

Fully Coupled Chemistry–Climate Model Simulations: Evaluation with Observations and Future Evolution of the Ozone Layer in a Changing Climate

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Knowledge for Tomorrow

WMO ozone assessment scientific content:

Challenges, questions and tasks regarding stratospheric ozone

- Detection of ozone return/recovery in the next 5 to 10 years due to the regulation of CFCs (Montreal Protocol), in particular the stratospheric chlorine content, but also due to the influence of climate change and other factors involved.
- Prediction of the future evolution of the stratospheric ozone layer in a changing climate, determining the dependence of ozone recovery in space (latitude and altitude) and time, especially investigating the evolution of the ozone layer in polar regions (ozone hole).
- How will ozone concentrations develop depending on the assumed climate scenarios (RCPs: Representative Concentration Pathways), e.g. detecting higher stratospheric ozone values ('super-recovery') as an indicator of climate change?



Chemistry-Climate Model (CCM) Initiative (CCMI)

CCMI is organized by IGAC/SPARC.

CCMI has been jointly defined CCM new reference and sensitivity simulations meant to

- support upcoming ozone (WMO) and climate (IPCC) assessments,
- address emerging science questions, and
- improve process understanding.



Strategy for CCM simulations

Three types of numerical model simulations covering the middle atmosphere and troposphere have been defined, as recommended by CCM:

- (1) A hindcast simulation with specified dynamics, i.e. nudged to observed meteorology from 1979 to 2013 (referred to [REF-C1SD](#)),
- (2) a free-running hindcast simulation representing the past (from 1950 to 2013; referred to [REF-C1](#)), and
- (3) a combined hindcast and forecast simulation (from 1950 until 2100; referred to [REF-C2](#) (RCP-6.0) either with fixed ocean temperature (SST) and sea-ice cover (SIC) or with an interactively coupled ocean).

In addition, several sensitivity simulations have been carried out, for instance with fixed boundary conditions regarding ozone depleting substances (ODSs) and greenhouse gases (GHGs).

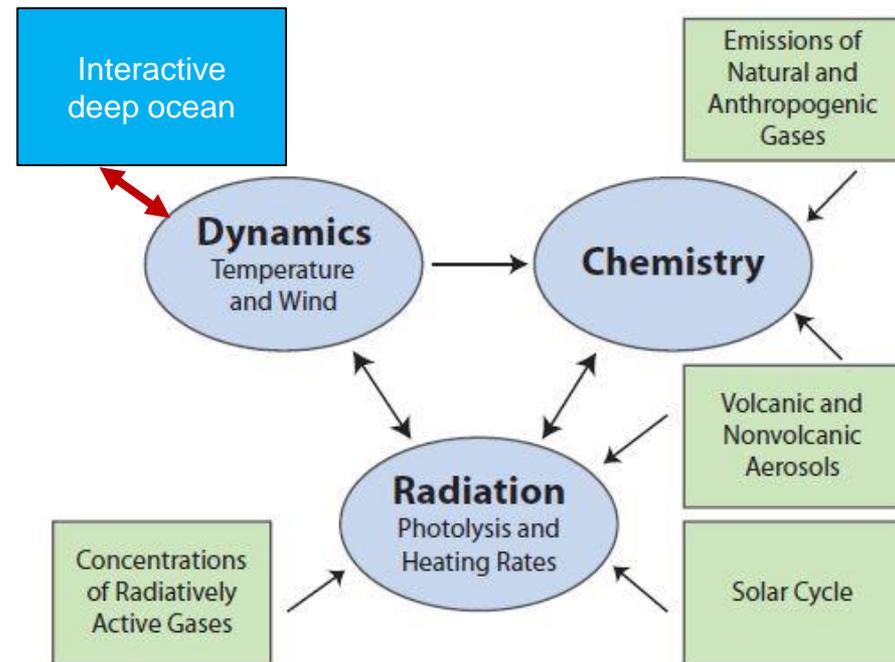


Example: The Chemistry-Climate Model EMAC

European Centre for Medium-Range Weather Forecasts - Hamburg (ECHAM) / Modular Earth Submodel System (MESSy) Atmospheric Chemistry (**EMAC**) model

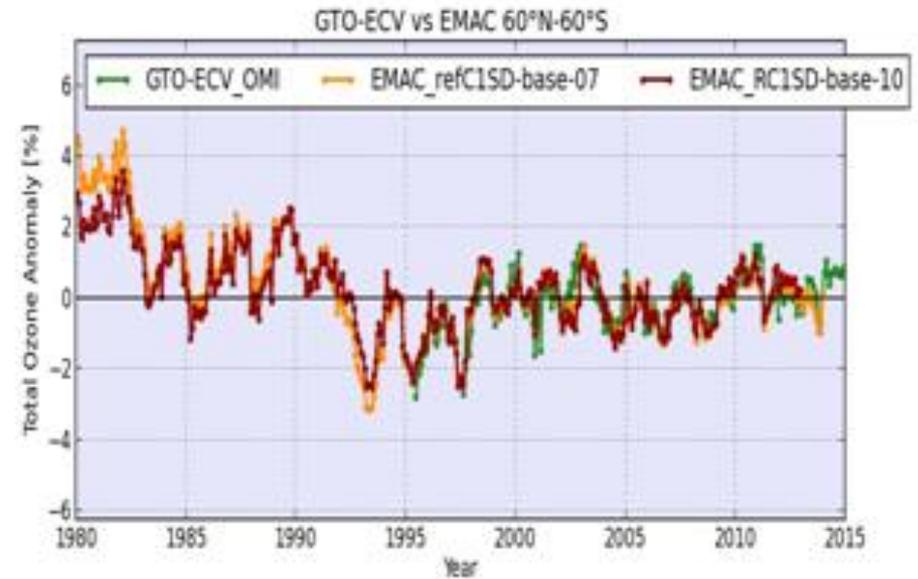
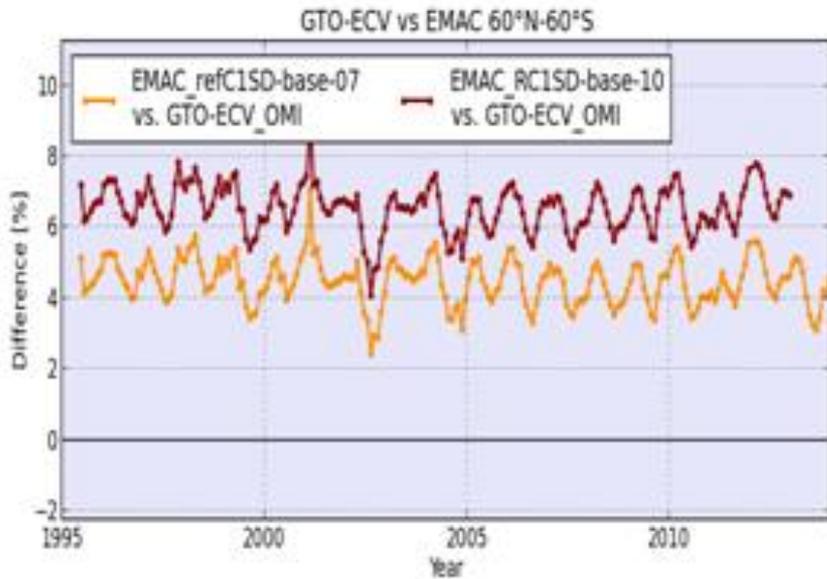
- using a full set of stratospheric and tropospheric chemistry;
- resolution: T42/L90 (T42: 2.8° x 2.8°, L90: 0-80 km).

