate.org/activities/ozone-trends/). The LOTUS Report also discussed ozone trends derived from CCMI-1 models (Eyring et al., 2013), using simulations from REF-C2 (1960-2100), ending our analysis in 2016.

Here we examine the evolution of changes in the zonal mean vertical distribution of ozone from the set of models participating in the CCMI-2022 project, using data from the REF-D1 historical hindcast simulation (1960 – 2018), with the model forcings following closely the observed historical evolution. Primary focus of the REF-D1 simulation is to *assess models against observations*

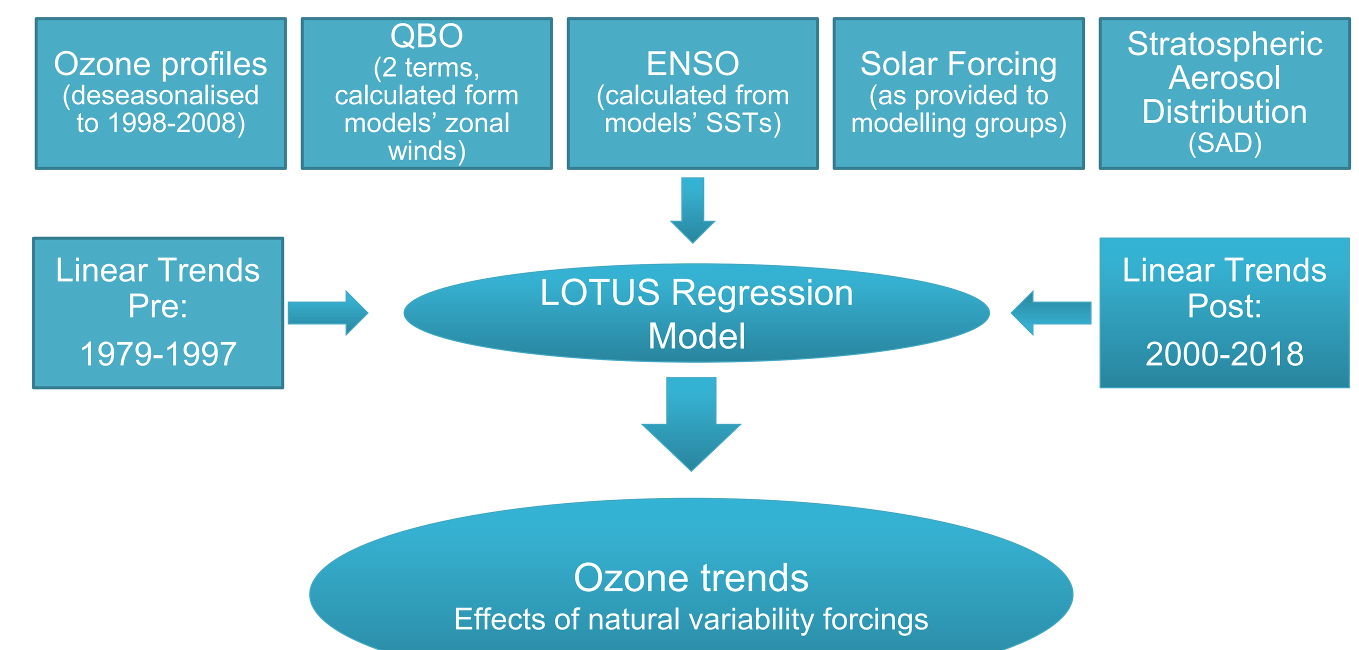
A summary of the experiments in July 2021 SPARC Newsletter (No. 57). Details and description of the full forcings in the reference simulations can be assessed in https://blogs.reading.ac.uk/ccmi/ccmi-2022/.

Ozone trends are calculated for the pre- and post-2000 periods (1979-1997 and 2000-2018), in accordance with the regression analysis and tools presented in the LOTUS Phase 1 Report and compared to satellite-derived trends for the same period.

Results are compared to CCMI-1 REF-C2 simulations, calculated for the same period, used in the LOTUS Project (Godin-Beekman et al., 2022), the difference between the two simulations being that while REF-D1 uses forcings close to observed (incl. volcanic forcing), in REF-C2 the ODS and GHGs follow the WMO projections (Figures 1-4). Effects of natural variability forcings, such as the Solar Cycle, El Nino/Southern Oscillation (ENSO) and SAD (Stratospheric Aerosol Distribution) on ozone profiles from the REF-D1 experiment are presented in Figures 5 and 6.

