Tropospheric ozone in UKESM1 and other CMIP6 models

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Based on DOI: 10.1525/elementa.2020.034 and 10.5194/acp-2019-1216

Code and Data available via Centre for Open Science https://osf.io/3hsz6/

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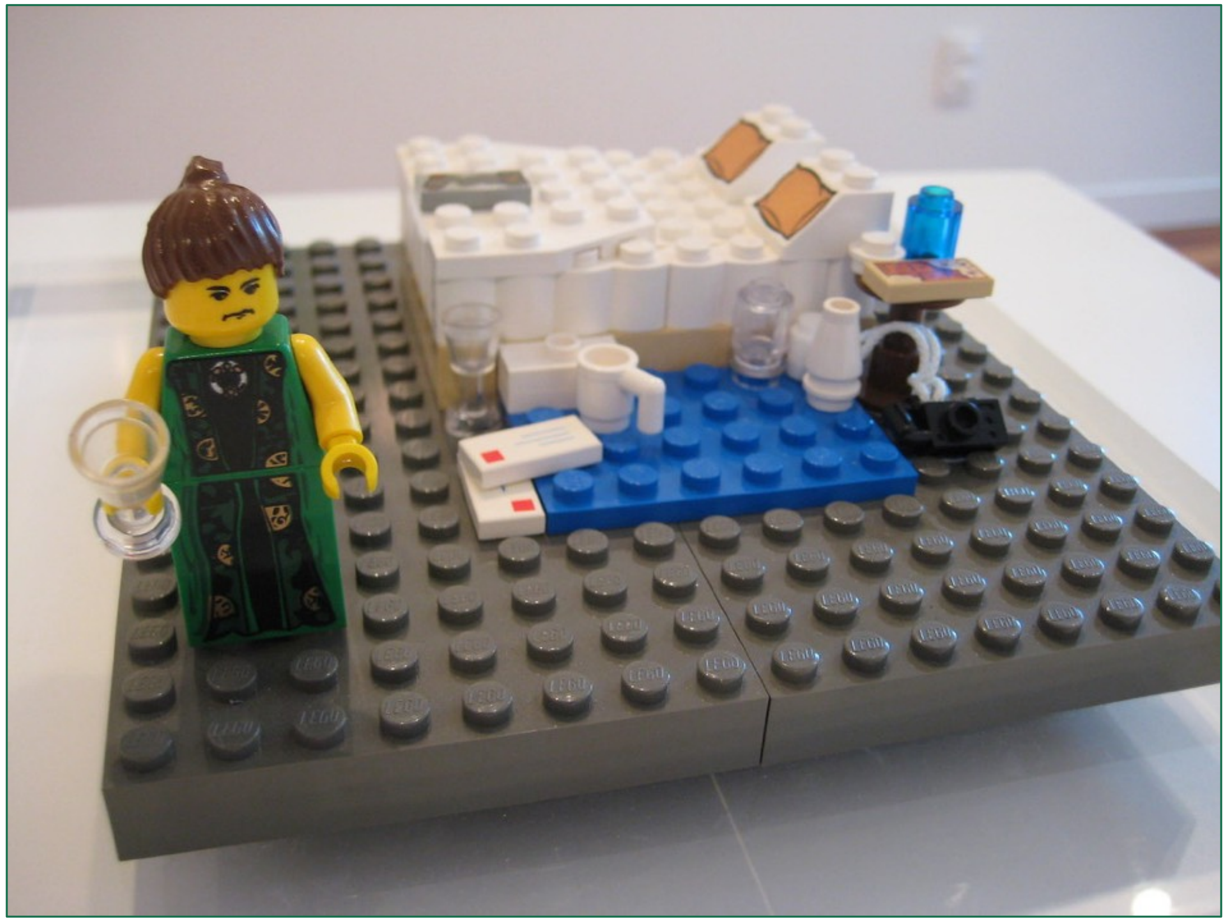
paultgriffiths

What does it mean to be a modeller?

Reality

Model



Thanks to Dr RJ Derwent, rdScientific

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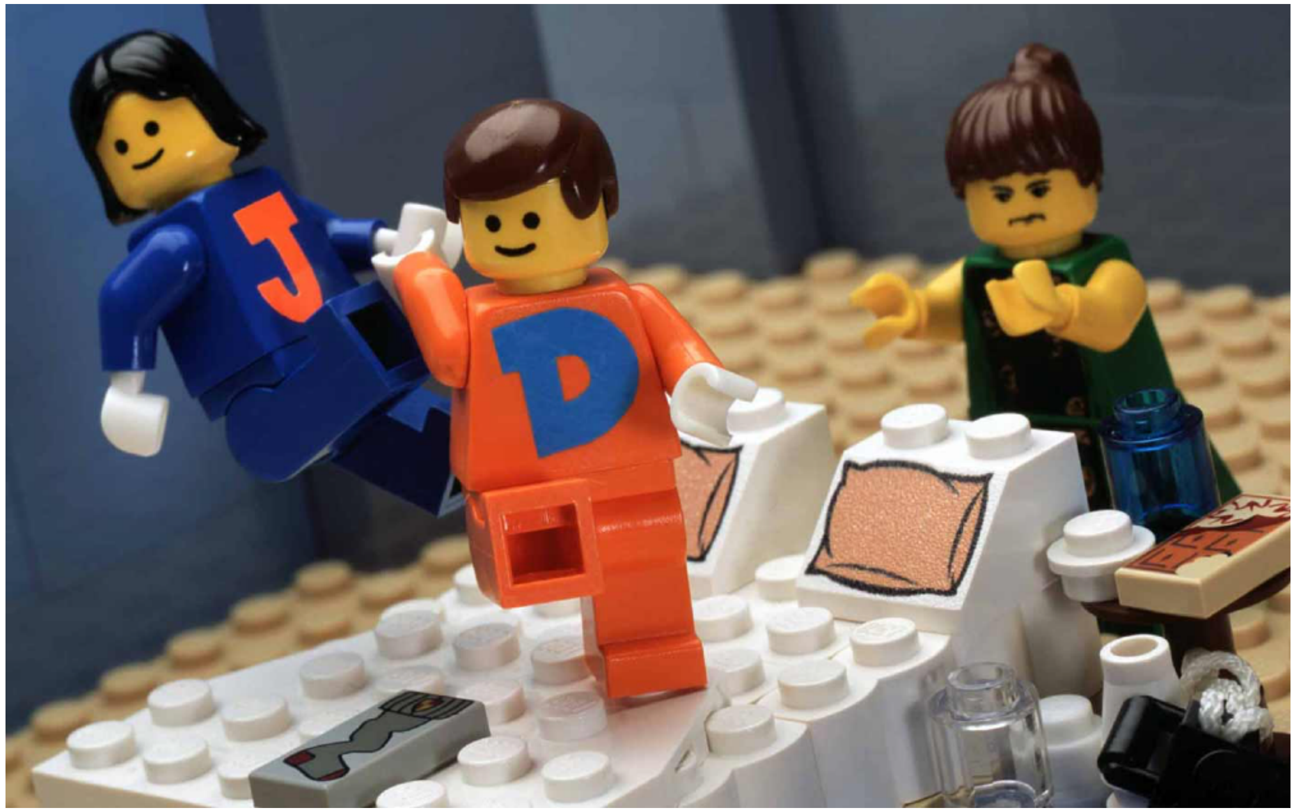
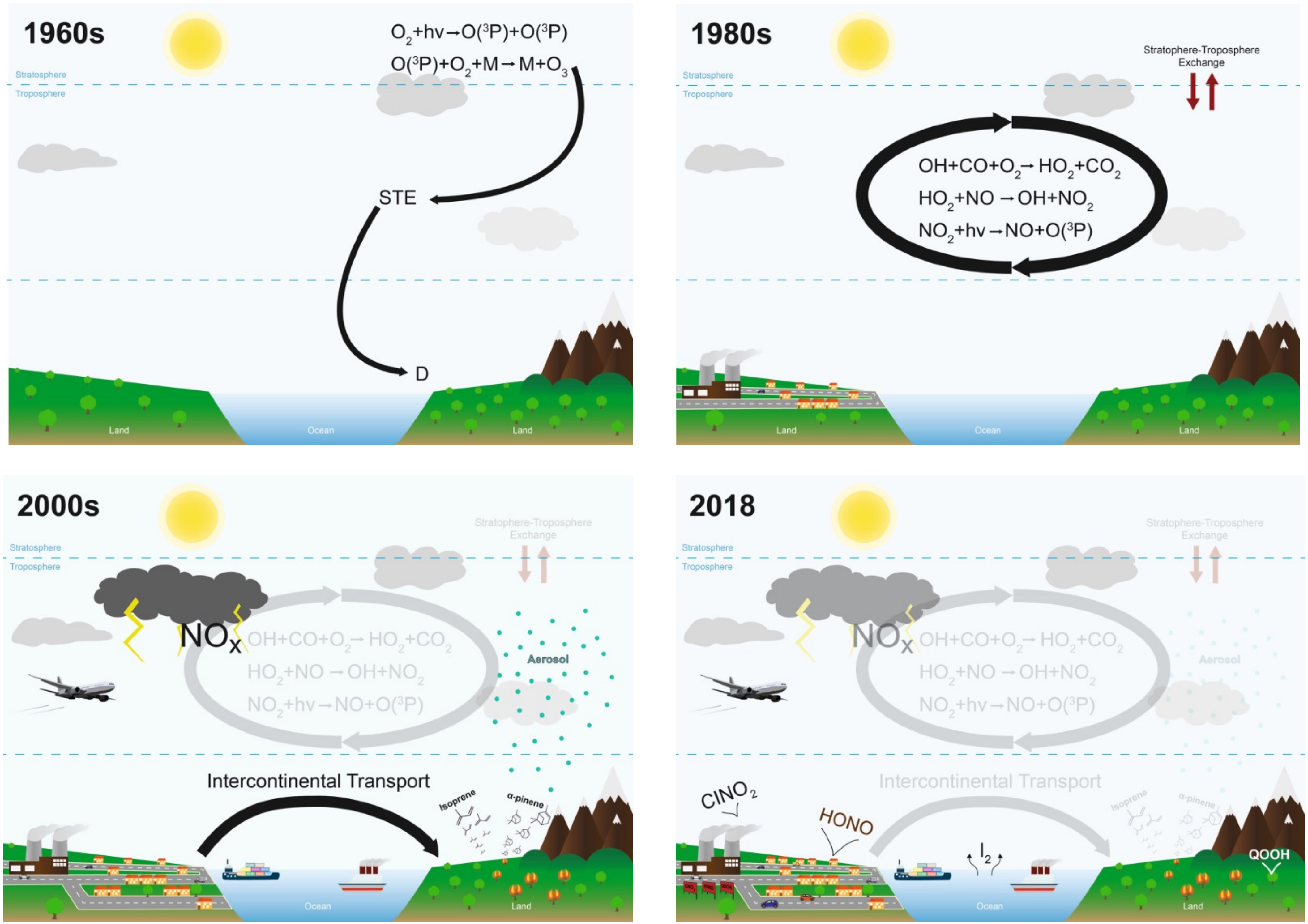


