The role of the stratosphere in the Earth-climate system

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Outline

- Short introduction of chemistry-climate interaction
  - Definition and importance of Chemistry-Climate Model (CCM)
  - Current strategy of CCM simulations (SPARC/IGAC CCMI)
- Some new results with respect to
  - Stratospheric ozone: past, present and future
  - Stratosphere-troposphere connection
  - Stratospheric water vapour: fluctuations and trends
- Concluding remarks

Climate-Chemistry-feedbacks in the stratosphere

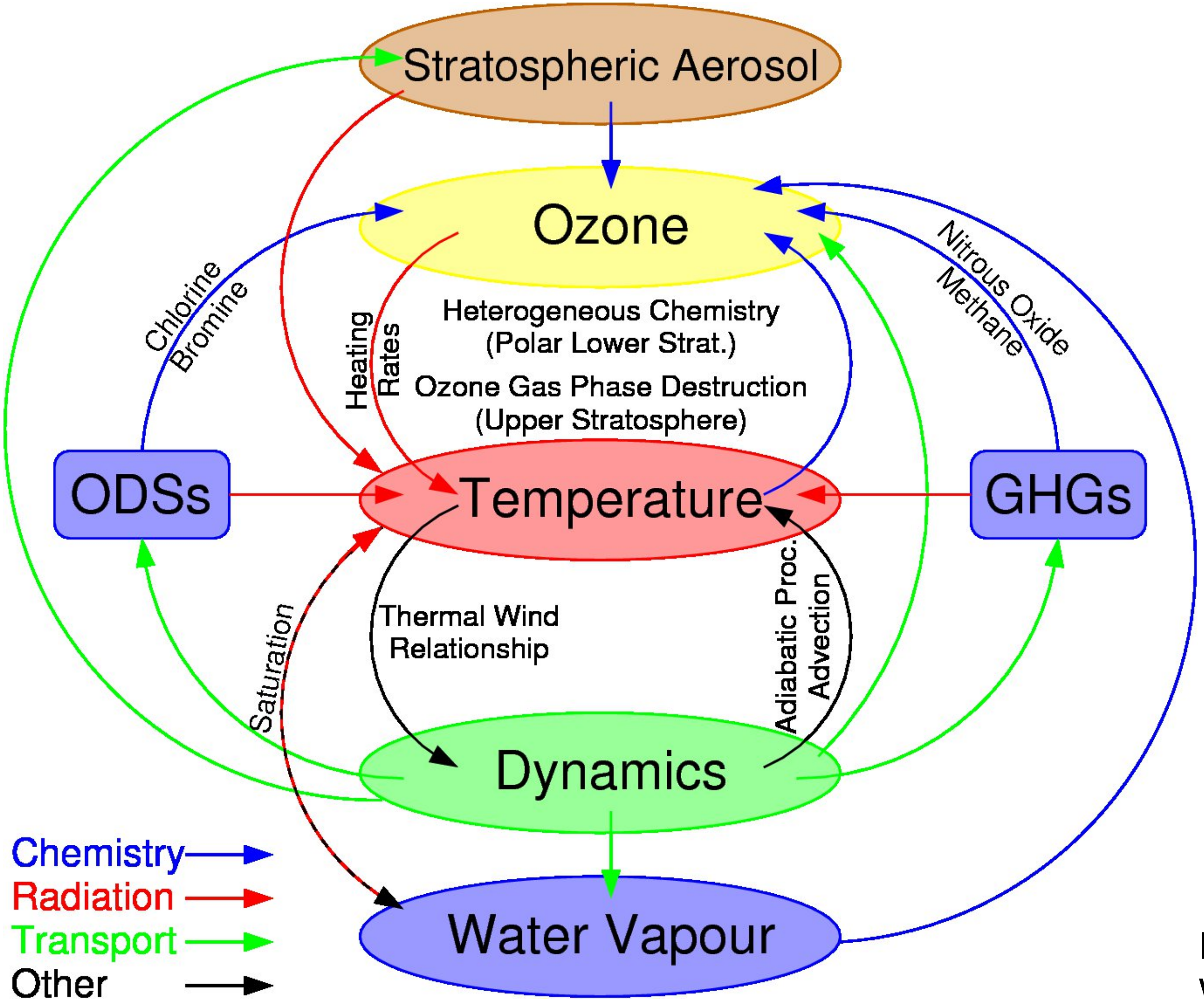

Figure 3-22 in WMO, 2011

The stratosphere in the climate system

It is evident that climate change is not only affecting the troposphere (⇒ warming) but is also modifying the stratosphere (⇒ cooling).

? How will climate change modify the stratosphere, in particular

- circulation (an intensified Brewer-Dobson circulation?!) as well
- transport of trace gases and
- chemical composition (e.g. enhanced water vapour concentration?!)

? Will the coupling processes (feedback) between the troposphere and stratosphere change under enhanced greenhouse gas concentrations?

? How important are expected stratospheric changes for the Earth-climate system?

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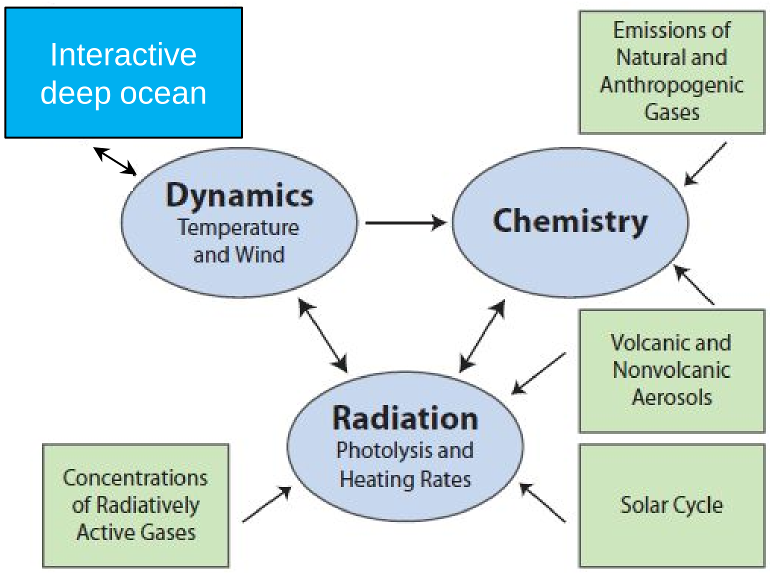
Chemistry-Climate Model: Definition and context

- A Chemistry-Climate Model (CCM) is an atmospheric general circulation model (AGCM) that is interactively coupled to a detailed chemistry module.
- The simulated concentrations of the radiatively active gases are used in the calculations of net heating rates.
- Changes in the abundance of these gases due to chemistry and advection influence heating rates and, consequently, variables describing atmospheric dynamics such as temperature and wind.

Schematic of a Chemistry-Climate Model (CCM)



Chemistry-Climate Model: Purposes

- First step, verification and evaluation CCM results with respect to observations.
- Then, CCM simulations in combination with respective observations are usually used for process-oriented investigations, in particular analyzing the feedback of physical and chemical processes.
- Such a detailed evaluation and analysis of CCM results is the foundation for future projections (e.g. for WMO ozone assessments).
- In addition to this, CCM simulation results can contribute and support investigations of individual (episodic) observations providing consistent data sets allowing a more comprehensive, three-dimensional view of the atmospheric system, in particular for longer time periods (up to several decades).

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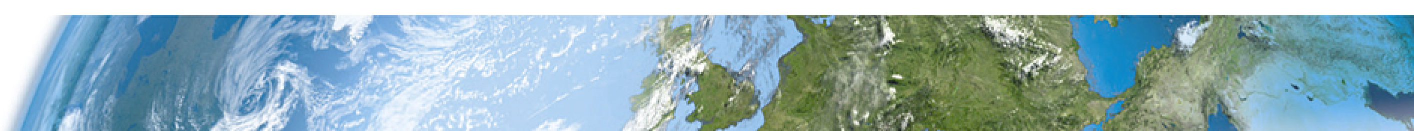


Strategy for CCM simulations

Three types of numerical model simulations covering the middle atmosphere and troposphere have been defined, as recommended by the SPARC/IGAC Chemistry-Climate Model Initiative (CCMI):

(1) A hindcast simulation with specified dynamics, i.e. nudged to observed meteorology from 1979 to 2013 (referred to RC1SD),

(2) a free-running hindcast simulation representing the past (from 1950 to 2013; referred to RC1), and

(3) a combined hindcast and forecast simulation (from 1950 until 2100; referred to RC2 and, in addition, RC2-O, i.e. with interactive ocean).

Strategy for CCM simulations

(1) The results of the RC1SD simulation can be used to reproduce observations of atmospheric composition in a consistent manner. It is suitable for evaluation purposes. Among others this helps to close gaps of episodic observations with different instruments, providing consistent time series.

(2) The RC1 simulation helps to identify the strength and weaknesses of the “free-running” model system, confronting the results of RC1 with RC1SD. Foundation for improvements of the model.

(3) The RC2 (RC2-O) simulations are the bridge to the future. They are based on the “best available” CCM. Therefore, robust assessments of future evolution can be expected.

In the following CCM simulation results are shown which have been performed recently with the EMAC model.

The CCM EMAC

The Chemistry-Climate Model EMAC (Jöckel et al., 2016)

- is based on ECHAM 5,
- using a full set of stratospheric and tropospheric chemistry;
- Resolution: T42/L90 (T42: 2.8°x2.8°, L90: 0-80 km).

For the EMAC RC1SD simulation,

- forcing: 6 hourly ERA-Interim with vertically varying relaxation time constants,
- the middle and upper stratosphere (>30 km) and mesosphere is free running.

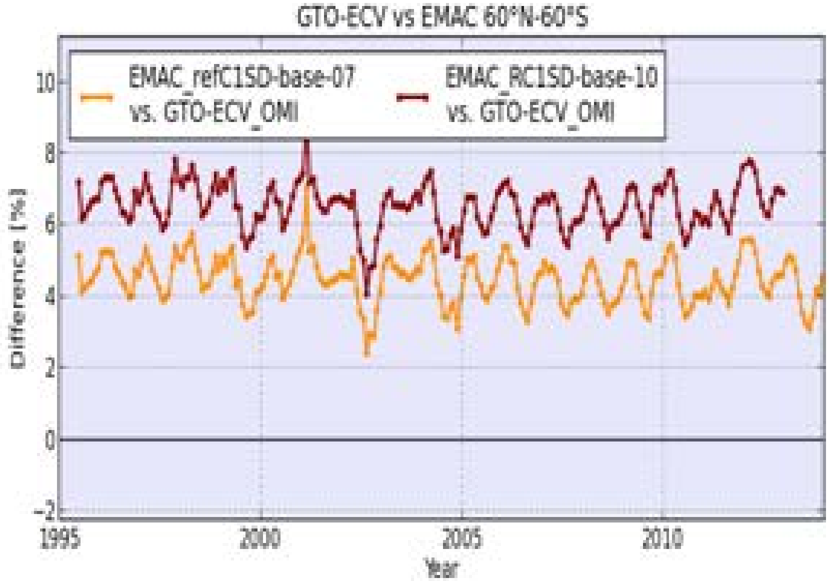
Scientific challenges, questions and tasks regarding stratospheric ozone

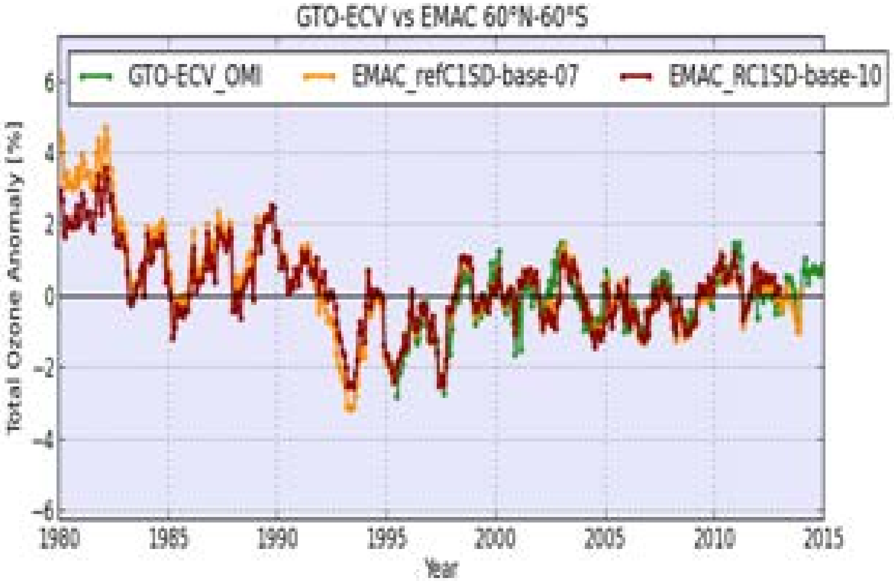
- Detection of ozone return/recovery in the next 5 to 10 years due to the regulation of CFCs. It has to be investigated if the recovery of ozone in the upper stratosphere is consistent with our expectations based on Cl_y, temperature, and other factors.
- Further monitoring of the ozone layer change over the 21^{st} century is necessary, in particular detecting higher stratospheric ozone values (‘super-recovery’) as an indicator of climate change.
- A comprehensive data base is needed to check the abilities of Chemistry-Climate Models (CCMs) to reproduce observed features and short- and long-term variability.

Scientific challenges, questions and tasks regarding stratospheric ozone

- CCM simulations are used to predict 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) as well as the tropics and its impact on surface climate.
- How will ozone concentrations develop depending on the assumed climate scenarios (RCPs: Representative Concentration Pathways)?
- Working on the importance of (changes in) stratosphere-troposphere coupling.
- Examination of the importance of ozone-radiative and ozone-dynamical interactions in the lower stratosphere and the impact of climate change on these interactions.

