

Mögliche Auswirkungen erhöhter Fluorchlorkohlenstoff-11 Konzentrationen auf die Ozonschicht

Possible implications of enhanced chlorofluorocarbon-11 concentrations on ozone

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Knowledge for Tomorrow



Motivation

- Unforeseen changes in chlorofluorocarbon-11 (CFC-11, CFCl_3) concentrations (Montzka et al., 2018).
- CFC-11 emissions are roughly stable from **2002 to 2012, about 65 Gg/yr**, and from **2014 to 2016, about 75 Gg/yr**, as shown in Figure ES-2 of WMO (2018) – see figure on the right

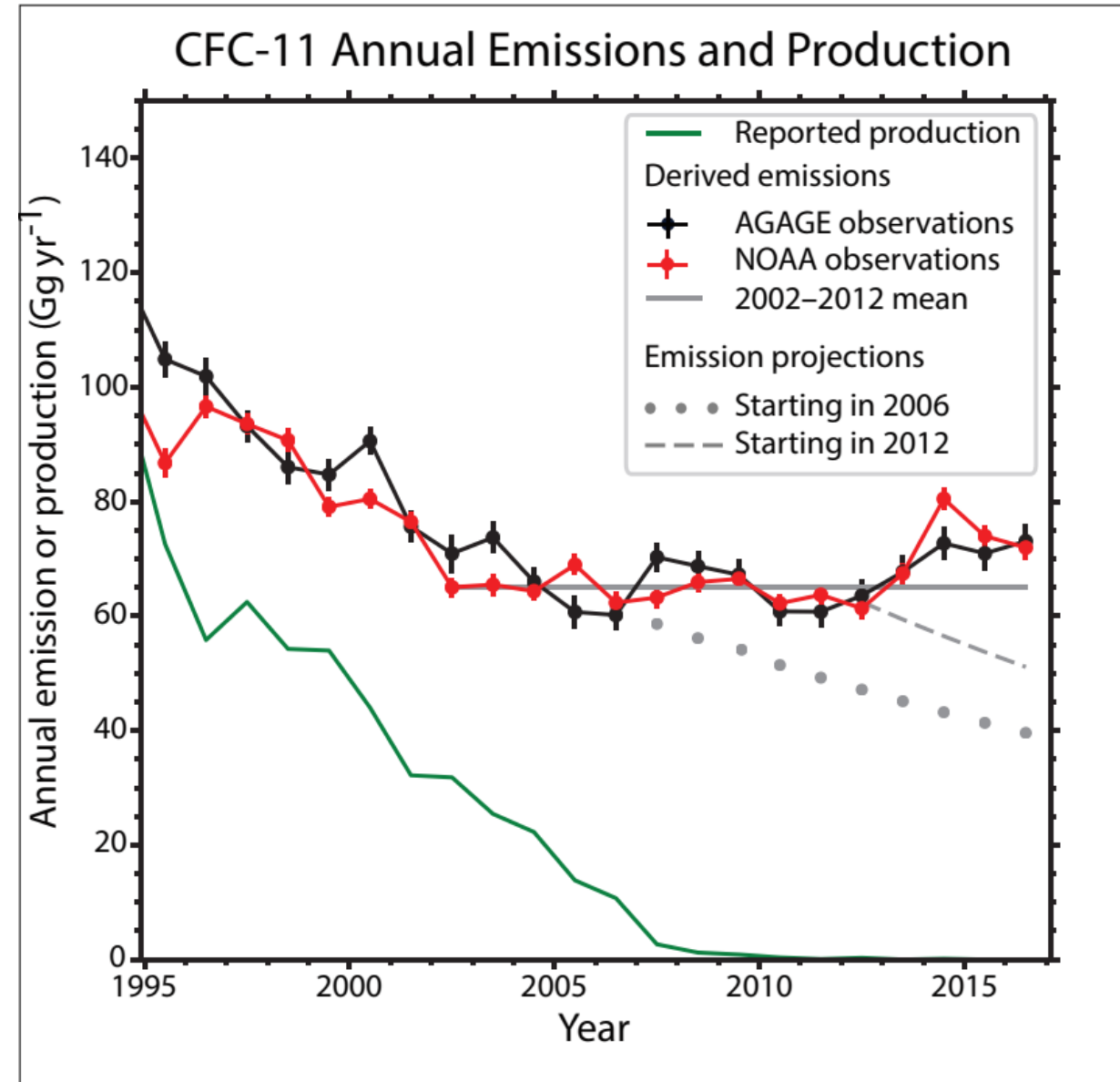


Figure ES-2 WMO (2018) Executive Summary



Update ...

- Unforeseen changes in CFC-11 concentrations (Montzka et al., 2018).
- Update by Harries et al. in the SPARC newsletter No. 53 (2019) – see figure on the right. Red points represent updated values to Montzka et al. (2018): further increase of CFC-11 emissions in **2017 about 80 Gg**

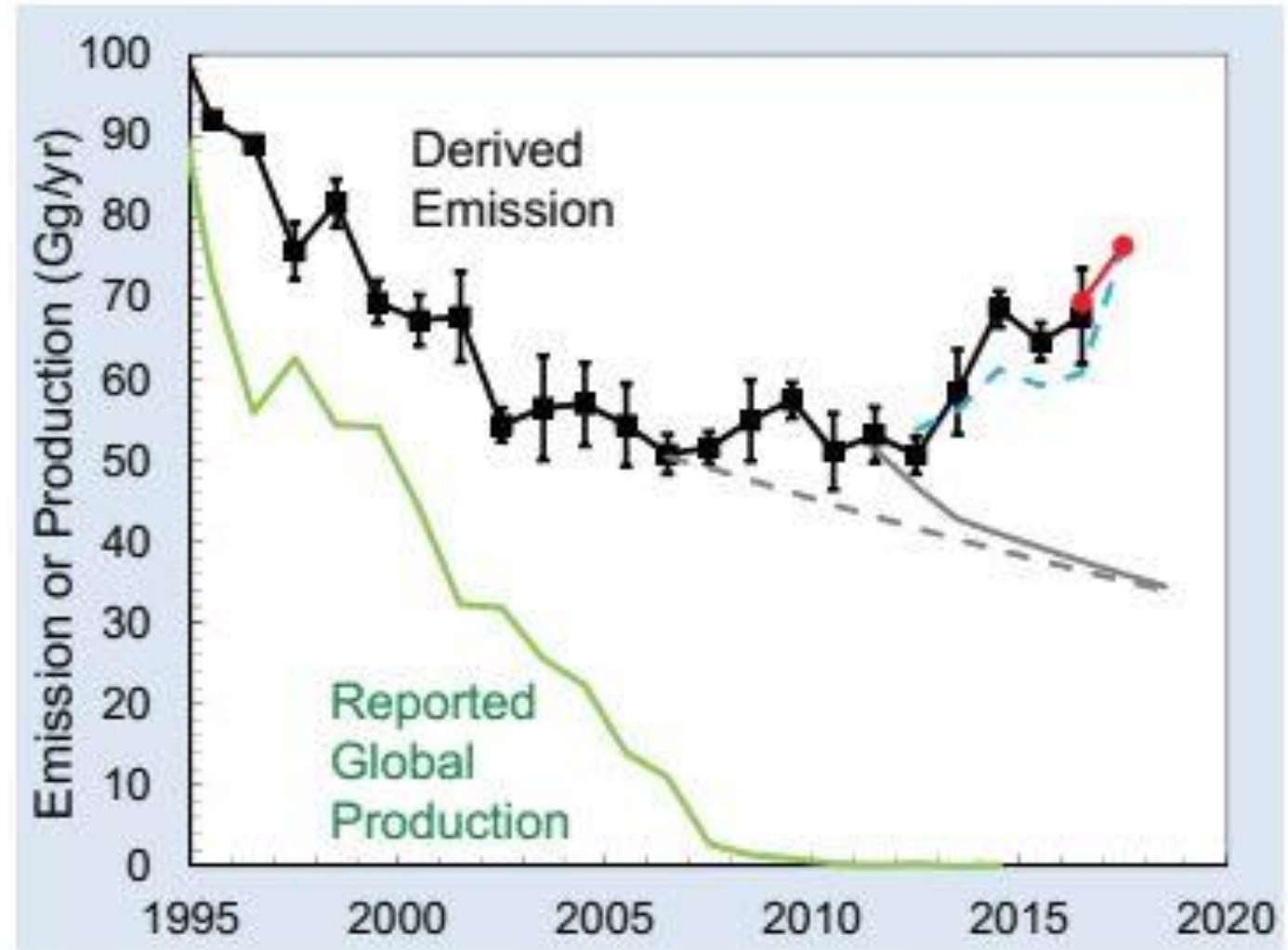


Figure 1 in Harris et al., SPARC newsletter No. 53. (2019)

Update ...

