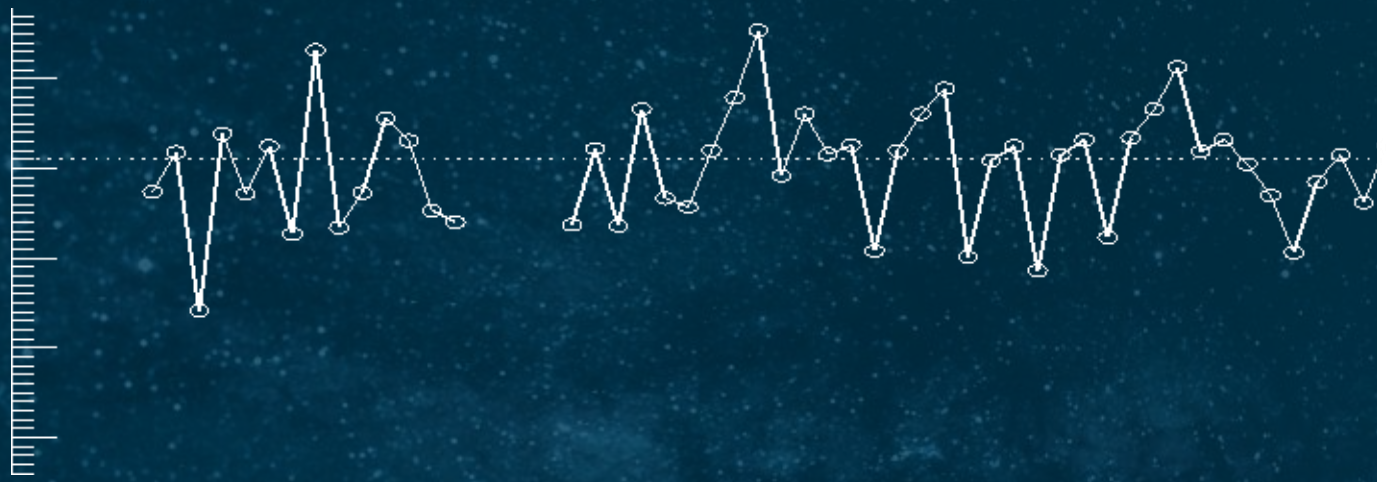

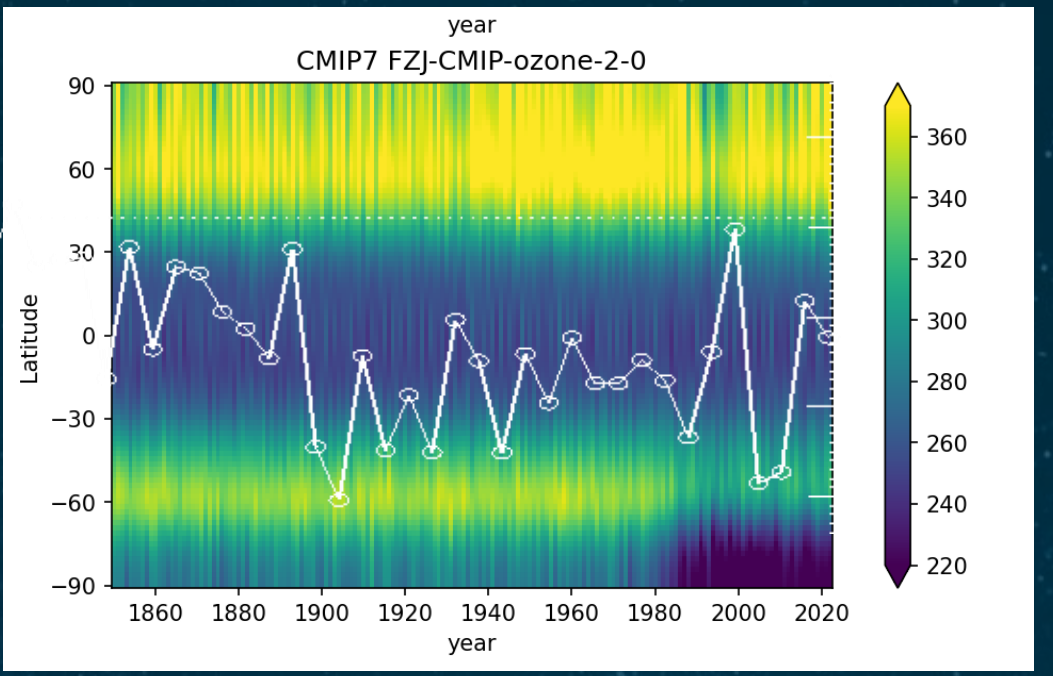

CMIP O3 FORCING

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24/03/2026

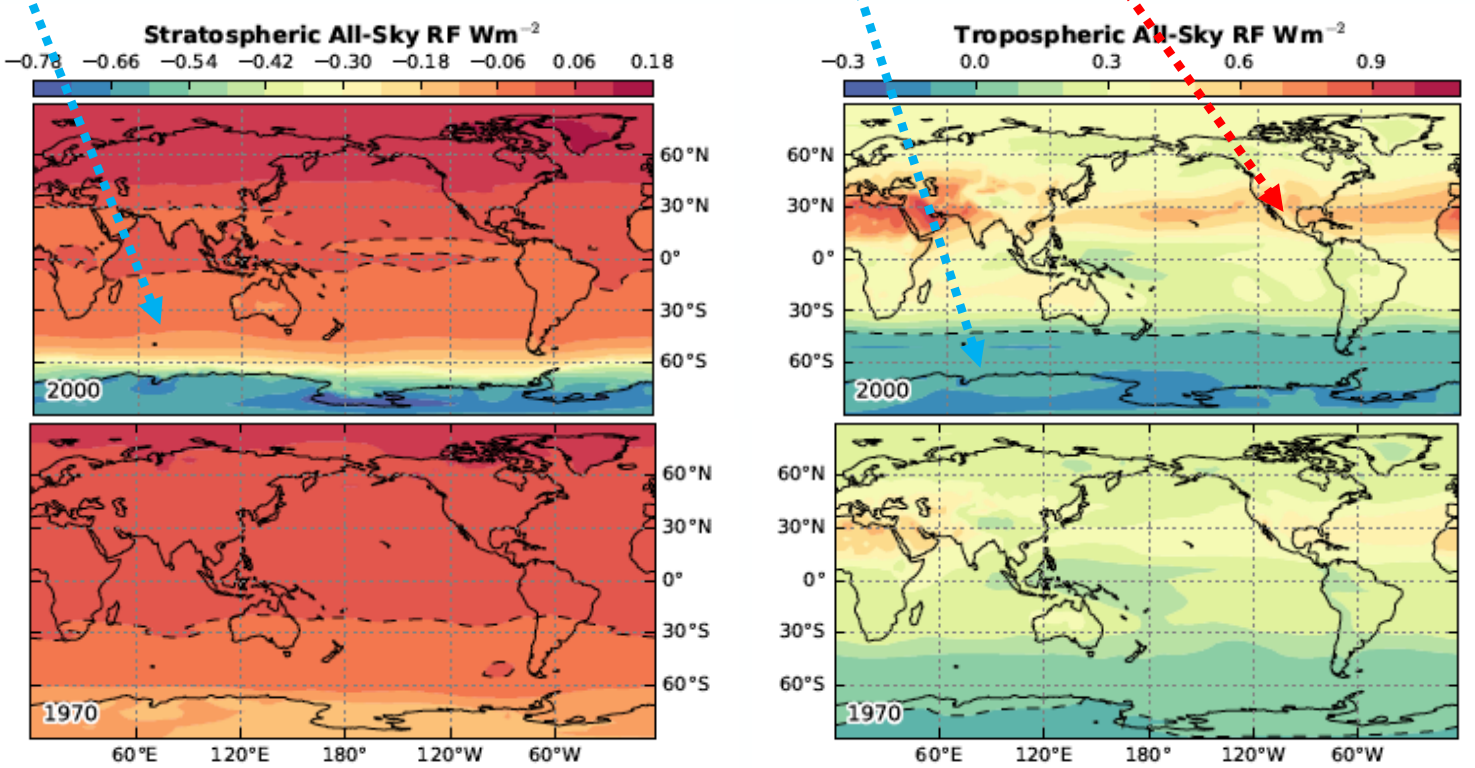
PROJECT OBJECTIVES

- **ITT project resulted from:** CMIP forcings (via CMIP forcings task team).
- **Timeframe:** May 2024 – May 2026
- **Goals of project:**
  - **Create** a robust ozone forcing for CMIP climate models that do not include interactive chemistry so to ensure that they accurately simulate real-world conditions and climate responses to the forcing.
  - Ozone forcing should be fully consistent with **external factors** (volcanoes, solar, anthropogenic emissions, land-use change) and **internal** (e.g., SSTs) that influence the climate system.
  - **Create** documentation to provide user guidelines.
- **Connections with wider community and policy activities:** Support of CMIP and ultimately IPCC AR7.

MOTIVATION

OZONE CHANGES DRIVE RADIATIVE FORCING

- **Stratospheric ozone depletion** caused pronounced negative radiative forcing in the SH.
- Effect of ozone depletion also seen in SH tropospheric ozone (less ozone STE, see *Williams et al ACP 2019*).
- **Tropospheric ozone increases** led to positive RF in the subtropics, especially in the NH.



Note the different scales used in the left and right panels!

Dashed denotes RF zero line.