(Detailed description: Jöckel et al., 2016.)



Ozone anomalies (1995-2015): 60°S-60°N

Example: Comparison of satellite-instrument- and model (EMAC) data



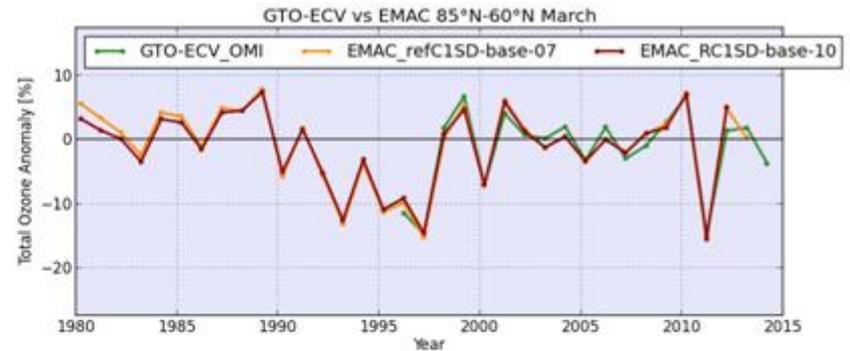
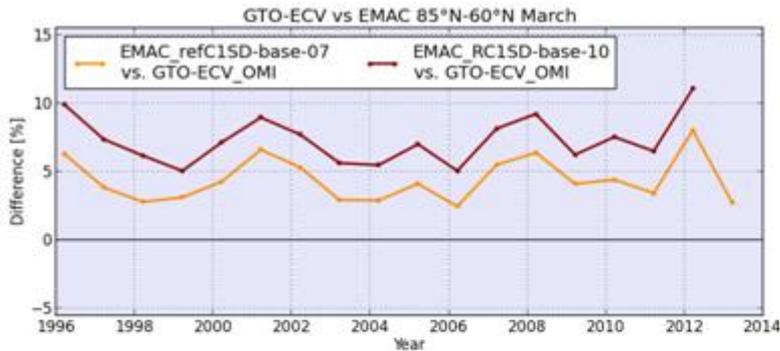
Near global mean:

ESA Ozone-cci data set *GTO-ECV_OMI* (since 1995) compared with two different [REF-C1SD](#) simulations by EMAC (red/orange: without/with nudging of the mean temperature)

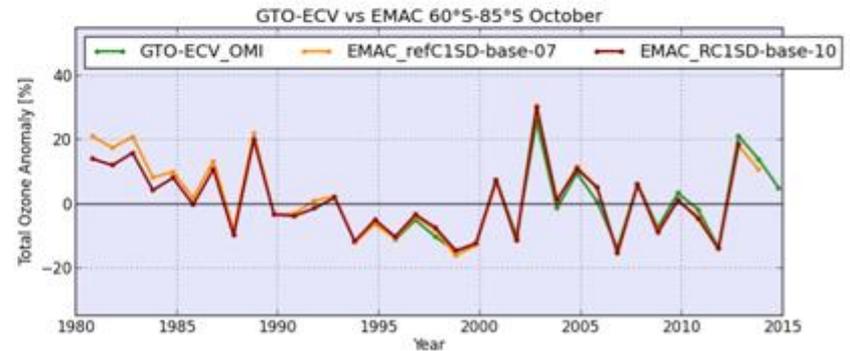
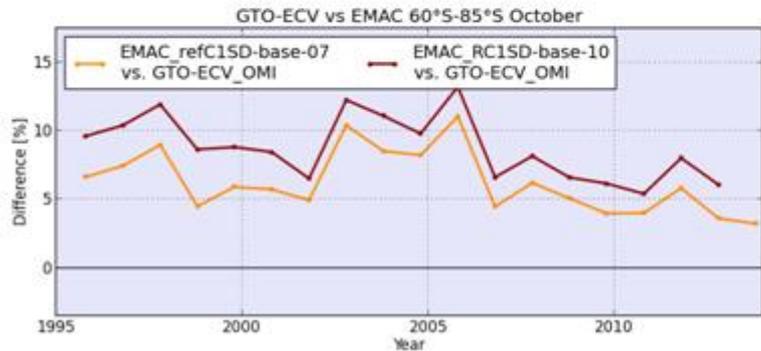