- Unforeseen changes in CFC-11 concentrations (Montzka et al., 2018)
- Update by Rigby et al. (2019) – see figure on the right

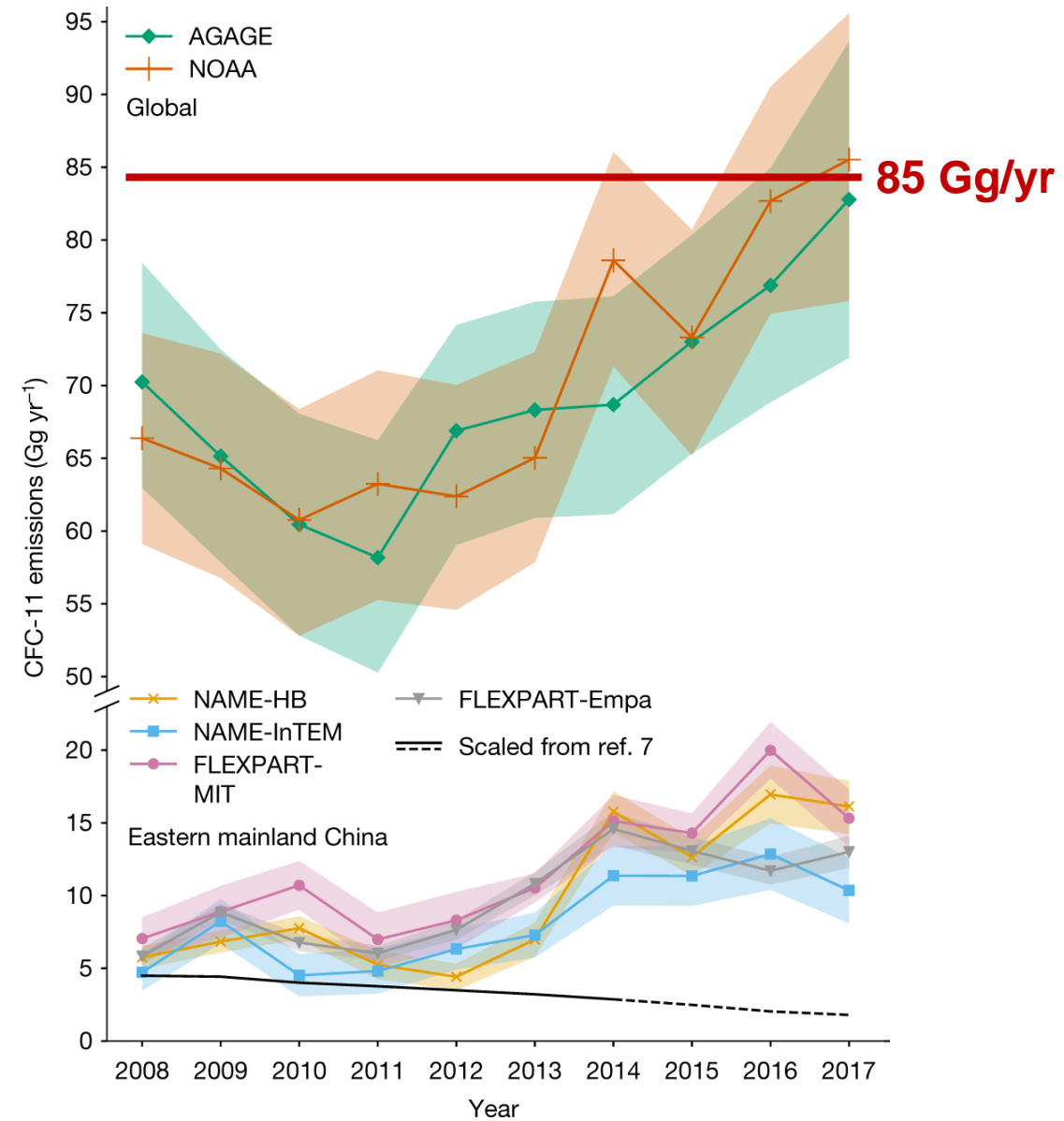


Figure 2 in Rigby et al. (2019)

Status of knowledge

- CFC-11 still contributes **one-quarter** of all chlorine reaching the stratosphere.
- A timely recovery of the stratospheric ozone layer depends on a sustained decline in CFC-11 concentrations.
- Montzka et al. (2018) showed that the **annual emissions of CFC-11** were **constant from 2002 to 2012**, and then **increased after 2014**. The stratospheric amount of chlorine is still going down.
- The increase in emission of CFC-11 appears unrelated to past production; this suggests unreported **new production**, which is inconsistent with the Montreal Protocol agreement to phase out global CFC production by 2010.
- Additional CFC-11 emissions over the baseline expectations result in **higher future levels of chlorine** in the stratosphere. In turn, larger ozone depletions can be expected in the future, with **delays in the recovery** of ozone to pre-1980 levels.
- A major problem with understanding the impact of the unexpected increased emissions is to create a **realistic projection of future CFC-11** levels.



Goals of our study

Assess the consequences of fixed CFC-11 concentrations at a higher level on

- ✓ the global mean ozone layer and especially on
- ✓ the Antarctic ozone hole
- ✓ evaluate changes in ozone production mechanisms



Model description and set up

- EMAC (ECHAM5 MESSy Atmospheric Chemistry) model (see Jöckel et al., 2016)
- Detailed tropospheric and stratospheric chemistry
- Typical setup:
 - T42L90MA (90 levels, roughly 2.8° horizontal resolution)
 - model top 0.01 hPa (approximately 80 km)
- Projection simulation until 2100 with **RCP 6.0** (cf. van Vuuren et al., 2011) as contribution to CCMI: **REF-C2**
- SST and SIC data fixed from CMIP5 HadGEM2-ES simulation (cf. Jones et al., 2011)

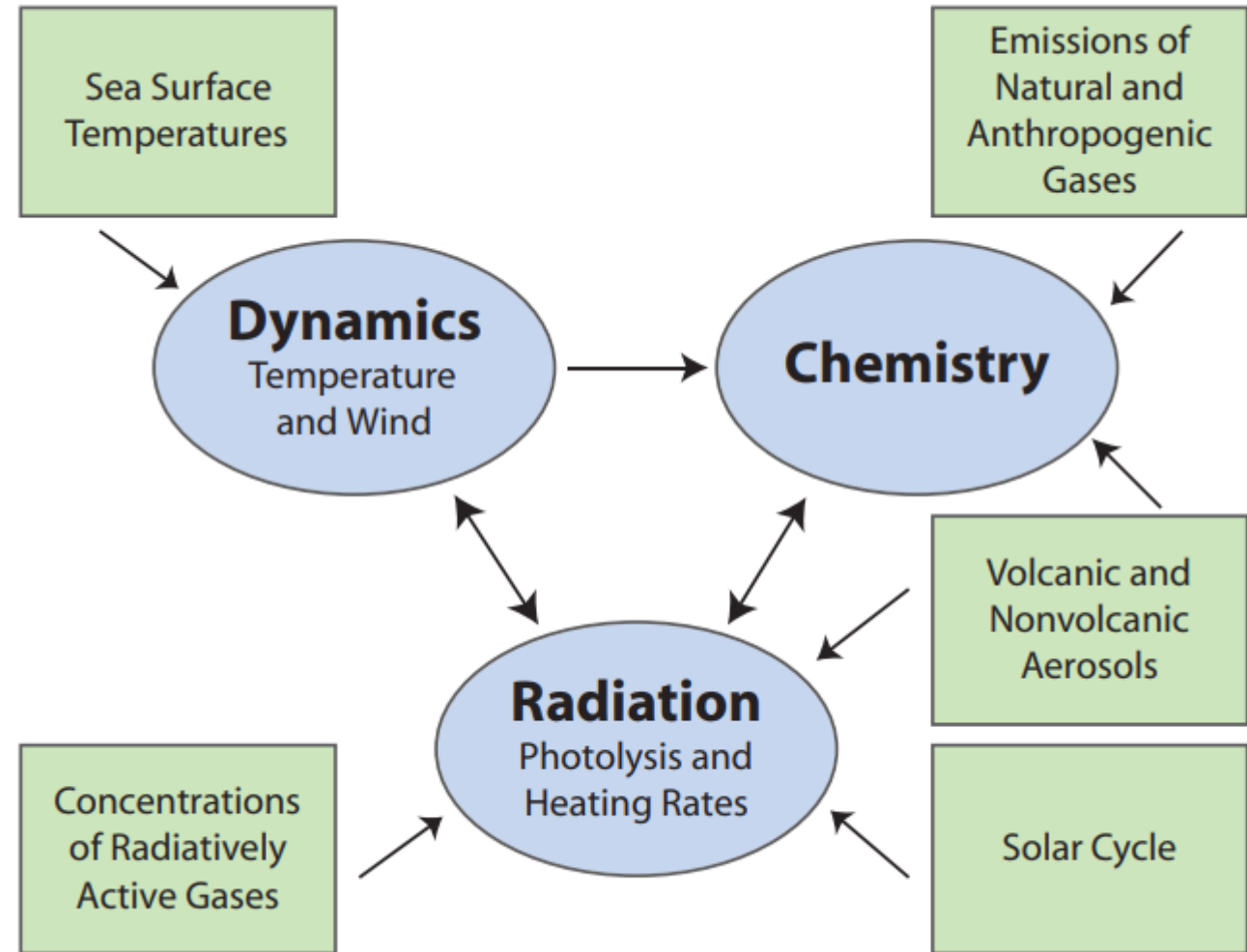


Figure 5-1 WMO (2007)



Model description and set up

CFC-11 emissions required to achieve constant surface mixing ratio value in our model after the year 2002 in **SEN-C2-fCFC11_2050** is about **90 Gg yr⁻¹**

Dameris, M., P. Jöckel, and M. Nützel, Possible implications of enhanced chlorofluorocarbon-11 concentrations on ozone, *Atmos. Chem. Phys.*, 19, 13759-13771, 2019.