Ozone anomalies (1995-2013): 60°S-60°N
Comparison of satellite-instrument- and model data

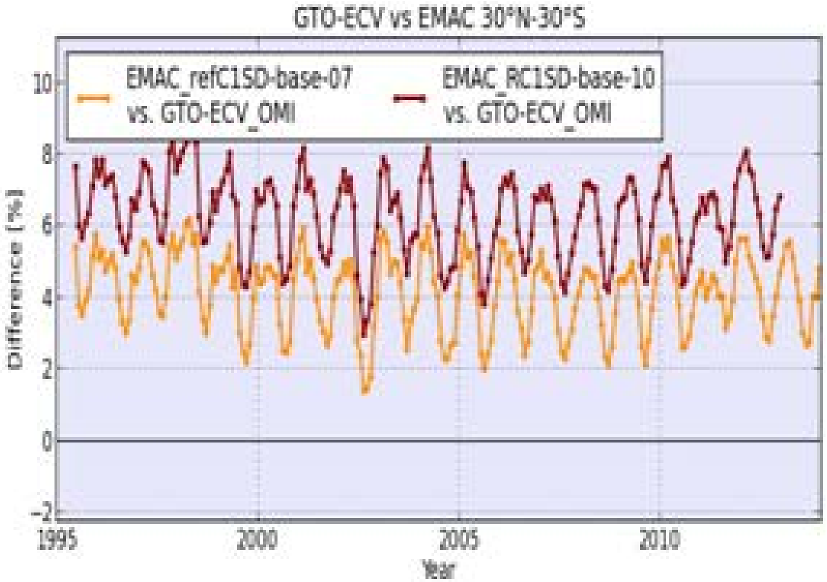


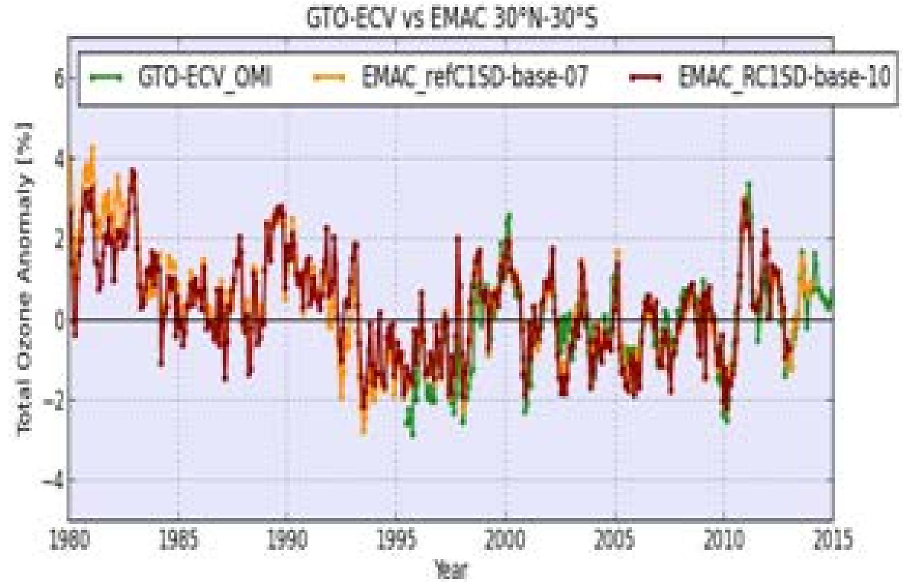


Near global mean:
ESA Ozone-cci data set (since 1995) compared with two different RC1SD simulations (red/orange: without/with nudging of the mean temperature)

Ozone anomalies (1995-2013): 30°S-30°N

Comparison of satellite-instrument- and model data





<u>Tropics</u>:

ESA Ozone-cci data set (since 1995) compared with two different RC1SD simulations (red/orange: without/with nudging of the mean temperature)

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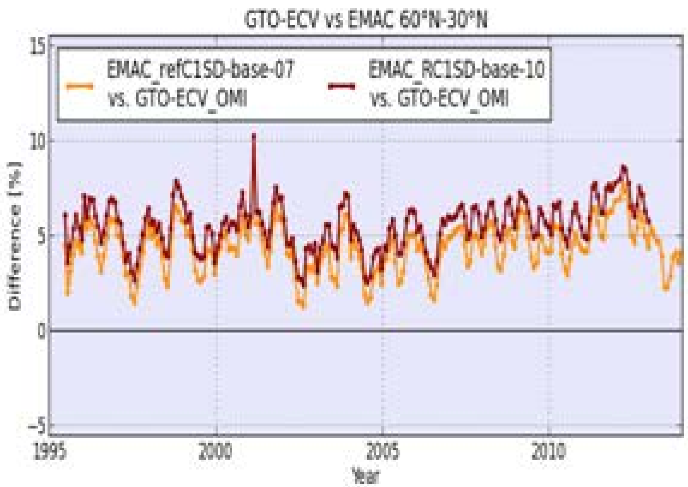
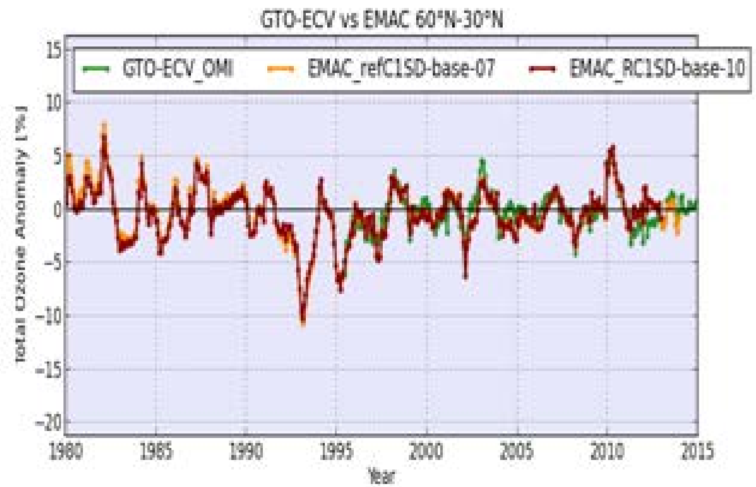
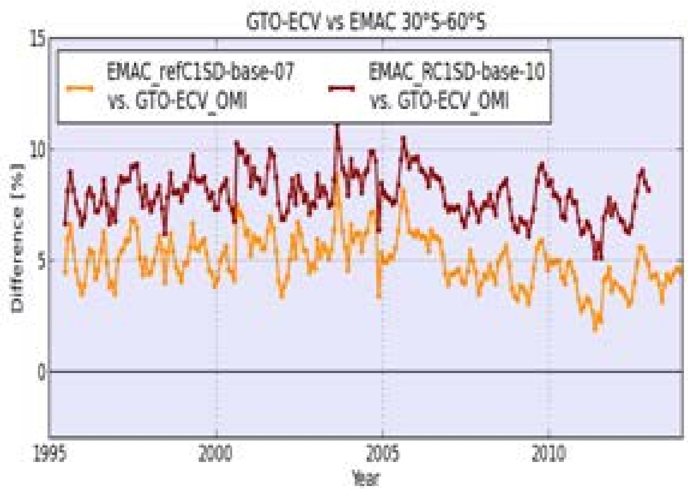
Ozone anomalies (1995-2013): mid-latitudes

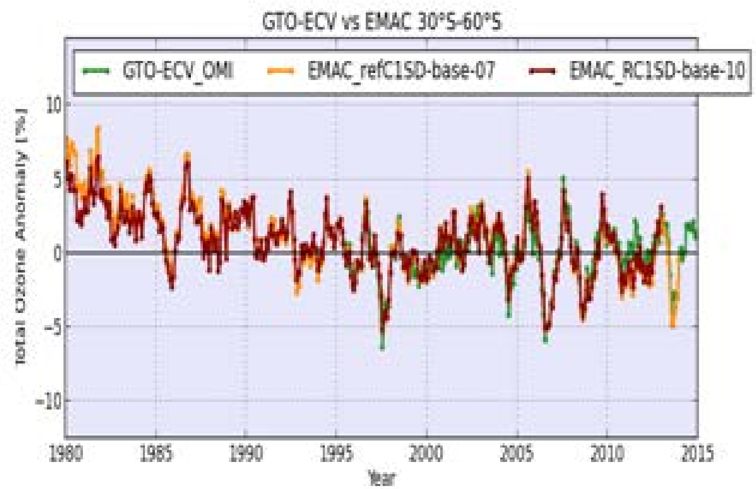
Comparison of satellite-instrument- and model data





NH





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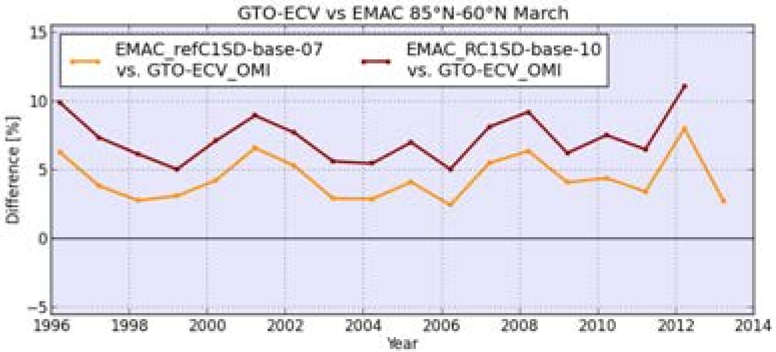
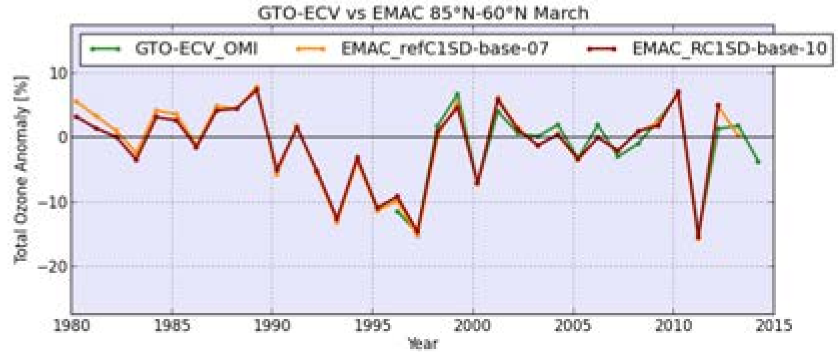
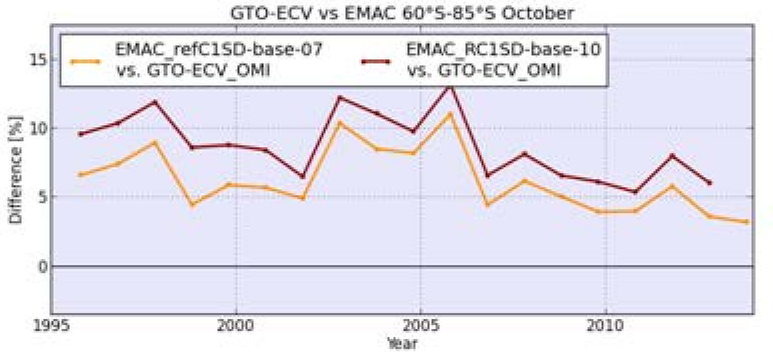
Ozone anomalies (1995-2013): polar regions, spring

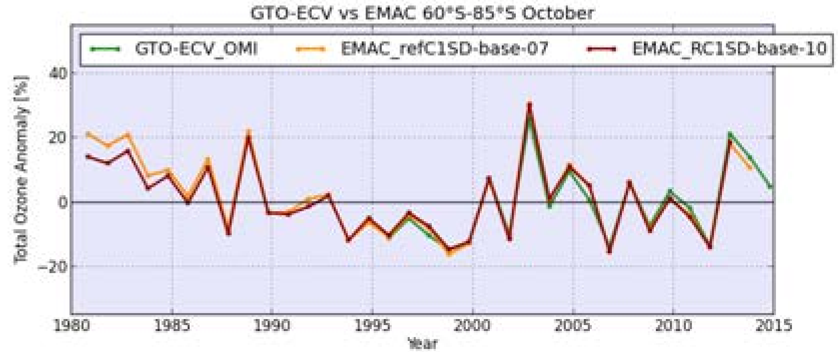
Comparison of satellite-instrument- and model data





NH
Mar





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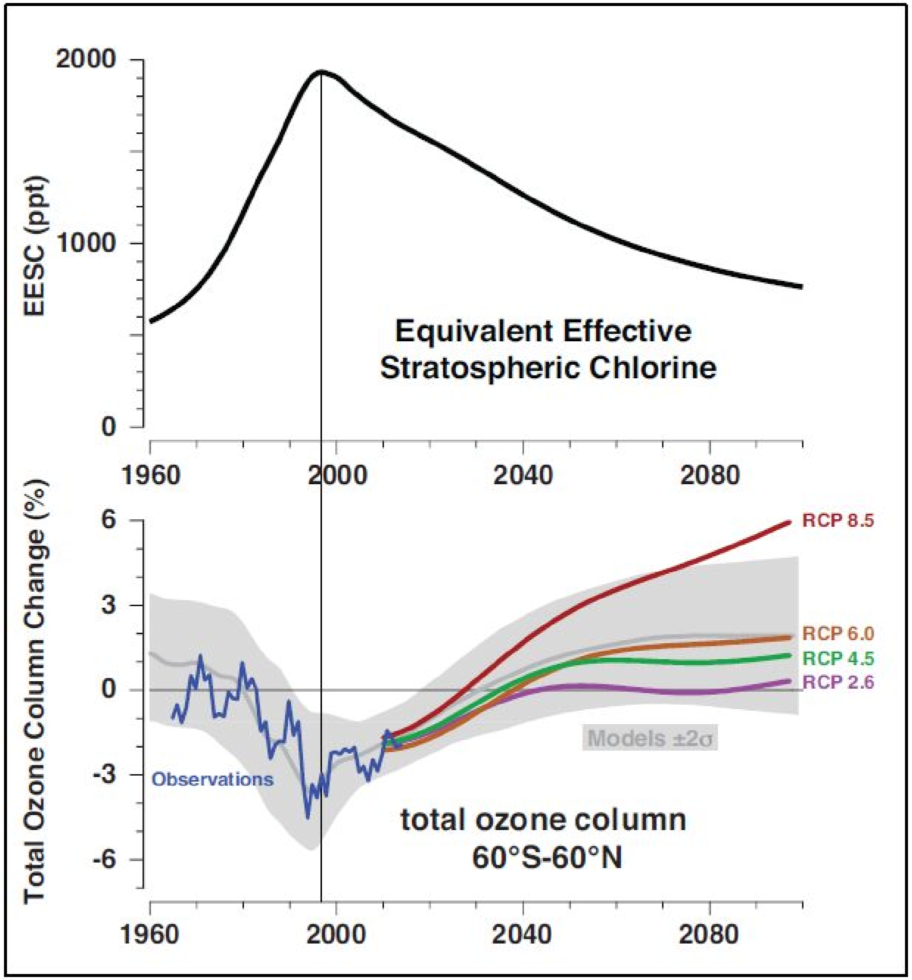
Evolution of the stratospheric ozone layer