Ozone anomalies (1995-2013): polar regions, spring

Comparison of satellite-instrument- and model (EMAC) data



NH
Mar

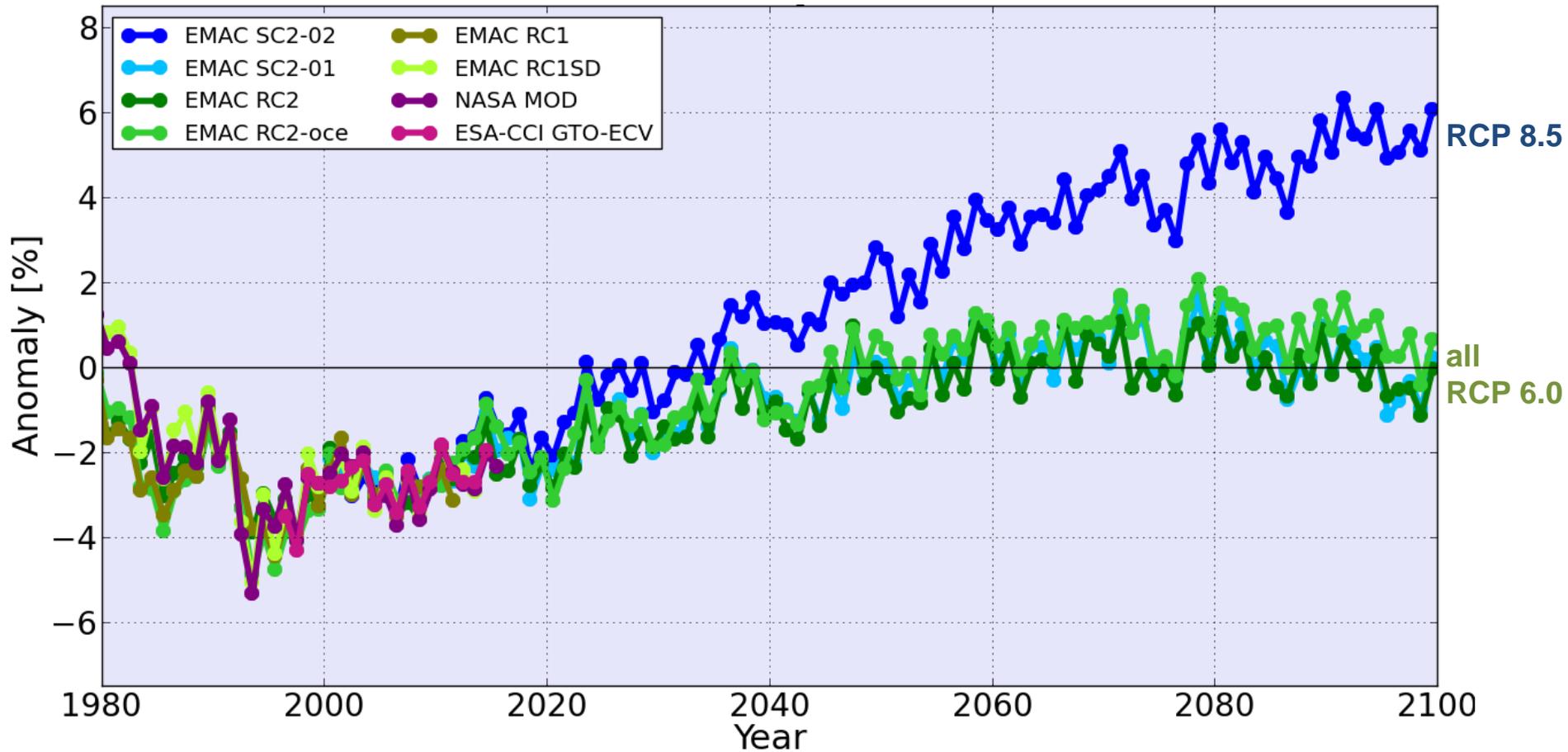


SH
Oct



Ozone anomalies (1960-2100): 60°S-60°N