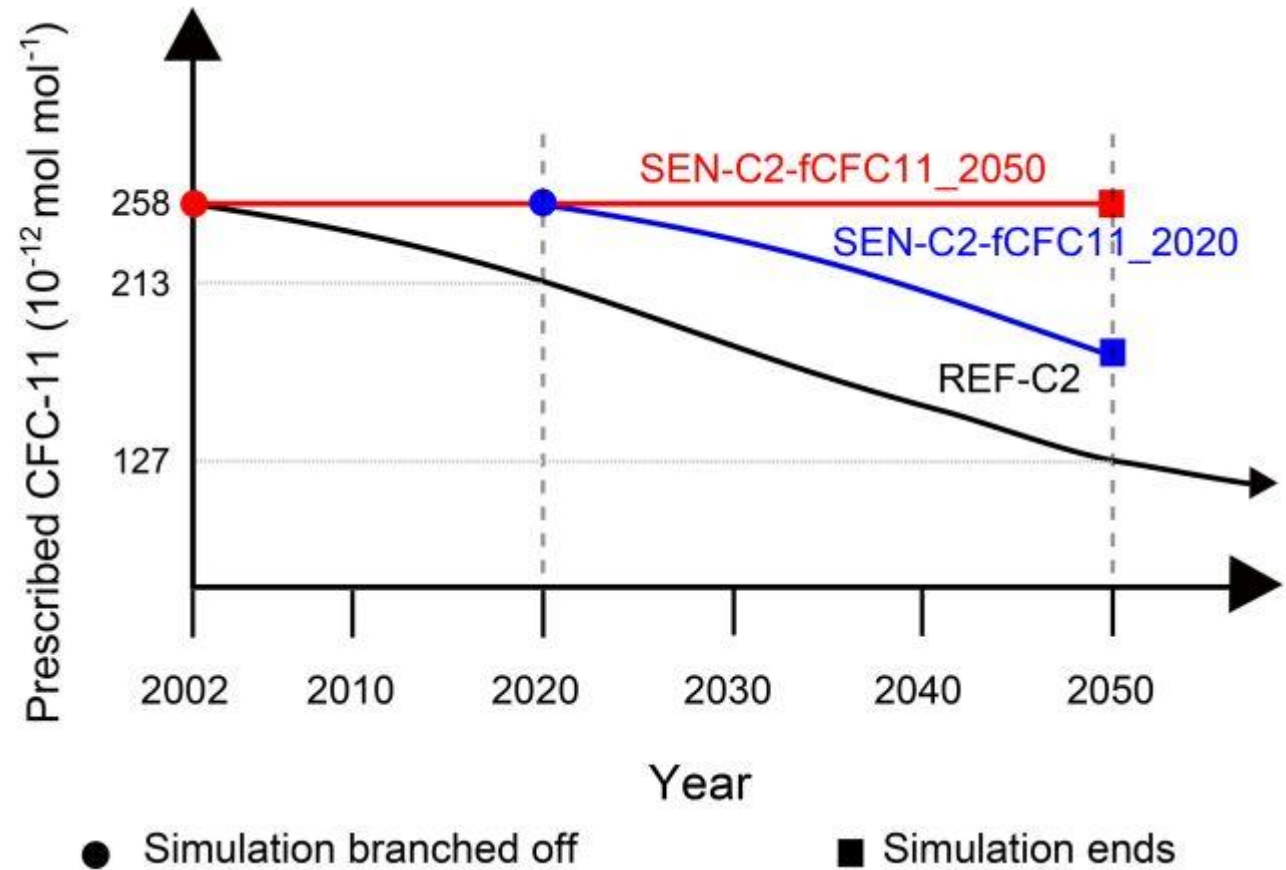


Figure 1. Schematic of the EMAC model simulations performed: a reference simulation (REF-C2) and two sensitivity simulations (SEN-C2-fCFC11_2020 and SEN-C2-fCFC11_2050) enabling an assessment of enhanced CFC-11 surface mixing ratios on the ozone layer. The prescribed CFC-11 surface mixing ratios are given on the nonlinear vertical axis. The prescribed CFC-11 surface mixing ratios are based on Table 5A-3 in Daniel et al. (2011).

Model description and set up

REF: Reference simulation

- 1960-2100, corresponds to REF-C2 from CCMI
- see „RC2-base-04“ in Jöckel et al. (2016)

SEN: Sensitivity simulations

- 2002-2050, branched off from REF
- but with constant CFC-11 surface mixing ratios after 2002 until 2050/2020:

✓ SEN-C2-fCFC11_2050

✓ SEN-C2-fCFC11_2020

→ Roughly 50 ppt difference between SEN-C2-fCFC11_2050 and REF in global mean ClO_x loading at 2 hPa by the end of the SEN simulation

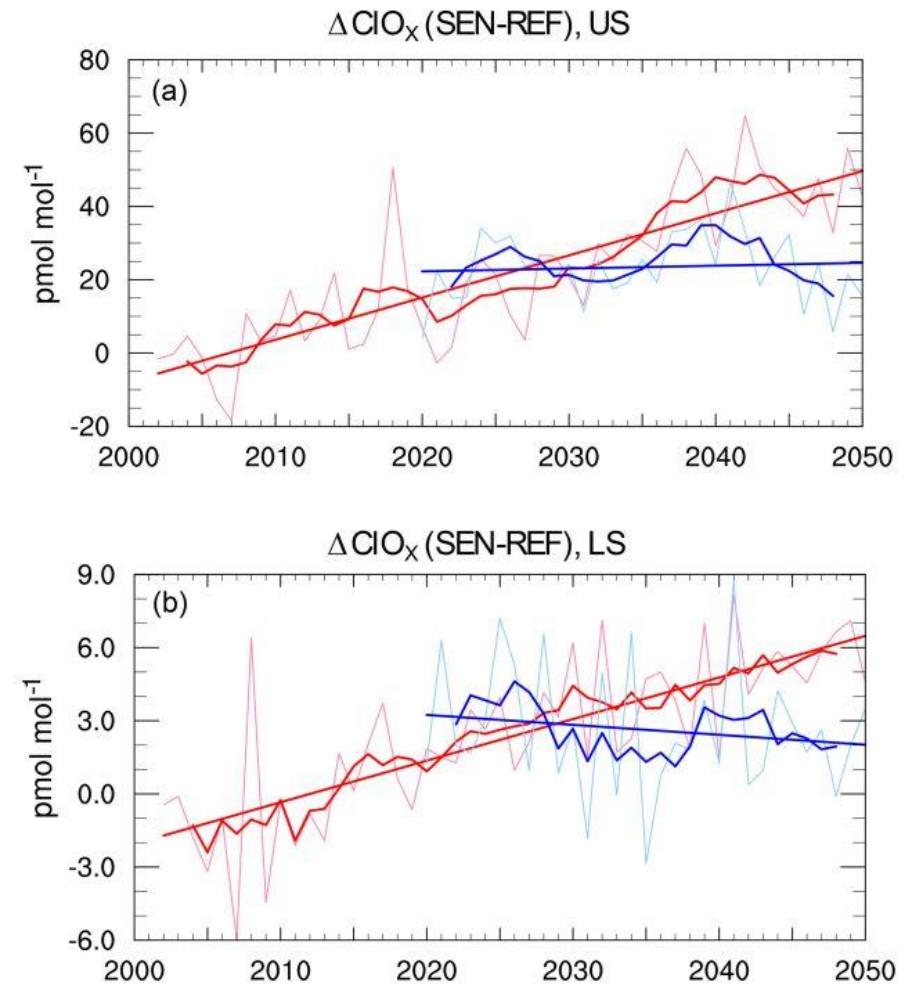


Figure 2. Temporal evolution of the annual global mean ClO_x mixing ratio differences (in mol mol^{-1}) at around 2 hPa (US, **a**) and 50 hPa (LS, **b**) between the SEN-C2-fCFC11_2050 and REF-C2 simulations (in red) and between the SEN-C2-fCFC11_2020 and REF-C2 simulations (in blue). The 11-year solar cycle (smoothed with a 1-2-1 filter) has been removed from both time series. The thicker curves in red and blue show the 5-year running means. The red and blue lines show the linear regression estimate of the unsmoothed time series.