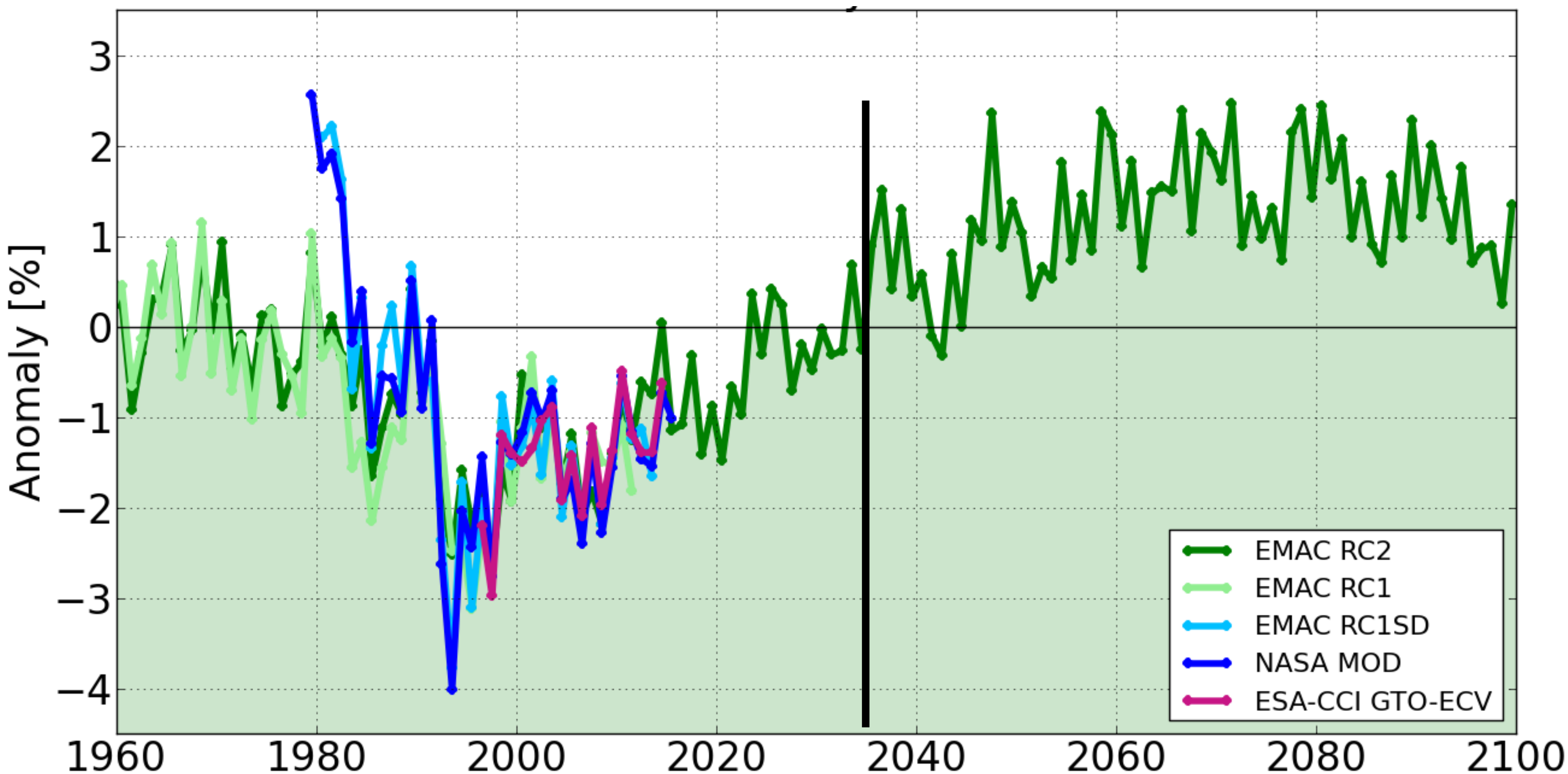
<u>Top figure</u>:
Variation of EESC in mid-latitudes from 1960 to 2100.

<u>Bottom figure</u>:
Evolution of the total ozone column depending on (four) different greenhouse gas scenarios (with different concentrations of CO_2, CH_4 and N_2O):
The four scenarios correspond to a global radiative forcing of +2.6 (blue), +4.5 (green), +6.0 (brown), and +8.5 (red) in W m^{-2}.

(WMO, 2014)

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

Comparison of Satellite-instrument- and model data; prediction (RCP6.0)



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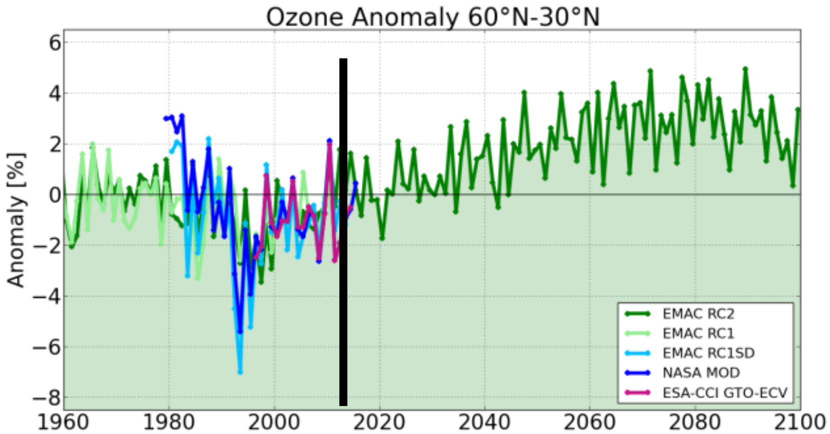
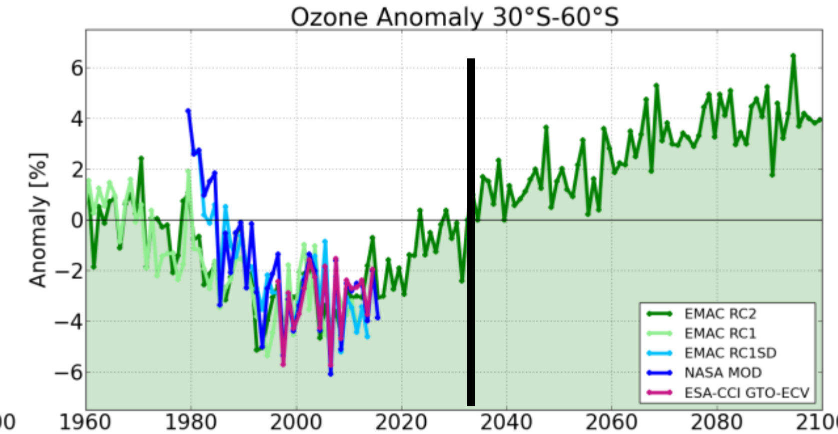
Ozone anomalies (1960-2100): mid-latitudes

Comparison of Satellite-instrument- and model data; prediction (RCP6.0)





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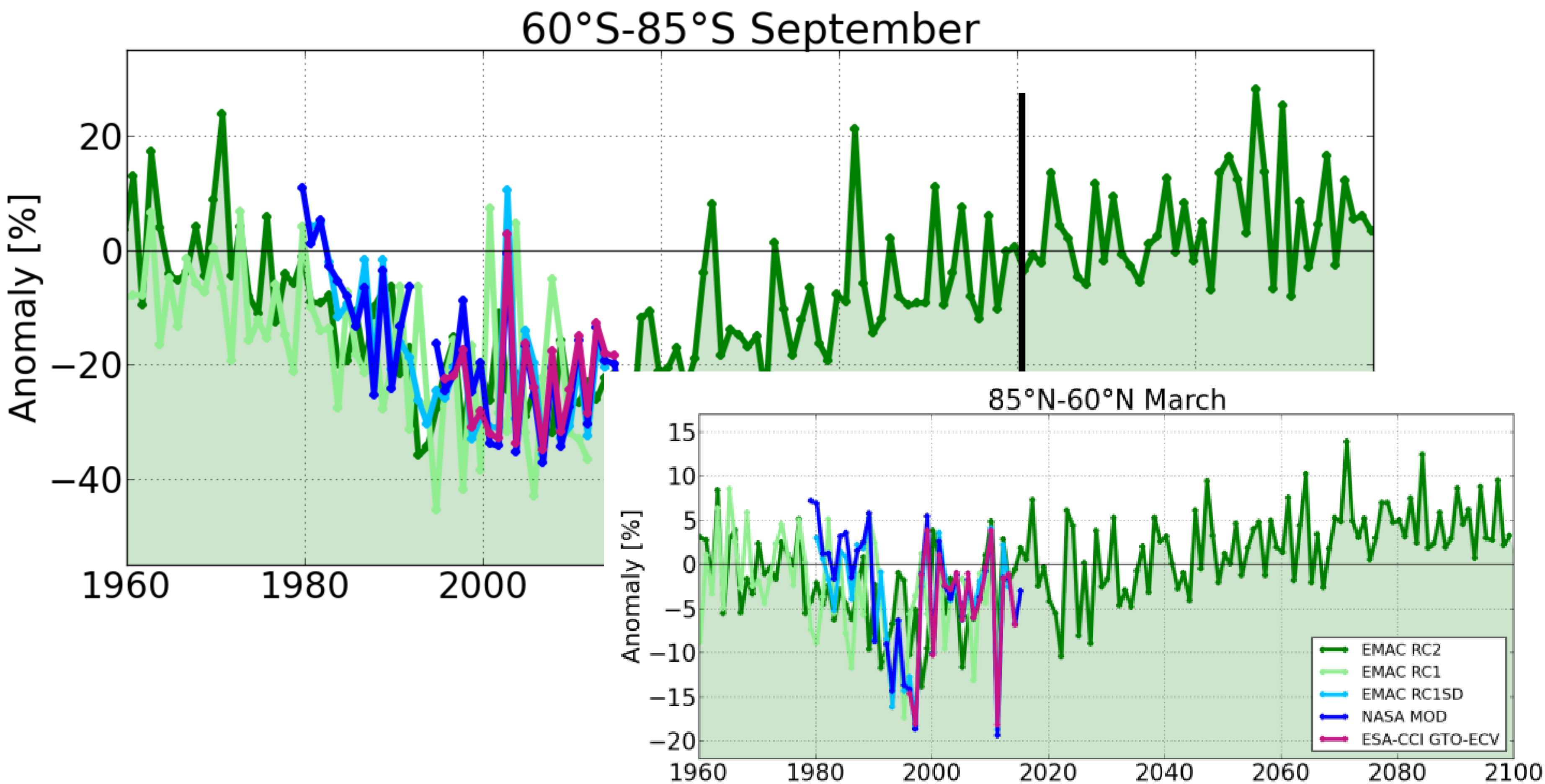
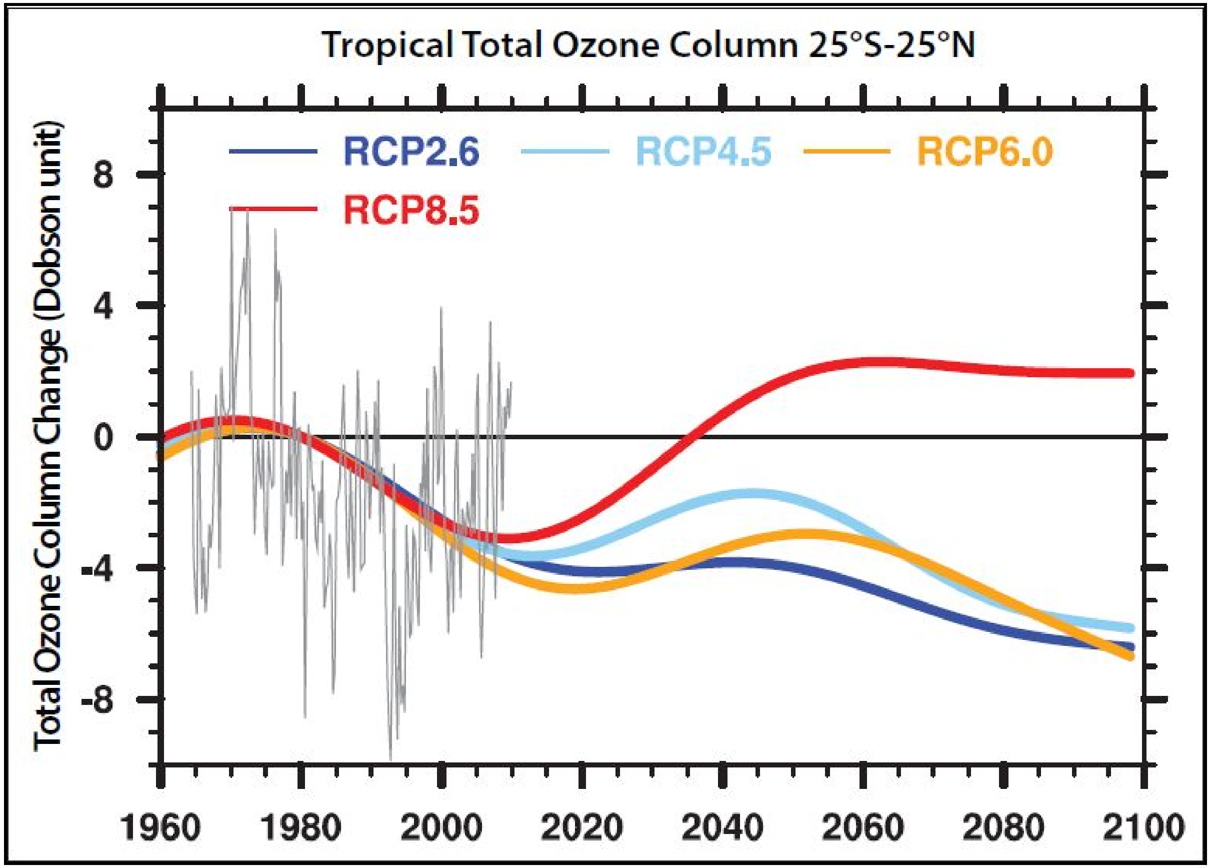
Ozone anomalies (1960-2100): polar regions