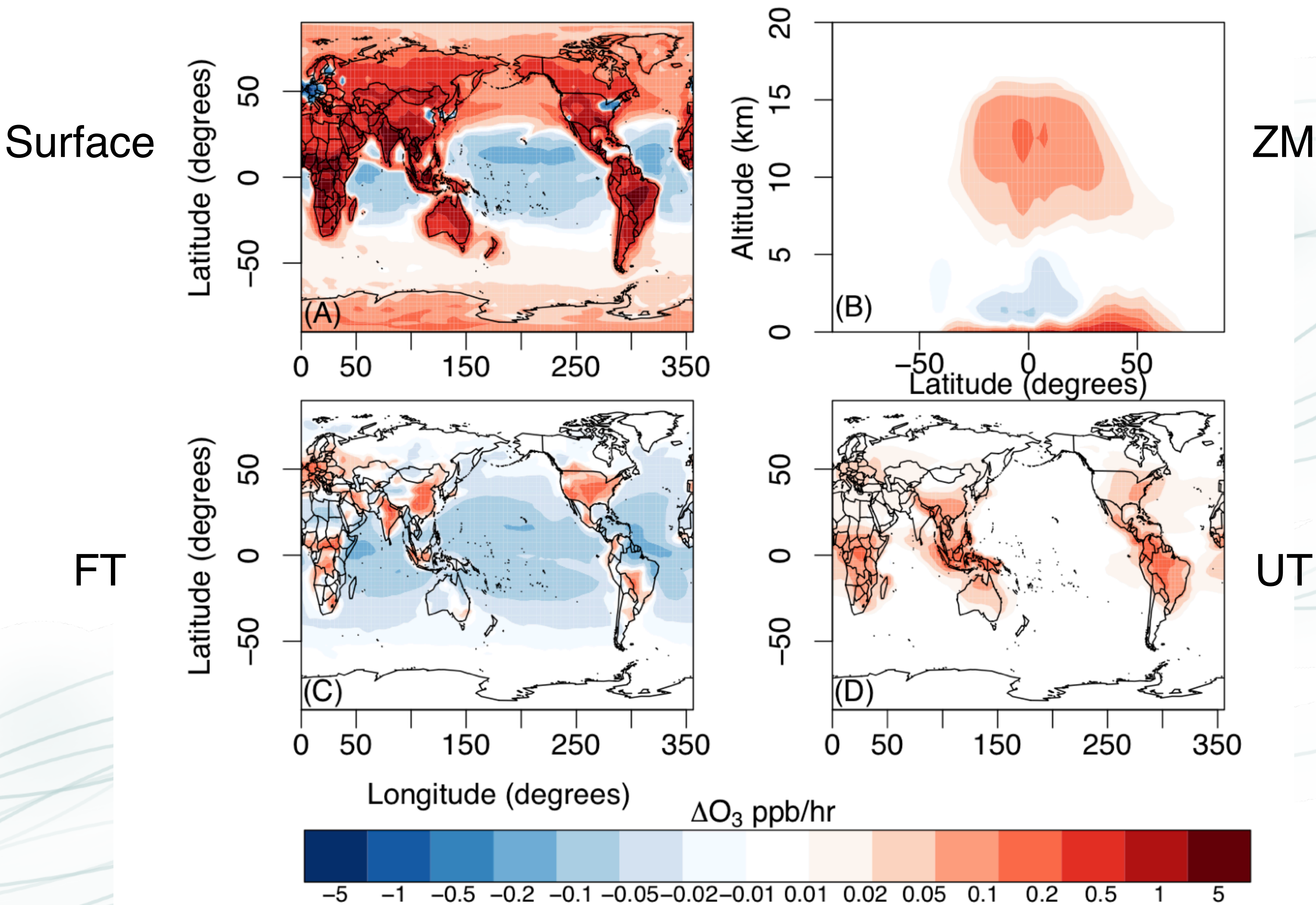
Lego art by Little Artists,
Thanks to Dr RJ Derwent, rdScientific

Ozone in CCMs – developing complexity



Archibald et al., TOAR "Budget", Elementa 2021

Multimodel ozone tendency - TOAR Budget



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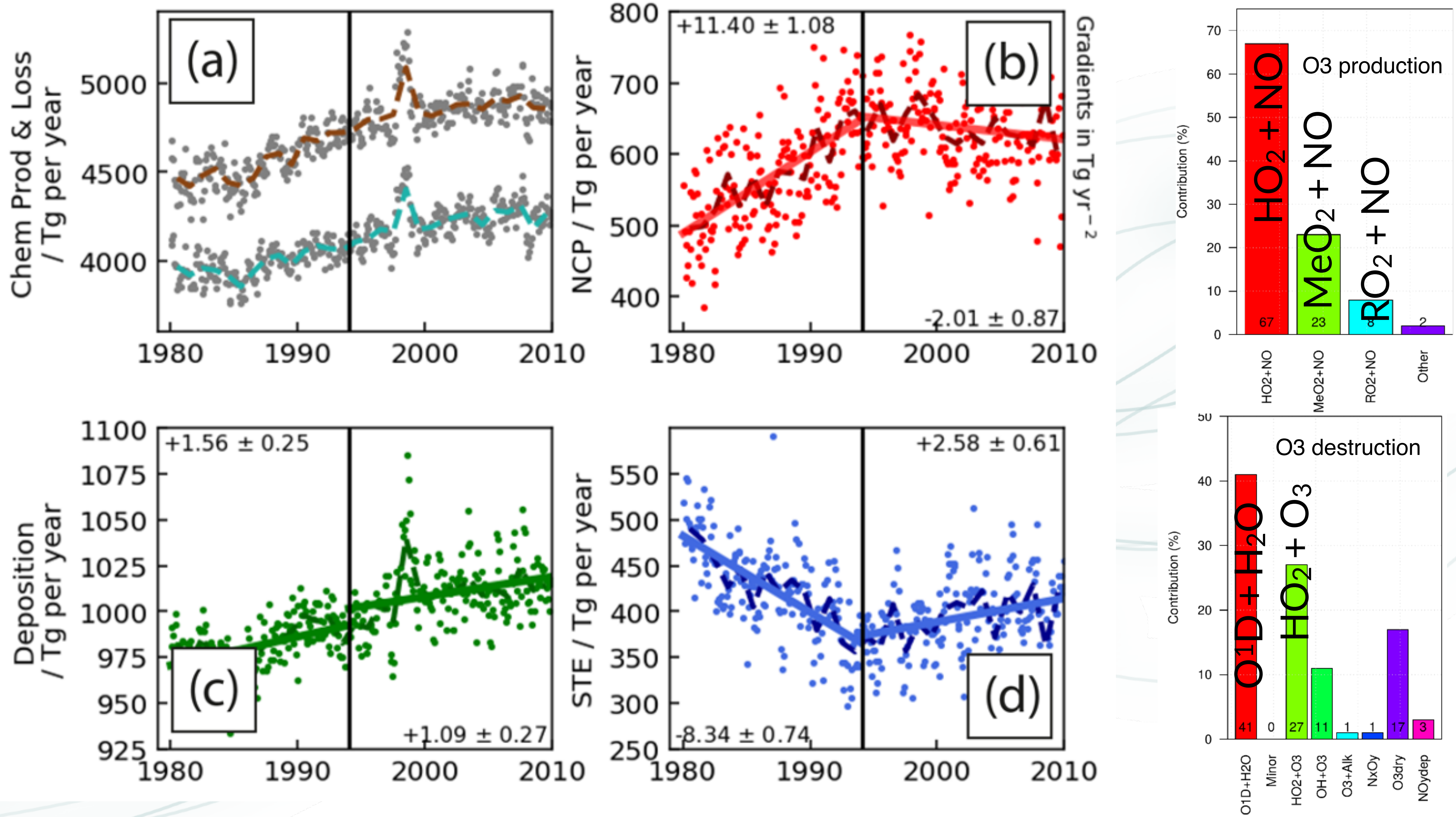
Archibald et al., TOAR “Budget”, Elementa 2021

Tropospheric ozone budget in CCMs - large, opposing terms



Griffiths et al., DOI: 10.1029/2019GL086901

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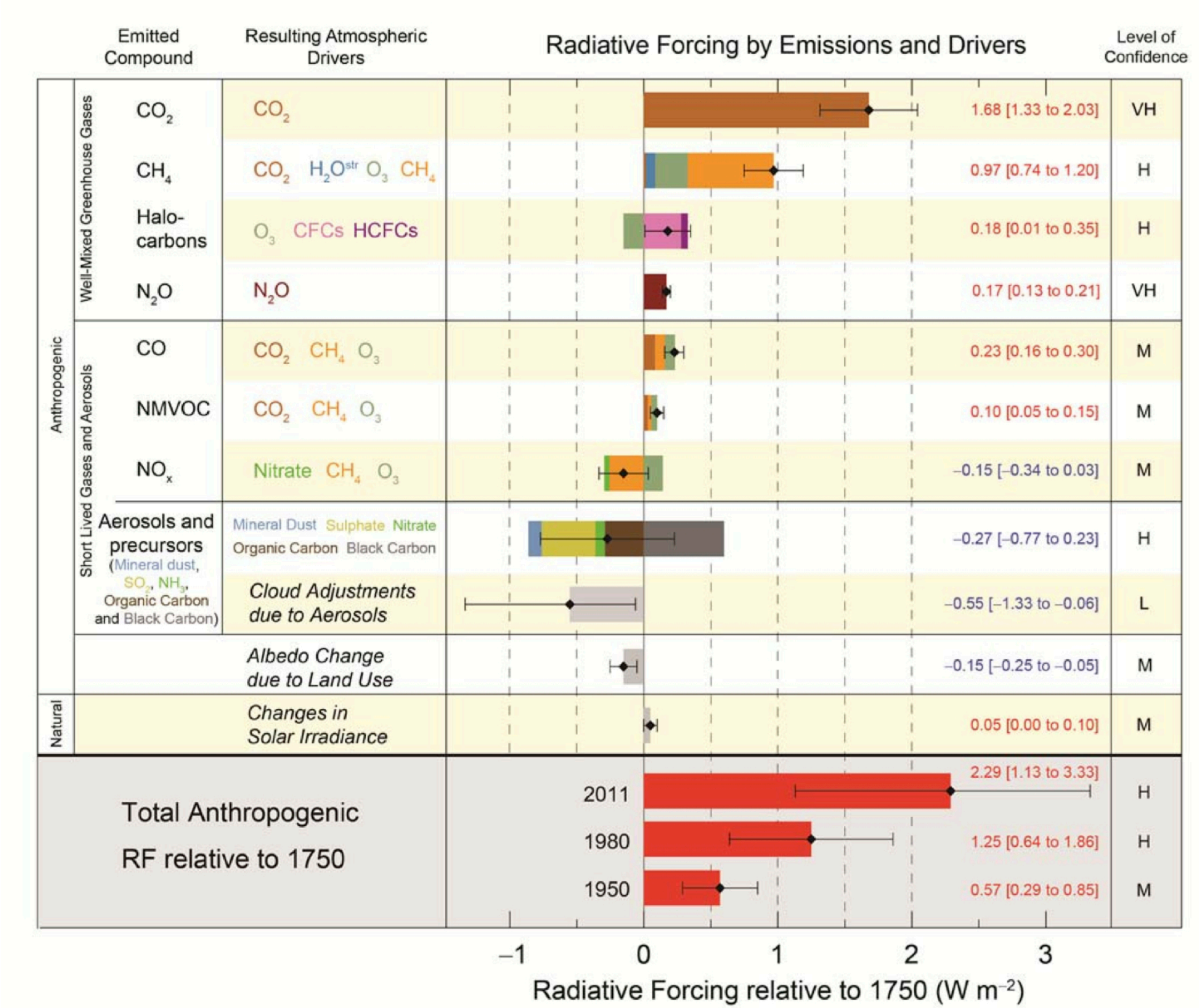
Effective radiative forcing - CMIP5 picture