Results: Total Column Ozone (TCO)

2041– 2050 mean TCO differences
(**SEN-C2-fCFC11_2050** minus REF-C2):

- relevant changes (30 DU – roughly 10%) for Antarctic winter/spring and Arctic winter/spring
- small changes mostly below +/-5 DU otherwise

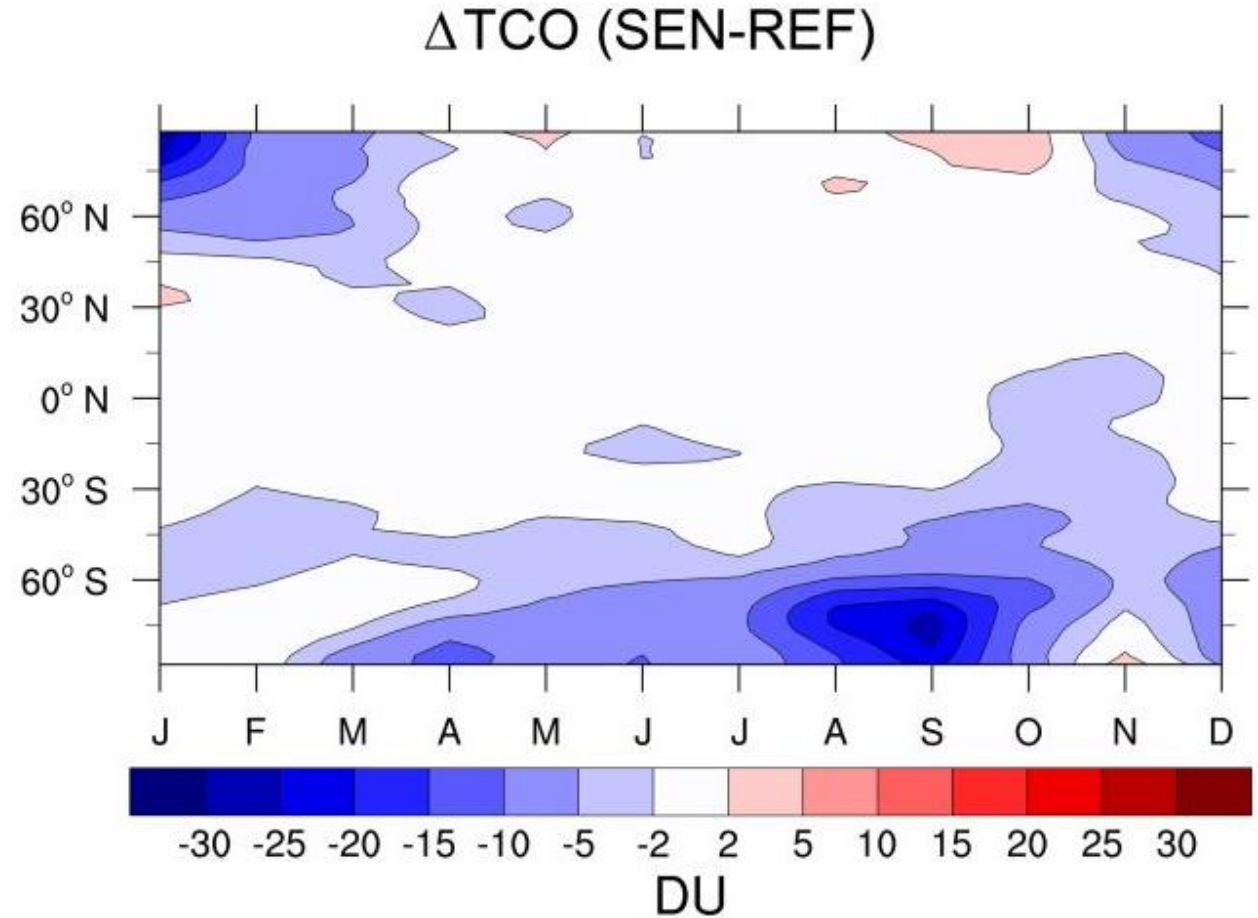


Figure 3. Mean annual cycle of total column ozone (TCO) differences (in Dobson units, DU) between SEN-C2-fCFC11_2050 and REF-C2 for the 2040s (i.e., SEN minus REF).

Results: Total Column Ozone (TCO)

Annual near global (60°S – 60°N) mean TCO differences (SEN-C2-fCFC11_2050 minus REF-C2):

- only small changes (around 2 DU in 2050)
- 2040s situation in agreement with previous latitude vs. time plot

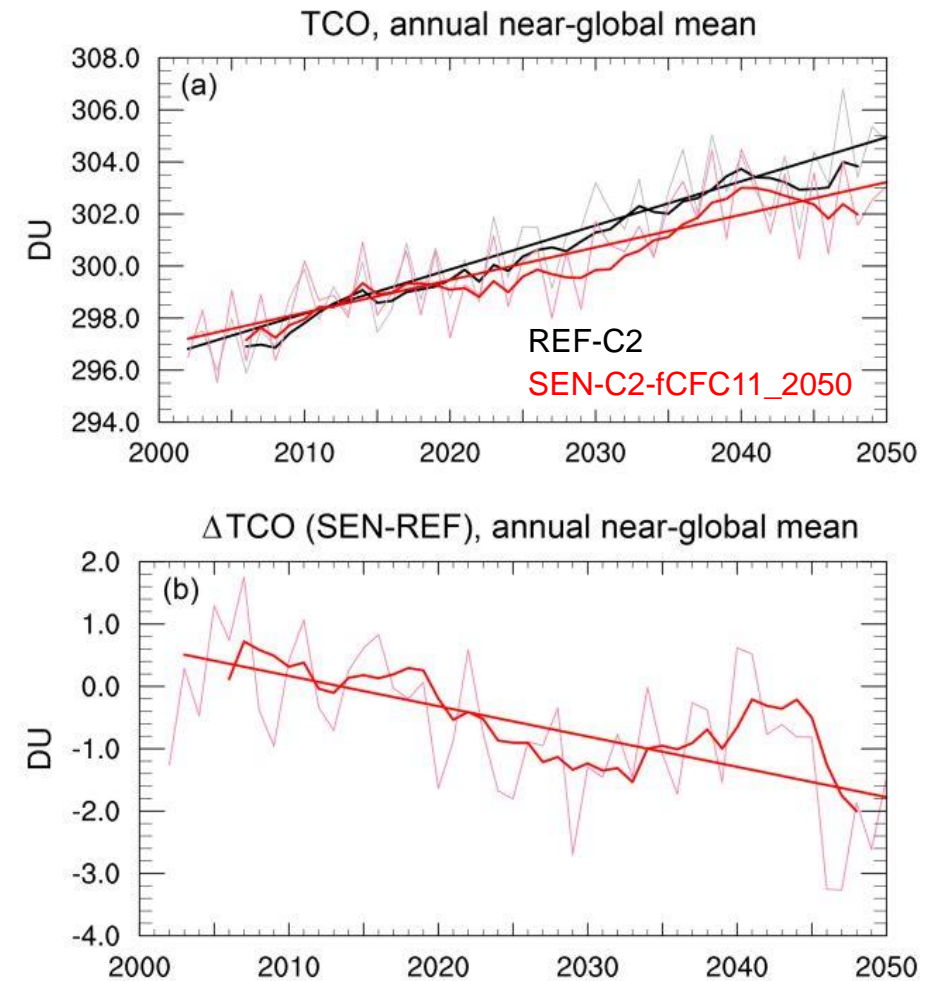


Figure 4. (a) Temporal evolution of total column ozone (TCO; in DU) for the annual near-global mean (60° S–60° N) in REF-C2 (black curves) and SEN-C2-fCFC11_2050 (red curves). (b) TCO differences (in DU) between SEN-C2-fCFC11_2050 and REF-C2 (i.e., SEN minus REF). For the absolute TCO time series (a) the 11-year solar cycle (smoothed with a 1-2-1 filter) has been removed. Thicker curves show the 5-year running means, respectively. The corresponding lines (a, b) show the respective linear regression estimates based on the unsmoothed data.