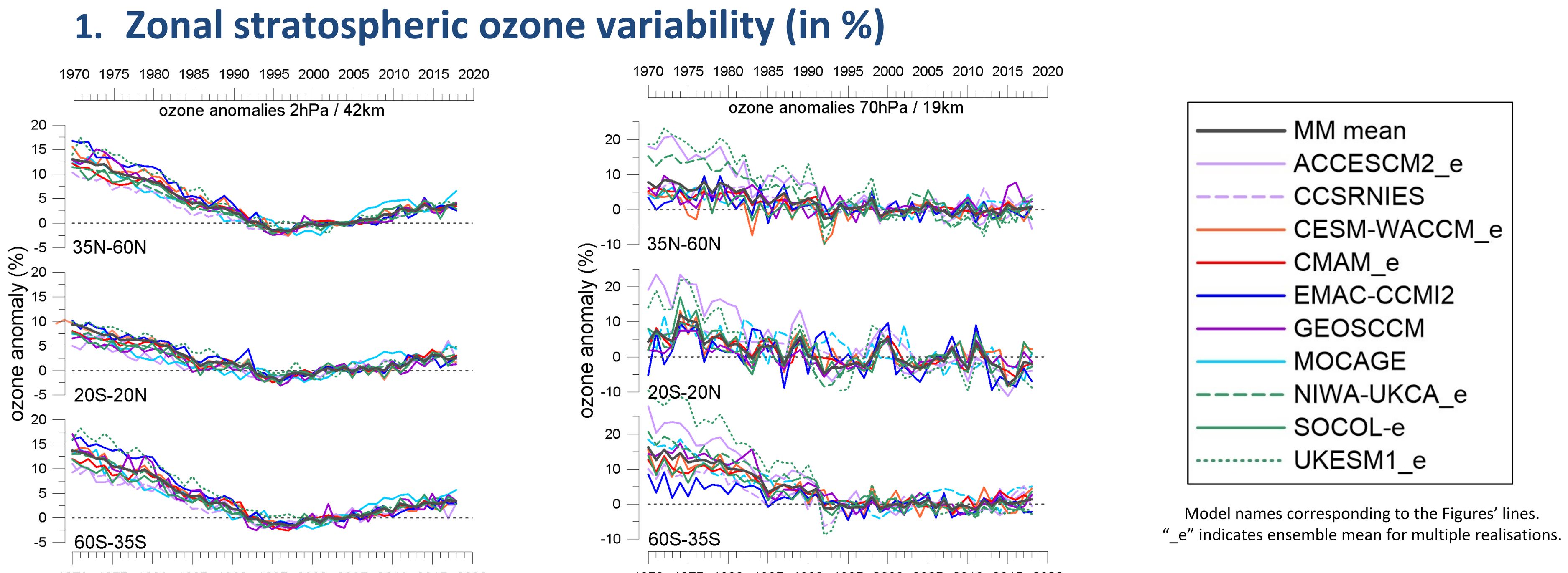
Data and Methodology

- Ozone trends were calculated using the LOTUS Regression Tool, set in the Independent Linear Trends (ILT) mode for both sets of model experiments (CCMI-1 Ref-C2 and CCMI-2022 Ref-D1).
- Model monthly zonal mean ozone values were deseasonalised to their 1998-2008 climatology.
- For each model (and each ensemble member) simulation, the proxies for QBO and ENSO were calculated from the model's zonal winds and SSTs. Proxies for solar and volcanic were derived from the forcings provided to the modelling groups.
- Calculations were performed for all pressure levels and for 5^0 lat bins, then averaged over the appropriate latitude bands: 60°S - 35°S, 20°S - 20°N, 35°N - 60°N
- Results were first averaged for each individual model and then for the multi-model mean.
- Ozone variability (in %) shown as annual averages for 3 lat bands: south mid-lats (60S-35S), tropics(20S-20N) and north mid-lats (35N-60N).
- Trends in ozone profiles are shown as averages for south mid-lats (60S-35S), tropics(20S-20N) and north mid-lats (35N-60N).