- The radiative forcing can be used to estimate the resulting global temperature change via $\Delta F = \lambda \Delta T$

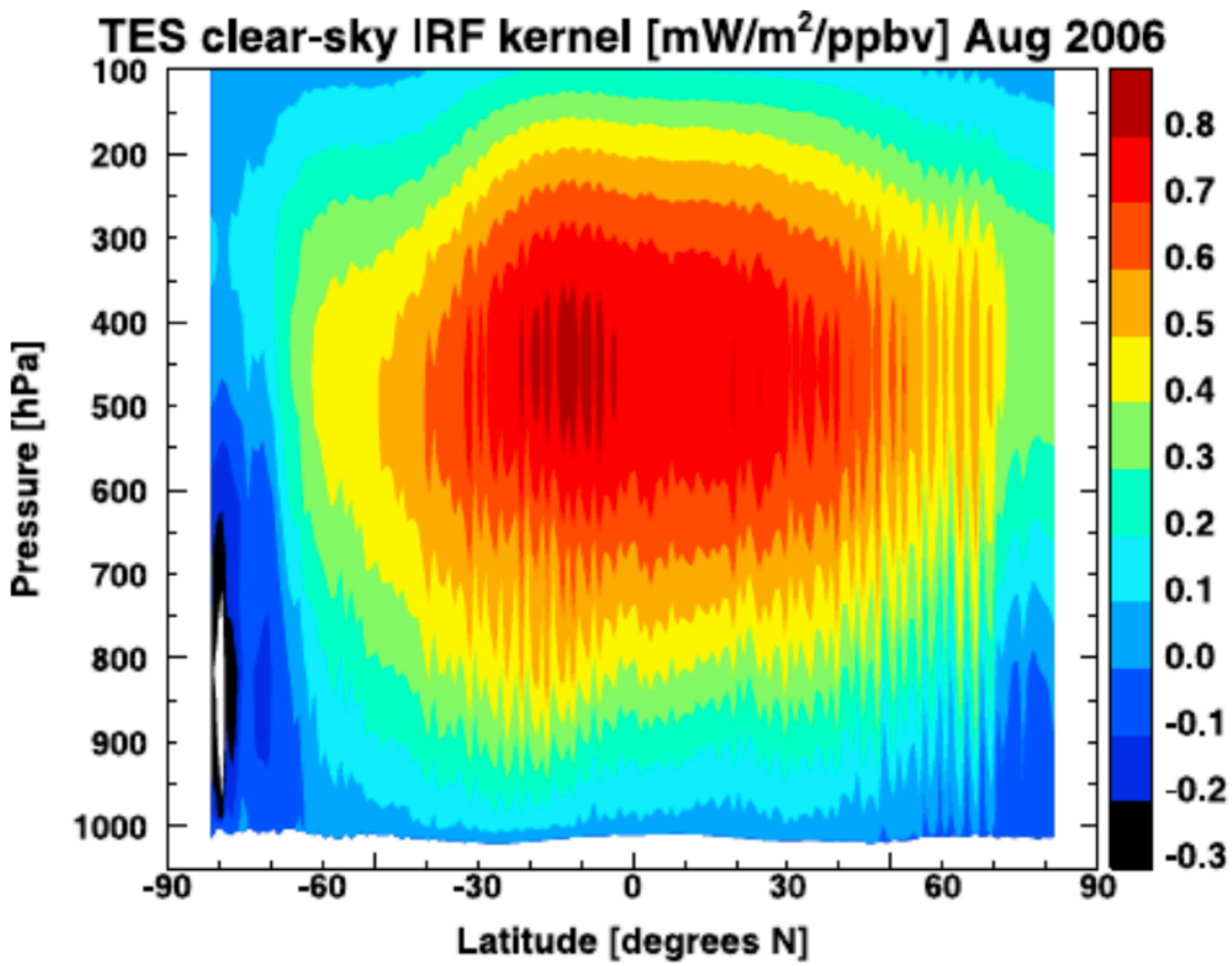
NTCF - CMIP6 picture

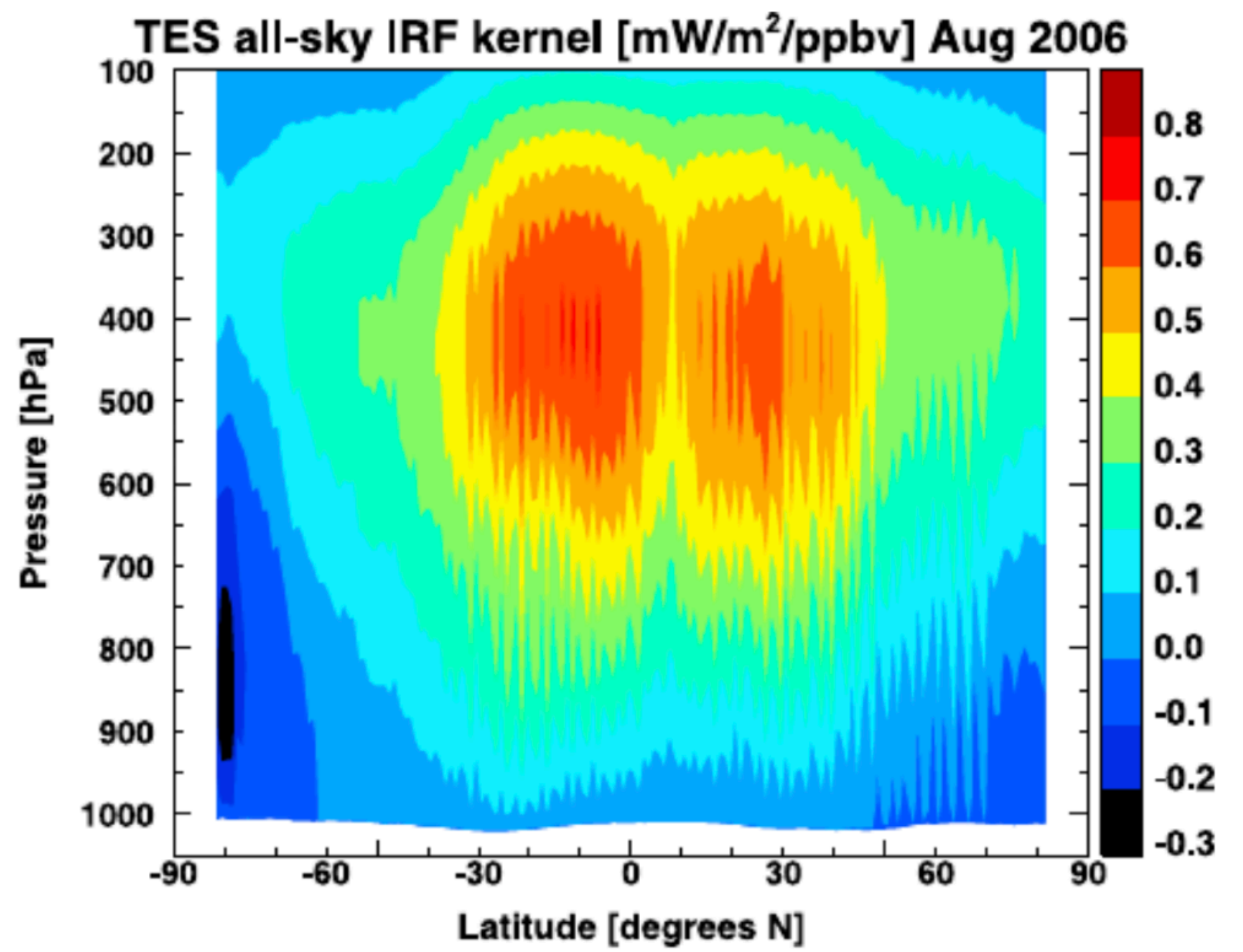
NTCF forcing

	From Allen et al. (2021)	O'Connor et al (2021)
Aerosols	$-0.9^{+0.5}_{-1.1}$	-1.09 ± 0.04
BC	+0.4 ± 0.35	+0.37 ± 0.03
O3	+0.4 ± 0.20	+0.21 ± 0.04 (VOC, CO,NOx)
CH4	+0.48 ± 0.05	+0.97 ± 0.04
SO2		-1.37 ± 0.04
OC		-0.22 ± 0.04
VOC		+0.33 ± 0.04
ODS		-0.18 ± 0.04
NTCF (BC,OC,SO2, VOC, NOX)		-1.03 ± 0.04

- Strong coupling between e.g. O3 and SO2 via CH4 (and hence OH)
    - makes designing an optimal NTCF mitigation strategy a challenge

Ozone IRF - depends on altitude





Aghedo et al. (2012), “Vertical distribution of ozone IRF from satellite…”

Ozone trends - Is there a problem?

- Parrish et al. point out that models:
  - overestimate absolute O3 mixing ratios, on average by ~5 to 17 ppbv in the year 2000
  - capture only ~50% of O3 changes observed over the past five to six decades, and little of observed seasonal differences
  - capture ~25 to 45% of the rate of change of the long-term changes.