Comparison of Satellite-instrument- and model data; prediction (RCP6.0)

Antarctic ozone hole



Evolution of the tropical stratospheric ozone layer

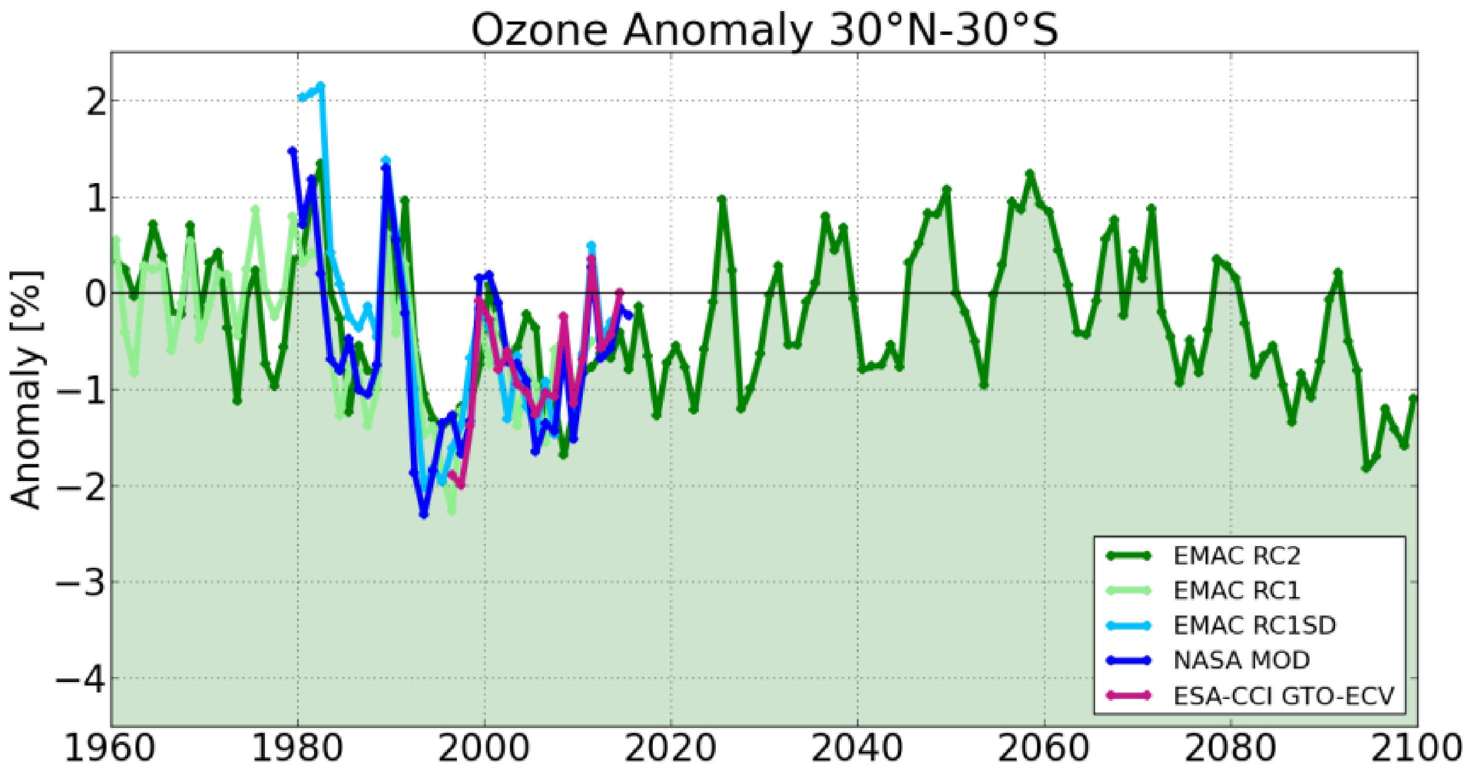


Evolution of total ozone column in the tropics (25°S-25°N) for the four greenhouse gas scenarios.

(WMO, 2014)

Ozone anomalies (1960-2100): tropics

Comparison of Satellite-instrument- and model data; prediction (RCP6.0)



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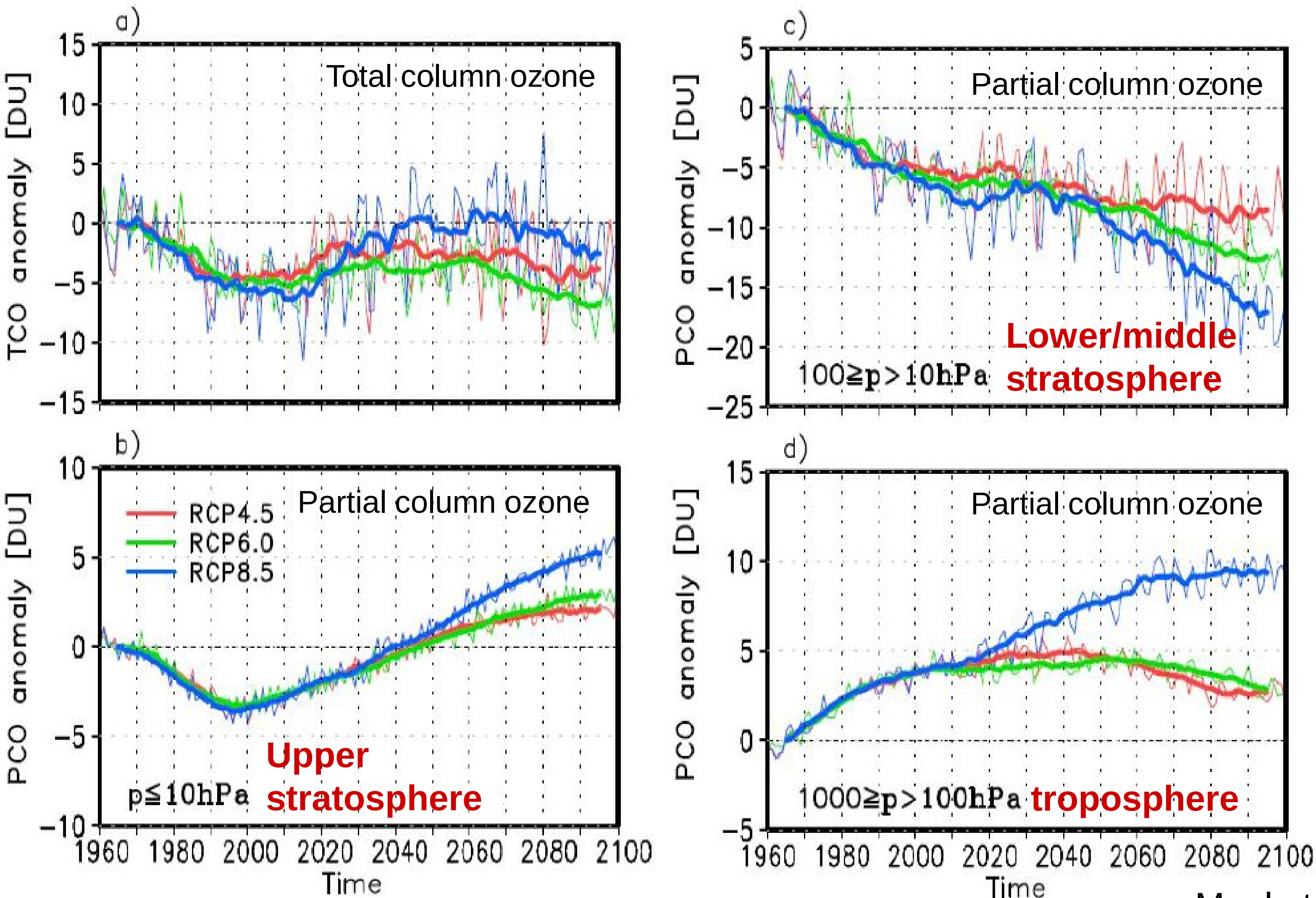
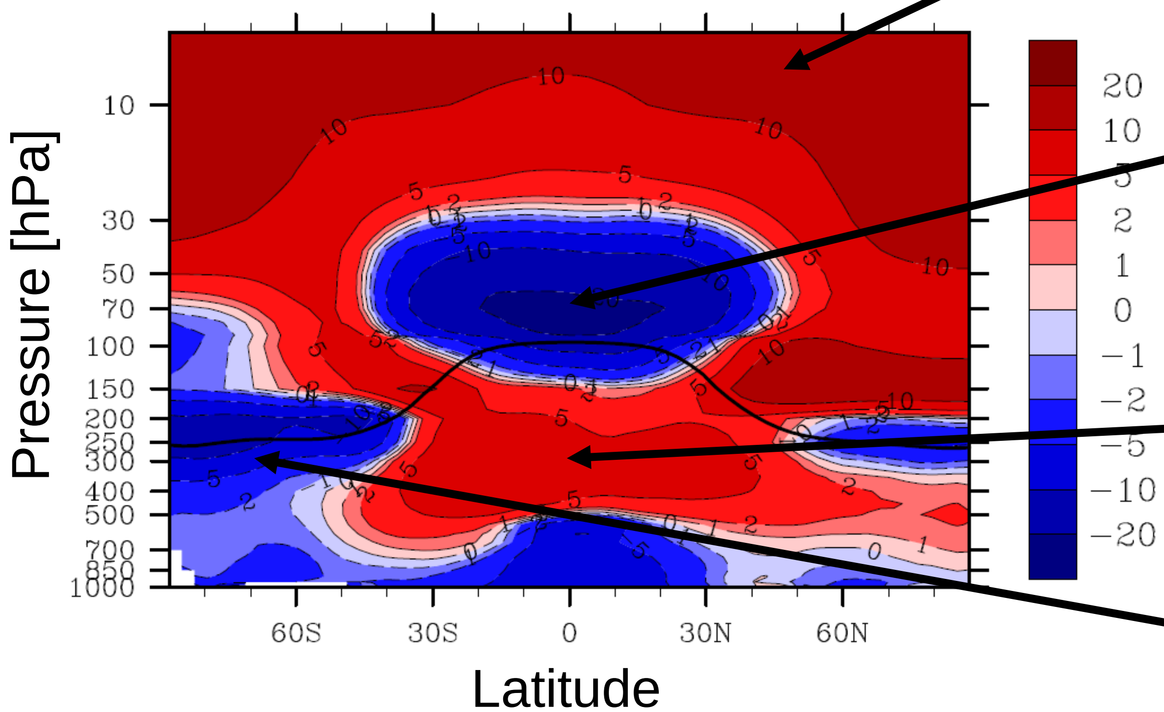
Evolution of the tropical stratospheric ozone layer



Meul et al., 2016

Ozone feedback in CO_2 increase simulations

Ozone concentration change [in %] under CO_2 doubling



Dietmüller et al., 2014

- Ozone destruction is reduced in the middle and upper stratosphere due to cooling.
- **Ozone reduced due to tropical upwelling which increases as troposphere warms.**
- Increased NO_y controls ozone response in the upper troposphere.
- Polar ozone reduced due to enhanced PSC formation.