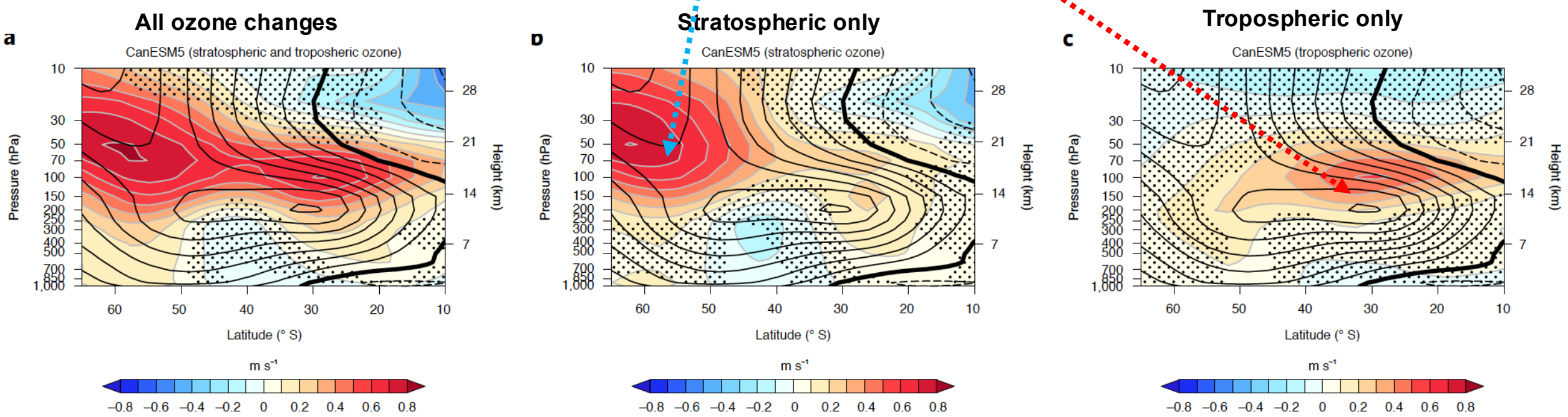
Checa-Garcia, Hegglin, et al., GRL 2018

MOTIVATION

OZONE CHANGES DRIVE RESPONSE IN SH CIRCULATION

Liu, Hegglin et al., *Nature Climate Change* 2022

- The regional differences in ozone changes drive distinct responses in zonal mean winds (1950-2014).
  - → **Stratospheric ozone changes** led to a strengthening of the SH polar vortex.
  - → **Tropospheric ozone changes** led to a strengthening and upward/equatorward shift of the subtropical jet.