Results

1. Zonal stratospheric ozone variability (in %)



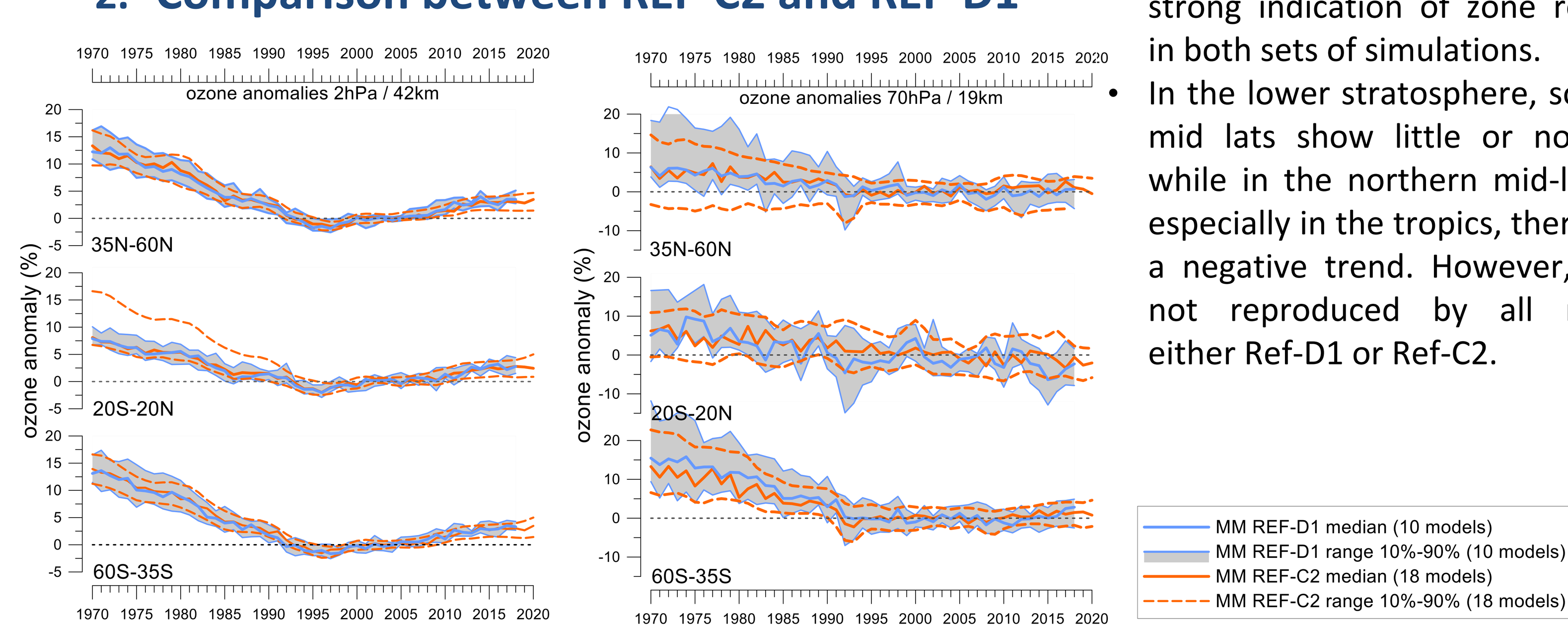
Model names corresponding to the Figures' lines. "_e" indicates ensemble mean for multiple realisations.

- Stratospheric ozone variability in the upper (2hPa) and lower (70hPa) stratosphere is shown as annual mean anomalies (in %) relative to the 1998-2008 climatology for each model along with the multi-model (MM) mean.
- Comparison of medians and 10-90 % range of anomalies between Ref-C2 and Ref-D1 shows good agreement between the two sets of simulations. Natural variability due to volcanic eruptions and aerosol forcing, absent in Ref-C2, is clearly seen in Ref-D1 variability. Differences in the range are due also to the larger number of models in Ref-C2 simulations.
- In the upper stratosphere, there is a strong indication of zone recovery in both sets of simulations.
- In the lower stratosphere, southern mid lats show little or no trend, while in the northern mid-lats and especially in the tropics, there is still a negative trend. However, this is not reproduced by all models, either Ref-D1 or Ref-C2.