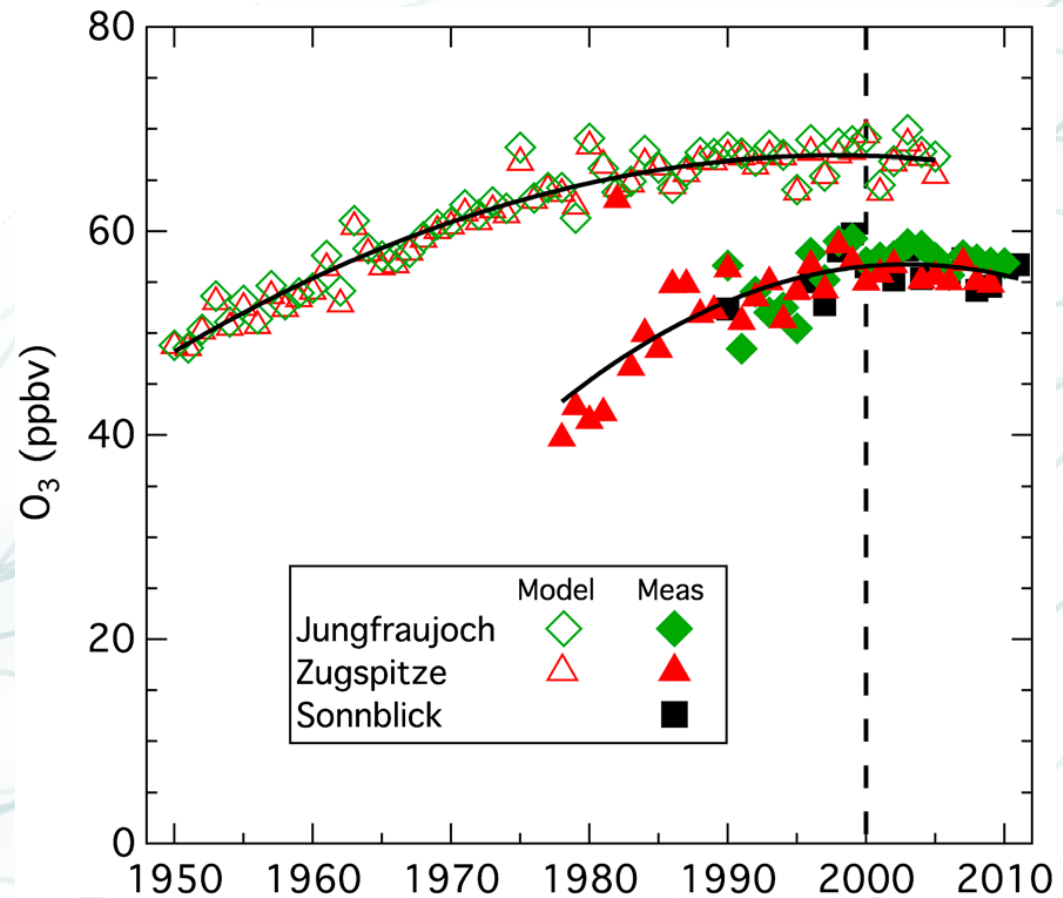


Figure 1. Seasonally averaged springtime (March, April, and May) O_3 concentrations at alpine sites in Europe. Closed and open symbols give measurements and GFDL CCM results, respectively. The solid lines give quadratic fits to respective results. The vertical dashed line indicates the year 2000 reference.

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Ozone trends - stratospheric contribution to variability?

- Lin, Cooper et al attribute much of the variability to circulation variability.
- High ozone events are linked to modes of climate variability.
- Profound influence of stratosphere on surface ozone

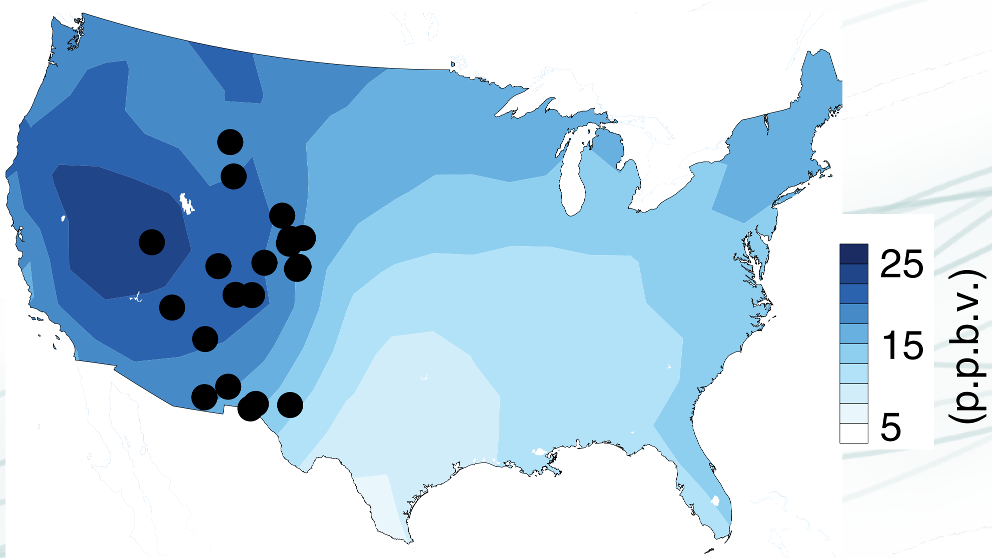

Figure 1 | Mean stratospheric contribution to US surface ozone during April–May. The 23-year climatology of O_3Strat from the model surface level is shown. Black filled circles denote locations of 22 surface ozone monitoring sites.

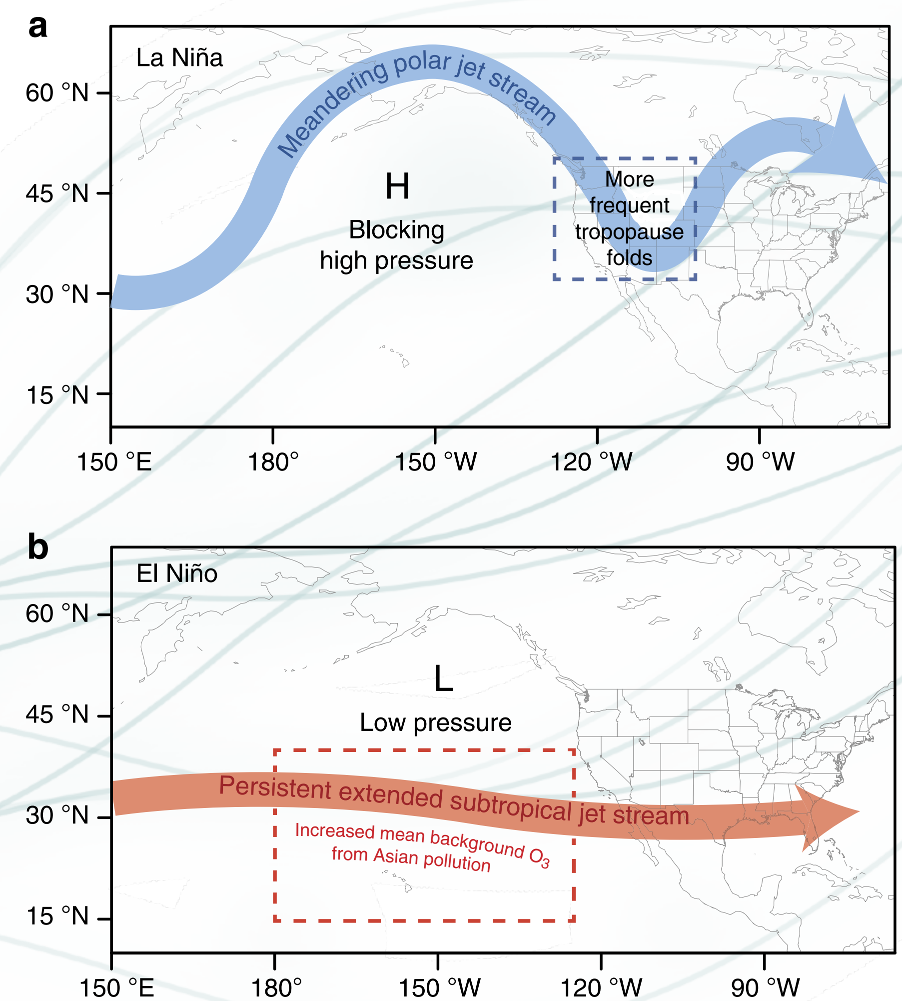

Figure 8 | Schematic for mid-latitude jet characteristics and sources of lower tropospheric ozone variability in winter extending into the spring months during strong La Niña versus El Niño events. The blue box in **a** denotes where frequent deep tropopause folds occur as a result of the meandering polar jet over the central WUS associated with La Niña. The red box in **b** indicates where mean background ozone increases due to more pollution transport from Asia as a result of the equatorward shift and eastward extension of the subtropical jet associated with El Niño. The figure is adapted from ref. 47.

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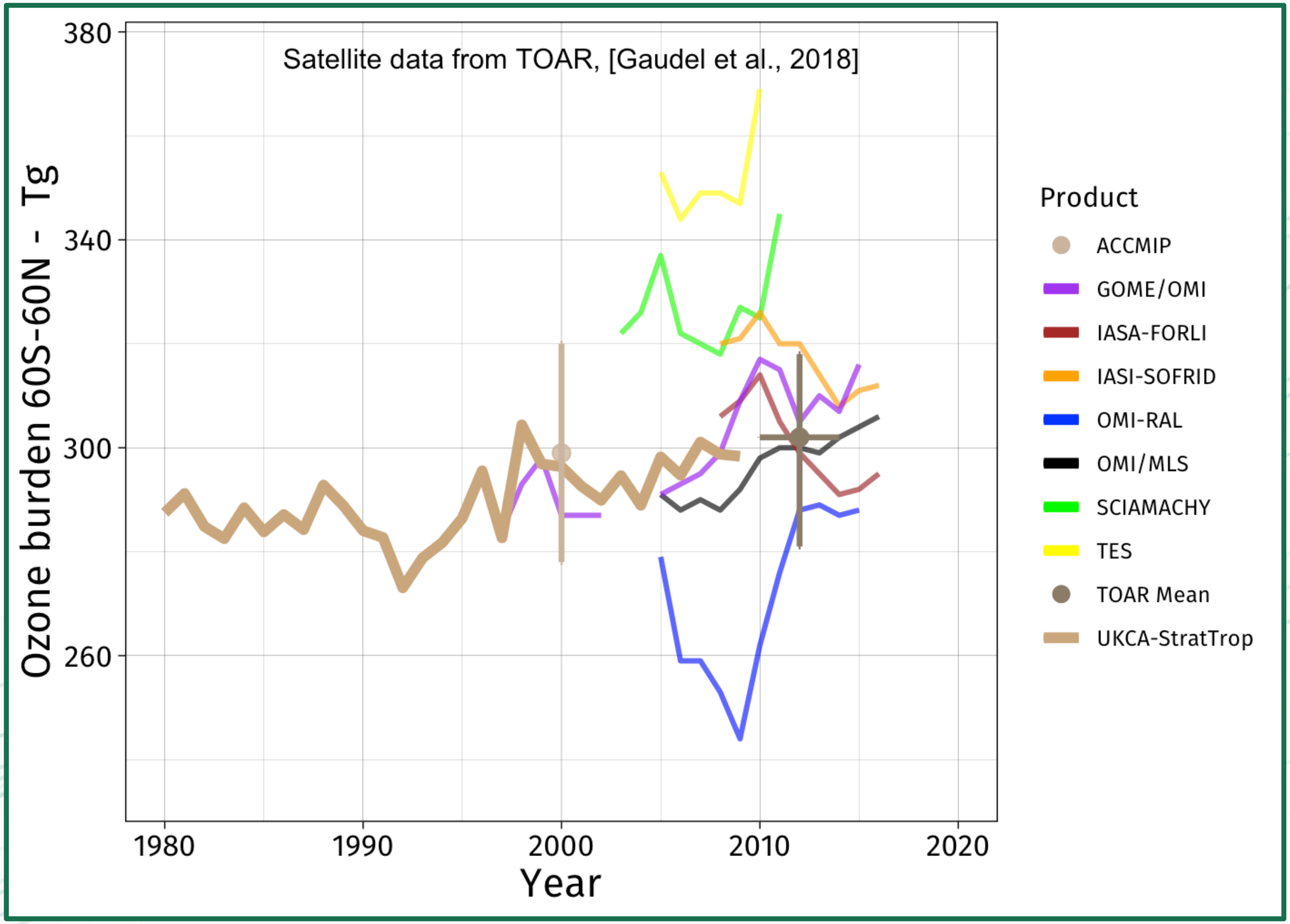
Evolution of ozone burden in CCMI