Results: Total Column Ozone (TCO)

Antarctic (90°S – 70°S) September TCO differences (SEN-C2-fCFC11_2050 minus REF-C2):

- relevant changes (approximately 20 DU in 2050, regression line)
- 2040s situation in agreement with previous latitude vs. time plot
- similar behavior in the NH polar region during spring (not shown)

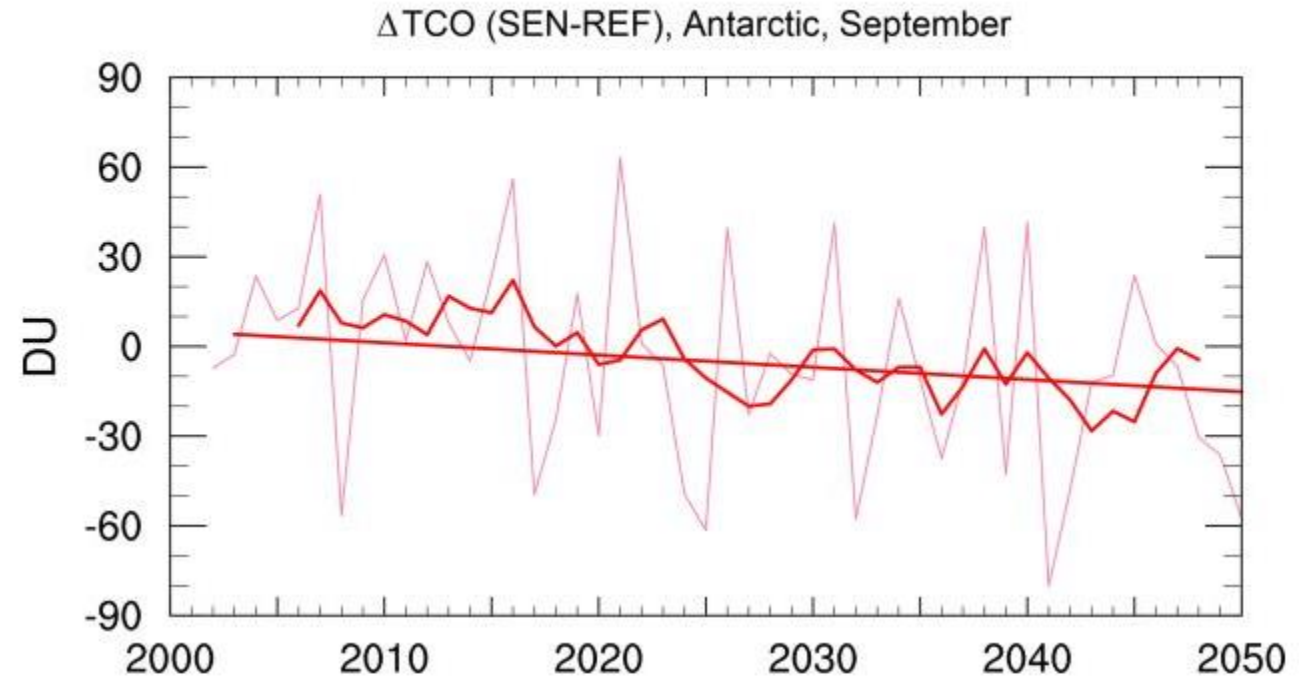


Figure 5. Temporal evolution of TCO differences (in DU) between SEN-C2-fCFC11_2050 and REF-C2 (i.e., SEN minus REF) for the Antarctic region (70–90° S) in September. The thicker curve shows the 5-year running mean. The corresponding line shows the trend estimate between the unsmoothed time series using a multiple linear regression – including differences of temperature anomalies as the dependent variable – which accounts for possible autocorrelation with lag 1 (see text for details).

Results: Antarctic Partial Column Ozone (PCO)

SEN-C2-fCFC11_2050 minus REF-C2:

For the US (above 10 hPa)

- small changes (roughly 2 DU in 2050)

For the LS (100 hPa to 10 hPa)

- relevant changes (somewhat below 20 DU by the end of the simulation 2050)
- strong interannual variability causes large fluctuations in the SEN-REF values

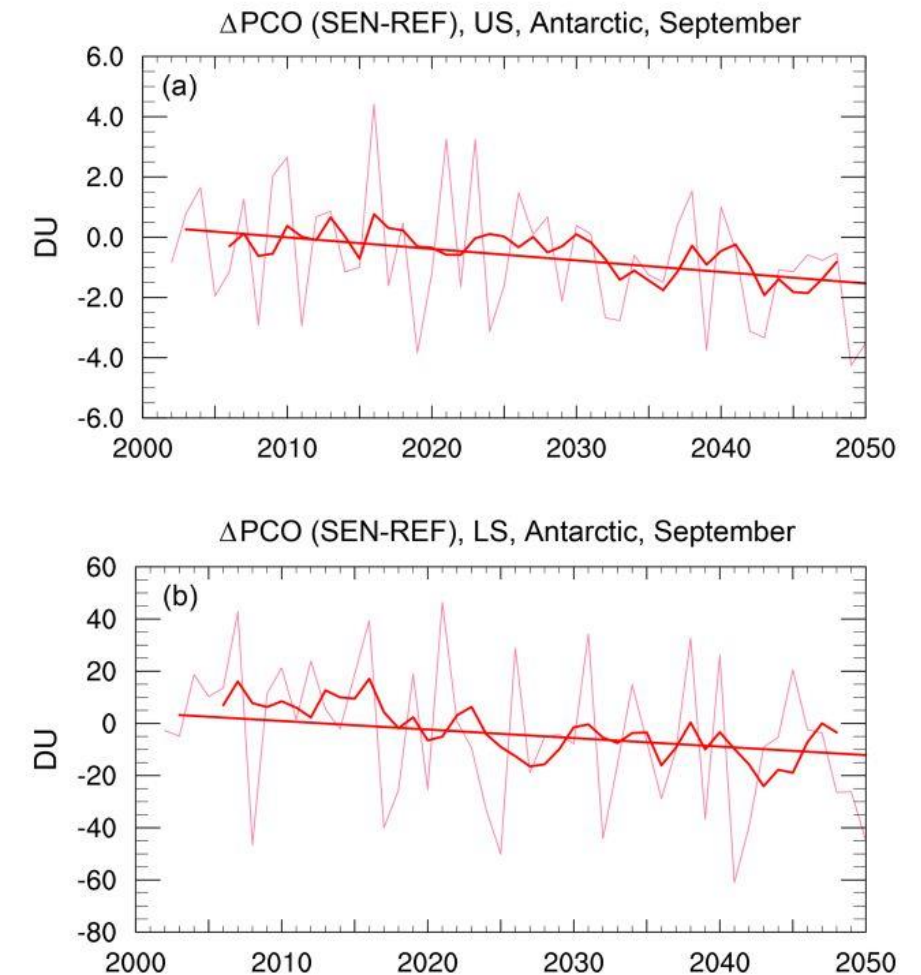


Figure 6. Temporal evolution of partial column ozone (PCO) differences (in DU) between SEN-C2-fCFC11_2050 and REF-C2 (i.e., SEN minus REF) for the Antarctic region (70–90° S) in September. Panel (a) shows PCO values for the US (above 30 km); panel (b) shows PCO values for the LS (below 30 km). Red thicker curves show the respective 5-year running means. The corresponding lines show the trend estimates for the unsmoothed time series using a multiple linear regression – including differences of temperature anomalies as the dependent variable – which accounts for possible autocorrelation with lag 1 (see text for details).