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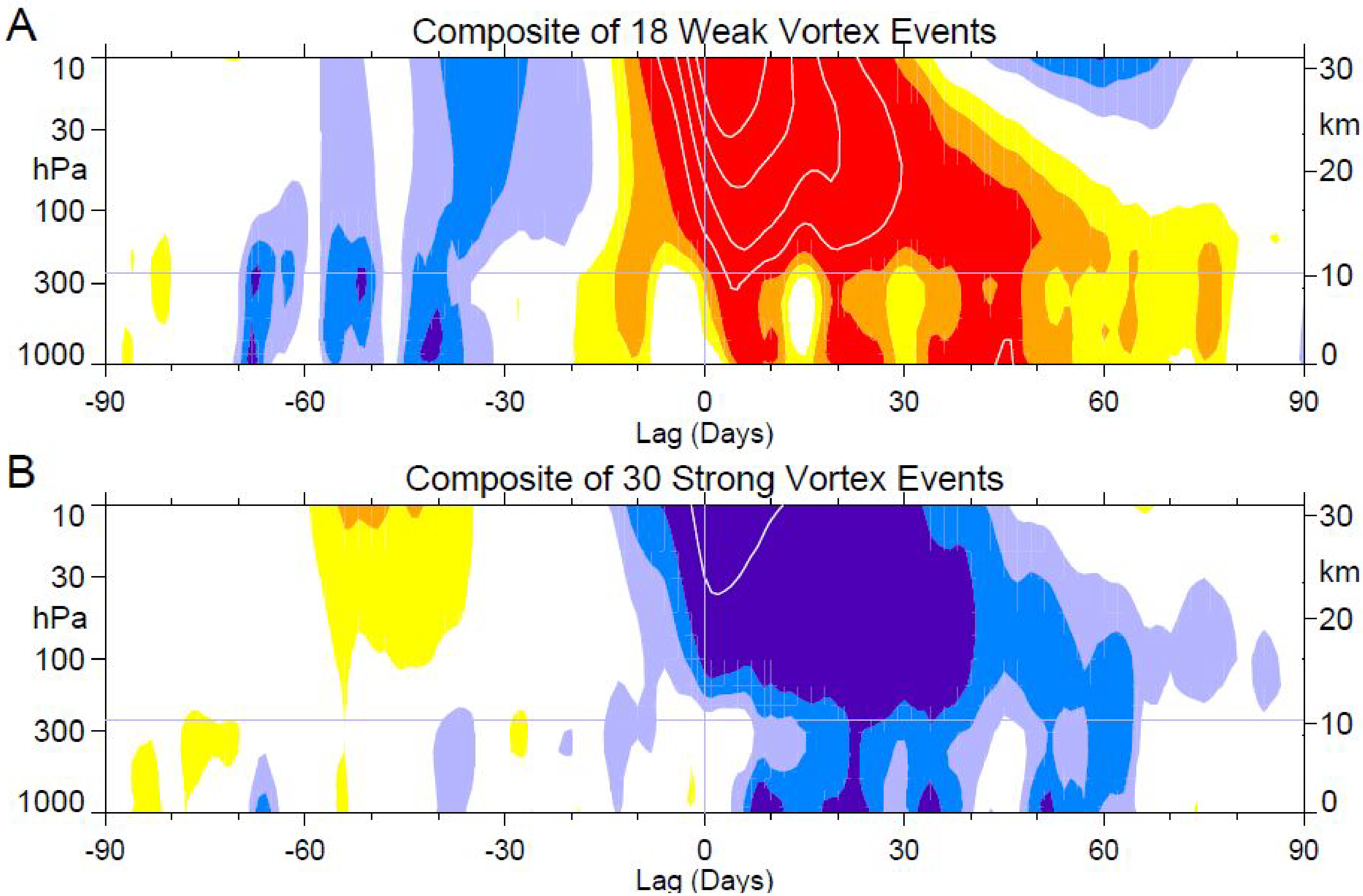
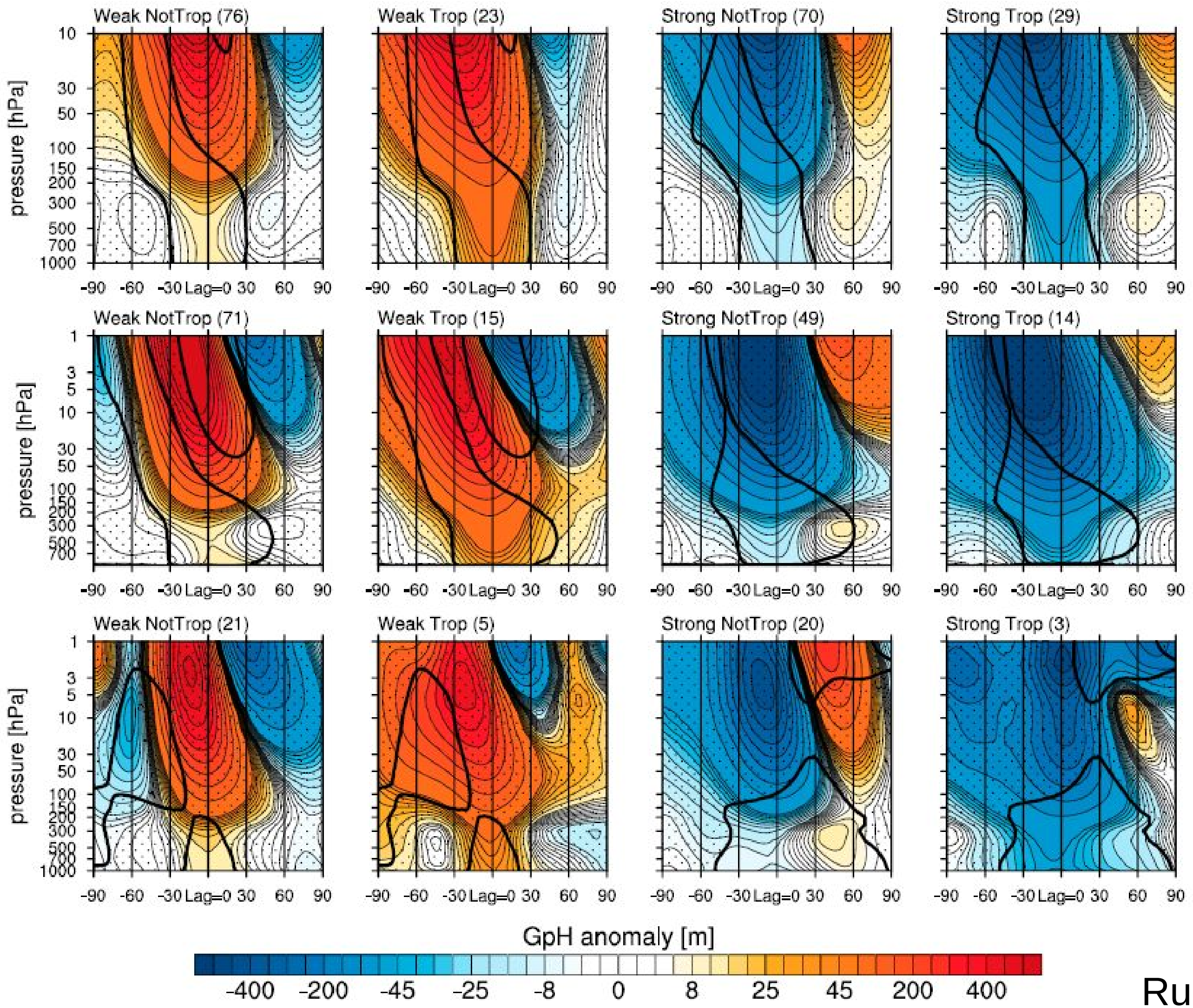
Stratosphere-troposphere coupling



Composites of time-height development of the NAM for (A) 18 weak vortex events and (B) 30 strong vortex events.

Baldwin and Dunkerton, 2001

Stratosphere-troposphere coupling



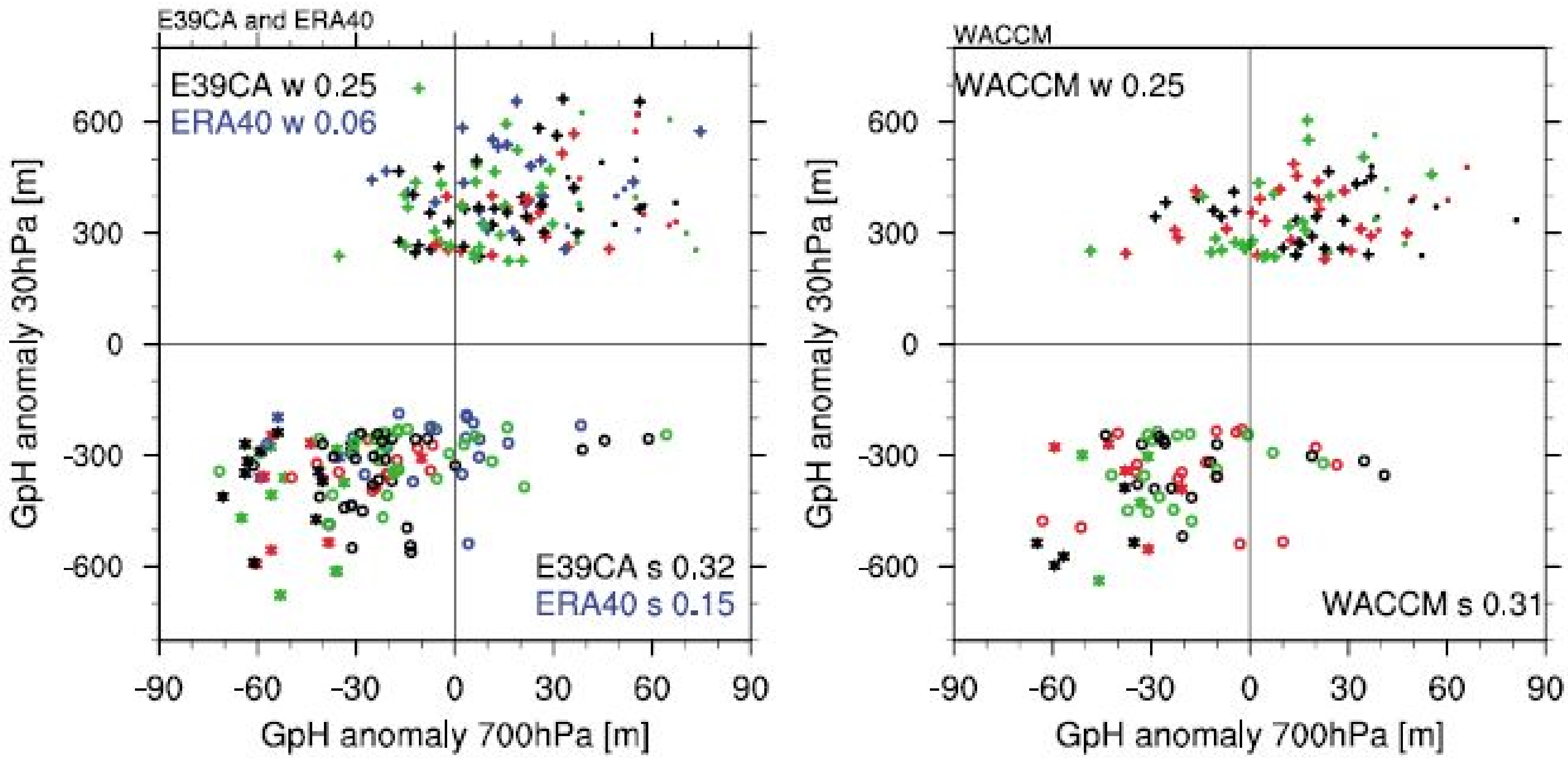
E39CA
(225y)

WACCM
(162y)

ERA40
(45y)

Runde et al., 2016

Stratosphere-troposphere coupling

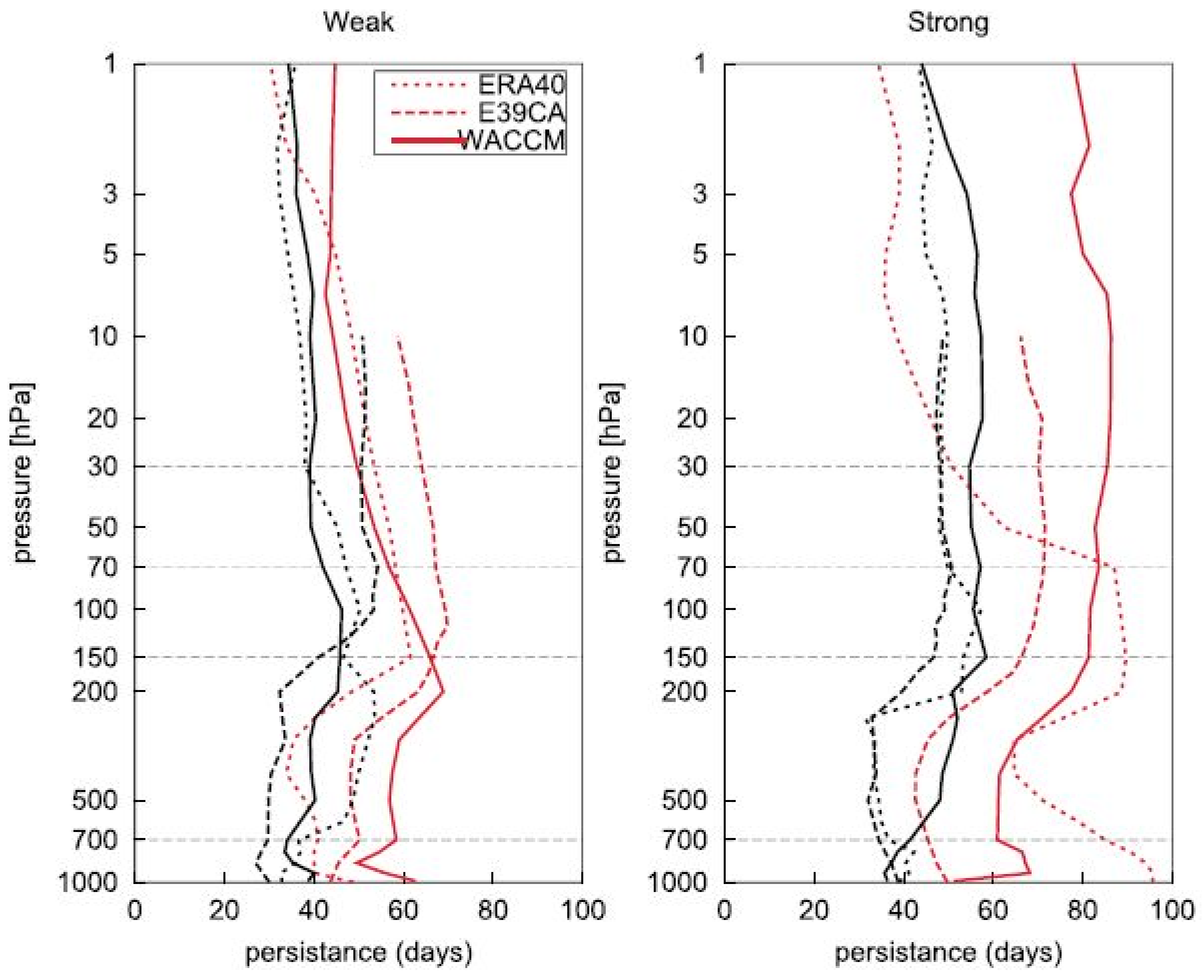


There is a high case-to-case variability of the anomalous stratospheric situations. Events of both types (Trop and NotTrop) span a large range of stratospheric GpH anomalies.

Dot (asterisk) denotes weak (strong) events of type Trop and plus (circle) denotes weak (strong) events of type NotTrop.