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Tropospheric ozone in CMIP6

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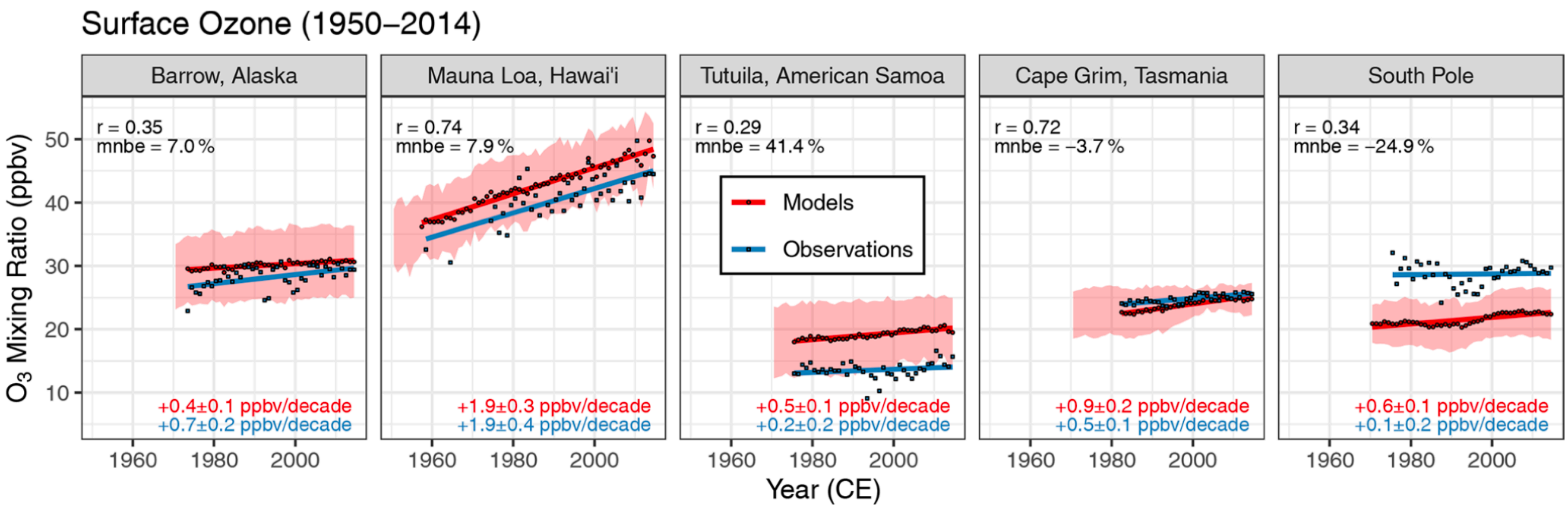
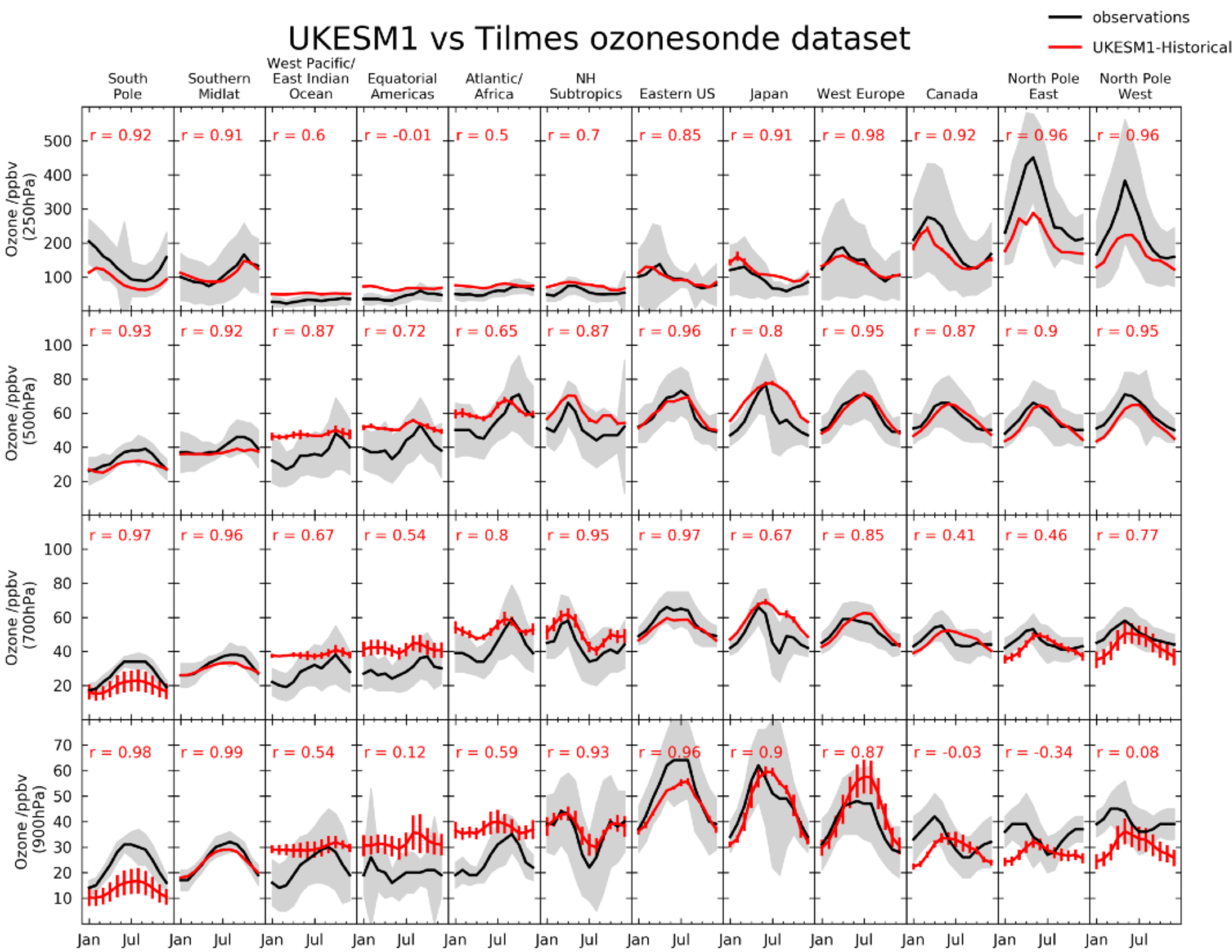
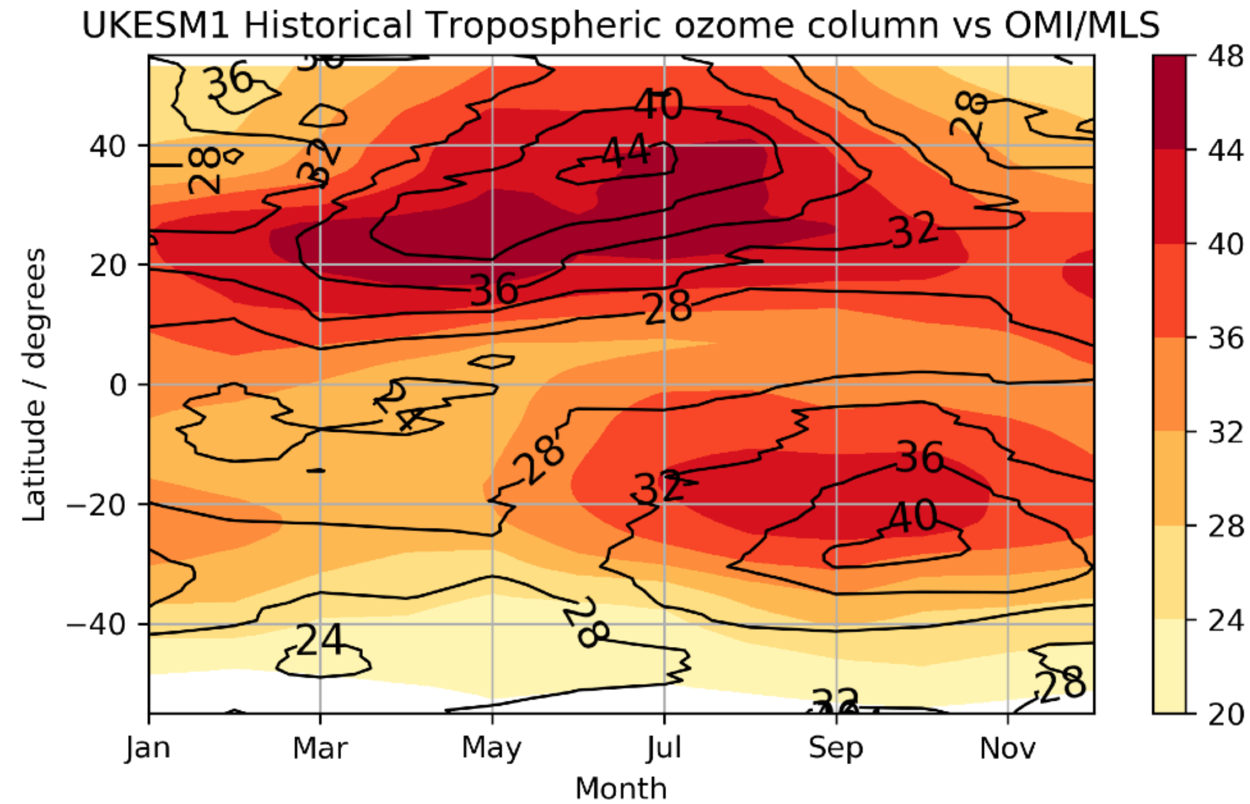
How does tropospheric ozone evolve in CMIP6? Comparison with obs