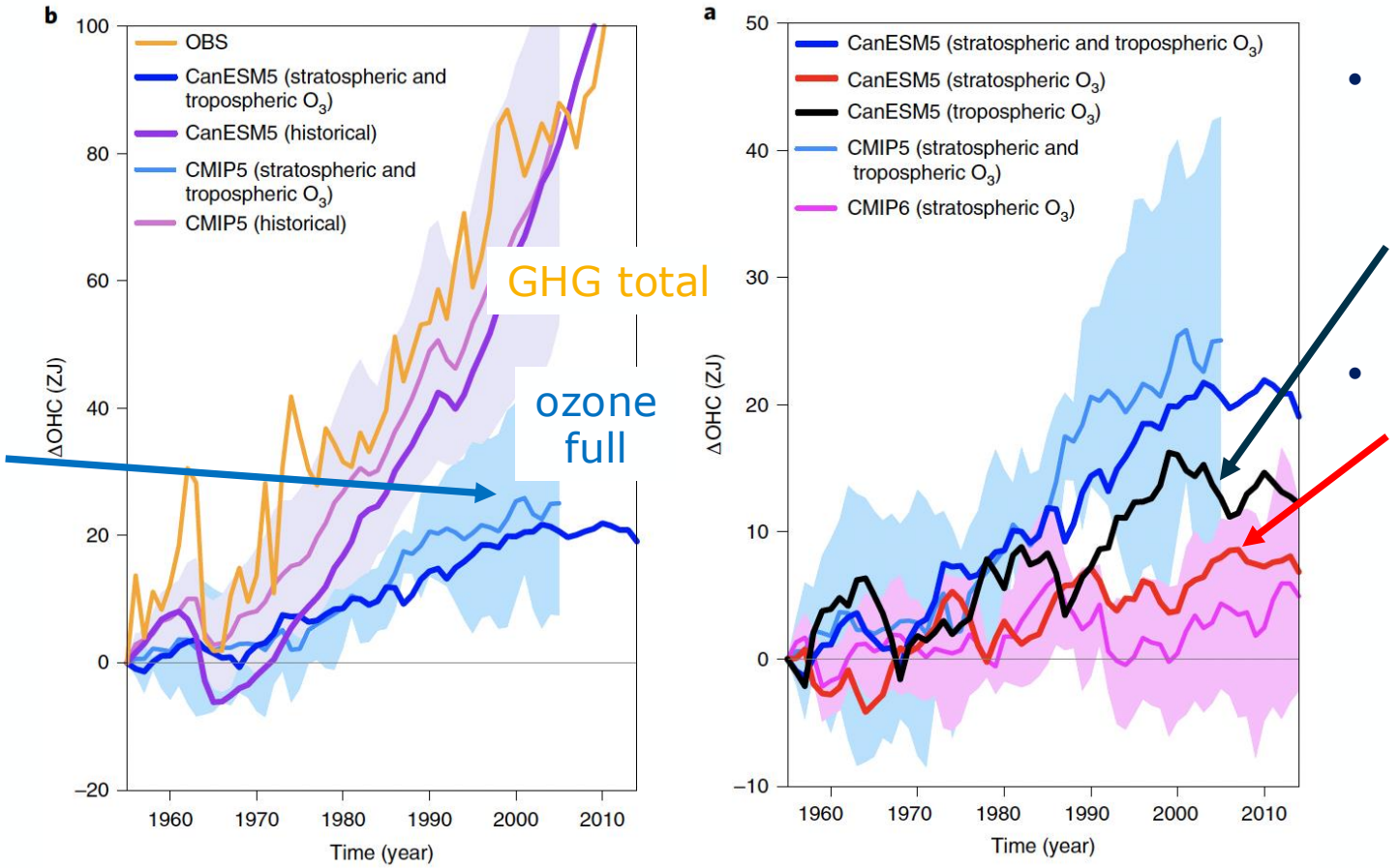
MOTIVATION

EVEN AFFECTING THE OCEAN …

Liu, Hegglin et al., *Nature Climate Change* 2022

→ Changes in atmospheric circulation impact ocean heat uptake!

- The ozone changes between 1955 and 2000 induced **about 30%** of the net simulated ocean heat content **(OHC)** increase in the upper 2,000 m of the Southern Ocean.

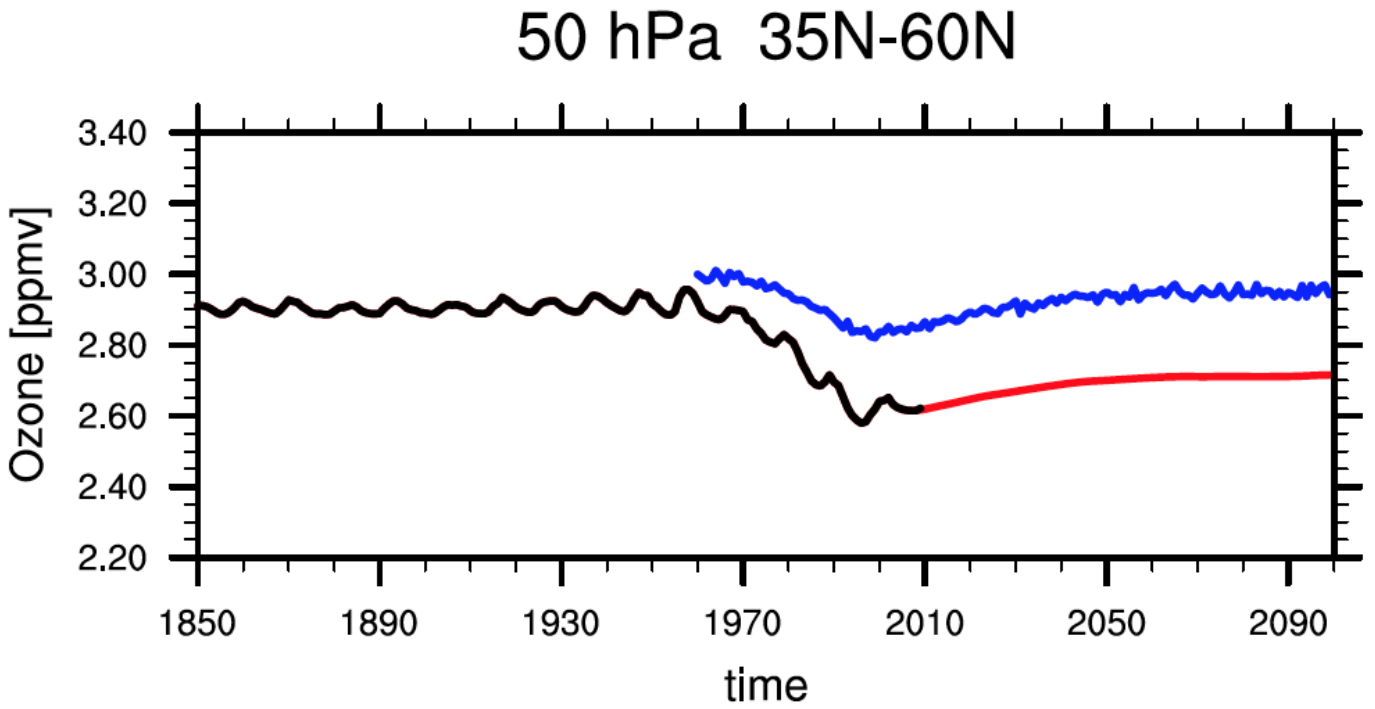


- Around **60%** of these changes are attributed to **tropospheric** ozone increases …
- … and **40%** to **stratospheric** ozone depletion.