Runde et al., 2016

Stratosphere-troposphere coupling



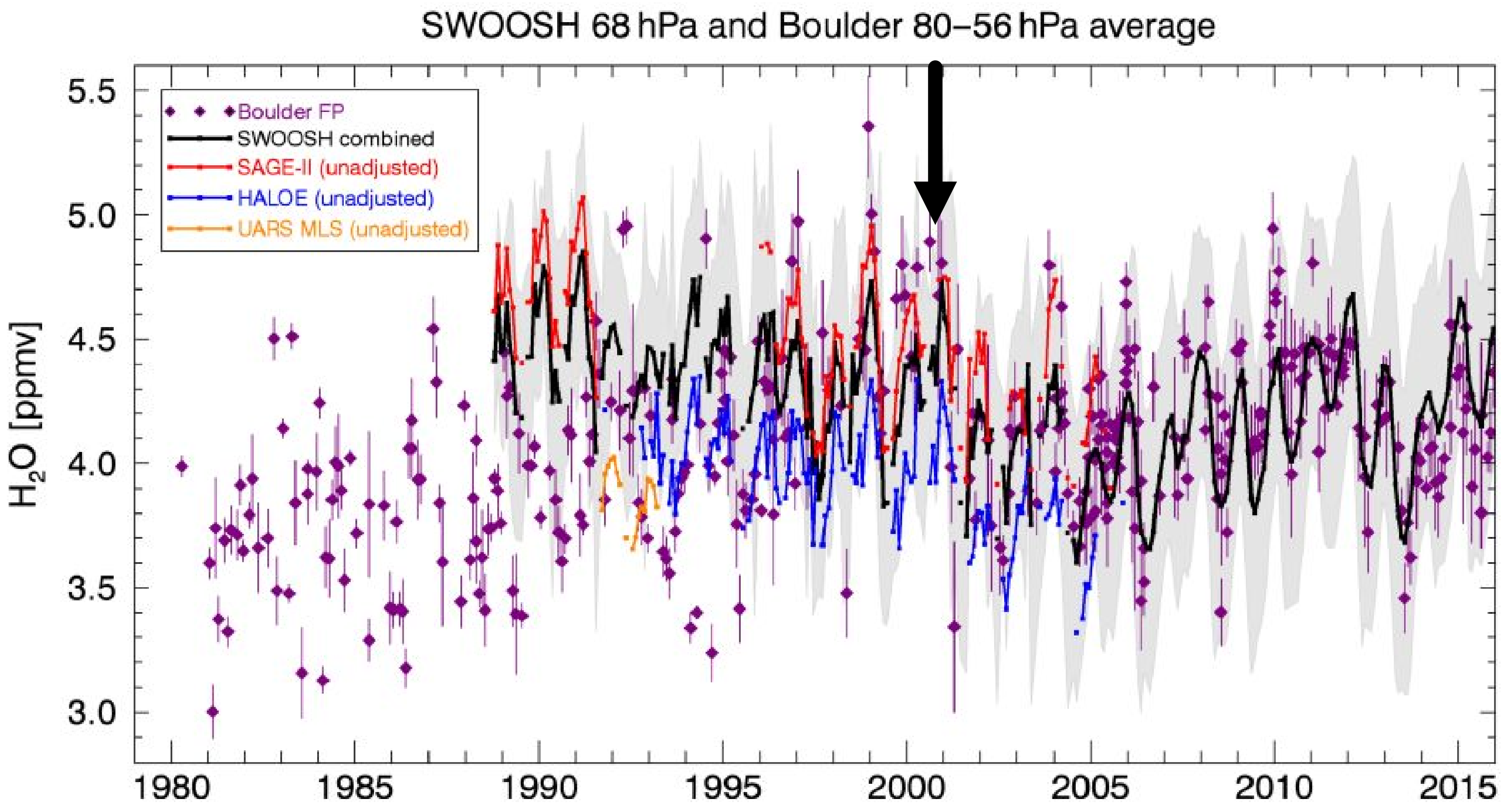
Persistence (i.e., duration of threshold exceedance) of weak and strong events of type **Trop** (red) and **NotTrop** (black) for ERA40 (dotted), E39CA (dashed), and WACCM (solid).

Runde et al., 2016

Scientific challenges, questions and tasks regarding stratospheric water vapour

- Consistent long-term observations are requested to enable identifying short- and long-term variability of stratospheric water vapour.
- Comprehensive data sets together with appropriate CCM simulations are needed for process-oriented investigations. (Foundation for future assessments!)
- How good are the relevant processes described in the CCMs?
- What are the dominant drivers for observed (strong) fluctuations?
- Can we determine significant long-term trends in the past?
- What does our CCM predict for the 21th century?

Water vapour anomalies and trends !?



Davis et al., 2016

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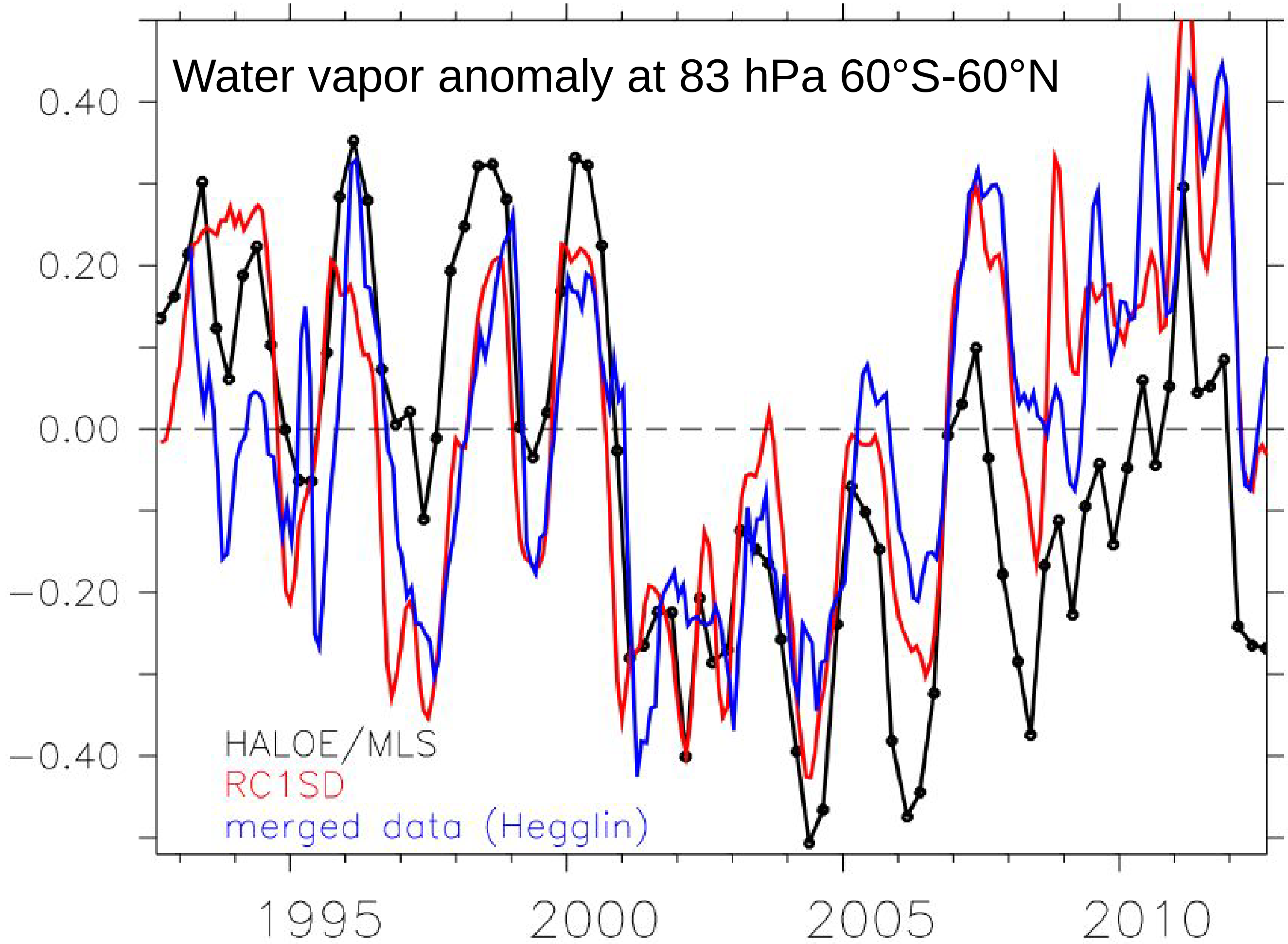
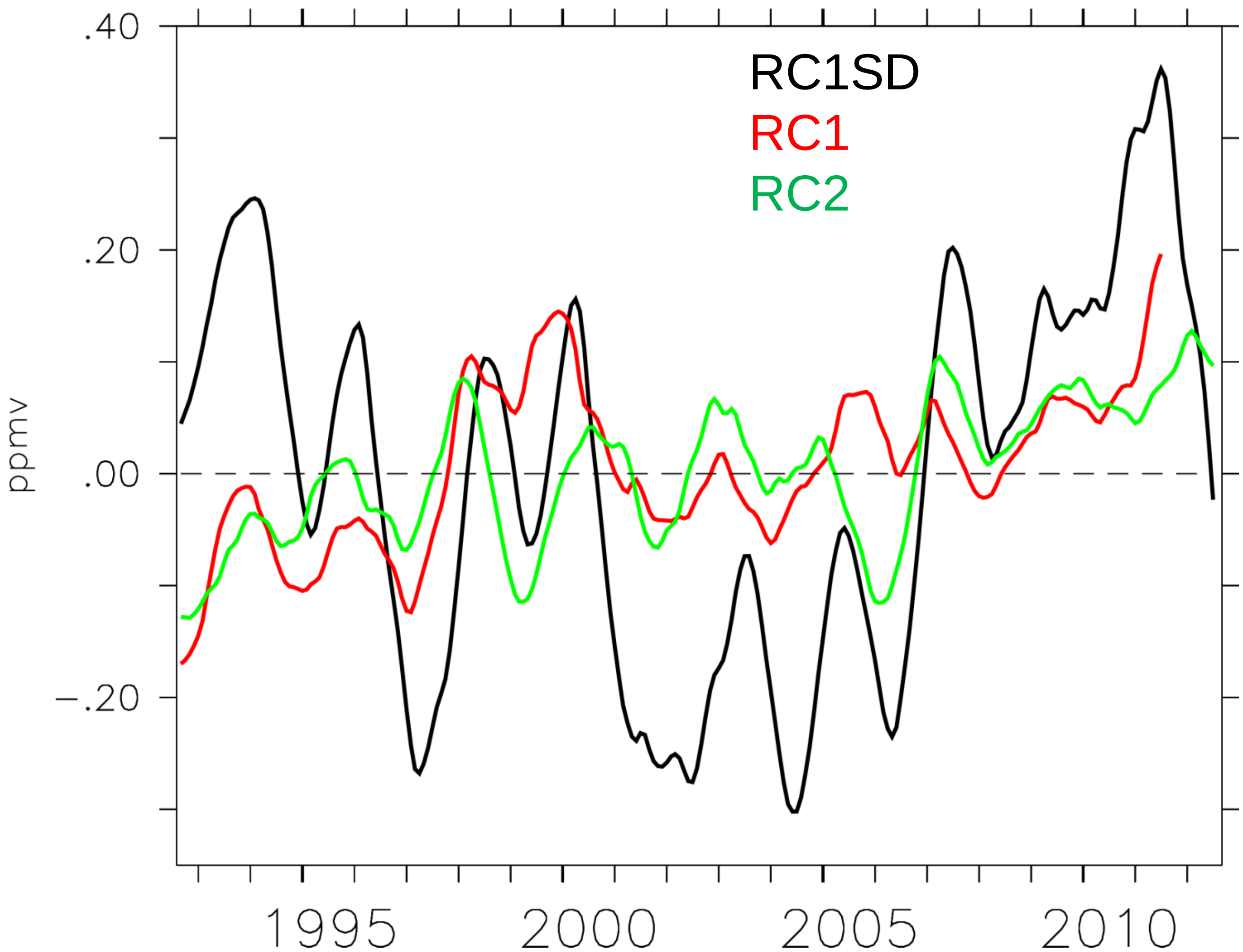
Example: Explanation of the millennium water drop



Brinkop et al., 2016

Water vapour anomaly at 83 hPa (60°S-60°N)



Brinkop et al., 2016

Correct (observed) tropical SSTs are very important for triggering the strong decline in water vapour!

SST changes due to a coincidence with a preceding strong El Niño-Southern Oscillation event (1997/1998) followed by a strong La Niña event (1999/2000).

This event is supported by the change of the westerly to the easterly phase of the equatorial stratospheric quasi-biennial oscillation (QBO) in 2000.

