Atmospheric Physics: Experiment meets Modelling

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Introduction to stratospheric modelling: **Chemistry-Climate connections**

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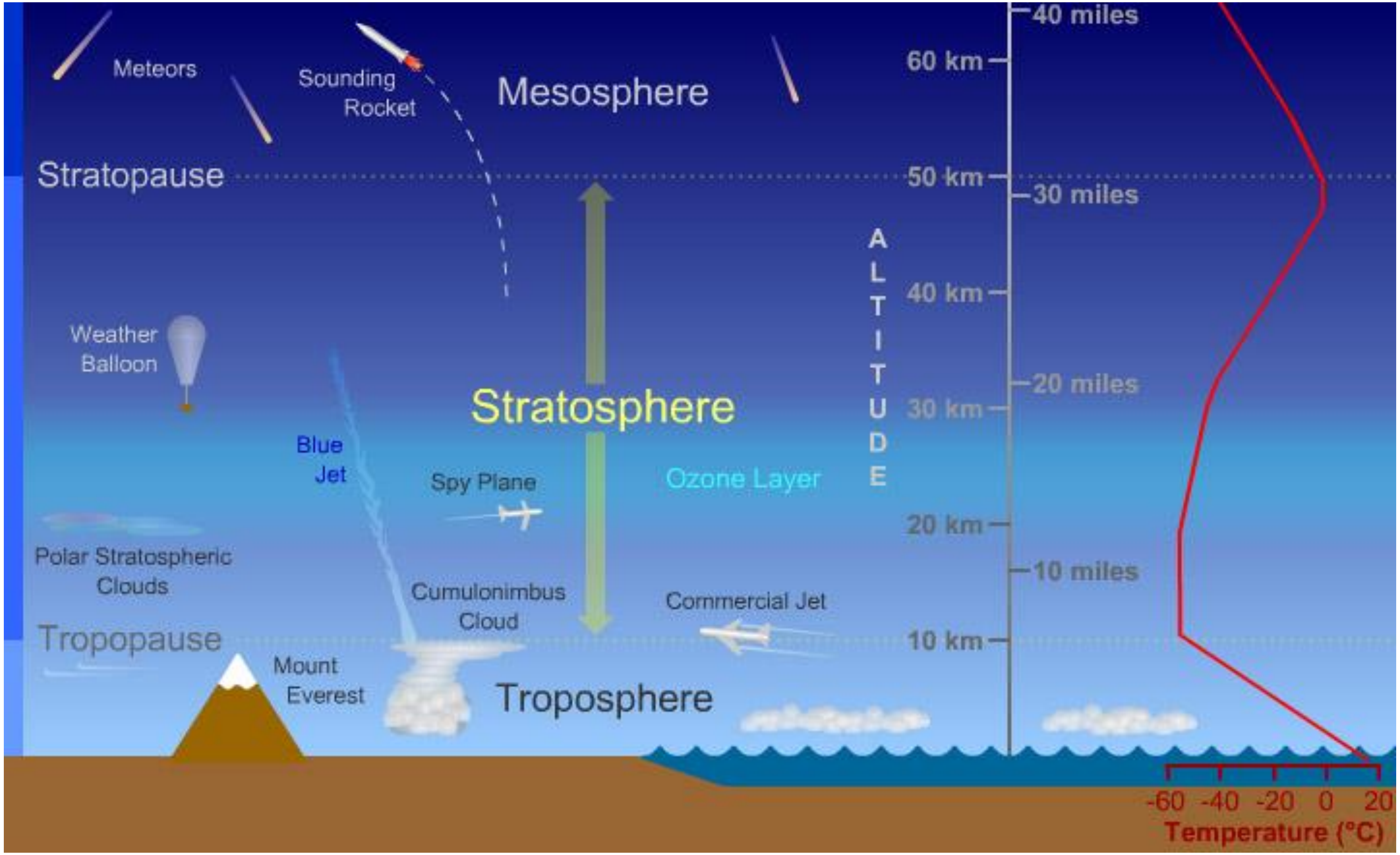
Introduction to stratospheric modelling:
Chemistry-Climate connections

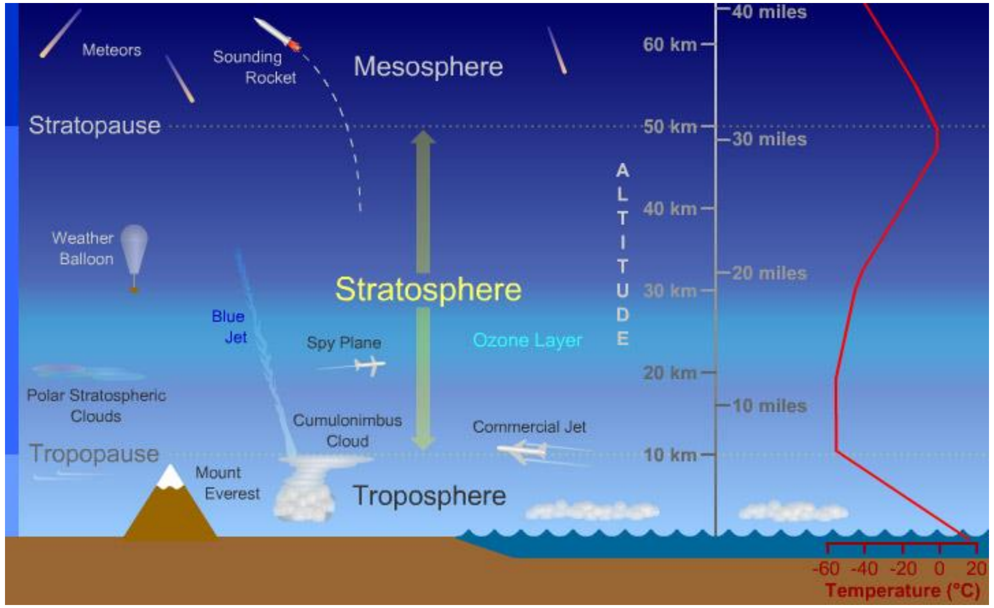
Outline

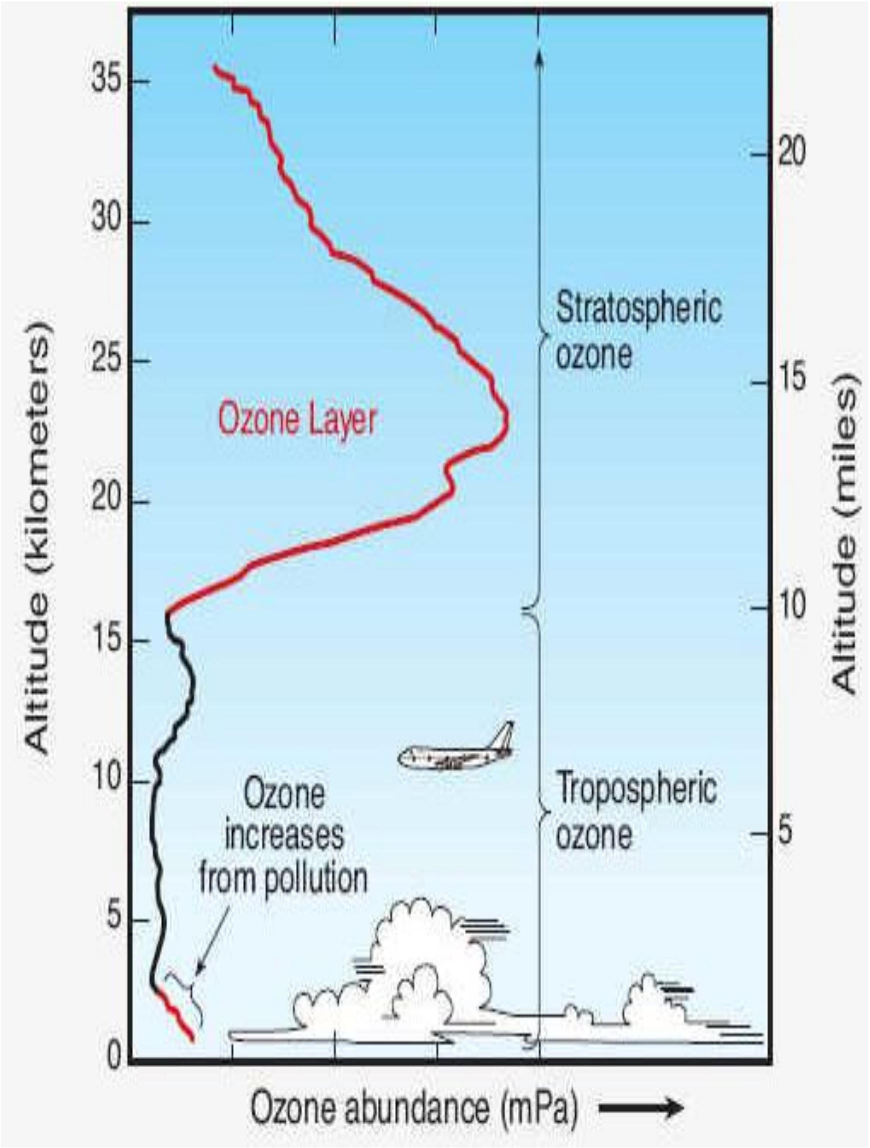
- What is the stratosphere? A short introduction
- Numerical models of the atmosphere
- Current research on chemistry-climate connections: Example of the stratospheric ozone layer

The stratosphere



The stratosphere





- 90% of atmospheric ozone is in the stratosphere (about 75% is between 15 and 30 km).
- Absorption of solar UV-radiation (100-380 nm).
- Ozone is an important radiative active gas (greenhouse gas) $\Rightarrow$ Absorption and emission of infrared (IR) radiation.