CMIP5 OZONE FORCING DATABASE

LEARNING FROM PAST EXPERIENCE

- **First heroic effort:** The IGAC/SPARC ozone database by *Cionni et al.* (2011).
- Featured **combination of observations** with ozone fields merged from a model with tropospheric and a model with stratospheric chemistry only.
- The past was reconstructed using an **MLR approach** **(ATTENTION PLEASE!!!)**



- Merging approach with observations led to unphysical behaviour!

→ **No ozone** recovery in the NH!

METHODOLOGY

CMIP7 OZONE FORCING DATABASE

- Merged ozone fields from three state-of-the-art chemistry-climate models:
  - CESM1-WACCM, EMAC-MESSy and CMAM (see *Morgenstern, Hegglin et al., ACP 2017*).
  - Input forcings are all from CMIP7.
  - Produced with full stratosphere-troposphere chemistry.
  - Global 3D fields (also in stratosphere in contrast to CMIP5, exception mesosphere).
  - Monthly mean fields.
  - Pecularity: includes nudging to observed QBO.
  - 96x144 latitude x longitude / 66 levels (1000 to 0.0001 hPa)

- Time periods covered
  - Pre-industrial control simulation.
  - Historical forcing (1850-2022)
  - Future scenarios (2023-2100) (currently done vl and h-scenarios, a couple more to come)

Datasets accessible via ESGF Input4MIPs: https://pcmdi.llnl.gov/search/input4mips/

OBSERVATIONS

EXTENSIVELY USED FOR VALIDATION

- Observations from the **Ozone_cci** (primarily the nadir ozone profiles for the troposphere (IASI/GOP-ECV) (e.g., Coldewey-Egbers et al., 2022) and total column ozone, MSR)

Product name	Type	More information	Contact	Time resolution	Time coverage	Horizontal resolution (lat x lon)	Horizontal coverage	Vertical resolution	Vertical coverage
GTO-ECV	Total ozone column	observations	DLR / BIRA	monthly	1995 - now	1 x 1	global	n/a	total column
MSR	Total ozone column	assimilation of observations	KNMI	monthly	1960 - now	0.5 x 0.5	global	n/a	total column
GTTO-ECV	Tropospheric ozone column (CCD)	observations	DLR / BIRA	monthly	1995 - now	1 x 1	20S - 20N	n/a	sfc - 270 hPa
GTO-LIMB	Tropospheric ozone column (LNM)	observations	FMI / DLR	monthly	2002 - now	1 x 1	global	n/a	sfc - (thermal tropopause - 3 km)
SAGE-CCI-OMPS+	Limb ozone profile	observations	FMI	monthly	1984 - now	10 x 360	global	1-2 km	10-50 km
MEGRIDOP	Gridded limb ozone profile	observations	FMI	monthly	2001 - now	10 x 20	global	1-2 km	10-50 km
LIMB-HIRES	Gridded limb ozone profile	combination of observations & model	FMI	monthly	2001 - now	1 x 1	global	1-2 km	900 - 0.02 hPa
GOP-ECV	Nadir ozone profile (UVVIS sensors)	observations	DLR / RAL	monthly	1995 - now	1 x 1	global	10-15 km	sfc - 80 km
IASI	Nadir ozone profile (IR sensors)	observations	ULB	monthly	2008 - now	1 x 1	global	10-15 km	sfc - 40 km

- Observations from the SPARC Data Initiative, which are currently being merged within the **WV_cci** to a new CDR for the stratosphere spanning 1978-2023 (Hegglin et al., 2021)
- ECMWF CAMS, a chemical reanalysis with assimilated satellite observations including short-lived ozone precursors such as NO_2 (Inness et al., 2019).
- In-situ (balloon-measurements from the World Ozone and Ultraviolet Radiation Cata Center, WOUDC) (https://climate.esa.int/en/projects/ozone/about/)
- Ground-based in-situ measurements (particularly over China, a highly polluted region of the world) for the troposphere