Results: Near-global mean and Antarctic TCO and PCO

SEN-C2-fCFC11_2050 minus REF-C2

SEN-C2-fCFC11_2020 minus REF-C2

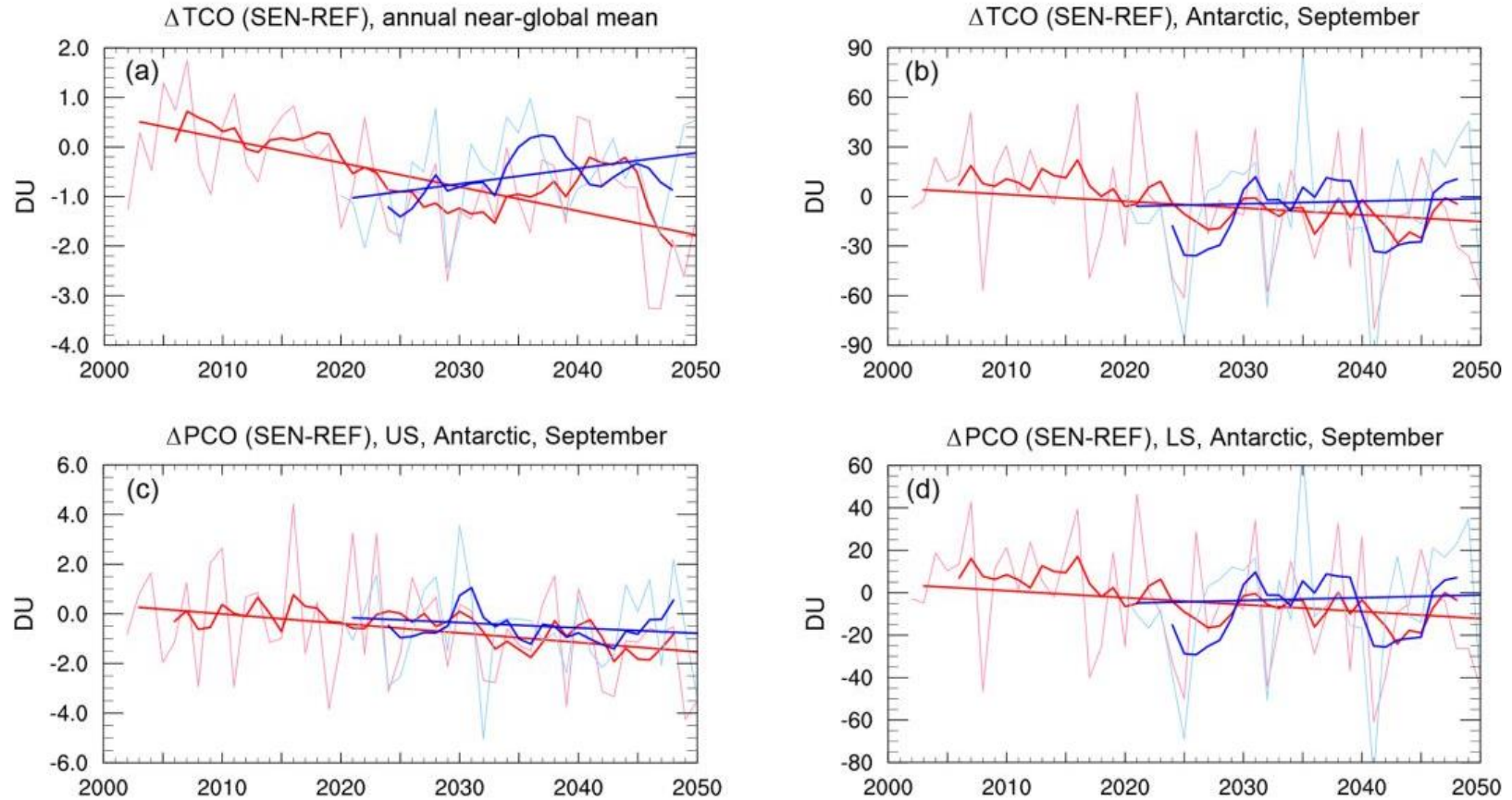


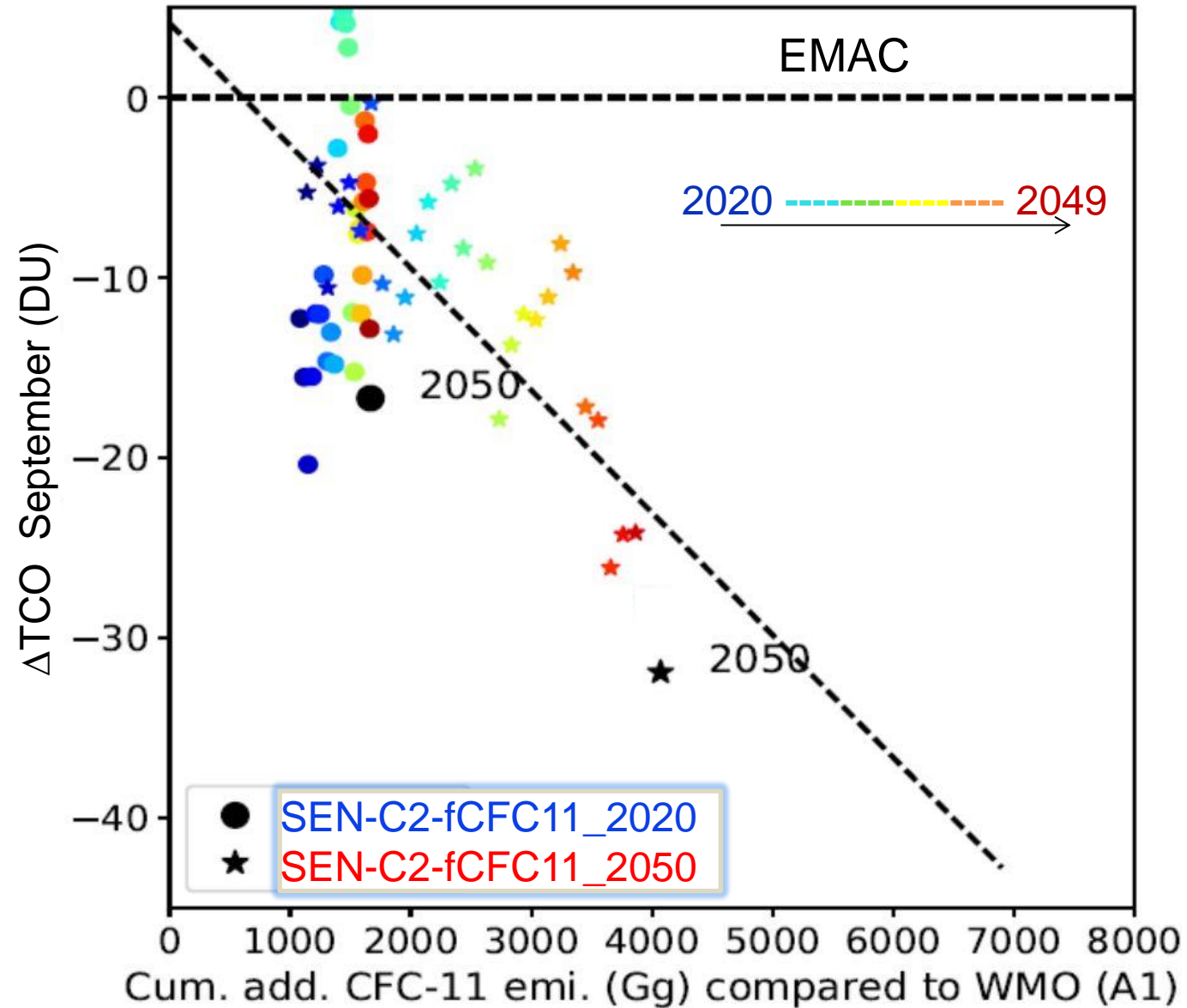
Figure 7. Different temporal evolution of column ozone differences (in DU) between the individual sensitivity simulations and the reference simulation (in DU): SEN-C2-fCFC11_2050 minus REF-C2 values are indicated in red, and SEN-C2-fCFC11_2020 minus REF-C2 values are shown in blue. (a) TCO for the annual near-global mean (60° S– 60° N); (b) TCO for the Antarctic (70° – 90° S) in September; (c) PCO for the Antarctic (70° – 90° S) in the US in September; (d) PCO for the Antarctic (70° – 90° S) in the LS in September. The red and blue lines show the trend estimates for the unsmoothed time series using a multiple linear regression – including differences in temperature anomalies as the dependent variable – which accounts for possible autocorrelation with lag 1 (see text for details).

Results: Antarctic spring

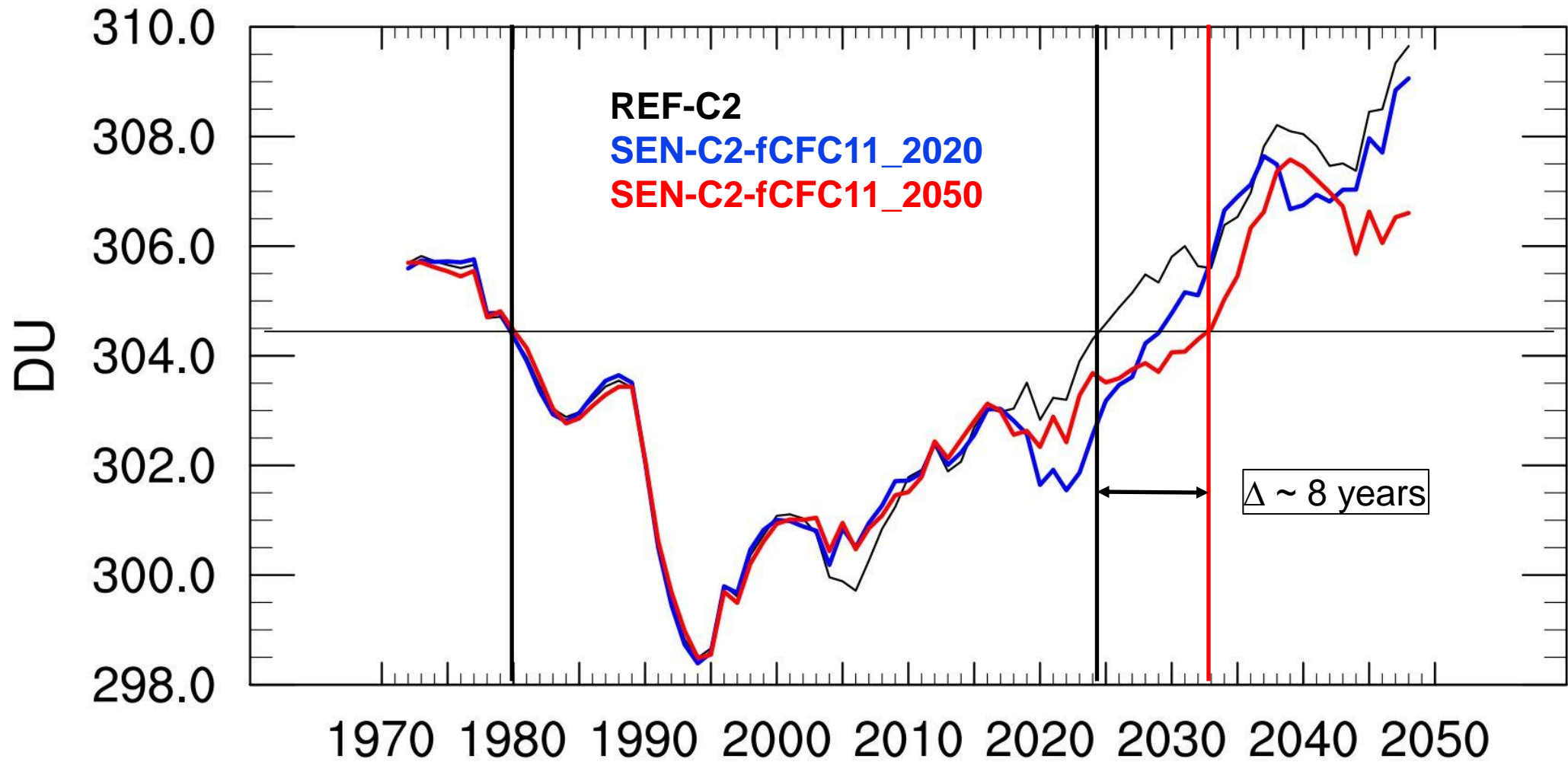
The cumulative CFC-11 emissions (from 2002 to 2050) result in about 4500 Gg (i.e., in **SEN-C2-fCFC11_2050** roughly **4100 Gg** more than in REF-C2)