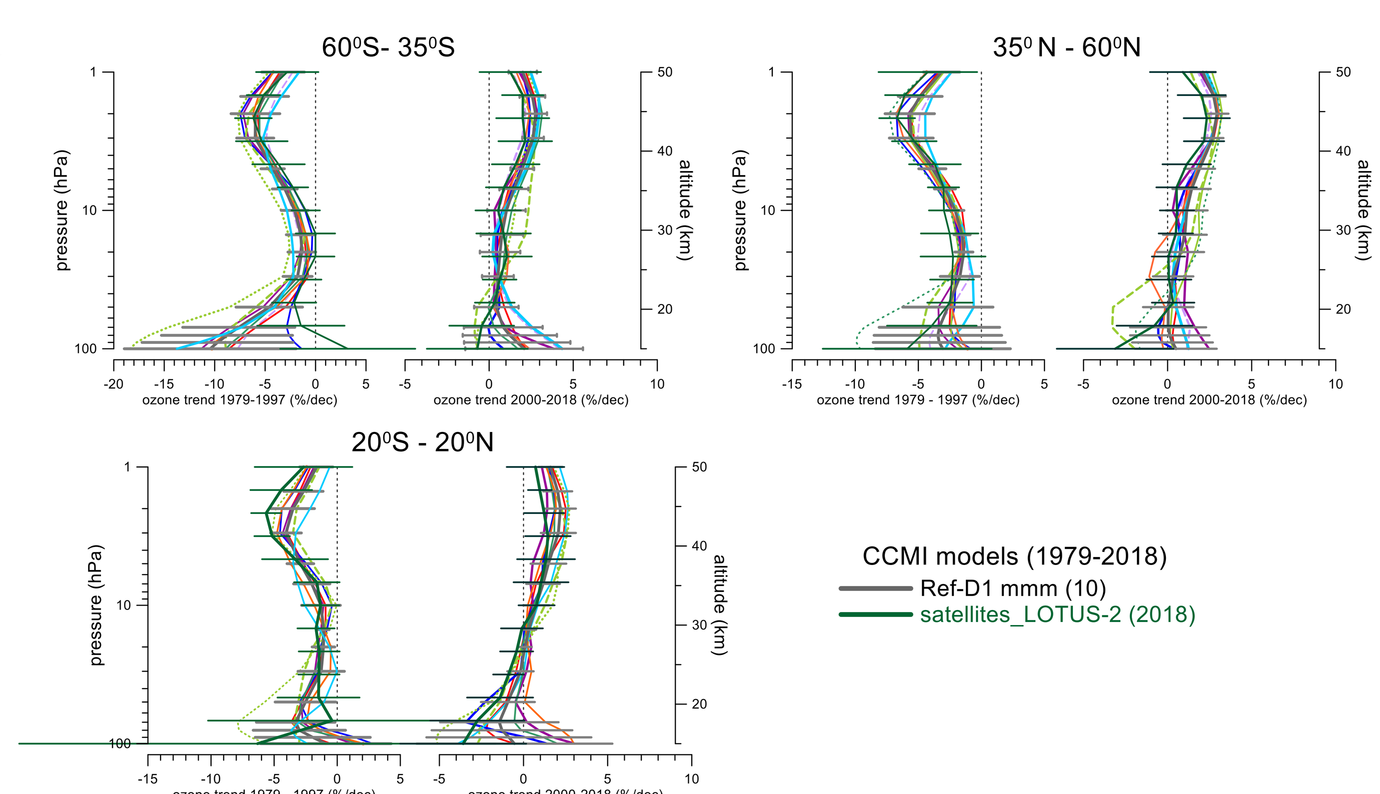
CCMI-2022 Models (REF-D1)

Model name	Institute
ACCESS-CM2-Chem	CSIRO-ARCCSS
CCSRNIES-MIROC32	NIES
CESM2-WACCM	NCAR
CMAM	CCCma
CNRM-MOCAGE	CNRM-CERFACS
EMAC	MESSy Consortium
GEOSCCM	NASA-GSFC
NIWA-UKCA2	NIWA
SOCOL	ETH-PMOD
UKESM1-StratTrop	NCAS-Cambridge