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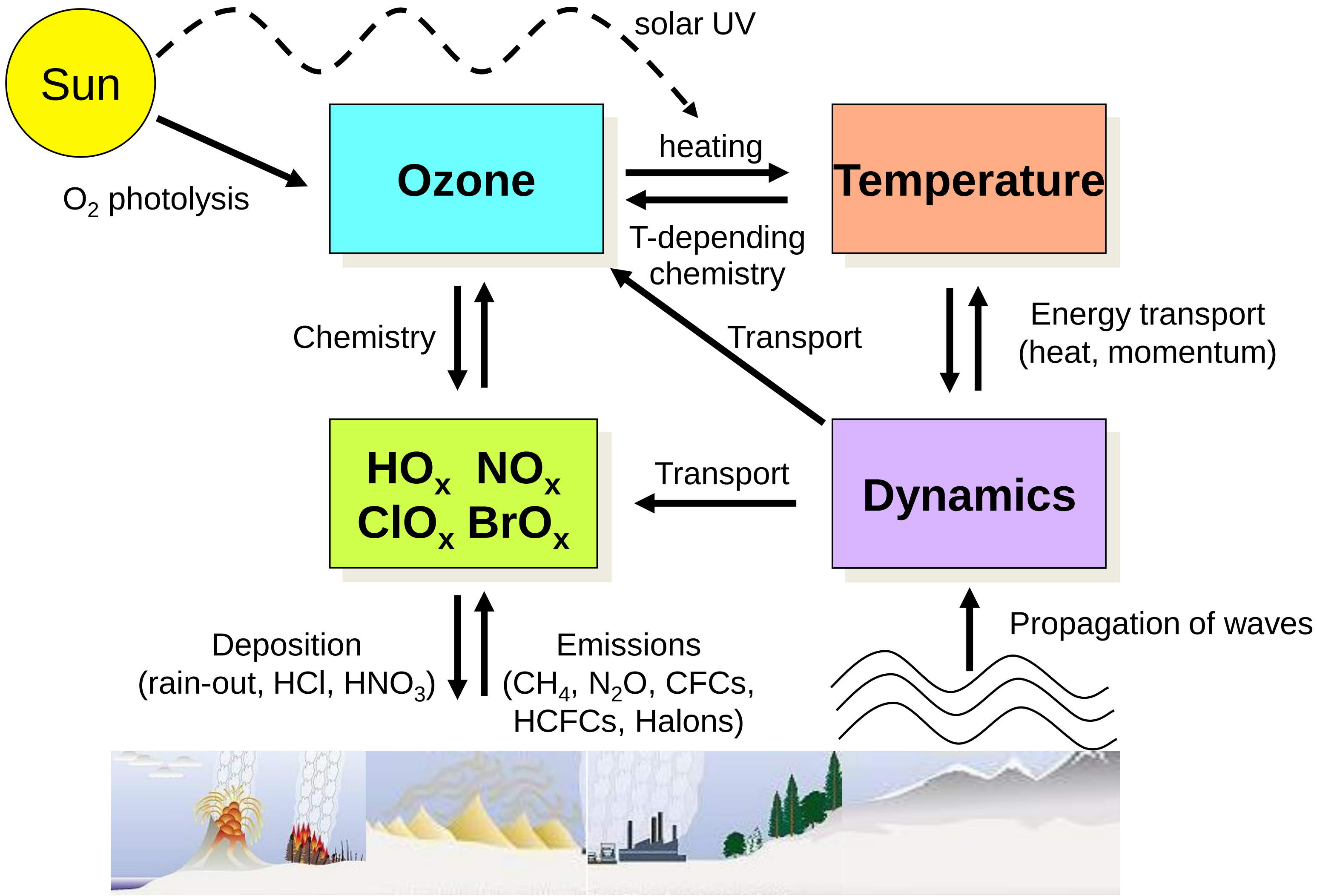
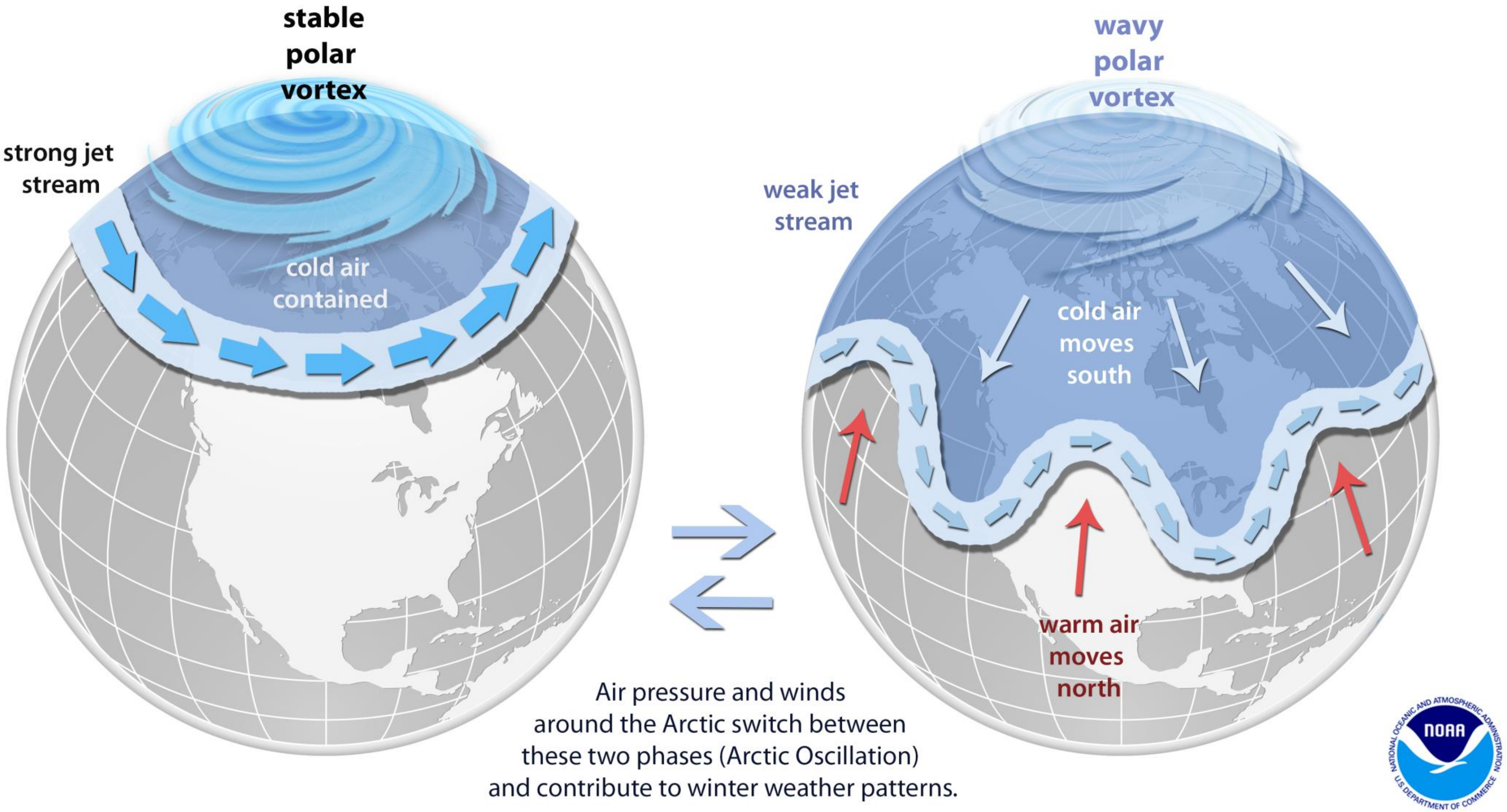
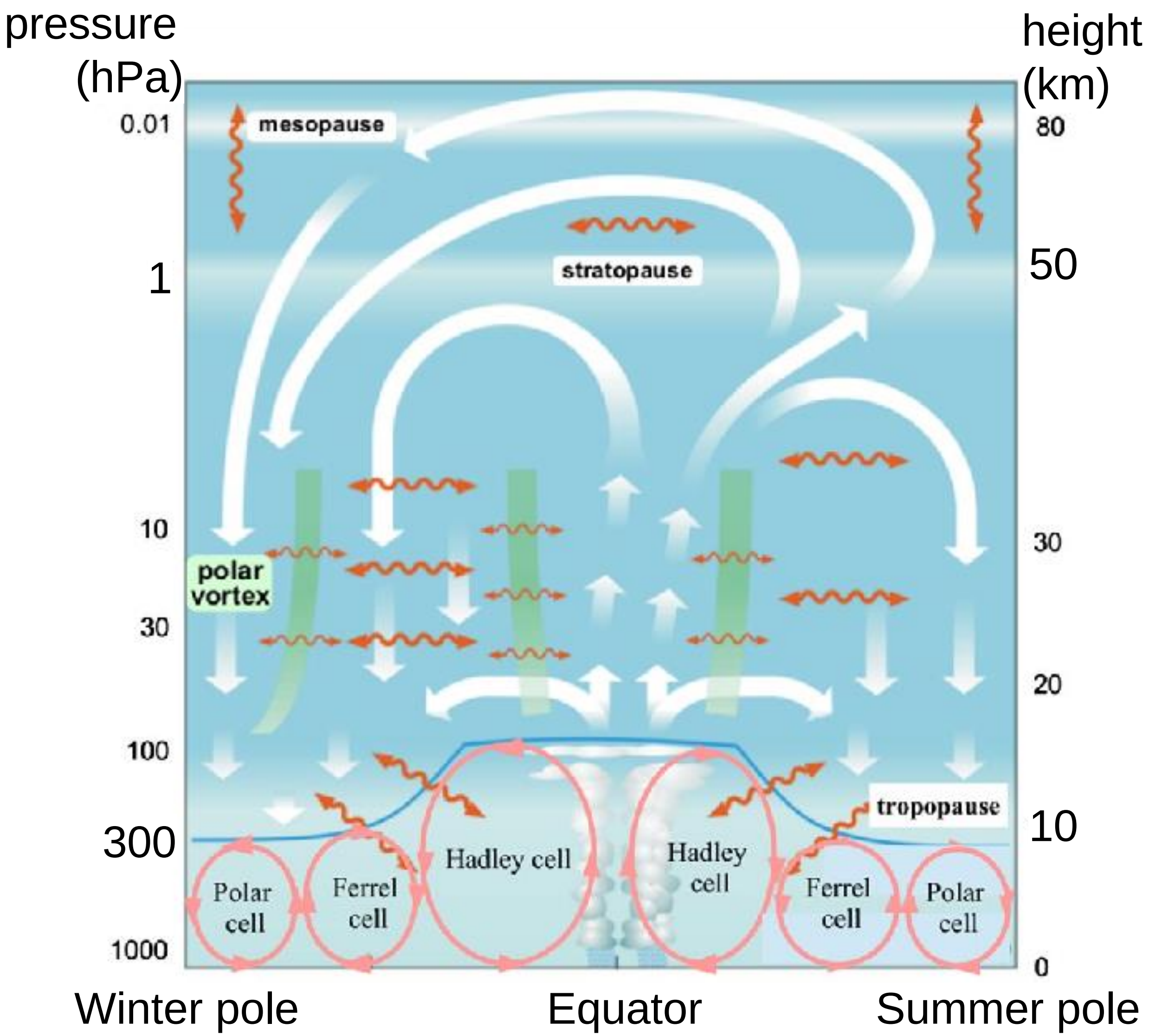
Schematic of the stratospheric system