Example: Comparison with satellite data and model (EMAC) prediction

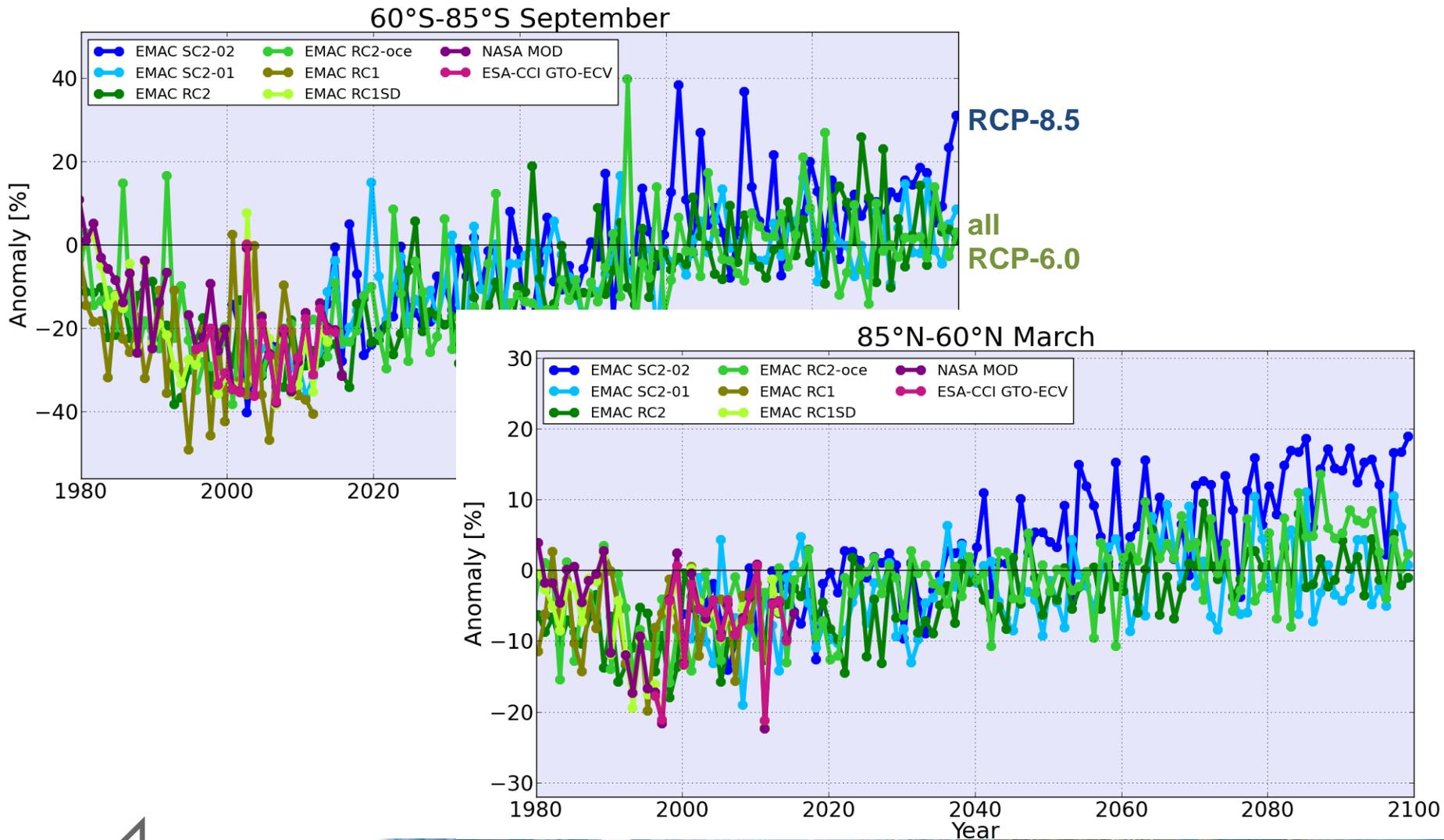


update of Jöckel et al., 2016



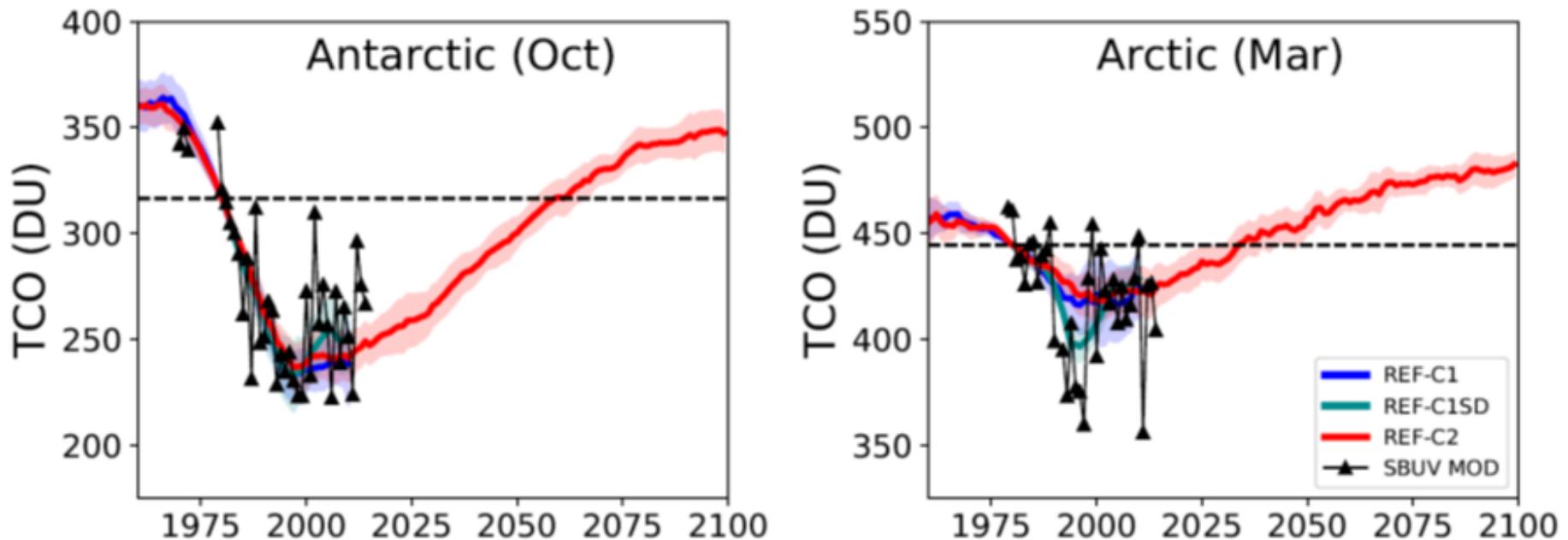
Ozone anomalies (1960-2100): polar regions