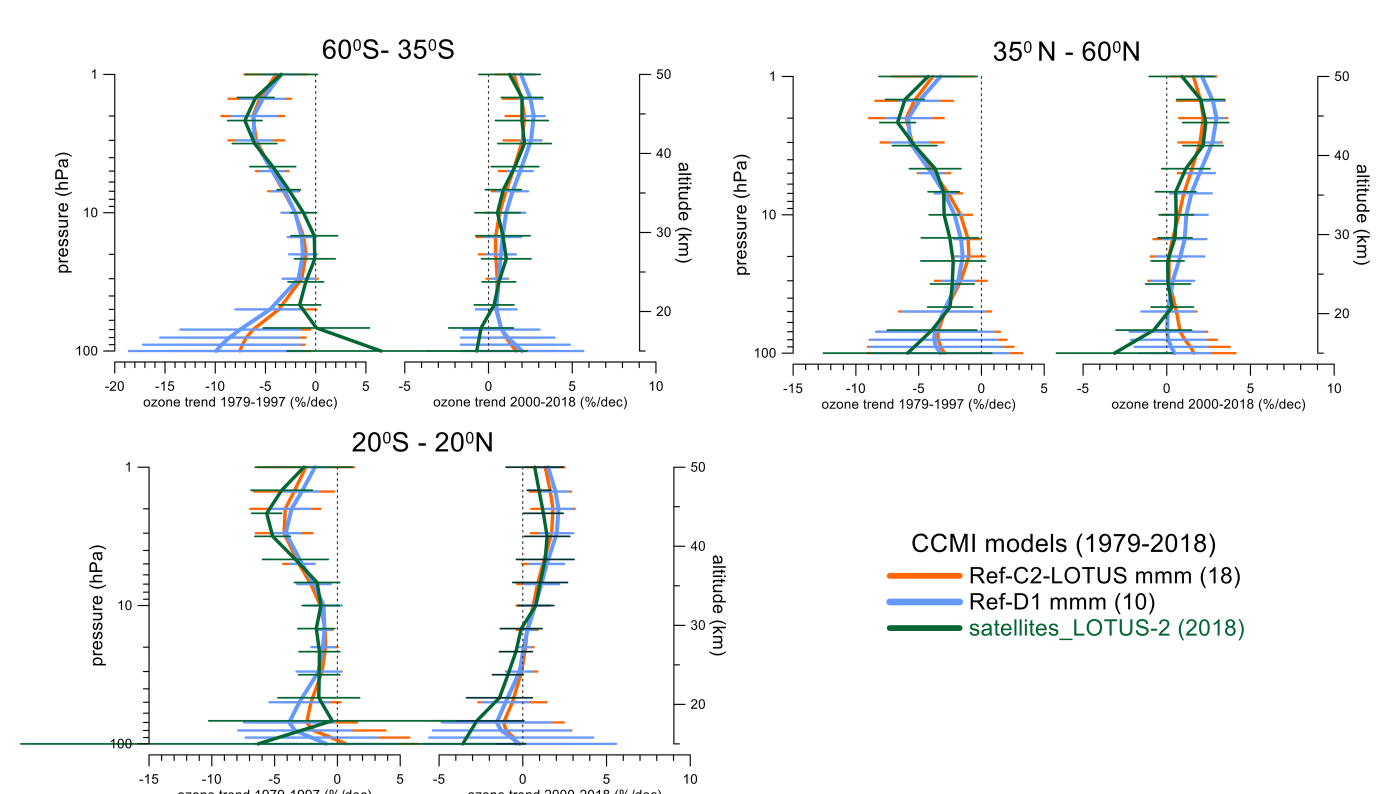
2. Comparison between REF-C2 and REF-D1



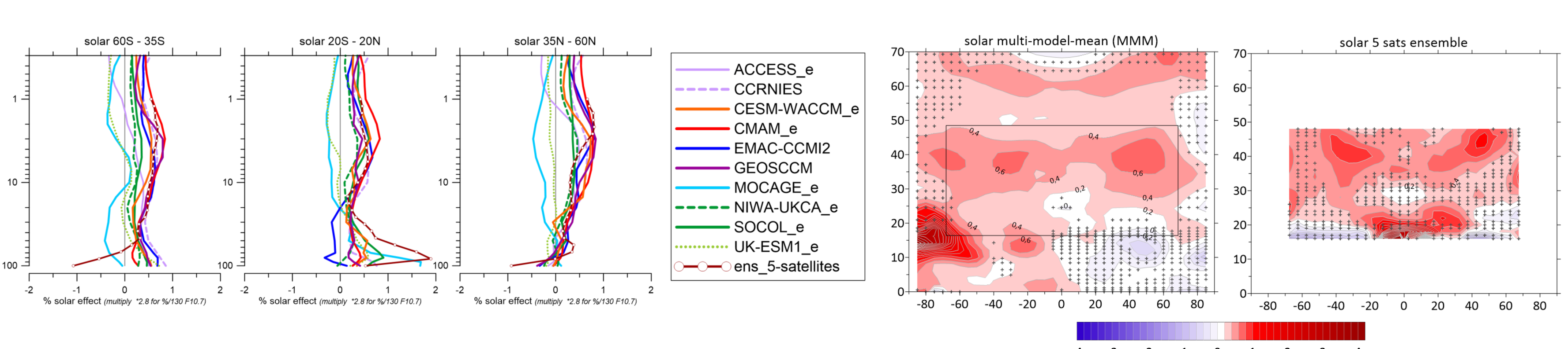
3. Trends from CCMI-2022 REF-D1



4. REF-D1 trends comparison to REF-C2 and LOTUS satellites



5. Solar effects

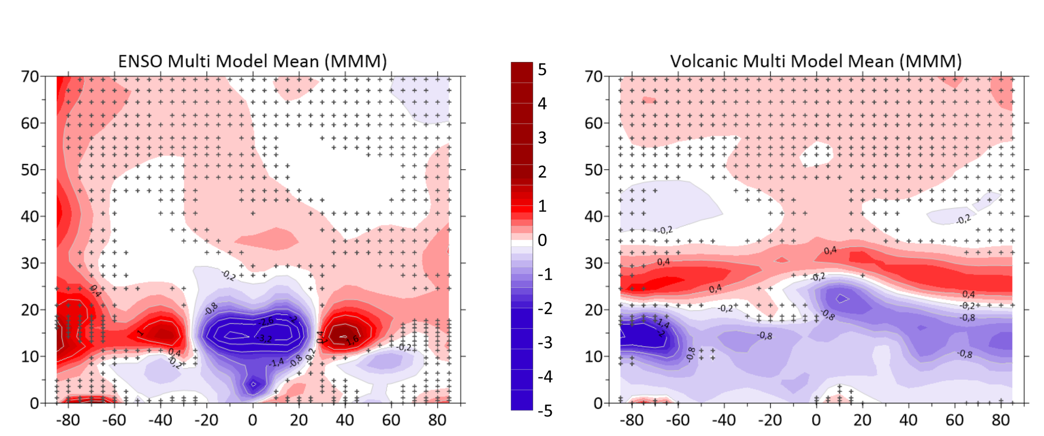


Solar forcing effects in Ref-D1 models for 3 latitude bands (left) and lat-alt plots (right), along with the effect seen in LOTUS satellites. Results are presented in % per solar proxy unit, for comparison to %/130 F10.7 effect multiply by 3.

Absence of stippling denotes areas with significant response (at 95% conf. level), and "e" after the model's names indicates ensemble mean for multiple realisations

- Sensitivity to solar forcing is not the same in all models. Results presented in the right panels (lat-alt plots) are averages over the 7 models with a solar response, as seen in the left panels where profiles of solar forcing effects are shown for southern mid-lats, tropics, and northern mid-lats.
- For ENSO and volcanic forcings, all models show the same type of response. Averages presented here are calculated over 10 (i.e., all) models.

6. ENSO and volcanic (SAD) effects



ENSO and volcanic effects (in %) resulting from the REF-D1 simulations analysis

Absence of stippling denotes areas with significant response (at 95% conf. level)

Summary

- We used data from REF-D1 experiment of CCMI-2022 activity, where all forcings were set as close as possible to observations (AODs, GHGs, SAD, SSTs, QBO nudged to observations, 11-year solar cycle).
- Trends and ozone variability shows a very good comparison between the two experiments REF-D1 and REF-C2, even though the first is driven by observed (or as close as possible to observed) forcings.
- Ozone recovery is seen in the upper stratosphere, while lower stratospheric ozone is small (positive) in the southern mid-lats, close to zero in the north but ozone continues to decline in the tropical lower stratosphere.
- Trends from LOTUS satellites for the post-2000 period are in good agreement in the upper stratosphere (closer to REF-C2), but more negative in the lower for all latitude bands.

References

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