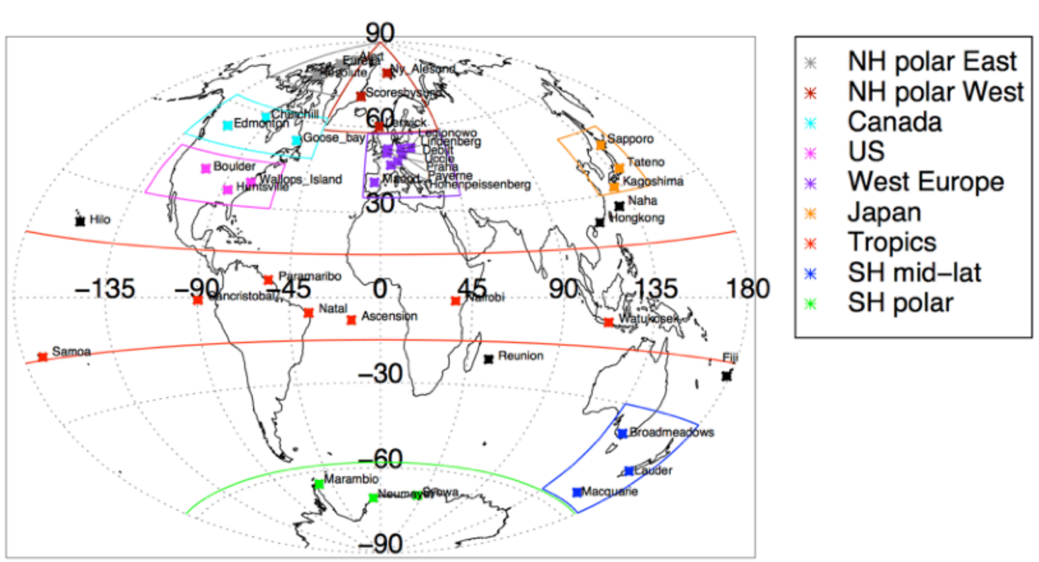


- Good agreement between models and observations for the remote sites studied here.
- Also nice agreement between in-situ ozone sonde measurements.
- Assessment using EO products more of a challenge - a role for ESMValTool?
- Aircraft data assessed in Paul Young’s TOAR report.
- Model deficiencies in simulating the seasonality of free-tropospheric ozone in equatorial America, Japan and northern high latitudes and near-surface ozone over northern and north-eastern Europe.

How does UKESM1 tropospheric ozone compare against observations?

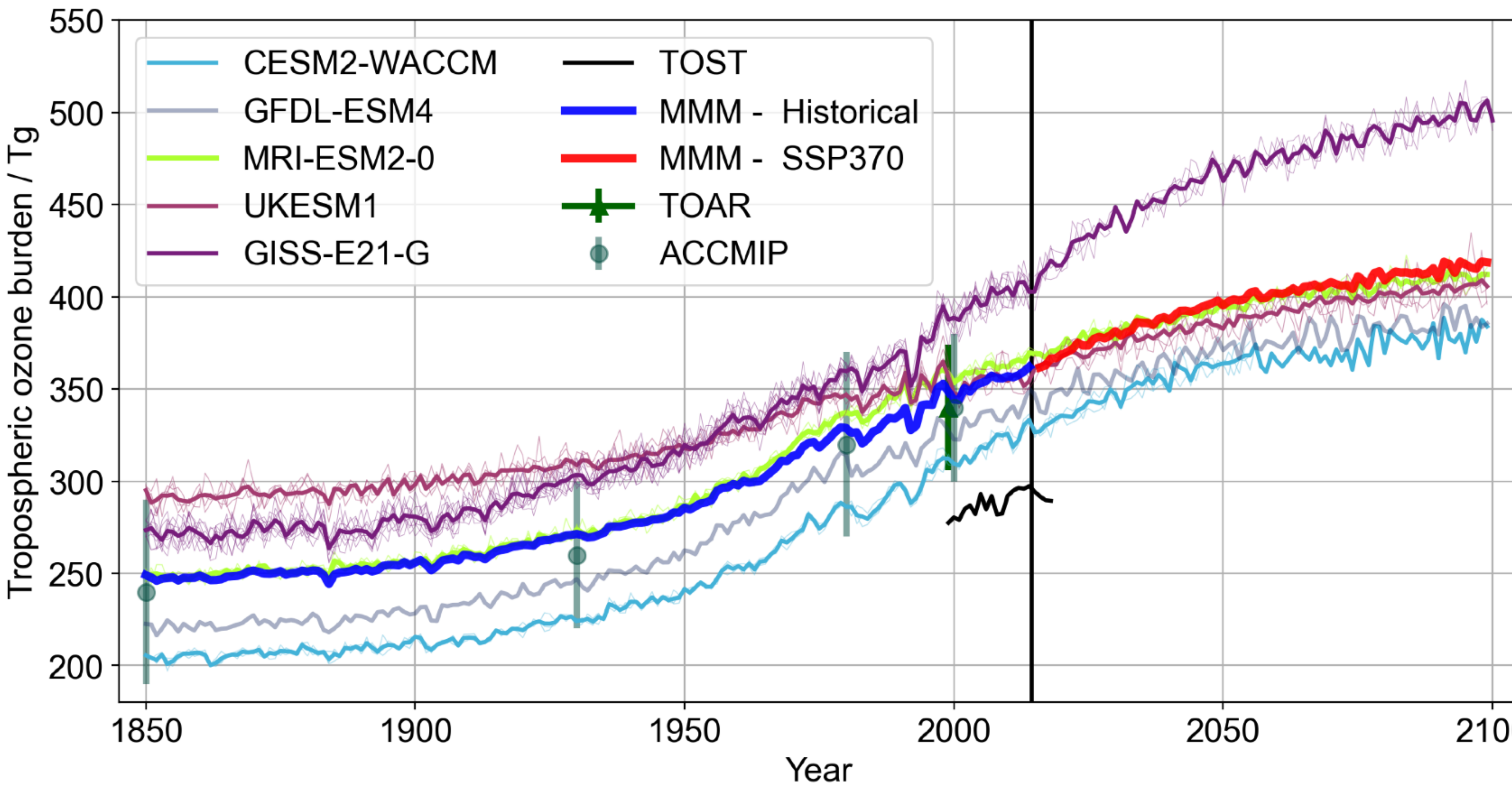






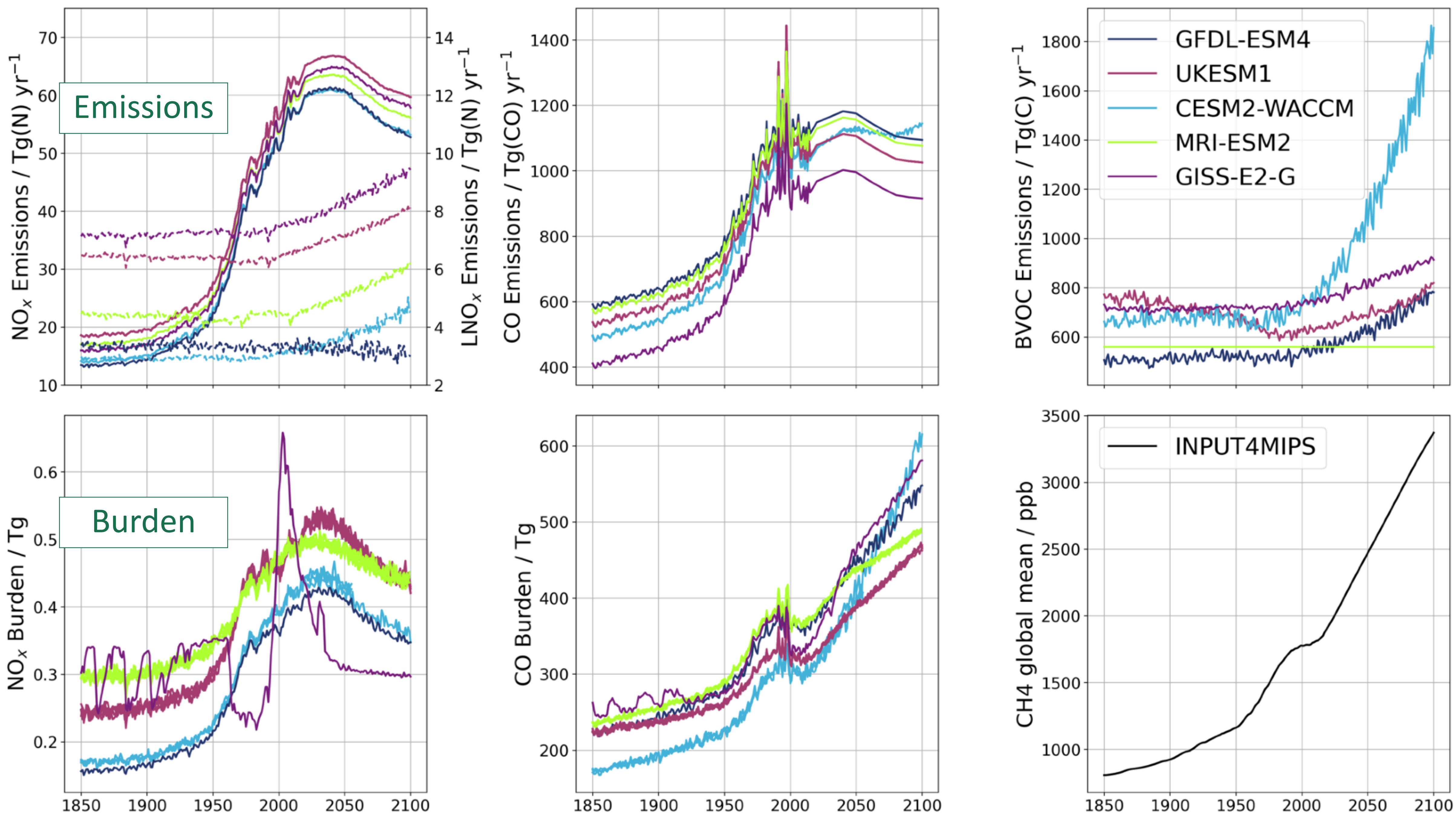
- UKCA tropospheric ozone compares well with observations, particularly in-situ measurements.
- Integrated quantities, such as column amounts, sensitive to tropopause definition.