Comparison with satellite data and model (EMAC) prediction



Ozone anomalies (1960-2100): polar regions

Comparison with satellite data and model (MMM) prediction

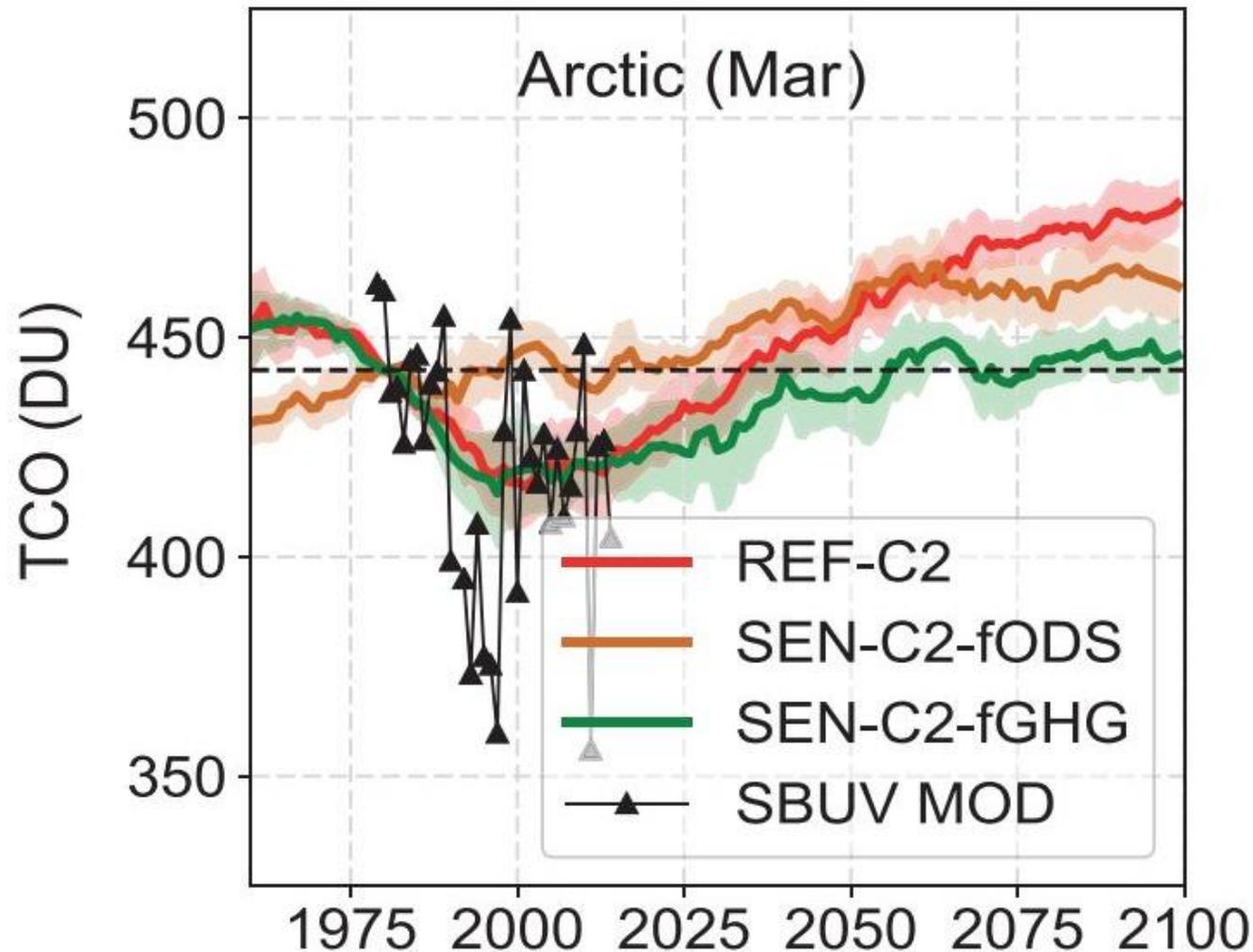


Multi-model mean (MMM) total column ozone (TCO) time series (in DU) from CCMi REF-C1 (blue), REF-C1SD (dark cyan) and REF-C2 (red) simulations for the (left) Southern Hemisphere polar (October) and (right) Northern Hemisphere polar (March) regions. Also shown are the merged SBUV observations. (Fig. 4-18 in WMO, 2018; adopted from Dhomse et al., 2018).



Ozone anomalies (1960-2100): polar regions

Comparison with satellite data and model (MMM) prediction

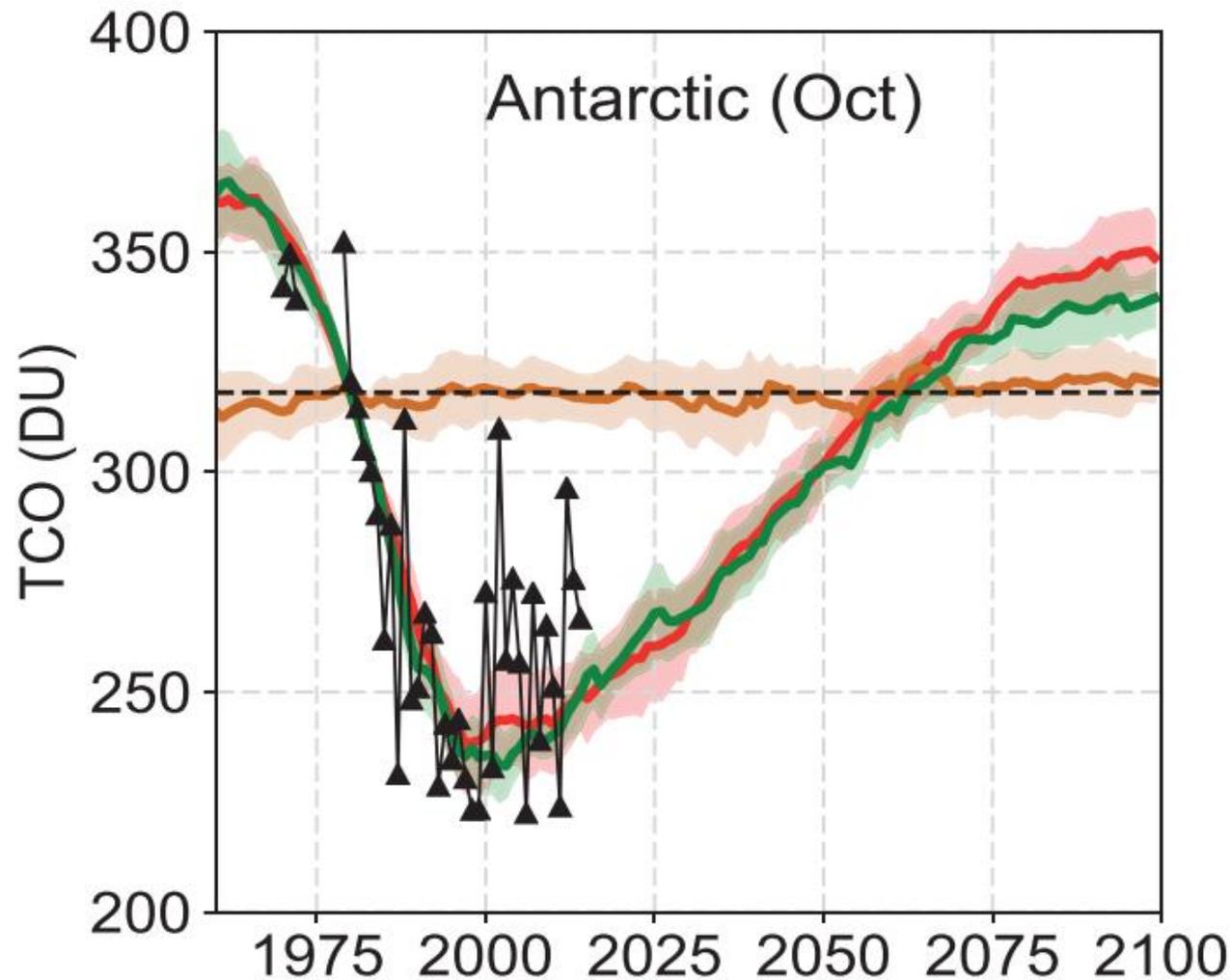
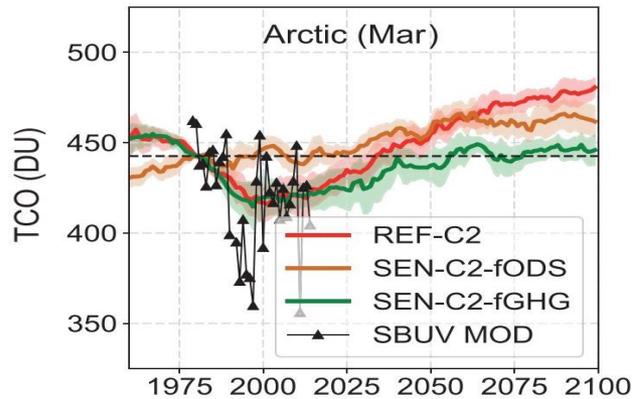