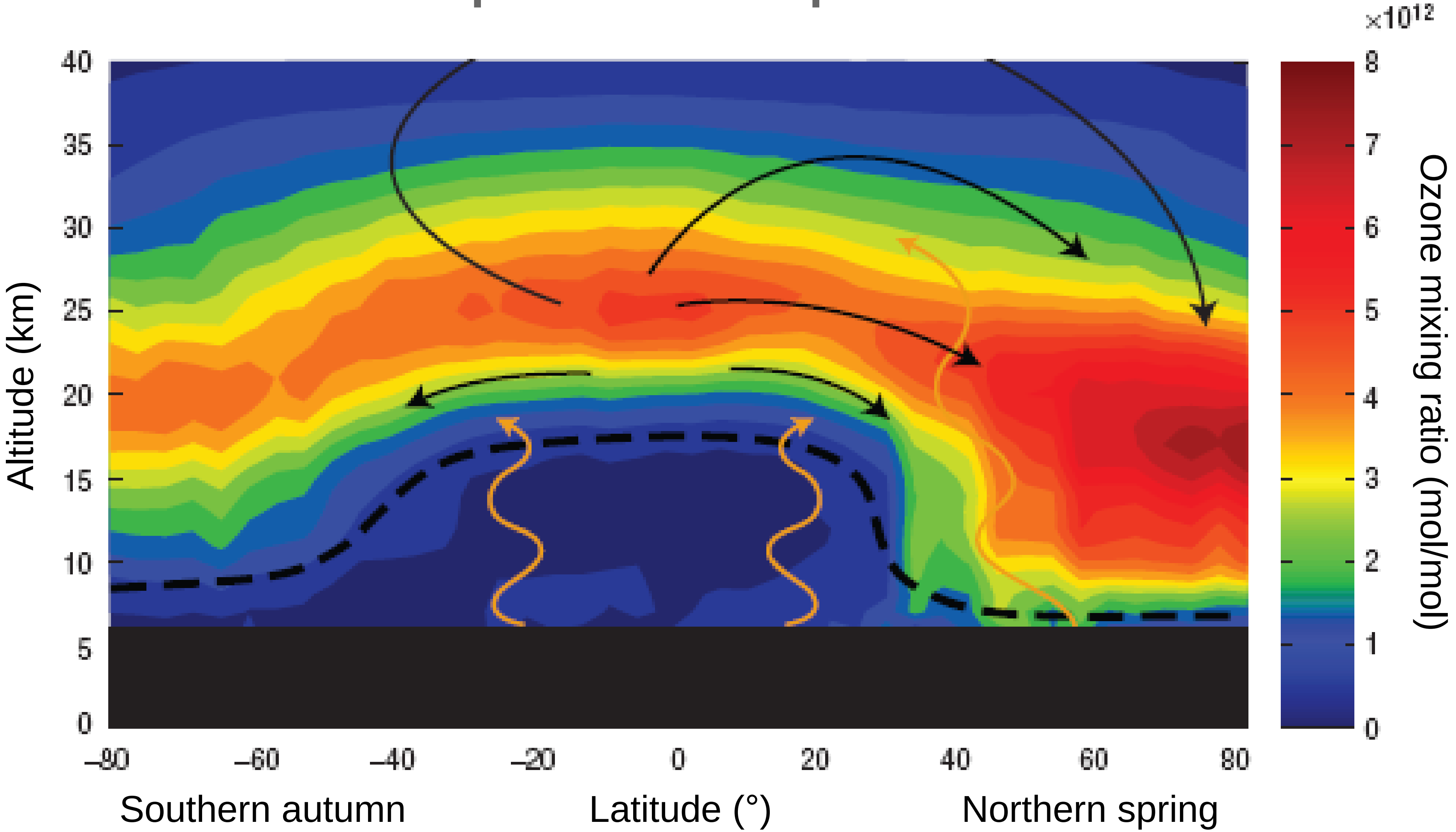
The stratospheric Northern Hemisphere polar vortex in winter