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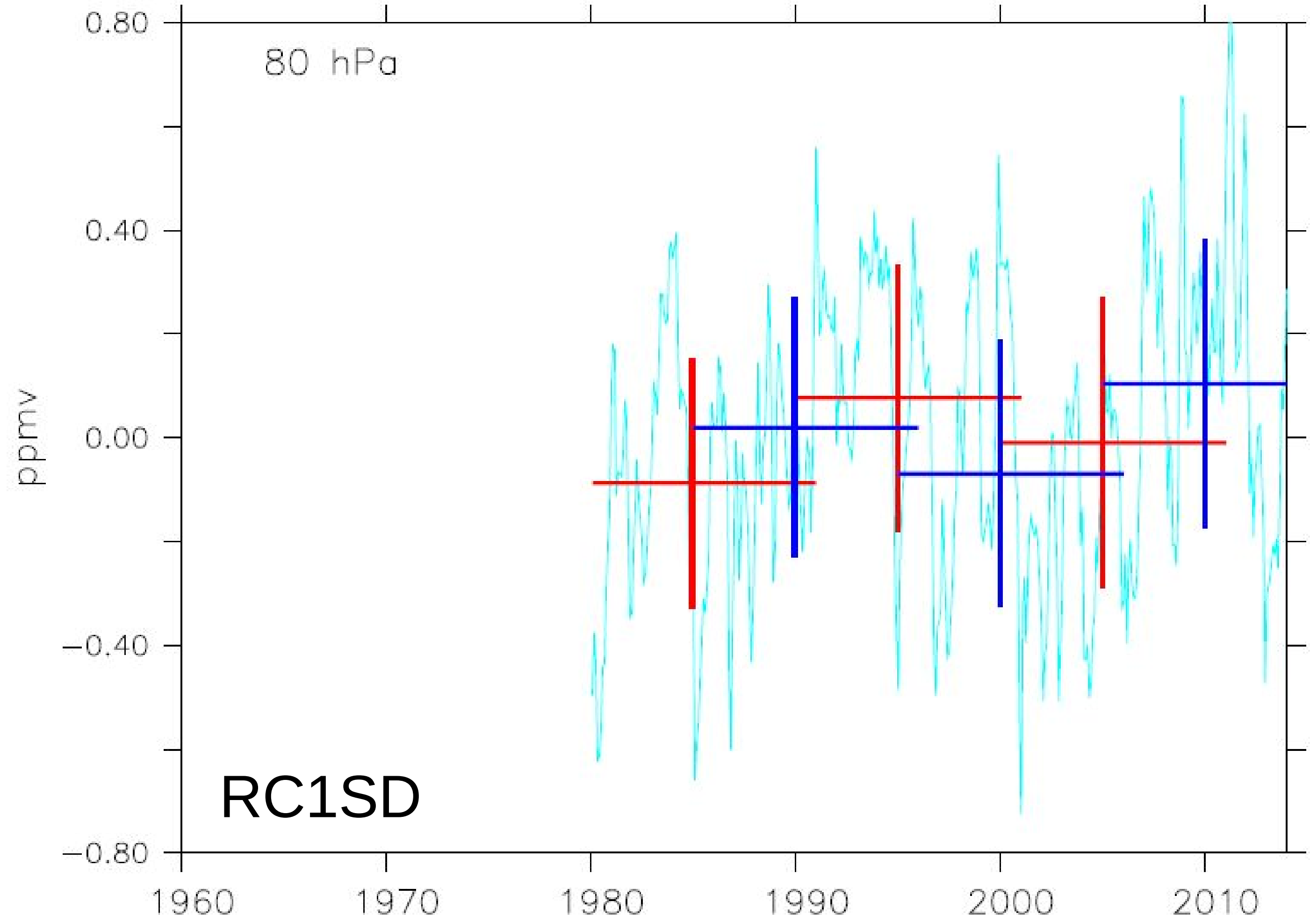
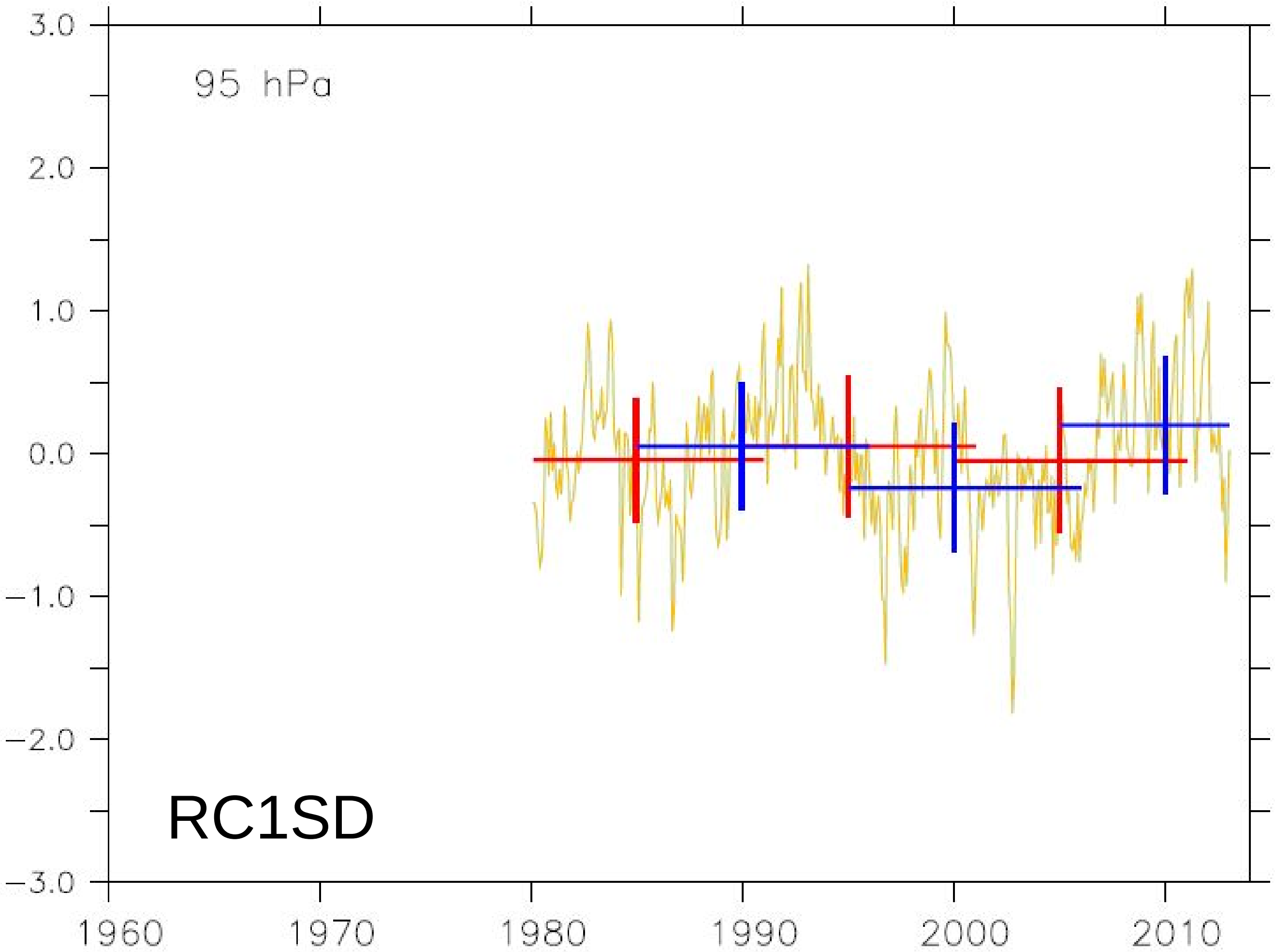
Stratospheric water vapour: fluctuations and trends

- Tropics (30°N-30°S), lower stratosphere (80 hPa)



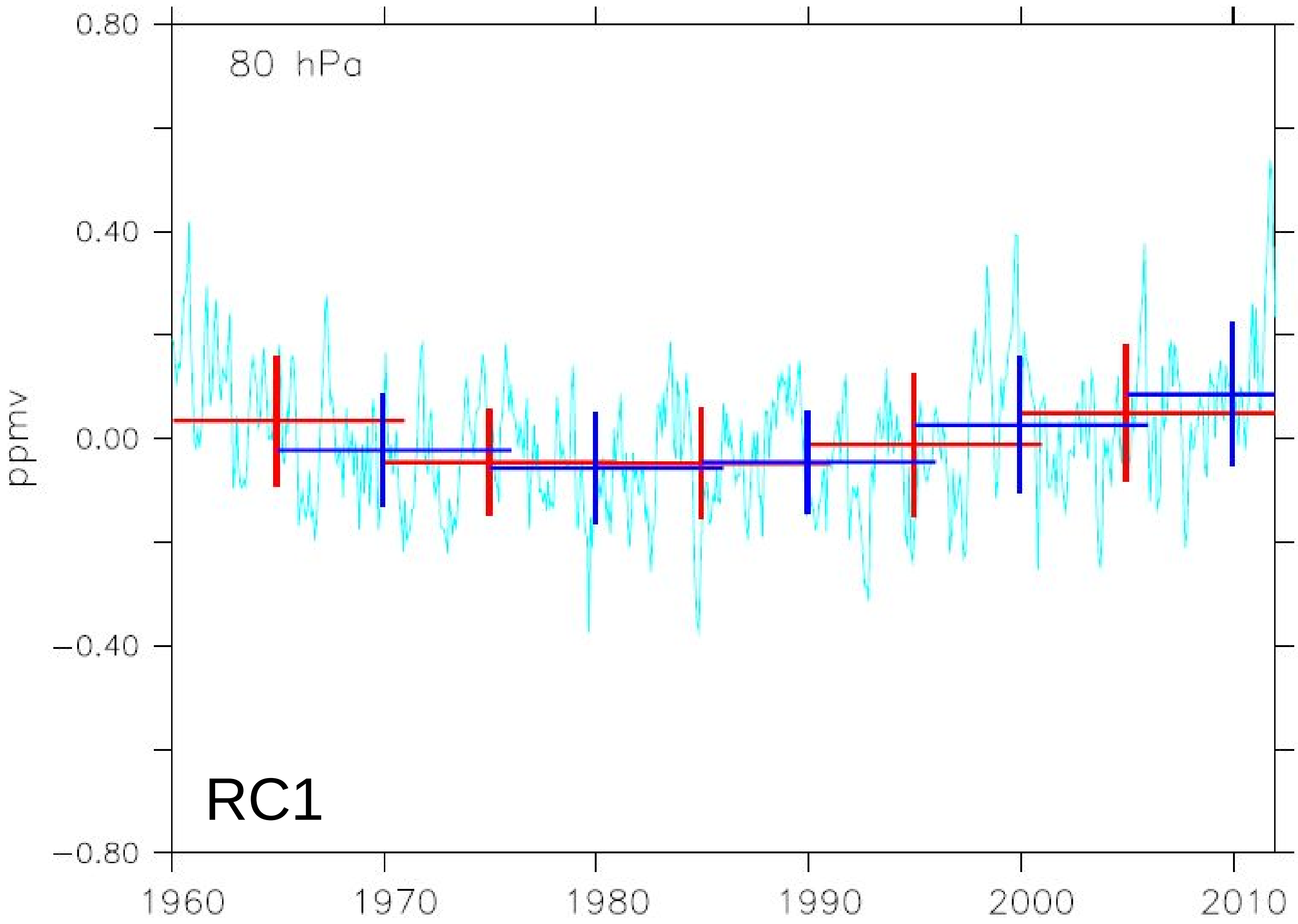
Stratospheric temperature: fluctuations and trends

- Tropics (30°N-30°S), lower stratosphere (95 hPa, near TP)



Stratospheric water vapour: fluctuations and trends

➢ Tropics (30°N-30°S), lower stratosphere (80 hPa)



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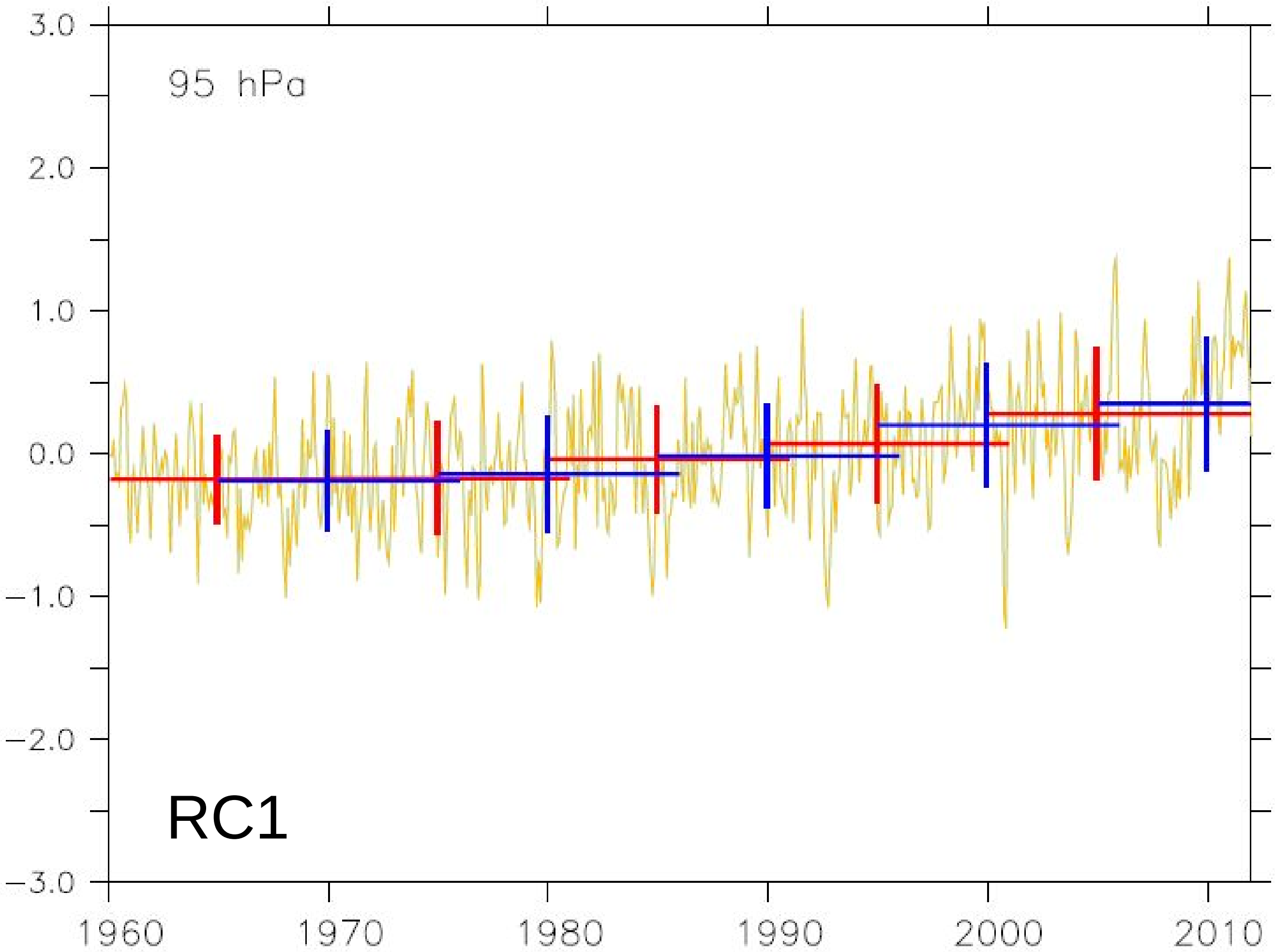

Stratospheric water vapour: fluctuations and trends

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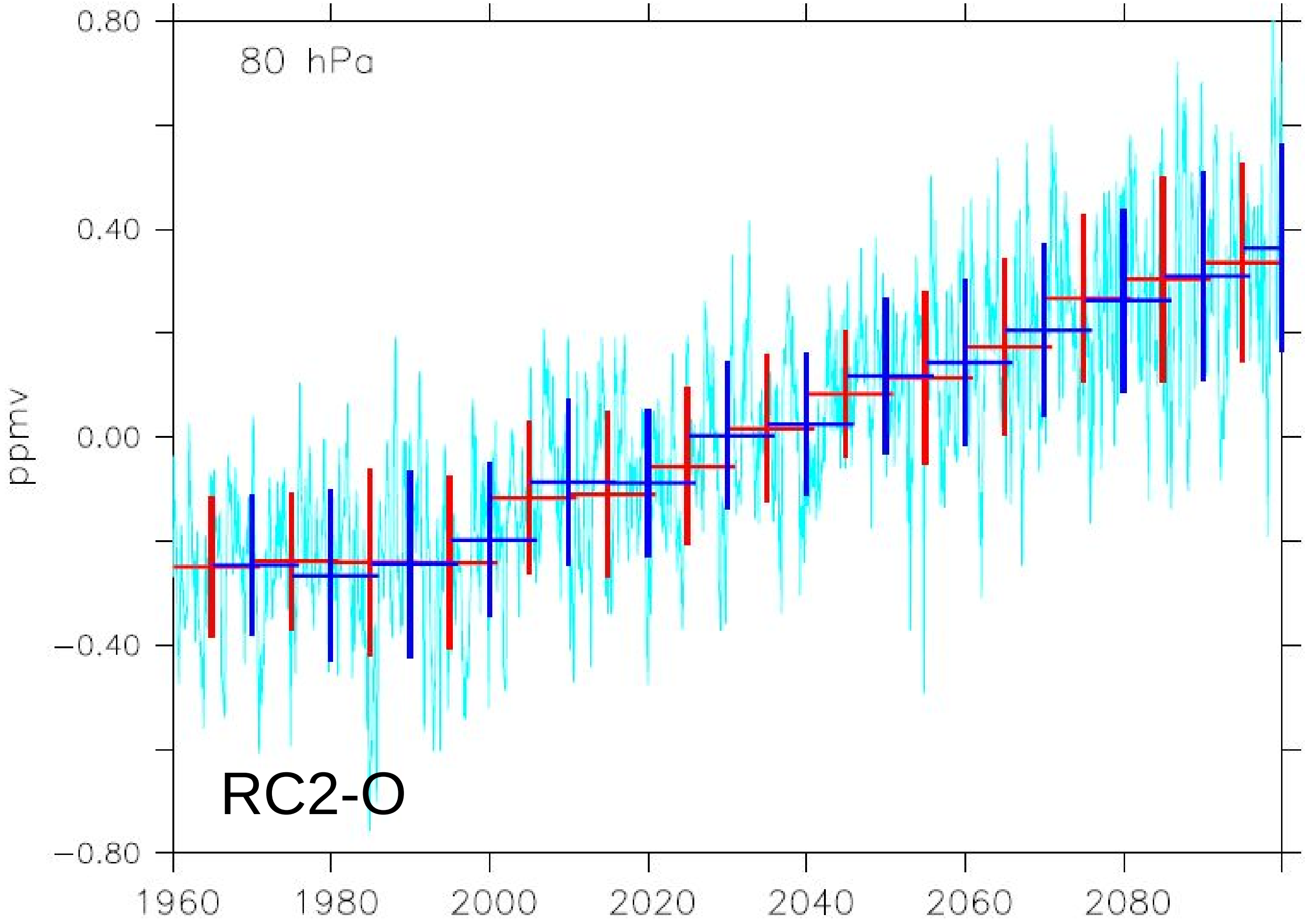