RESULTS

ZONAL MEAN CROSS SECTION O_3 ESA CCI / SPARC DATA INITIATIVE

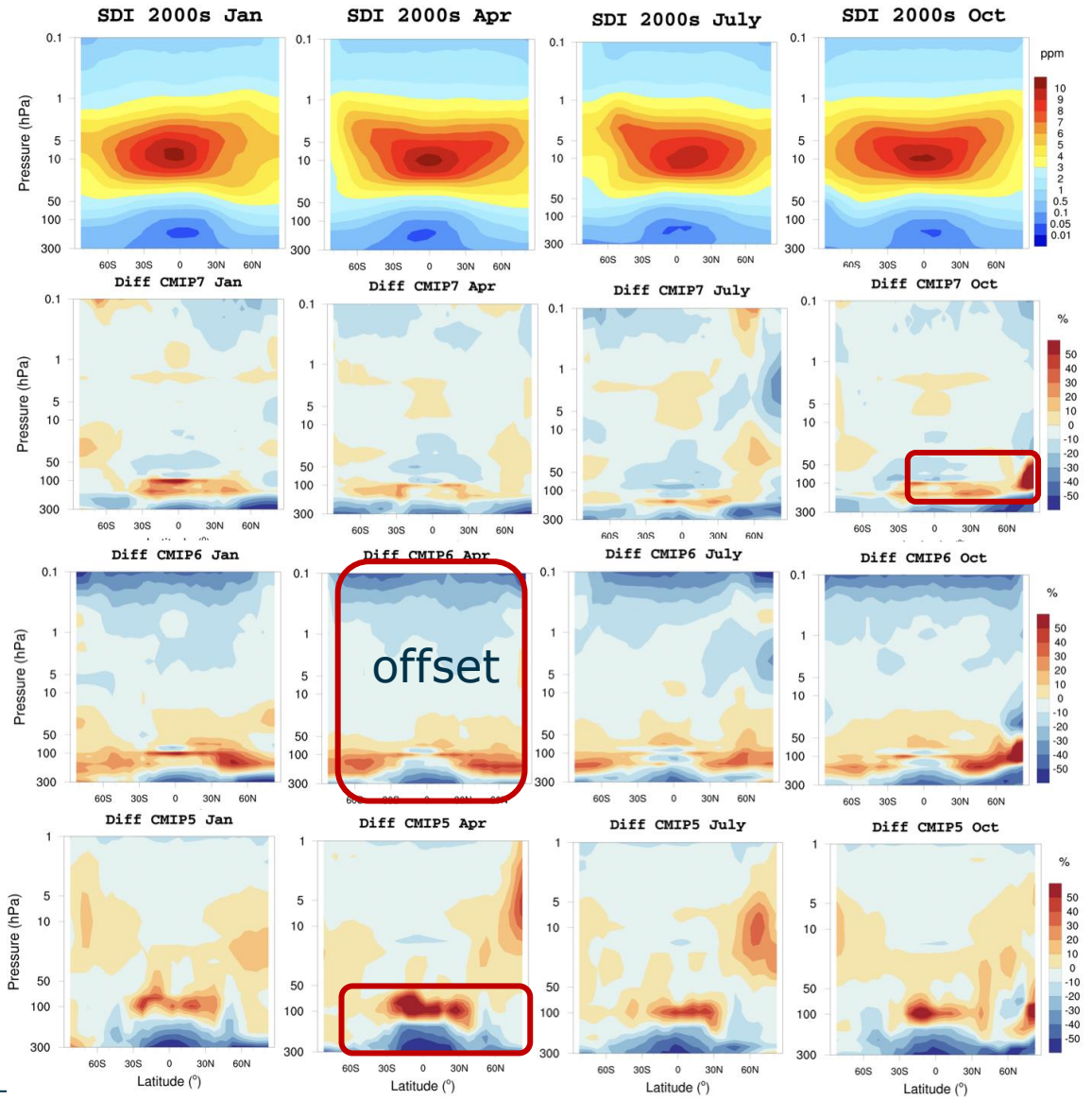
- **CMIP5** has strong biases at the interface between troposphere and stratosphere.
- **CMIP6** better, but now shows strong positive biases in the lowermost stratosphere.
- **CMIP7** even better, with smaller biases across the whole lowermost stratosphere region.
- Here comparison to SDI data.