The meridional circulation of the stratosphere

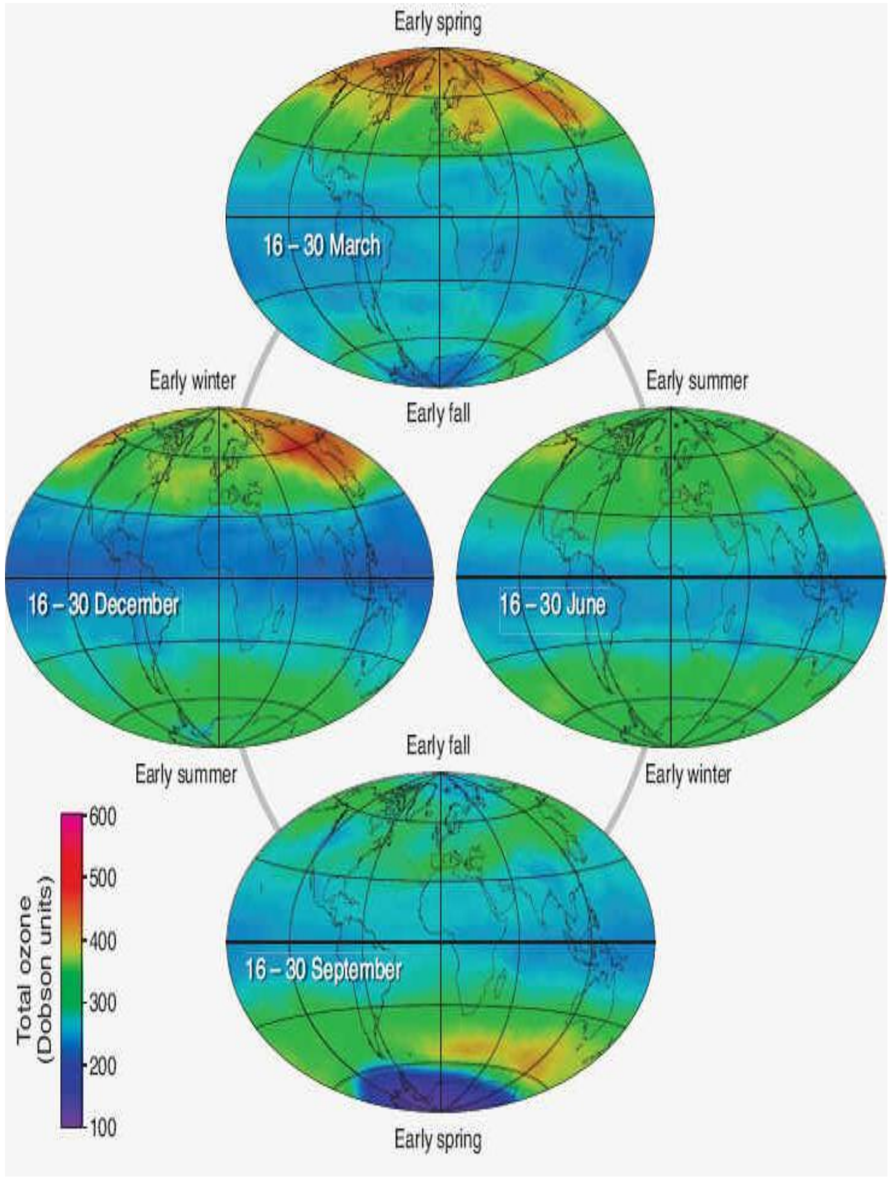


Transport of stratospheric ozone



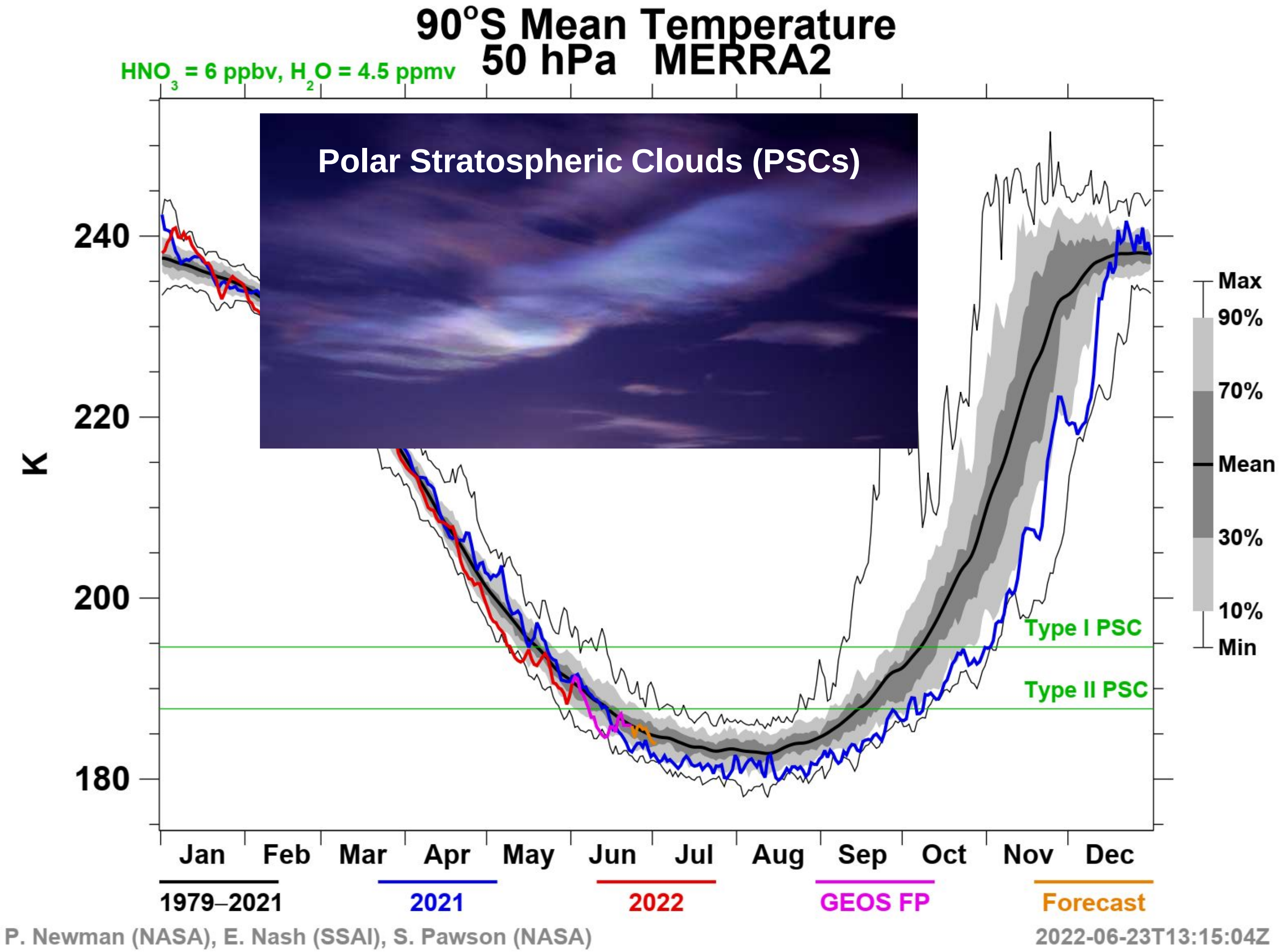
Shaw and Shepherd, 2007

Total column ozone distribution for the four seasons (Unit: Dobson Unit)