(Fig. 4-19 in WMO, 2018; adopted from Dhomse et al., 2018)



Ozone anomalies (1960-2100): polar regions

Comparison with satellite data and model (MMM) prediction

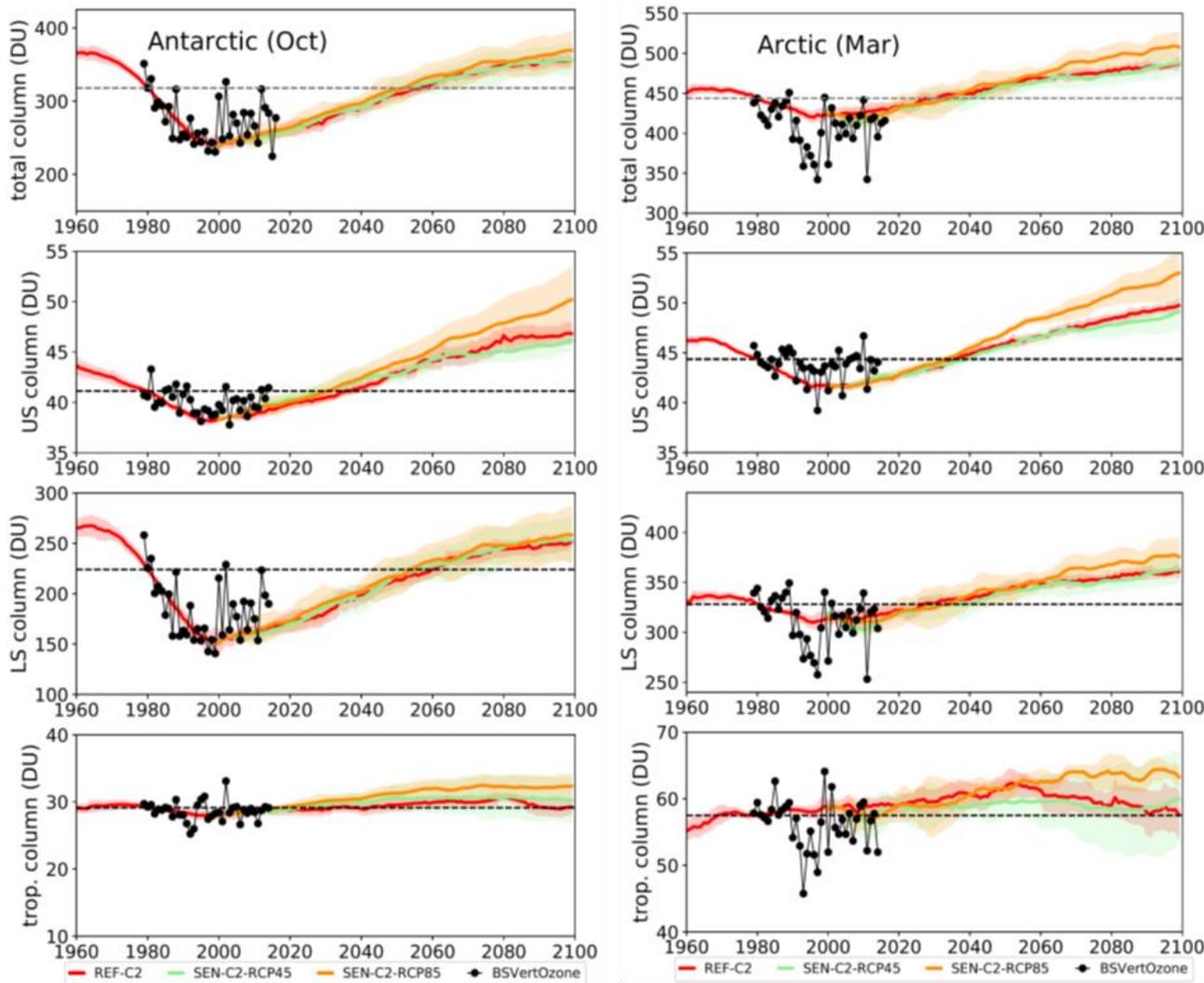


(Fig. 4-19 in WMO, 2018; adopted from Dhomse et al., 2018)



Ozone anomalies (1960-2100): polar regions in spring

in future under different climate scenarios (total and partial columns)