The cumulative CFC-11 emissions (from 2002 to 2050) result in about 2100 Gg (i.e., in **SEN-C2-fCFC11_2020** roughly **1700 Gg** more than in REF-C2).

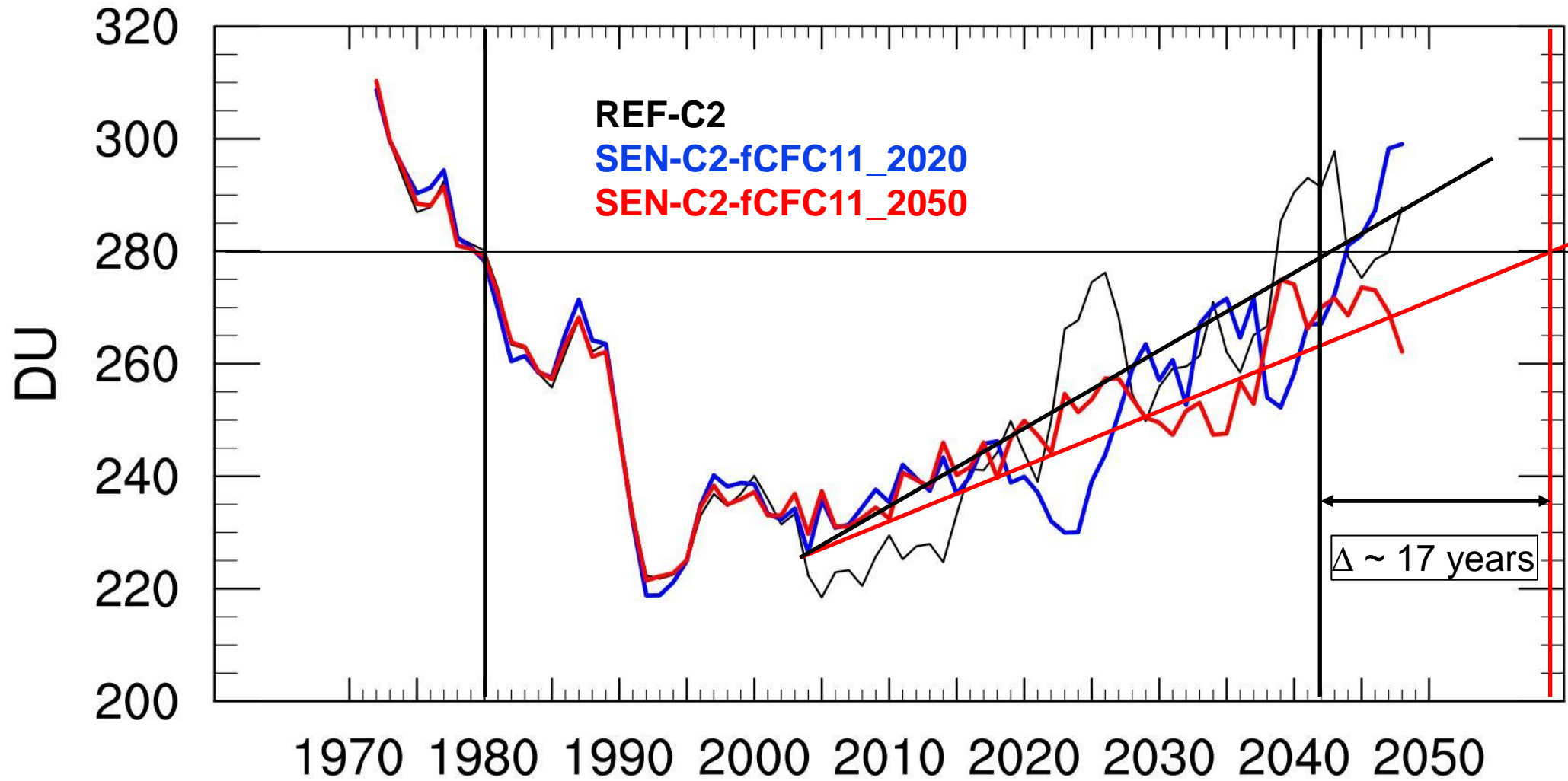
Linear dependence between cumulative CFC-11 emission on total ozone changes



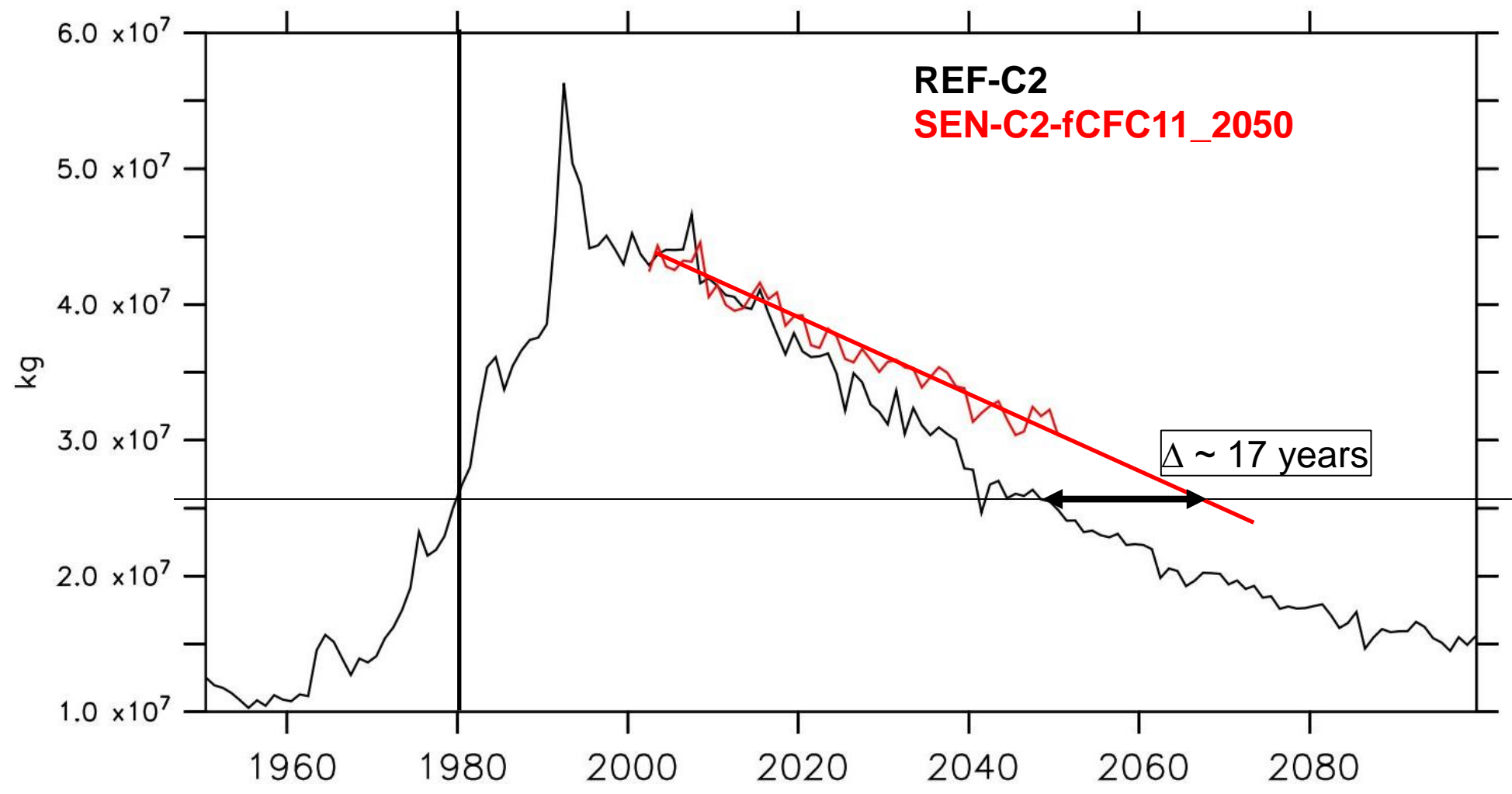
Results: Global mean TCO



Results: Antarctic September TCO



Results: Total mass of chlorine [kg]