Example: 2009

Variability of stratospheric dynamics



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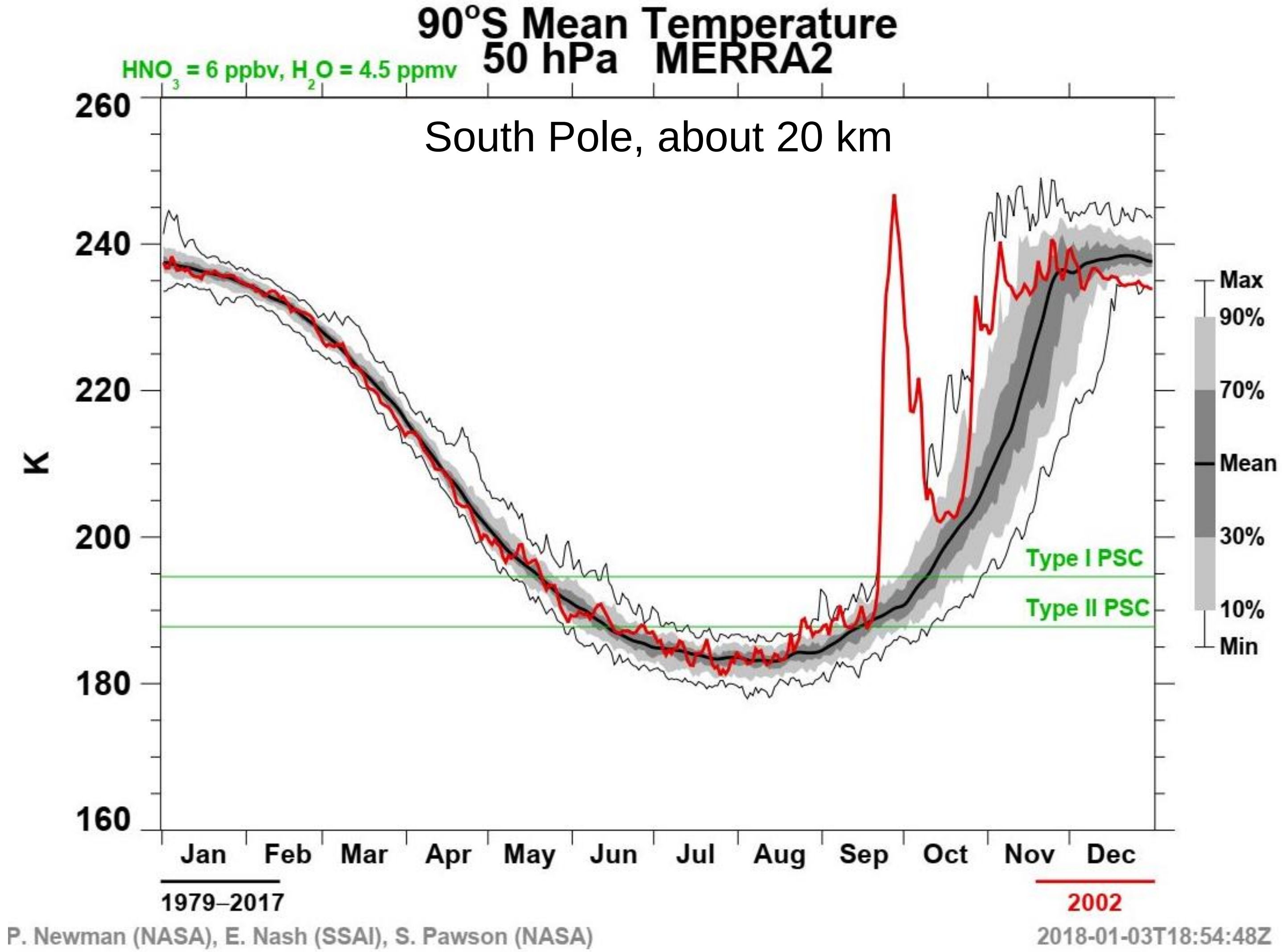
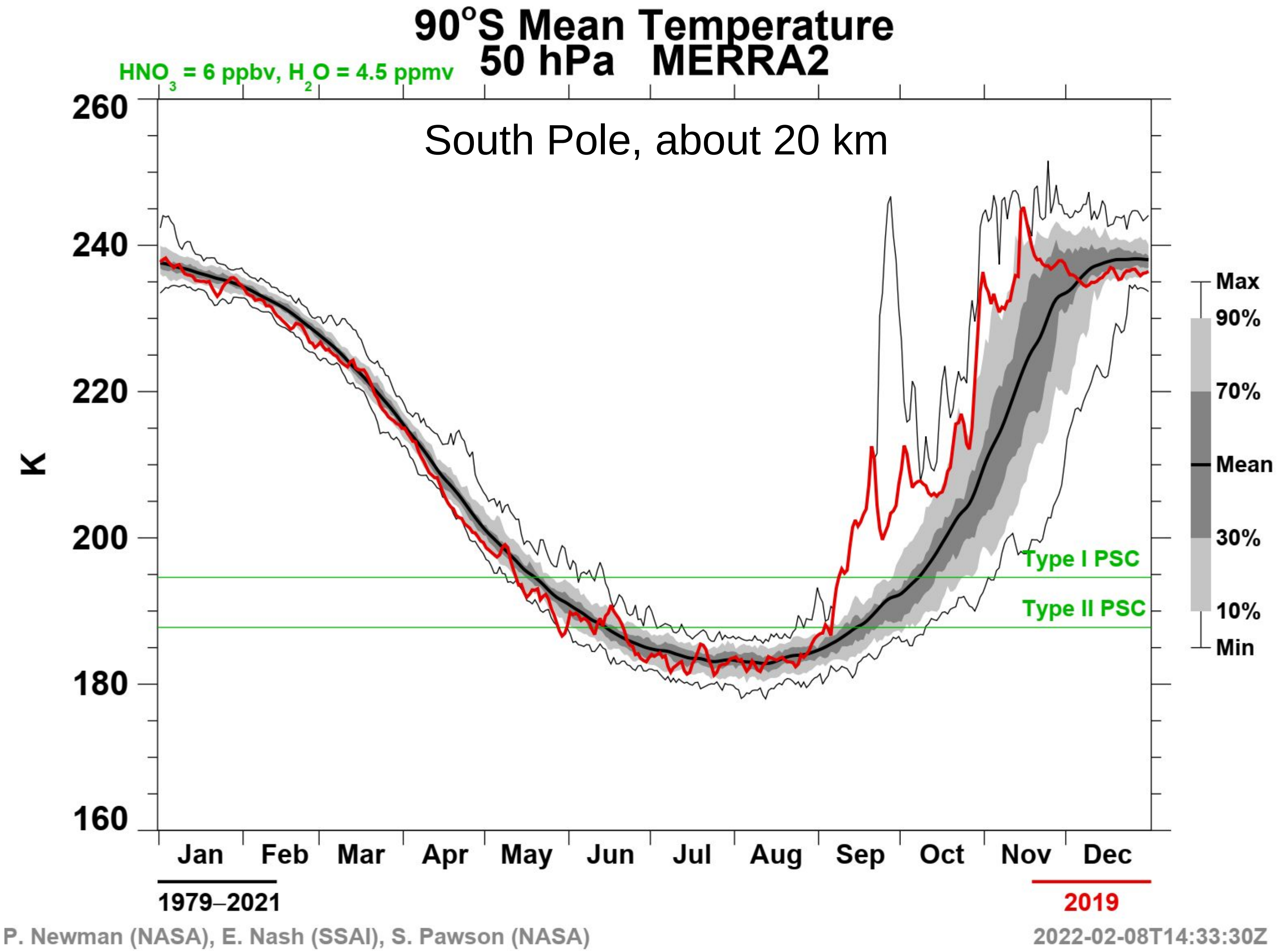
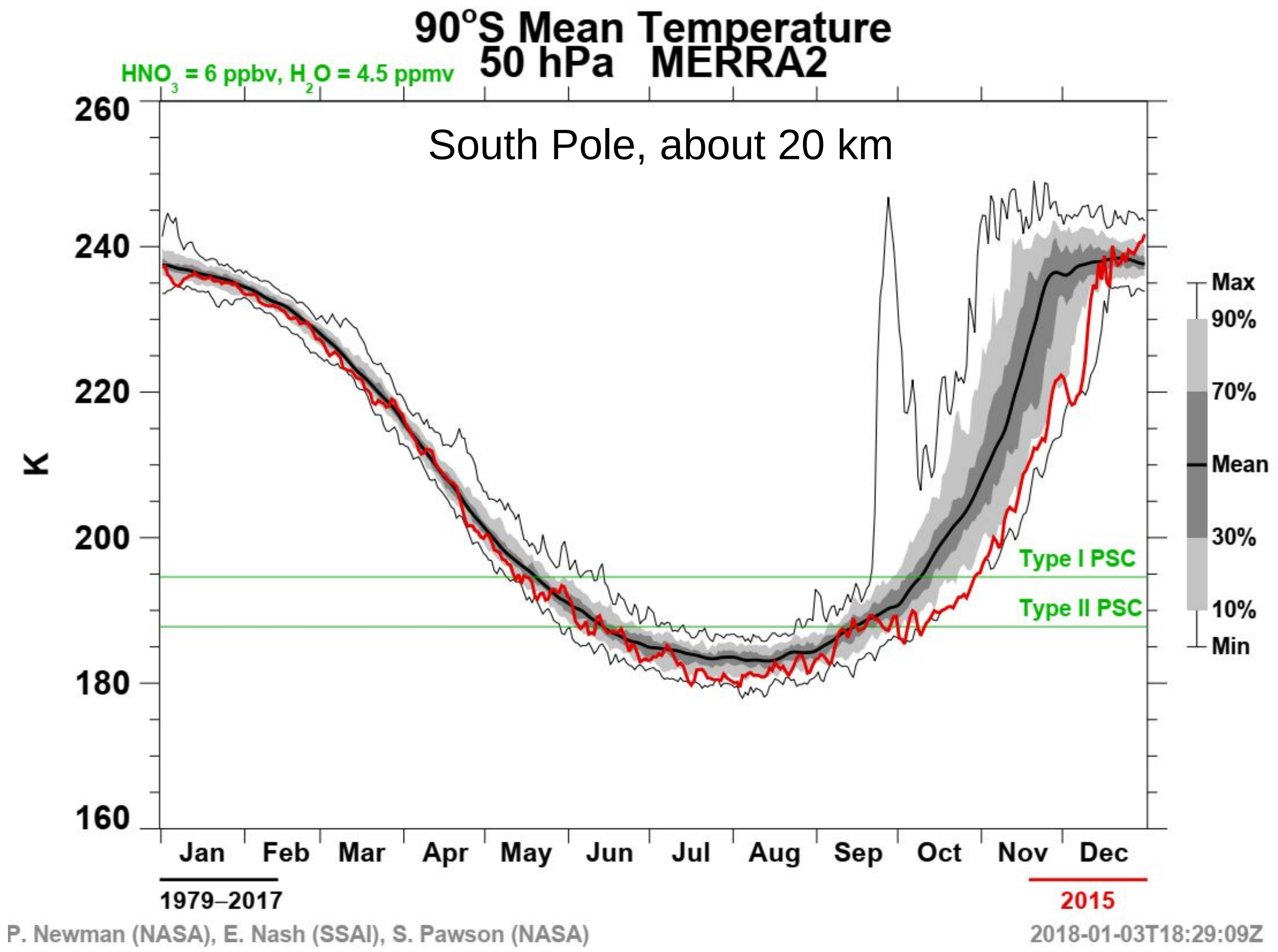
Variability of stratospheric dynamics