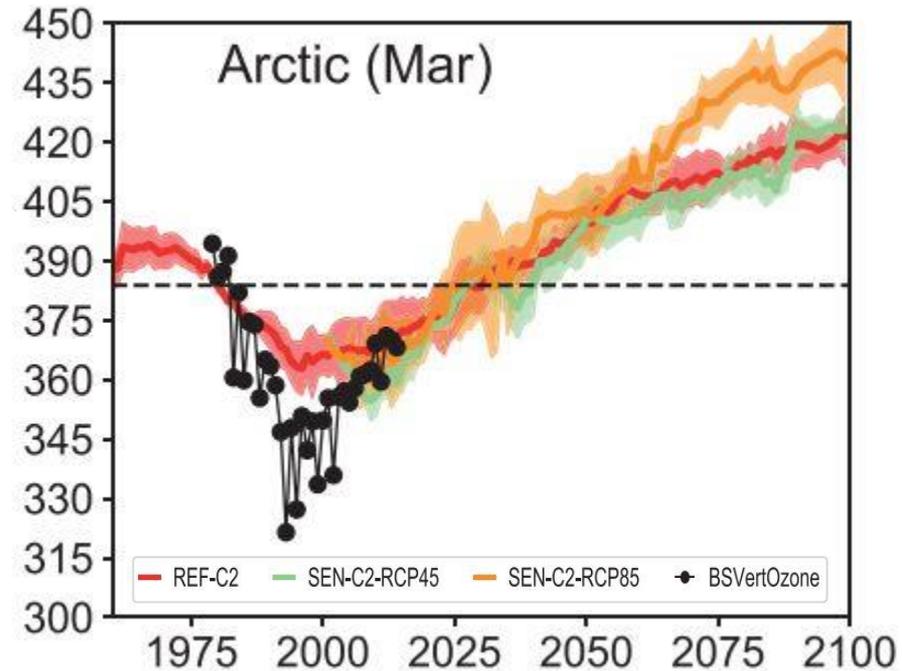
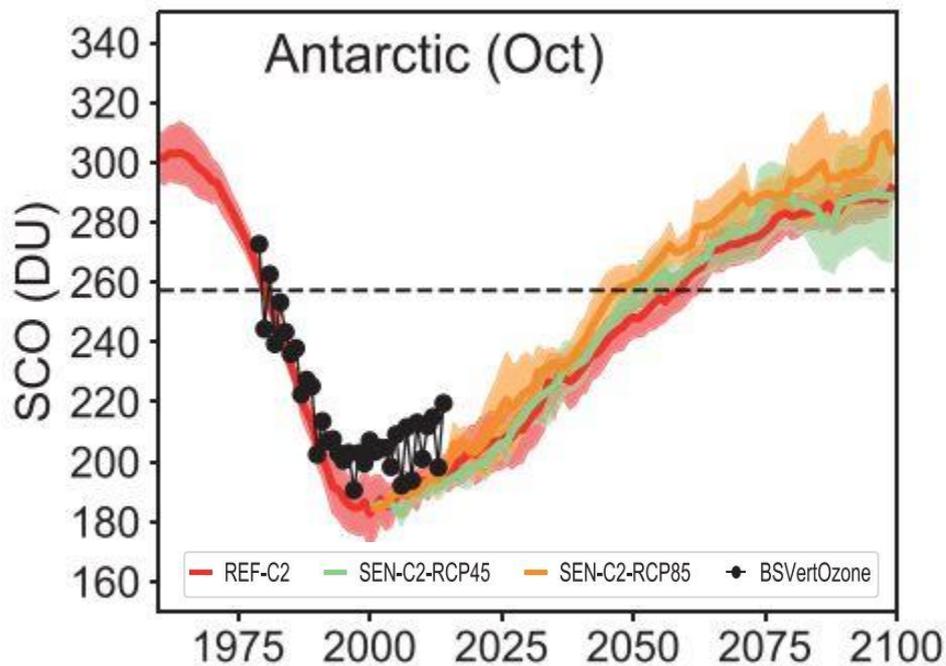


(top) Evolution of **TCO** (in DU) MMM for the CCM1 REF-C2 simulation (i.e. RCP-6.0; red lines) and the CCM1 RCP scenario simulations SEN-C2-RCP45 (green lines) and SEN-C2-RCP85 (orange lines). Also shown are the partial ozone columns for the upper stratosphere (**US**; second row), the lower stratosphere (**LS**; third row) and the troposphere (**trop.**; bottom). For comparison the respective total and partial ozone columns are shown as derived from BSVertOzone data (Bodeker et al., 2013; Hassler et al., 2018; Fig. 4-20 in WMO, 2018; adopted from Dhomse et al., 2018).