How does UKESM1 tropospheric ozone evolve in CMIP6?



- Analysis so far has focused on CMIP Historical and ScenarioMIP SSP3-70 experiments, for which suitable diagnostic output was available.
- Picture has changed little since CMIP5/CCMI, MM range is also similar.
- Ozone burden increased by about 40% from 1850 levels of 240 Tg (MMM) with steepest rate of increase around 1960.
- In SSP3-70, the rate of growth of the burden declines further, as NOx emissions start to fall along this pathway after 2050.
- Nevertheless, strong local changes in ozone seen regionally at the end of the century.

What drives UKESM1 tropospheric ozone in CMIP6?



- Decline in precursor emissions in SSP3-70 experiments but steady increase in ozone burden - Strat O3 recovery increasing role + LiNOx

How does tropospheric ozone burden evolve in CMIP6?

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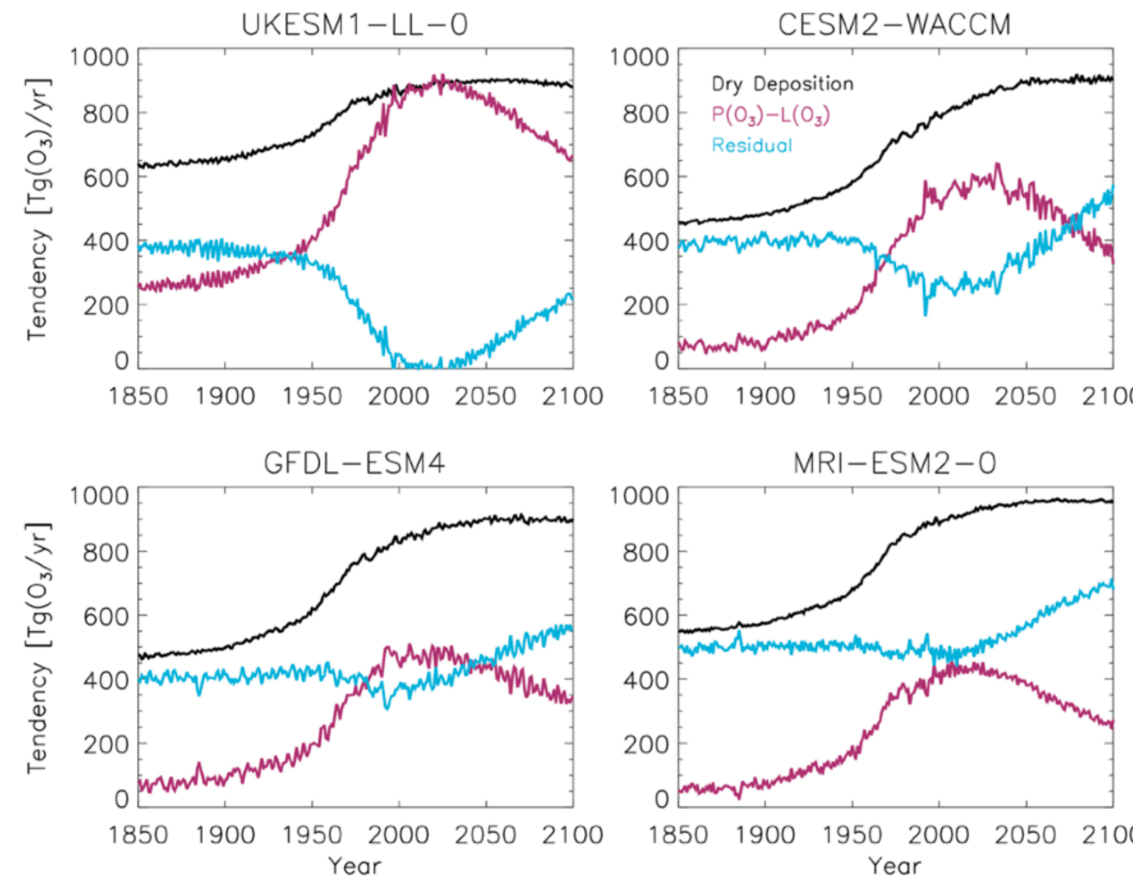
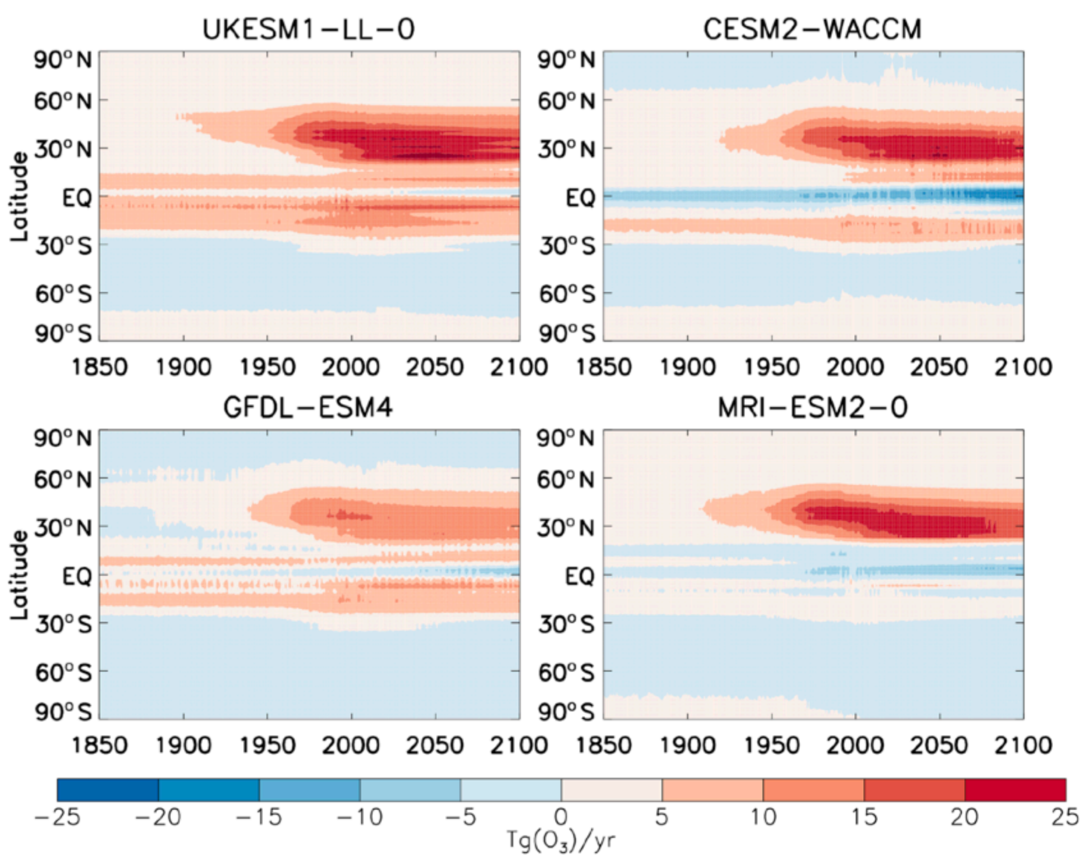
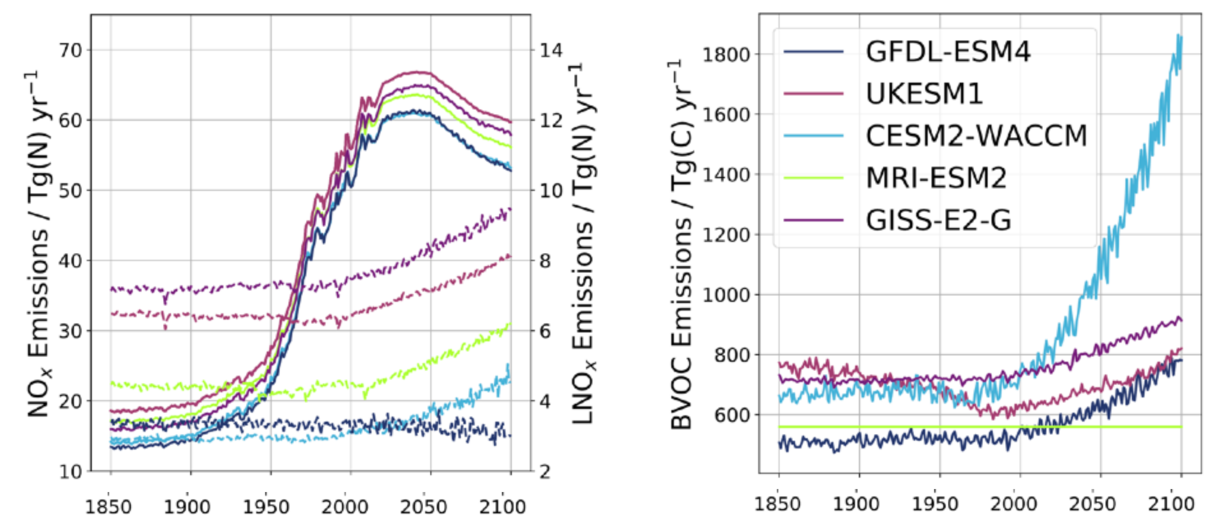
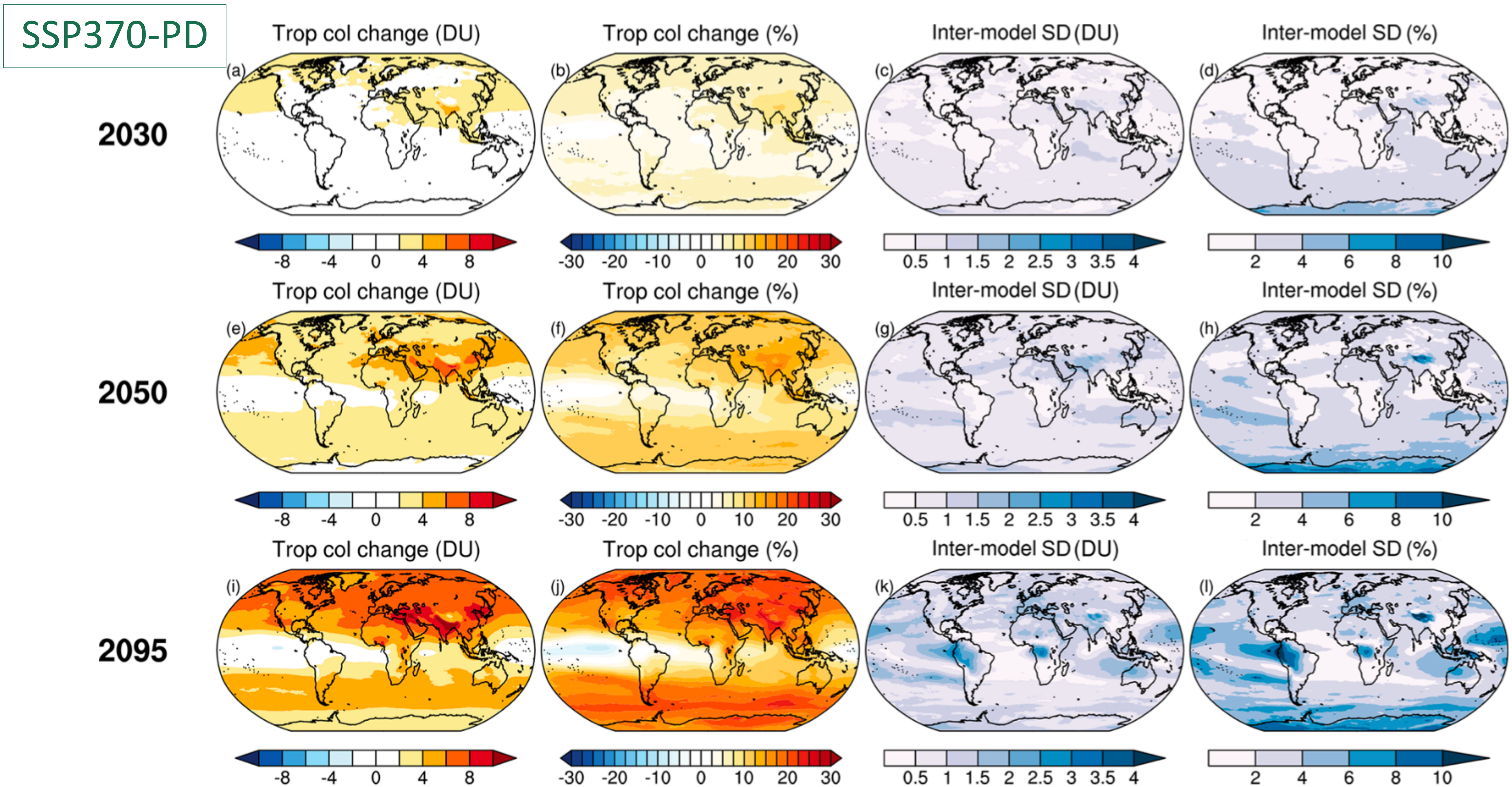