Summary

- EMAC results show that ozone depletion has a strong **linear dependence** on the cumulative amount of CFC-11 emissions
 - ✓ This finding is very much in line with Fleming et al. (JGR, accepted, 2020).
- Shift of ozone recovery in time
 - Estimates based on EMAC (**SEN-C2-fCFC11_2050** vs. REF-C2) show a delay of ozone recovery to 1980 values in **global TCO by about 8 years** and **Antarctic spring TCO by less about 20 years**.
 - ✓ Fleming et al. (2020): Constant CFC-11 emissions of 72,5 Gg/yr out to 2100 result in global TCO and Antarctic spring TCO depletion of about 1% and 7%, respectively, and delay the recovery to 1980 levels by about 8 and 25 years.
 - ✓ Keeble et al. (ACPD, 2019): found that for every 200 Gg Cl emitted the timing of global TCO recovery is delayed by 0,56 years
 - with respect to our SEN-C2-fCFC11_2050 this means a delay of ozone recovery in global TCO by about 11,5 years.



Results: Stratospheric ozone budget

Changes of stratospheric O₃ production (ΔP) from **SEN-REF** normalised to total production in REF (%) using MESSy tool StratO3bud (cf. Meul et al., 2014):

$$\Delta P_{SEN-REF}^{prc}(lev) = \frac{\sum_{lat \in R} P_{SEN}^{prc}(lat, lev) - \sum_{lat \in R} P_{REF}^{prc}(lat, lev)}{\sum_{lev} \sum_{lat \in R} P_{REF}^{tot}(lat, lev)}$$

Production (P) processes (**prc**) are e.g.: photolysis, ClO_x-cycle, NO_x-cycle,...

P^{Tot} denotes the sum off all positive production processes (loss processes are negative production processes).

R denotes a certain region (e.g. SH polar cap, global)



Ozone production rate

Left: annual global mean

- additional O_3 production through photolysis at (grey line) below the additional O_3 loss through ClO_x (max. at 2 hPa, dashed purple line)
- other processes cause a relative O_3 production that compensates the additional loss through ClO_x

Right: Antarctic ($90^\circ S - 70^\circ S$) in September

- additional loss from ClO_x in the LS and US and from BrO_x in the LS
- the latter also related to higher ClO (cf. Meul et al., 2014)

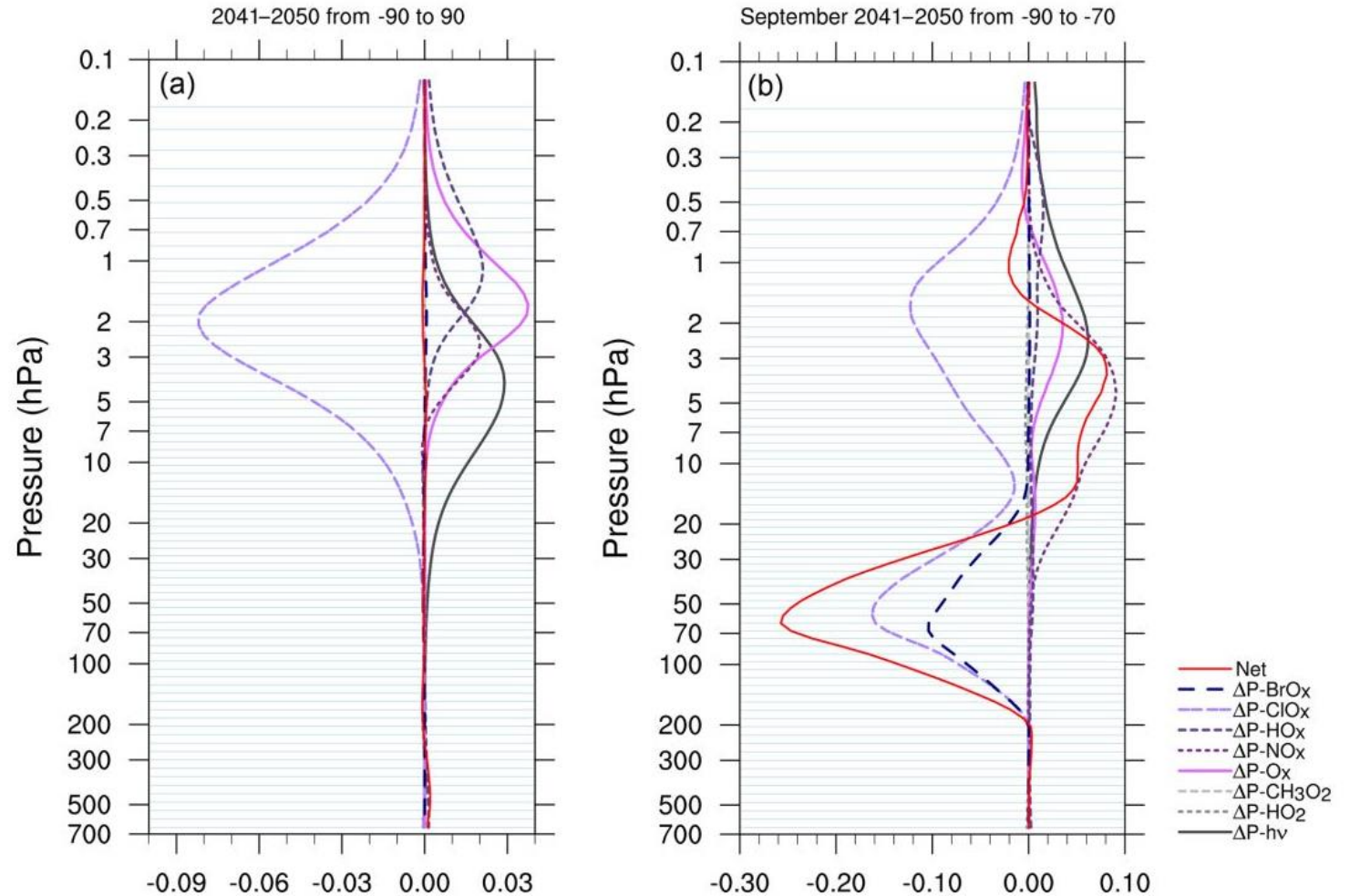


Figure 8. The relative change in ozone production rates (in %), which are normalized to the total column production (through photolysis $h\nu$, HO_2 , and CH_3O_2) in the REF-C2 simulation. For the individual ozone production and loss processes, mean differences are shown that have been derived from the REF-C2 and SEN-C2-fCFC11_2050 (i.e., SEN minus REF) simulations for the 2040s (from 2041 to 2050). The change in the net ozone production rate, which refers to the sum of all changes, is indicated by the red line. Panel (a) shows the mean annual global mean profiles, and panel (b) shows the values for the south polar region ($70-90^\circ S$) in September. Negative values indicate an intensified ozone loss or a decreased ozone production in the SEN-C2-fCFC11_2050 simulation, whereas higher values indicate more ozone production or less loss via a specific process. Thin horizontal lines indicate the nearest pressure levels to the model grid boxes.

Discussion and conclusion

- Relatively small changes regarding annual mean TCO
- Small changes in tropical and mid-latitude ozone (mostly below 5 DU throughout the year)
- Relevant changes in TCO for the polar regions in winter to spring period up to 30 DU
- Relevant PCO changes in the LS during SH spring
- Small changes in temperature (no important changes regarding PSC, not shown)
- Global mean ozone budget: shifts in ozone production and loss are offsetting stronger loss through enhanced ClO_x
- Global mean ozone budget: biggest shifts in the production rates are found in the US
- Polar spring ozone budget compensating effects exist as well – still the signal is quite large (about 20 DU)
- Polar spring ozone budget: strongest additional loss occurs in the LS (max. at 50–70 hPa) from ClO_x and BrO_x cycles; in the US compensation occurs

Final statement: If quick action is taken regarding to the unexpected CFC-11 emissions in recent years, no significant delay in the timing of ozone recovery is expected.



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THANK YOU !