Stratospheric temperature: fluctuations and trends

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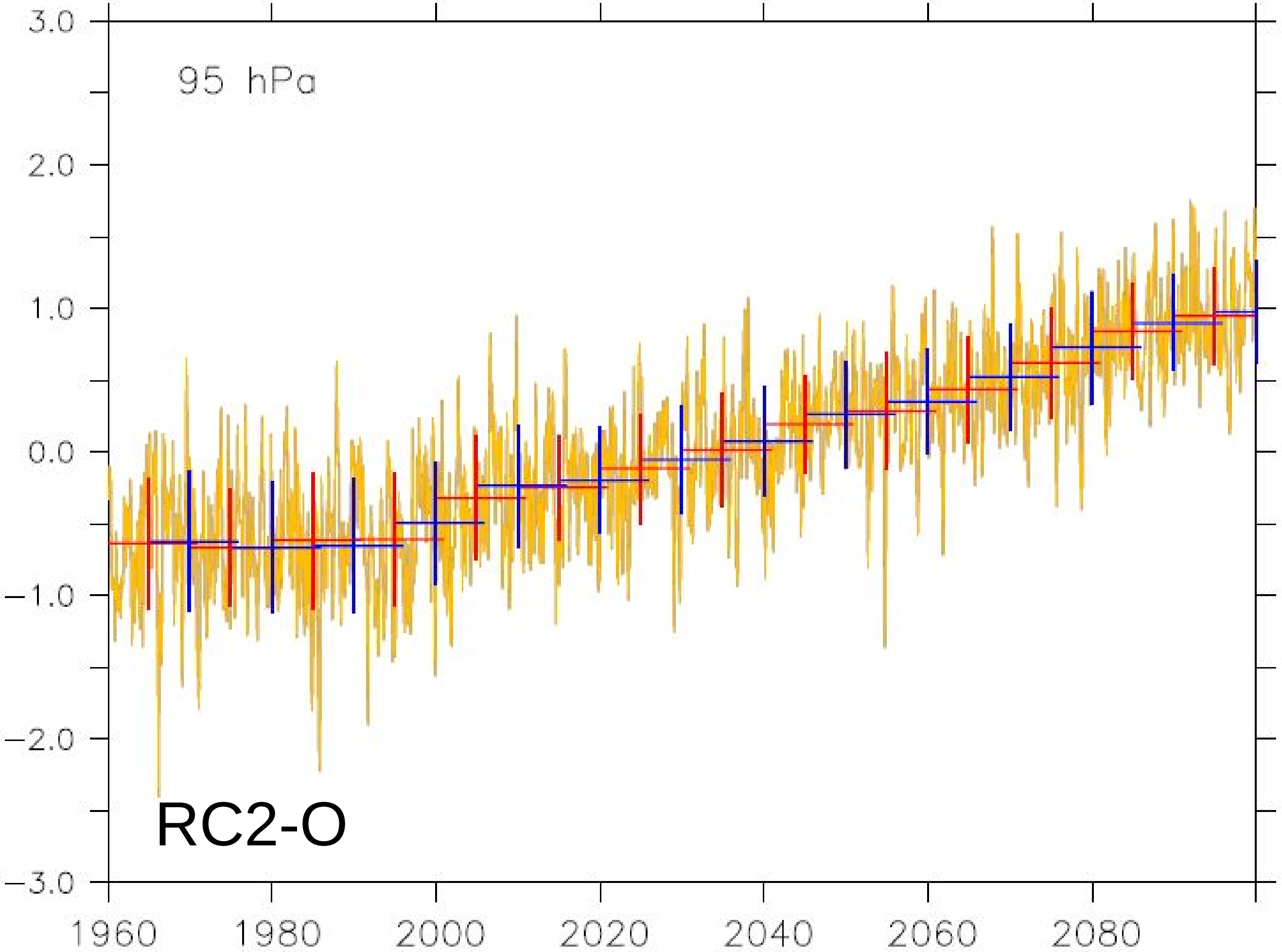
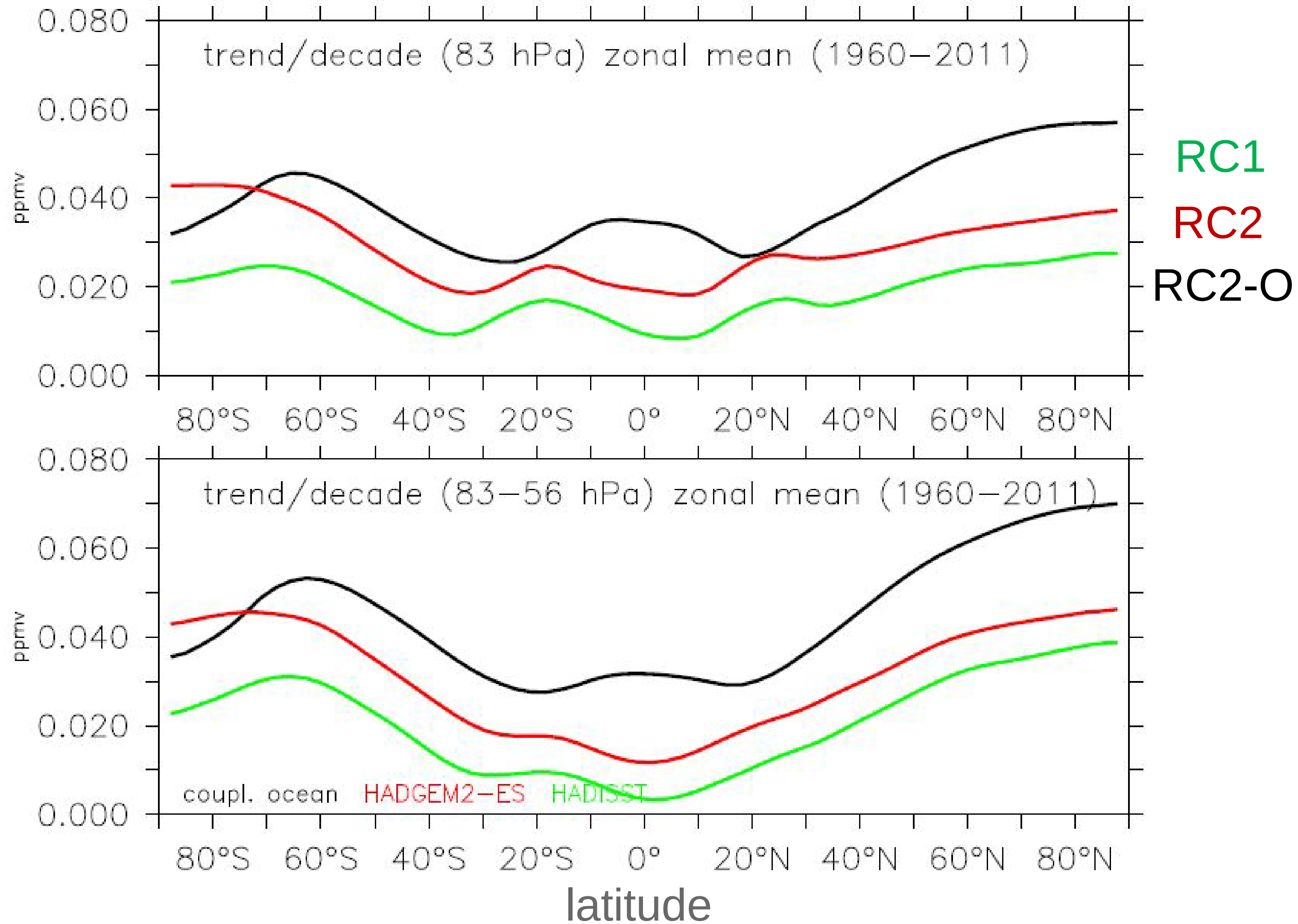
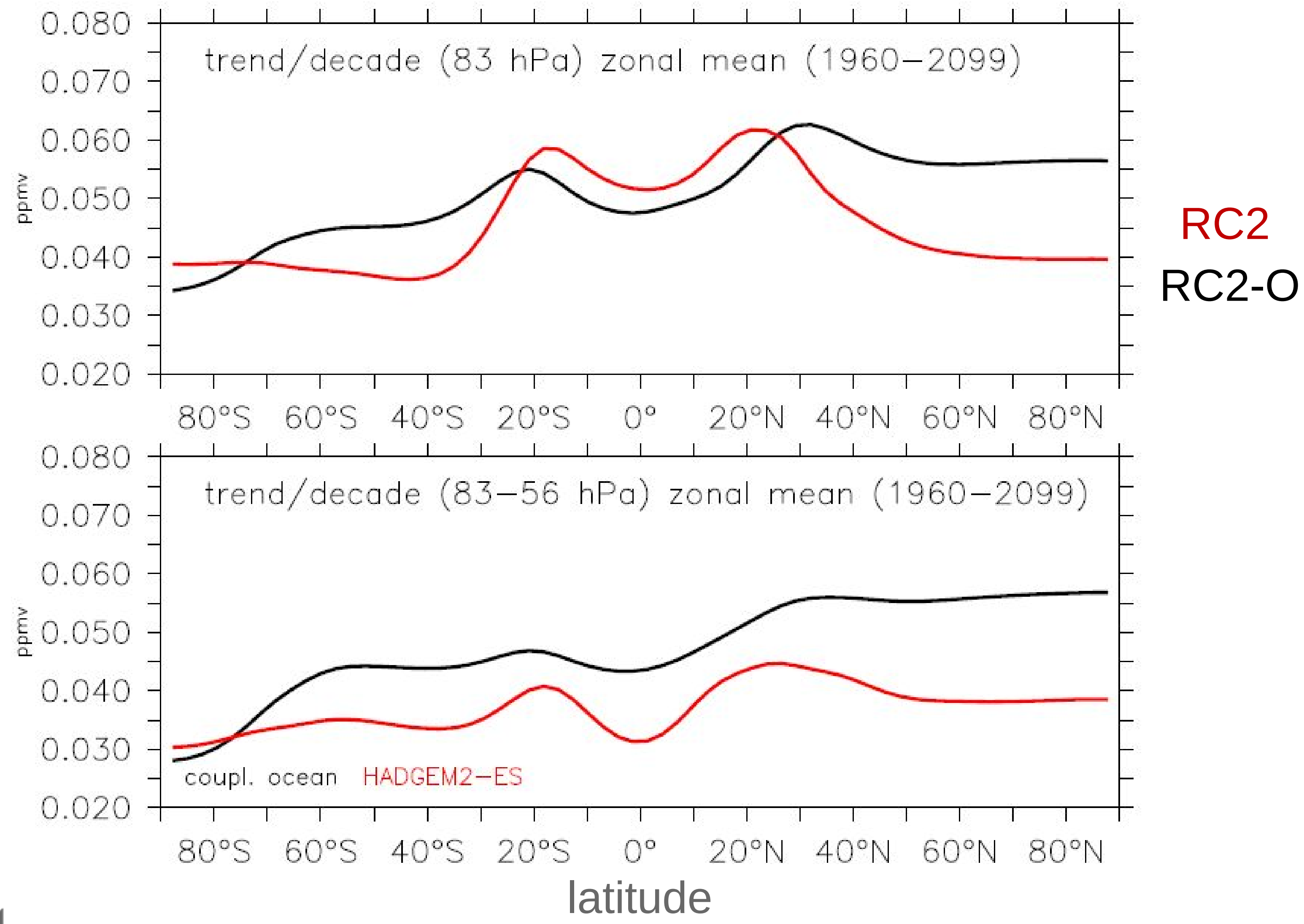


Estimation of past water vapour trends



Estimation of future water vapour trends



Concluding remarks (1)

- A hierarchy of new CCM simulations have recently been conducted and the output of many CCMs is now available (CCMI archive).
- A detailed comparison of CCM data with observations is required.
- Sensitivity studies with CCMs can verify the importance of specific processes and feedback mechanisms and therefore can help to understand the variability of the atmospheric system.
- Long-term CCM simulations (several decades) can support merging individual measurements (e.g. shorter satellite records) into a consistent long-term record and therefore providing additional information which cannot be received from the observations alone.
- More robust investigations can be carried out on the long term (e.g. identification of significant trends, their causes and effects).
- Cooperation between “observers” and “modellers” is essential!

Concluding remarks (2)

Stratospheric ozone

- Regional differences with respect to the timing of full recovery
- Strong impact of climate change
- Important changes are expected in the tropics (surface UV)

Stratosphere-troposphere downward coupling

- Strength of stratospheric disturbance is not important to receive significant responses in the troposphere
- Most important is the persistence of the stratospheric event
- In about 20% of the extreme cases the troposphere is clearly affected

Stratospheric water vapour

- Fluctuations are driven by SST variability and El Nino/La Nina events
- No significant trend is found in the last 50 years
- Future increase due to climate change is expected