Ozone anomalies (1960-2100): polar regions in spring

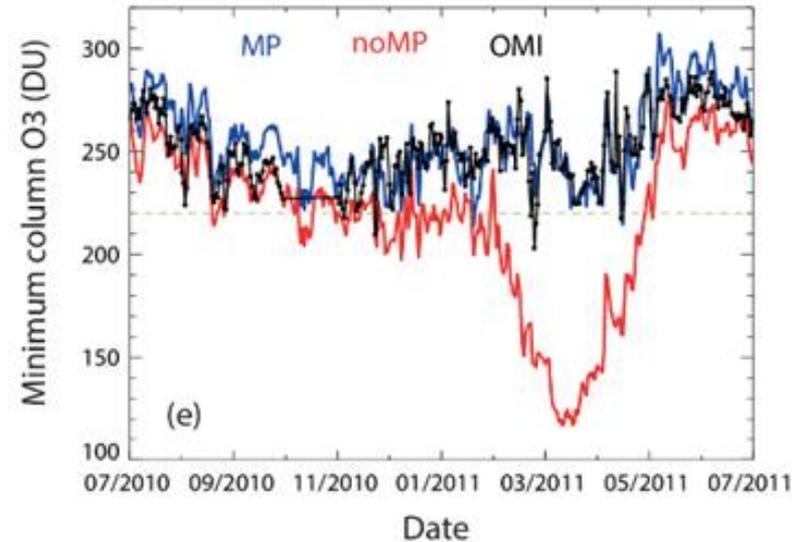
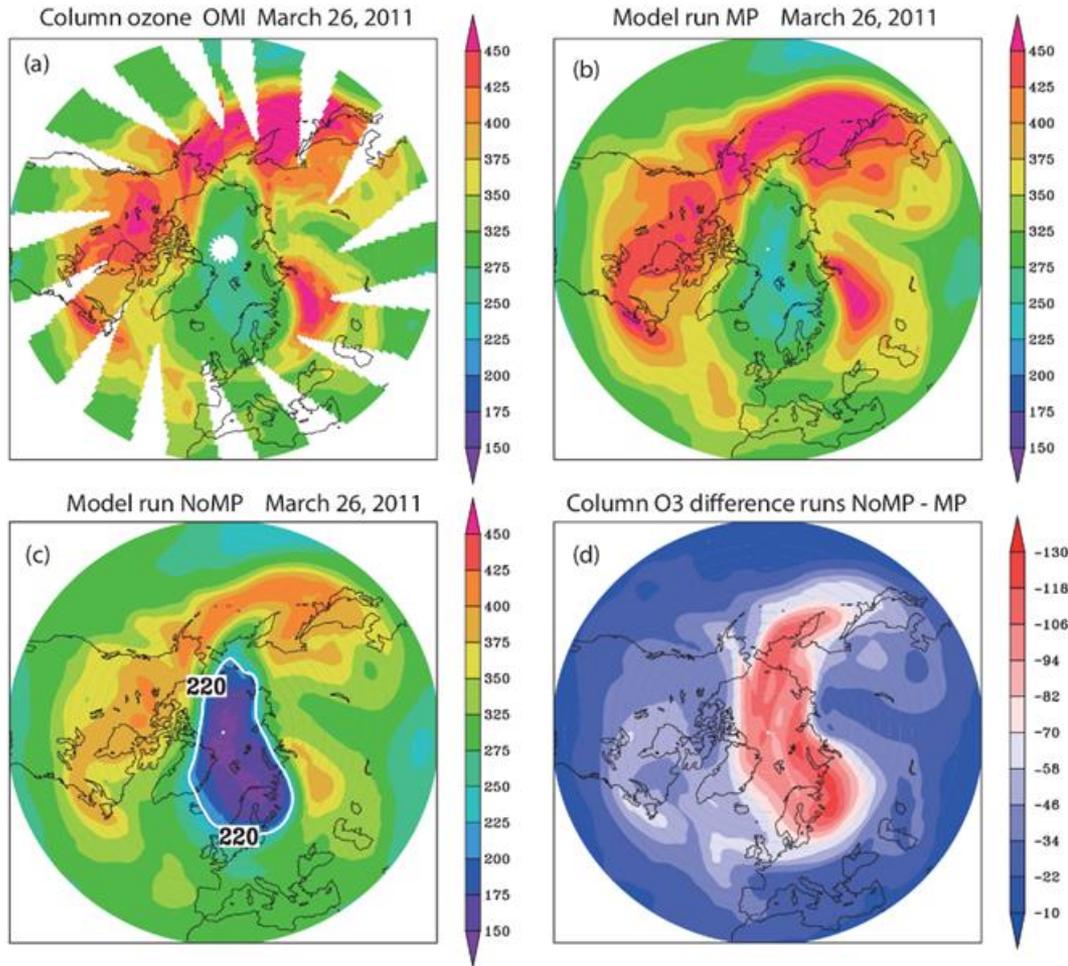
in future under different climate scenarios (stratospheric columns)



Multi-model mean (MMM) **stratospheric column ozone** (SCO) time series (in DU) from CCMI for REF-C2 (i.e. RCP-6.0) and the RCP scenarios SEN-C2-RCP45 and SEN-C2-RCP85. Also shown is the stratospheric partial column ozone derived from BSVertOzone data (Bodeker et al., 2013; Hassler et al., 2018; figure adopted from Dhomse et al., 2018).



Evolution of column ozone in the Arctic from satellite observations (OMI) and model results for winter 2010/11



Left: TCO for **March 26, 2011**, derived from (a) OMI, (b) a model run with ODSs controlled by the Montreal Protocol (MP), and (c) from model run with uncontrolled ODSs (noMP). (d) shows the difference of noMP-MP. Top: (e) Minimum TOC (latitude >45°N) in 2010/11.

(Fig. 4-17 in WMO, 2018; adopted from Chipperfield et al., 2015)



Concluding remarks (see also Chapter 4 in WMO, 2018)

- There are emerging indications that the Antarctic ozone hole has diminished in size and depth since the year 2000, with the clearest changes occurring during early spring (especially in September). Although accounting for natural variability is challenging, the weight of evidence suggests that the decline in ODSs made a substantial contribution to the observed trends.
- Even with these early signs of recovery, an Antarctic ozone hole continues to occur every year, with the severity of the chemical loss strongly modulated by meteorological conditions (temperatures and winds).
- In the Arctic, year-to-year variability in total column ozone is much larger than in the Antarctic, precluding identification of a statistically significant increase in Arctic ozone over the 2000-2018 period.
- In the Arctic, the exceptionally low ozone abundances of spring 2011 have not been observed again in the last seven years (including 2018).



Concluding remarks (see also Chapter 4 in WMO, 2018)

- Important contribution of CCMI to the UNEP/WMO Scientific Assessment of Ozone Depletion: 2018.
- The MMM of CCM simulation results regarding stratospheric ozone shows good agreement with space-based observations for the past.
- Model simulations show that the Montreal Protocol and its Amendments and adjustments have already brought about substantial ozone benefits.
- CCM projections based on full compliance with the Montreal Protocol and assuming the baseline estimate of the future evolution of GHGs (RCP-6.0) have confirmed that the Antarctic ozone hole is expected to gradually close, with springtime TCO returning to 1980 values shortly after mid-century (about 2060).
- The timing of the recovery of Arctic TOC in spring will be affected by anthropogenic climate change. Arctic springtime TOC is expected to return to 1980 values before mid-century (2030s).
- In the second half of the 21st century CO₂, CH₄, and N₂O will be the dominant drivers of Arctic ozone changes, assuming full compliance with the Montreal Protocol.



Concluding remarks (see also Chapter 4 in WMO, 2018)

- The wide range of possible future levels of CO₂, CH₄, and N₂O represents an important limitation to making accurate projections of the ozone layer.
- In the coming decades, substantial Arctic ozone loss will remain possible in cold winters as long as ODS concentrations are well above natural levels.
- Protecting stratospheric ozone depends on continued compliance with the Montreal Protocol.