SDI

CMIP7

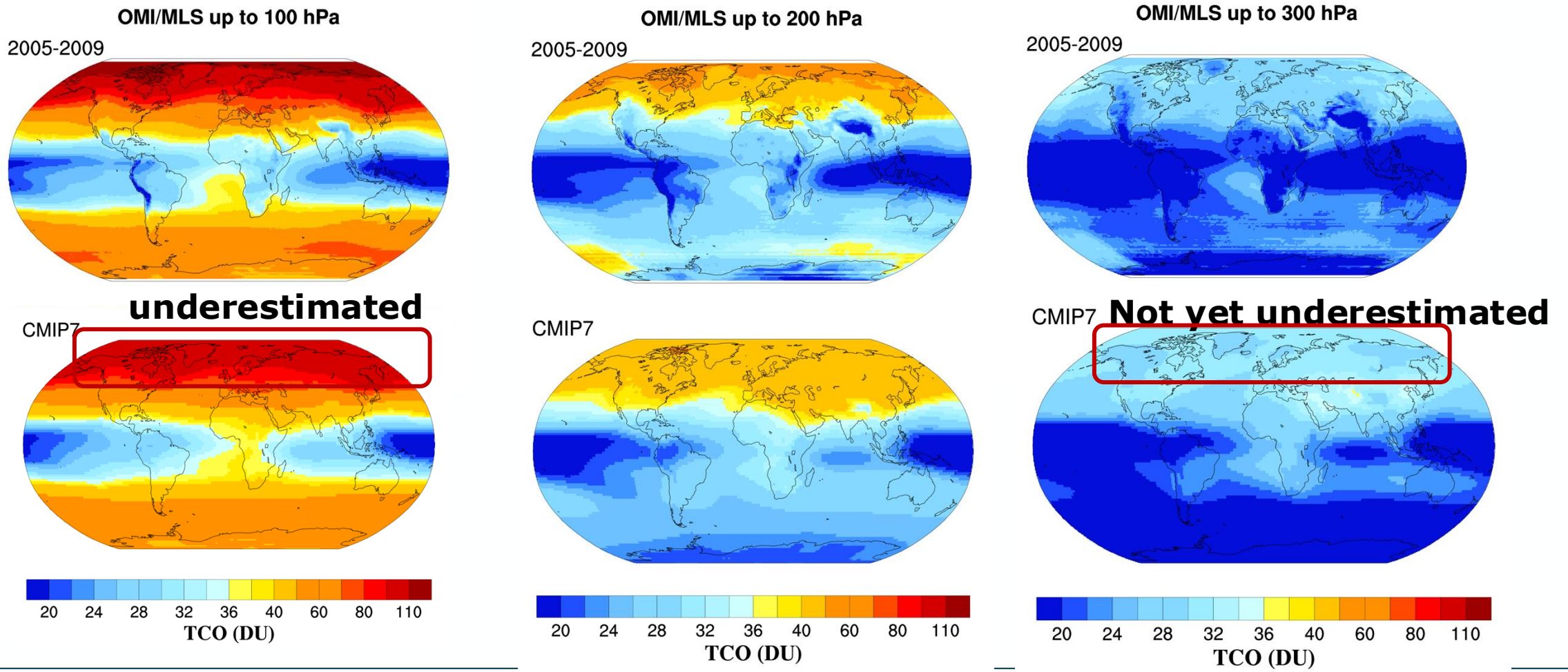
CMIP6

CMIP5



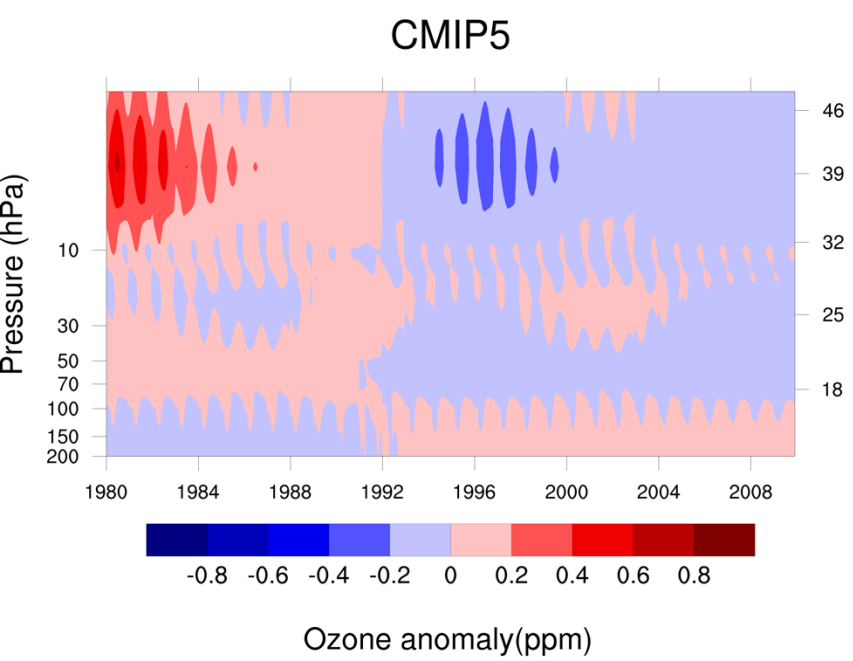
RESULTS
PARTIAL OZONE COLUMN

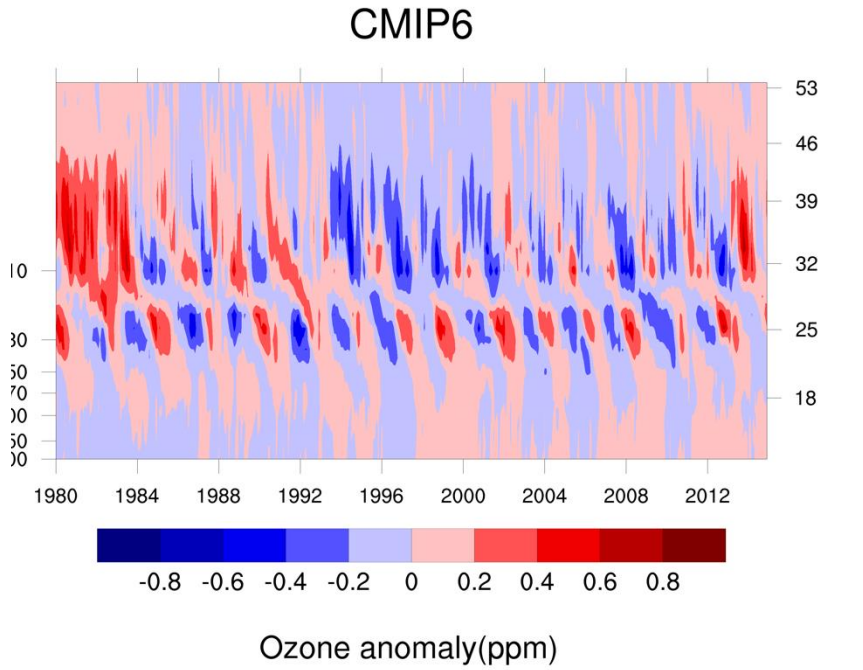
- Partial column ozone in troposphere with good agreement with OMI/MLS up to 200 hPa.
- Underestimation though in lowermost stratosphere. Problem (likely) remedied in v2.0.