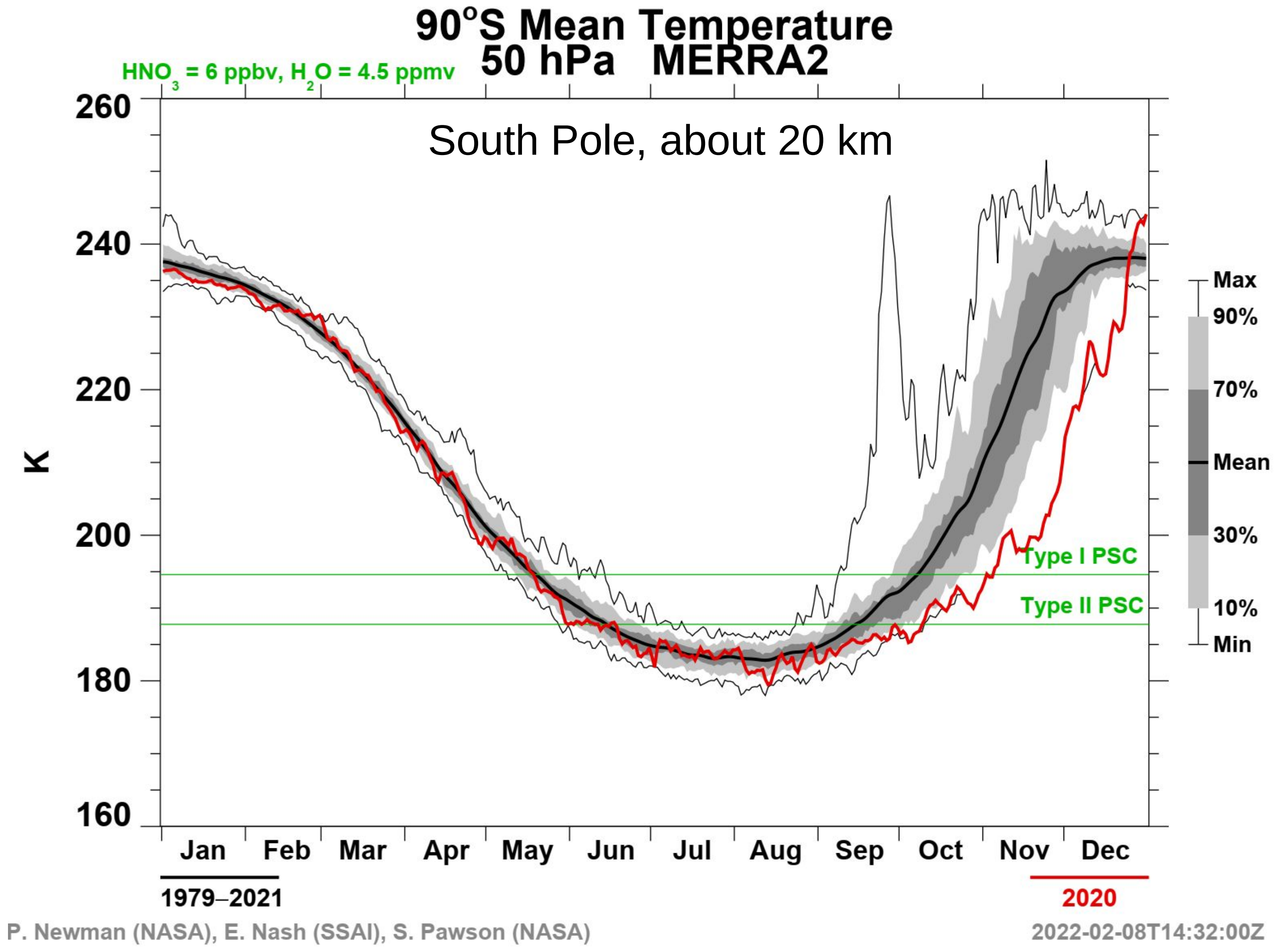
Variability of stratospheric dynamics



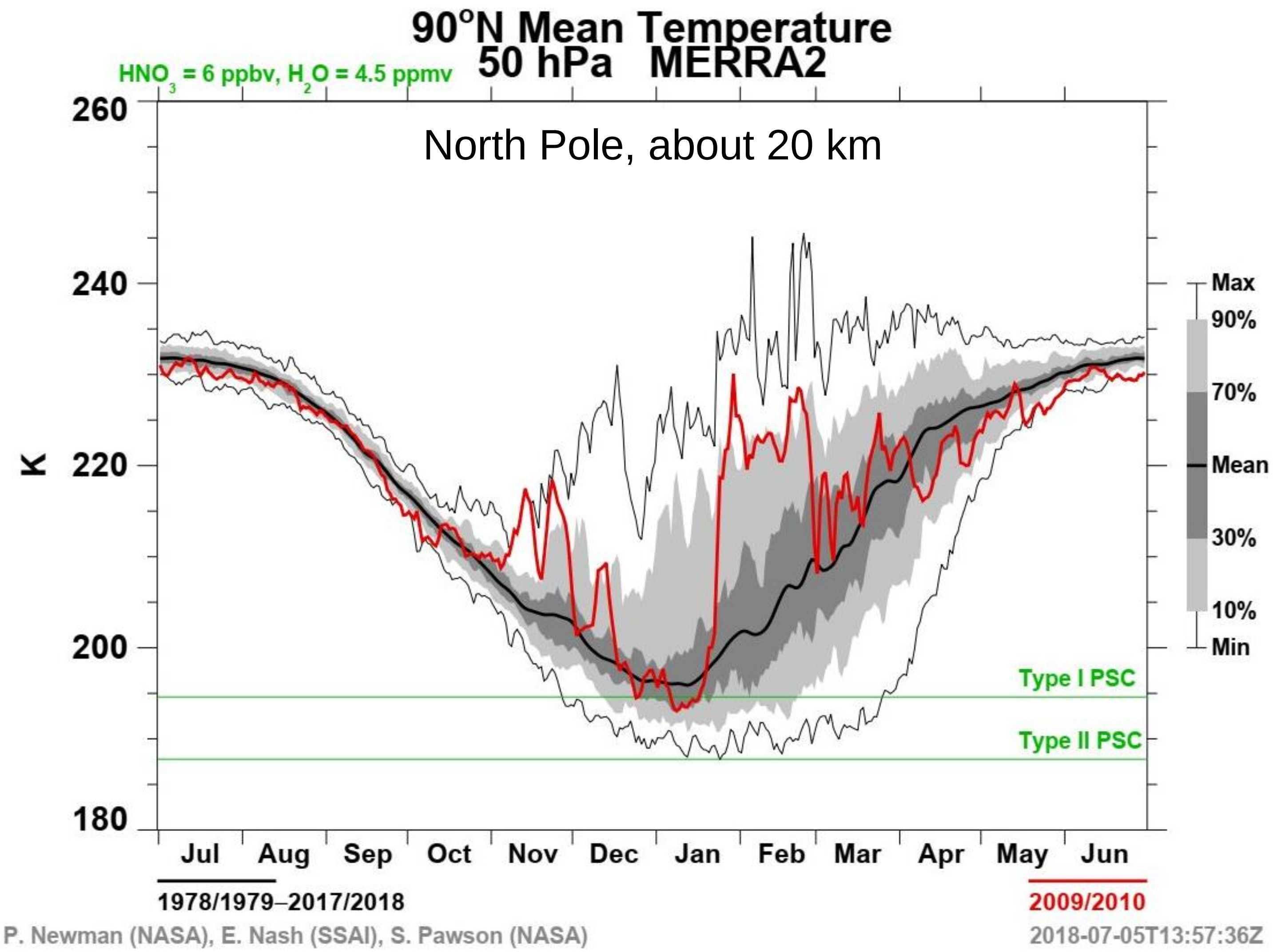
Variability of stratospheric dynamics



Variability of stratospheric dynamics



Variability of stratospheric dynamics



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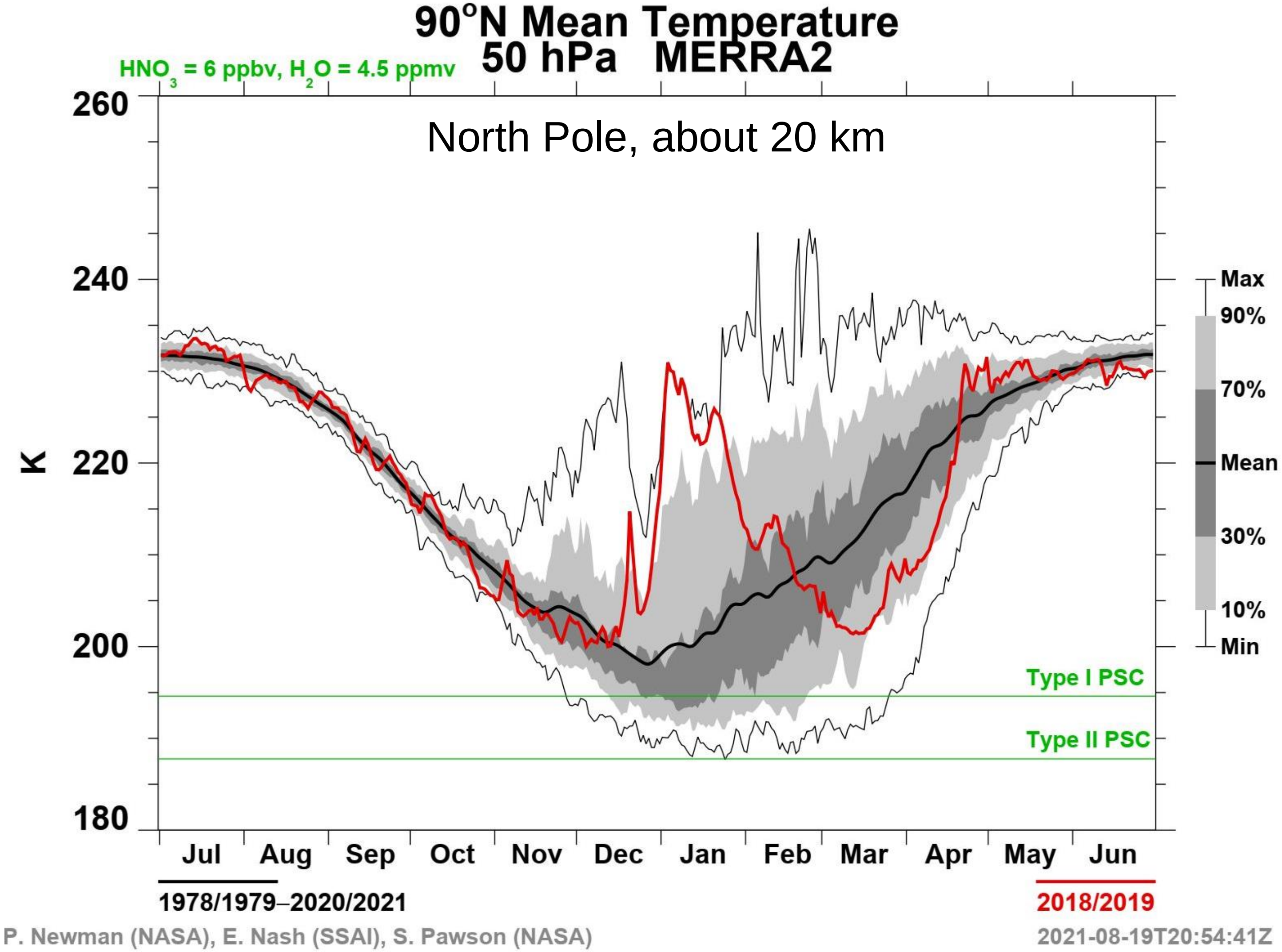
Variability of stratospheric dynamics