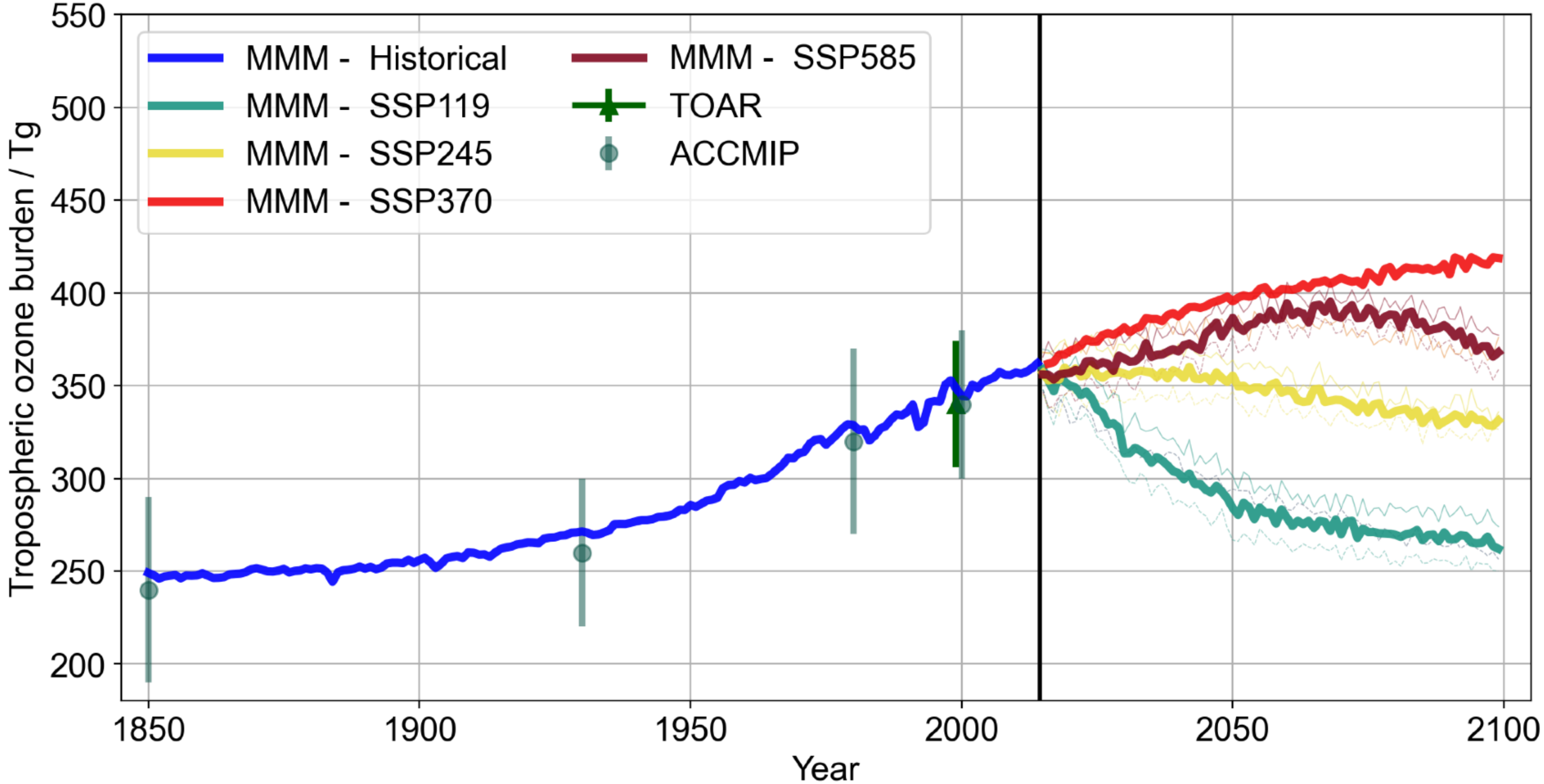


Tropospheric ozone precursor emissions

How does tropospheric ozone burden evolve in CMIP6?



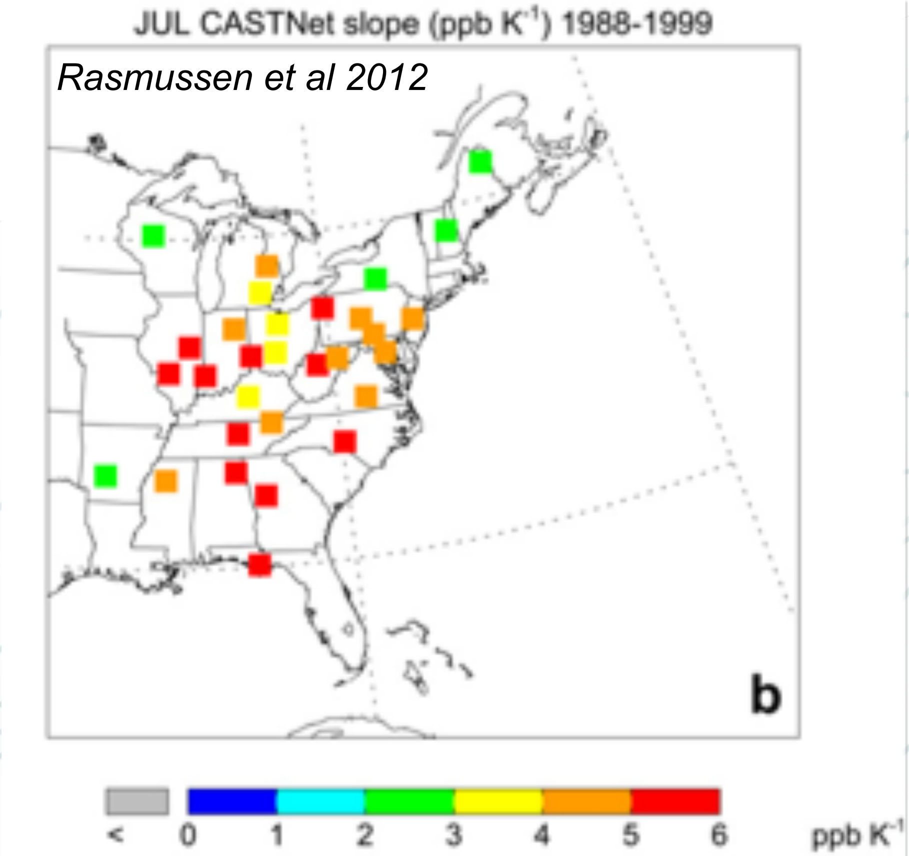
Attribution of tropospheric ozone burden changes



Models with online whole-atmosphere chemistry featured in CMIP6 with data on BADC as of 2021-12-04								
Model	**SSP119**	**SSP126**	**SSP245**	**SSP370**	**SSP434**	**SSP460**	**SSP534**	**SSP585**
UKESM1-0-LL								
CESM2-WACCM								
MRI-ESM2-0								
GFDL-ESM4								
GISS-ES2-1-G								

What drives future behaviour of ozone?

Process	$\Delta[O_3]$ under warmer conditions	Confidence?
Tropospheric water vapour	**Decrease**	High
Methane oxidation	**Increase**	High
Ozone transport from Stratosphere	**Increase**	Medium
Regional stagnation	Increase	Medium
Heatwaves	Increase	Medium
Wildfires	Increase	Medium
Soil NOx	Increase	Medium
Dry deposition	***Decrease***	Low
Non-methane BVOC changes	Increase	Low
NOx from lightning	**Increase**	Low
Chemical production	**Increase**	Low



- $[H_2O]\uparrow$ $[O_3]\downarrow$
- Stagnant air means less mixing and $[O_3]\uparrow$
- Methane acts as fuel for $[O_3]\uparrow$

Alex Archibald, After Fu and Tian 2019

Summary

- Tropospheric ozone is controlled by chemical production and destruction, physical deposition and transport from above into the troposphere.
- Looking at CMIP6 data, we see important roles for methane, NOx (particularly LNOx) and changing land-use (modifying deposition).
- Stratospheric ozone recovery is increasingly important to tropospheric ozone burdens in the later 21st Century.
- There are indications that this may couple to other aspects of the climate system via e.g. ozone RF, modification of cloud albedo, secondary organic aerosol and ecosystem function.
- Ozone burden is sensitive to the SSP and therefore to future emissions. Ozone also has impacts on other aspects of RF via e.g. methane sinks, secondary aerosol formation.

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Thank you

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