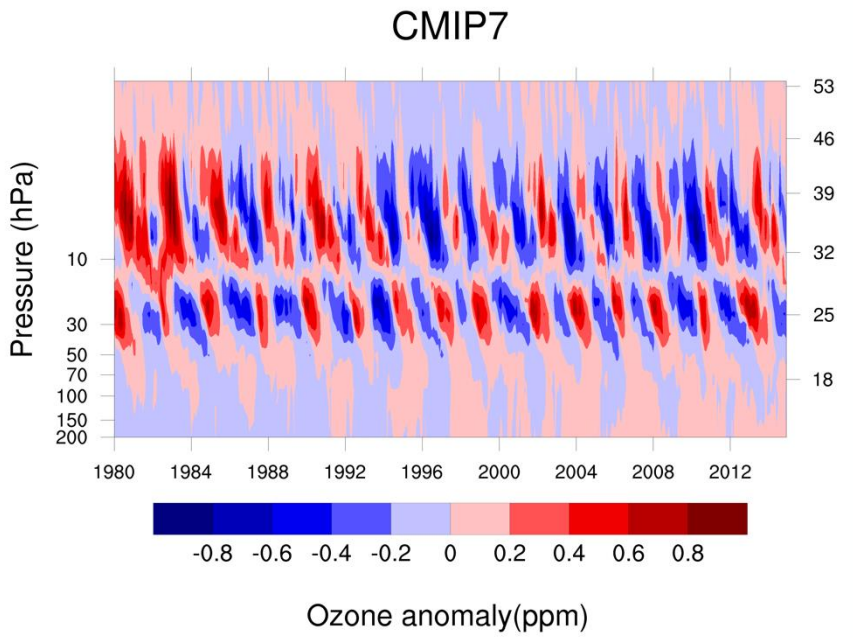


RESULTS
QBO

- **CMIP5** has only some indications of a QBO.
- **CMIP6** better, but still not very regularly and somewhat too weak a signal.
- **CMIP7** even better, with realistic QBO feature.



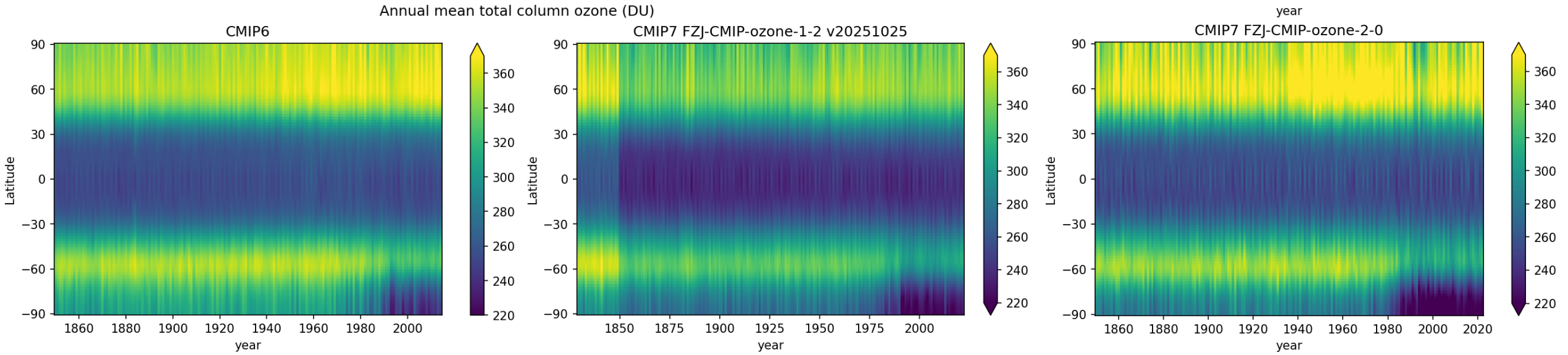




RESULTS

TOTAL COLUMN OZONE

- Total column ozone revealed discontinuity between CMIP7 v1.2 PI and historical forcing
- Problem remedied in v2.0



RELEVANCE TO COMMUNITY

IS FASTER BETTER?

- The importance of ozone forcing in climate modelling is well established.
- However, generating these forcings remains computationally expensive (~3–4 years of simulation per day).
- Since we are downstream of the production line, any delay in any input forcing will affect the delivery of the ozone forcing.
- Problems show up all the time.
- Emulation is being considered for CMIP8 (Horizon EU project) and could potentially make production much faster — but can it deliver sufficient accuracy and reliability?
- Stay tuned.