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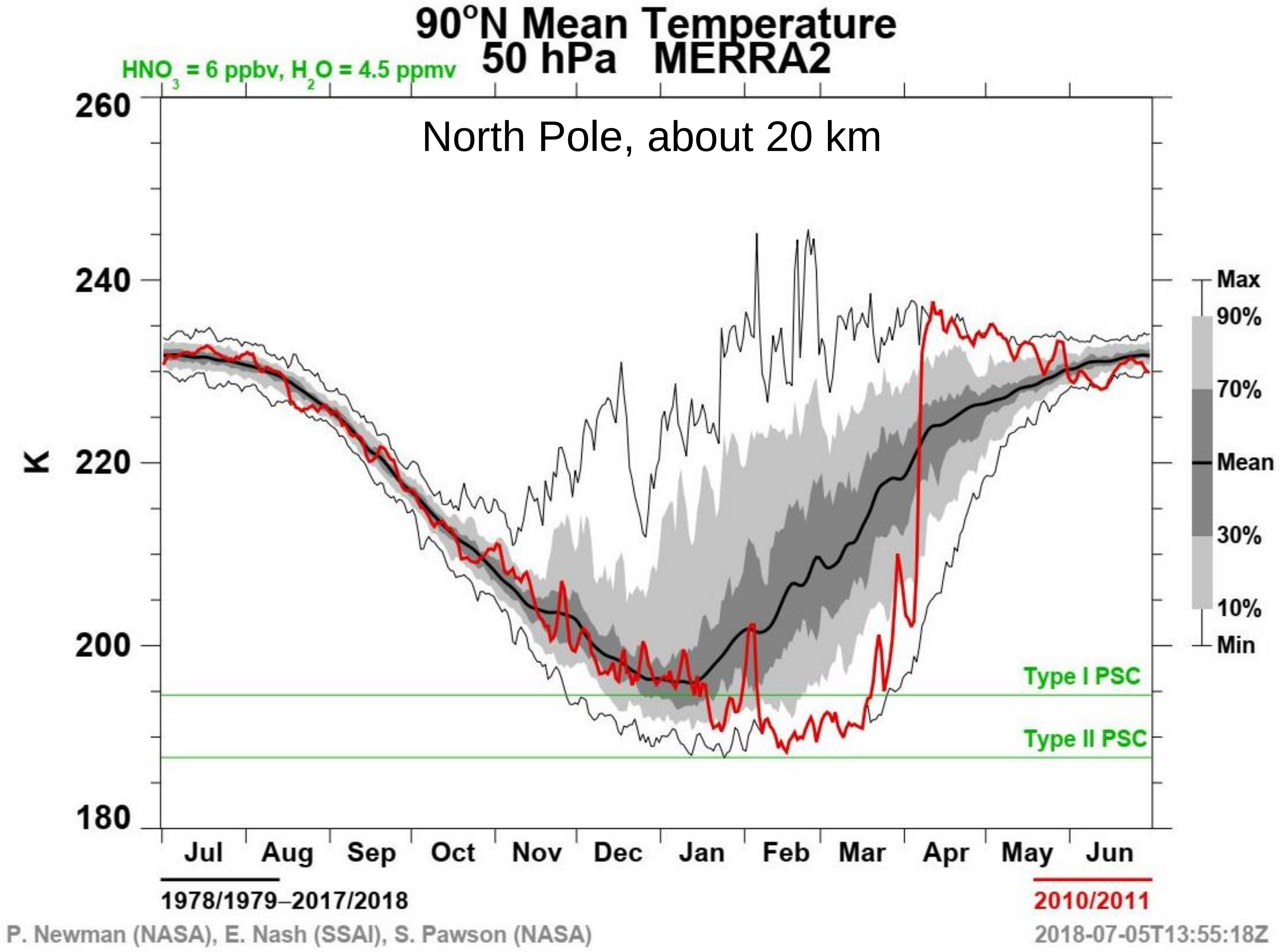
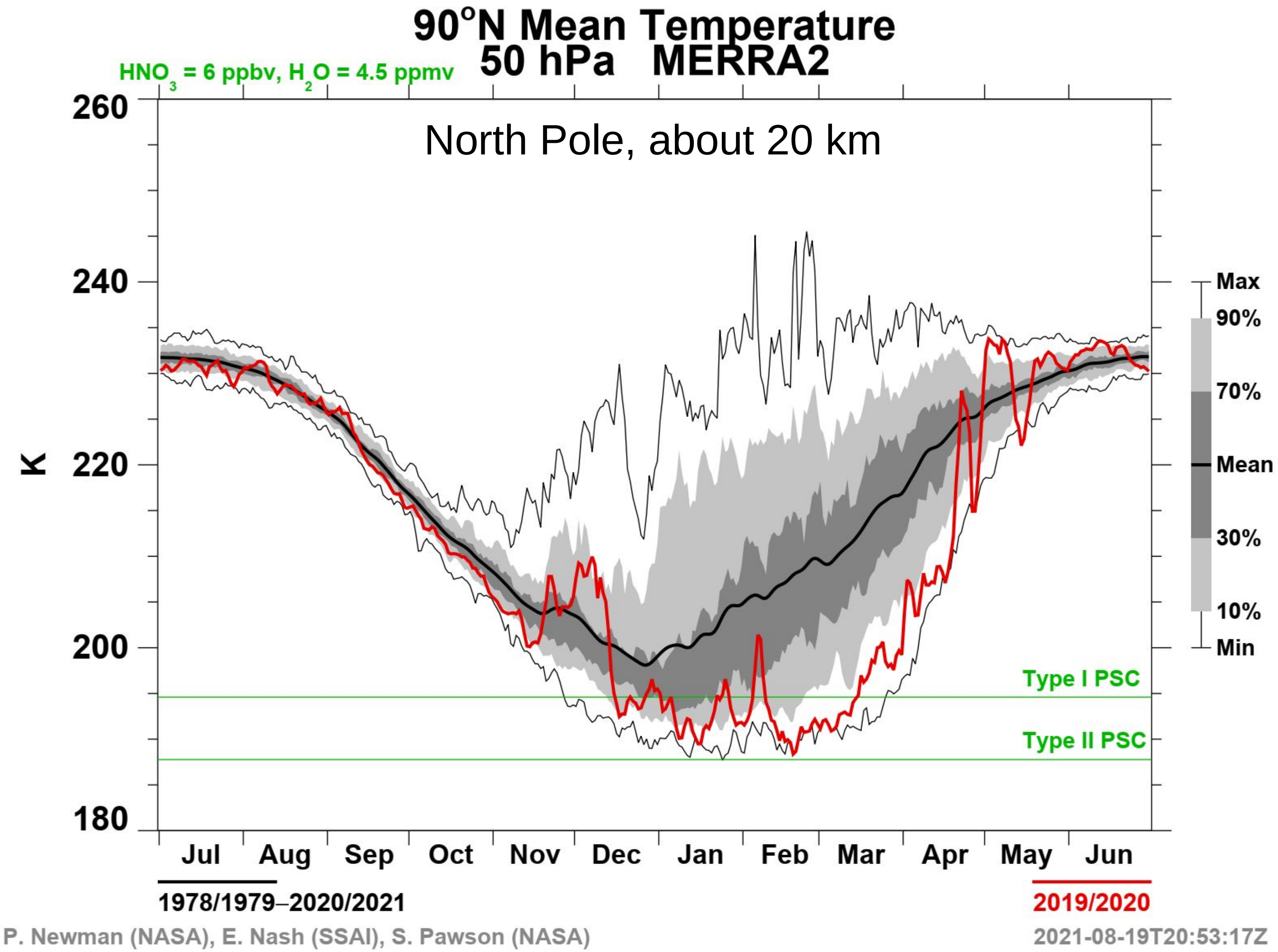
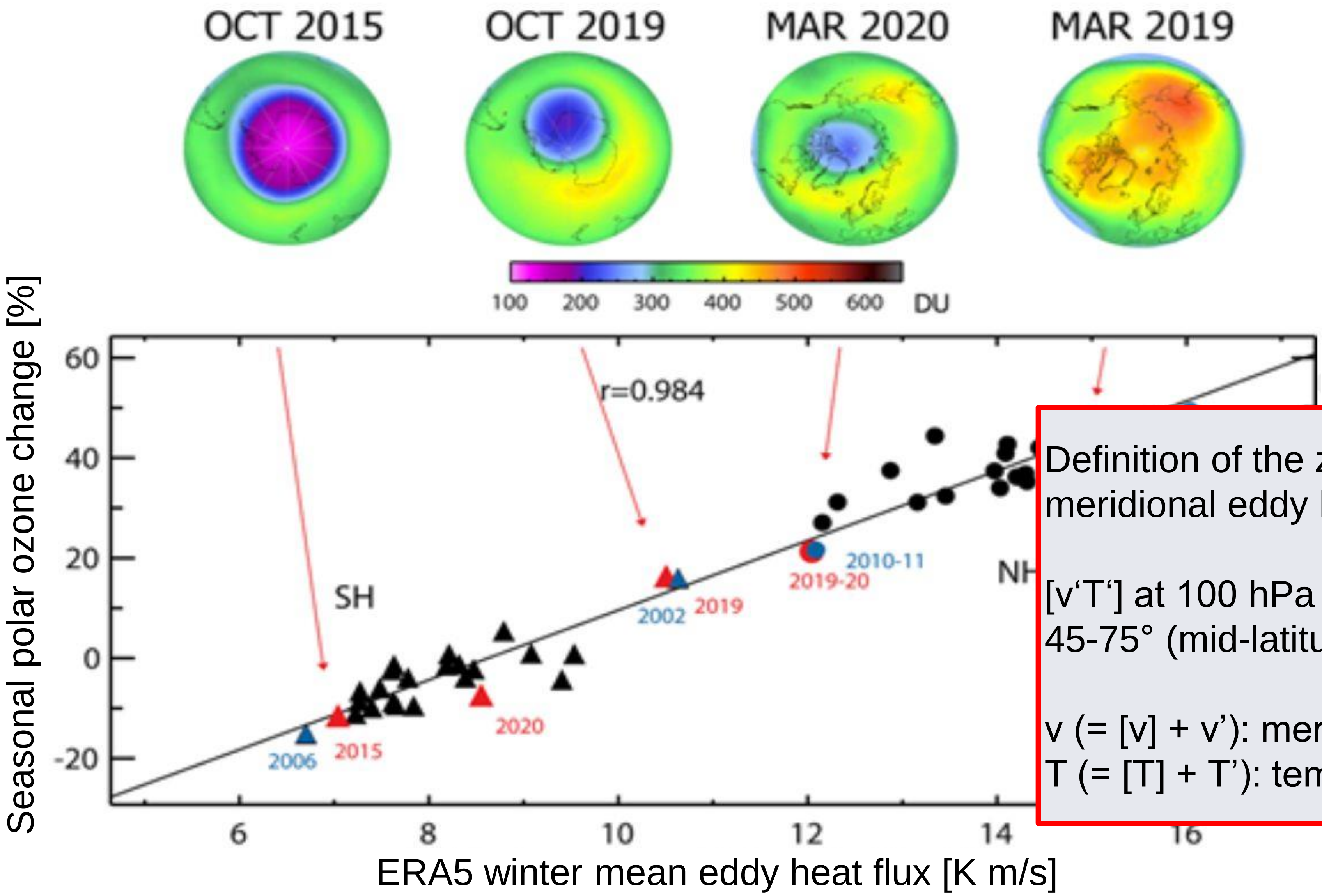
Variability of stratospheric dynamics



Variability of stratospheric dynamics



Variability of polar ozone: Impact of stratospheric dynamics



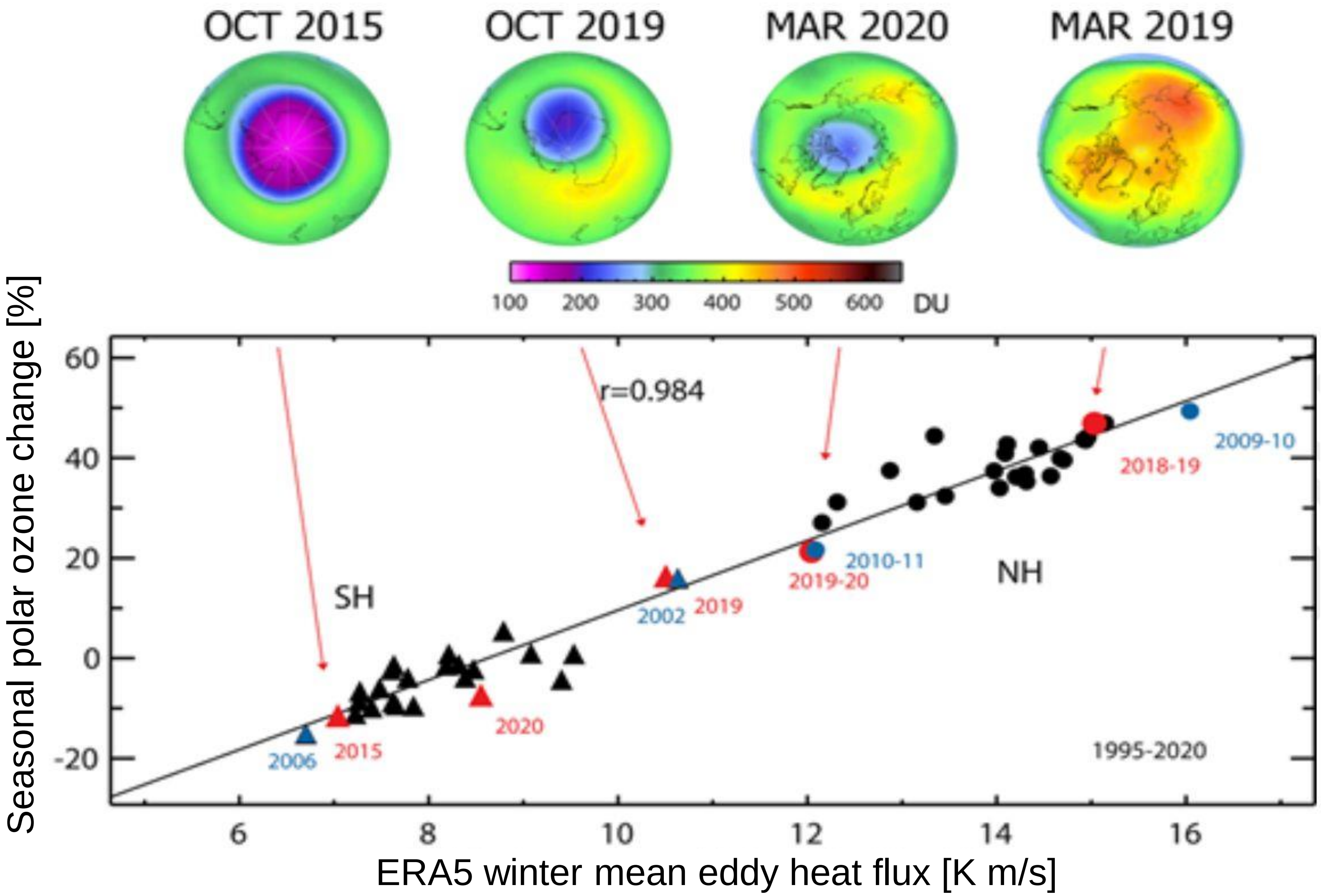
Definition of the zonal mean meridional eddy heat flux:

[v'T'] at 100 hPa (pressure level), 45-75° (mid-latitude), winter values

v (= [v] + v'): meridional wind speed
T (= [T] + T'): temperature

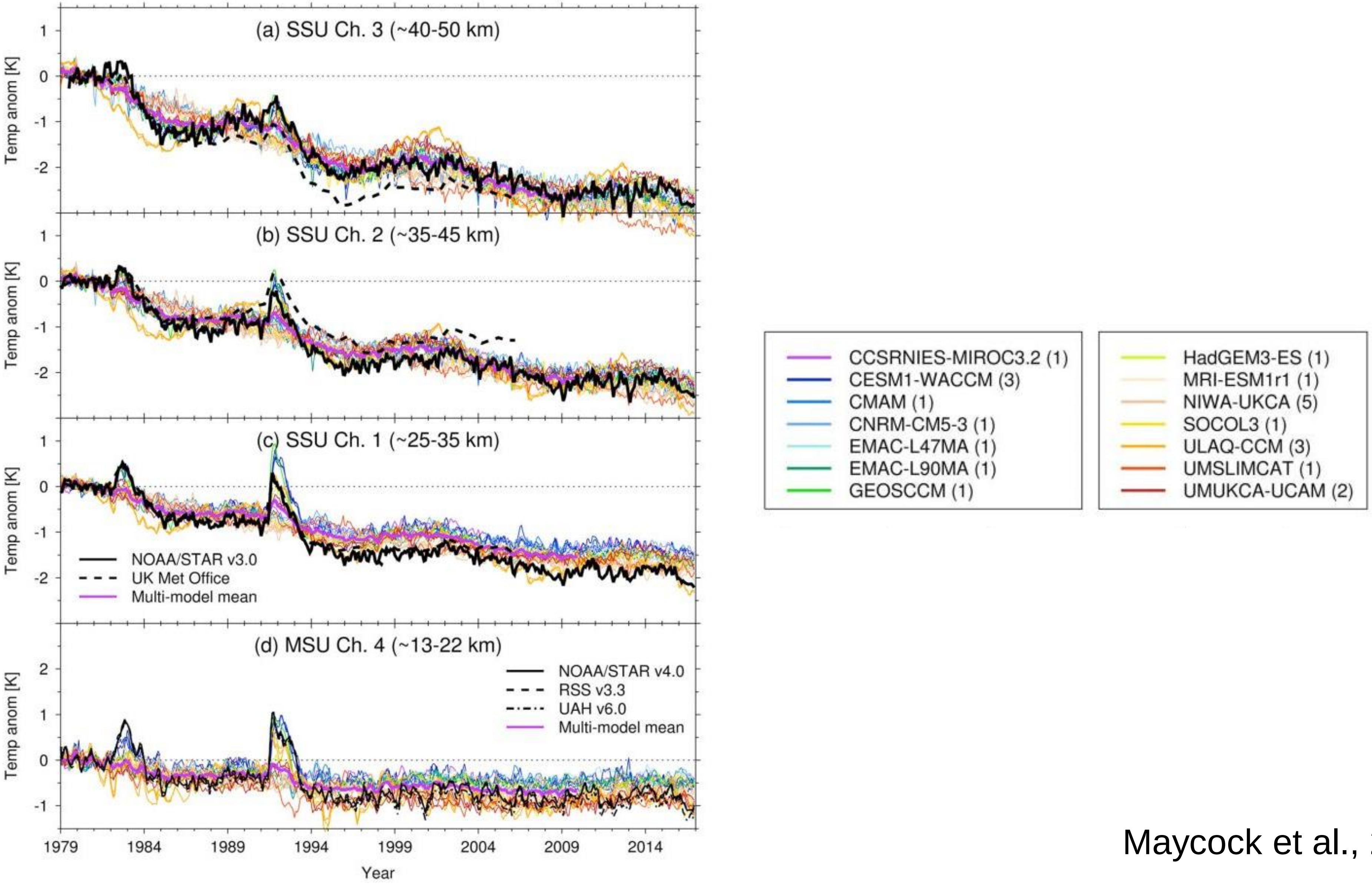
WMO, 2022

Variability of polar ozone: Impact of stratospheric dynamics



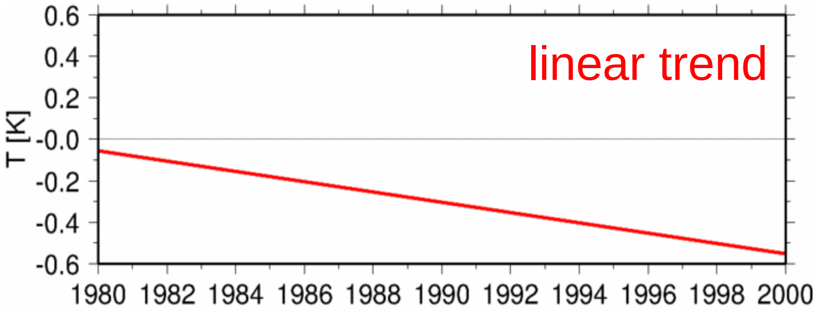
WMO, 2022

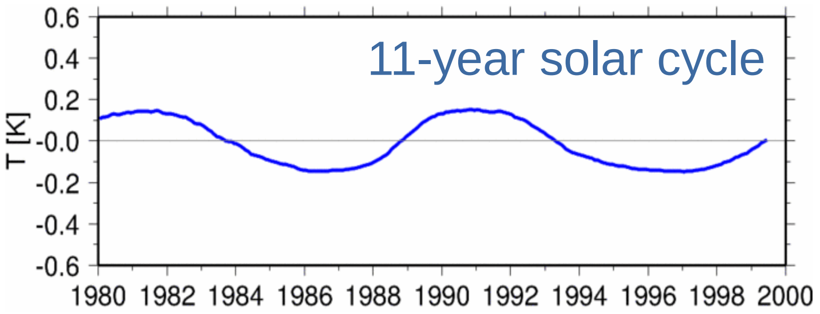
Recent stratospheric temperature changes

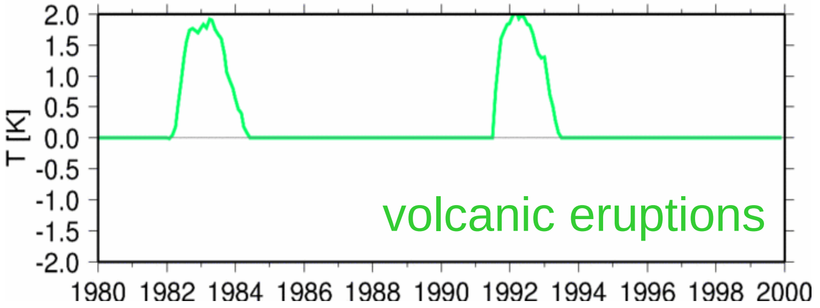


Maycock et al., 2018

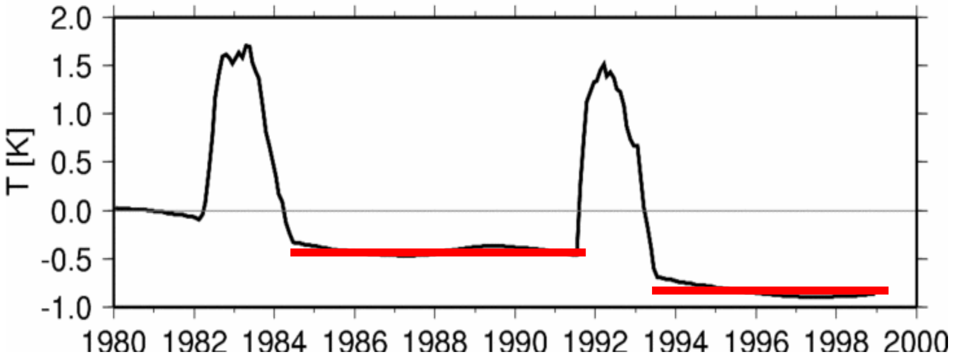
Recent stratospheric temperature changes







trend + solar cycle + volcanoes



⇨ „step-like" cooling of the stratosphere

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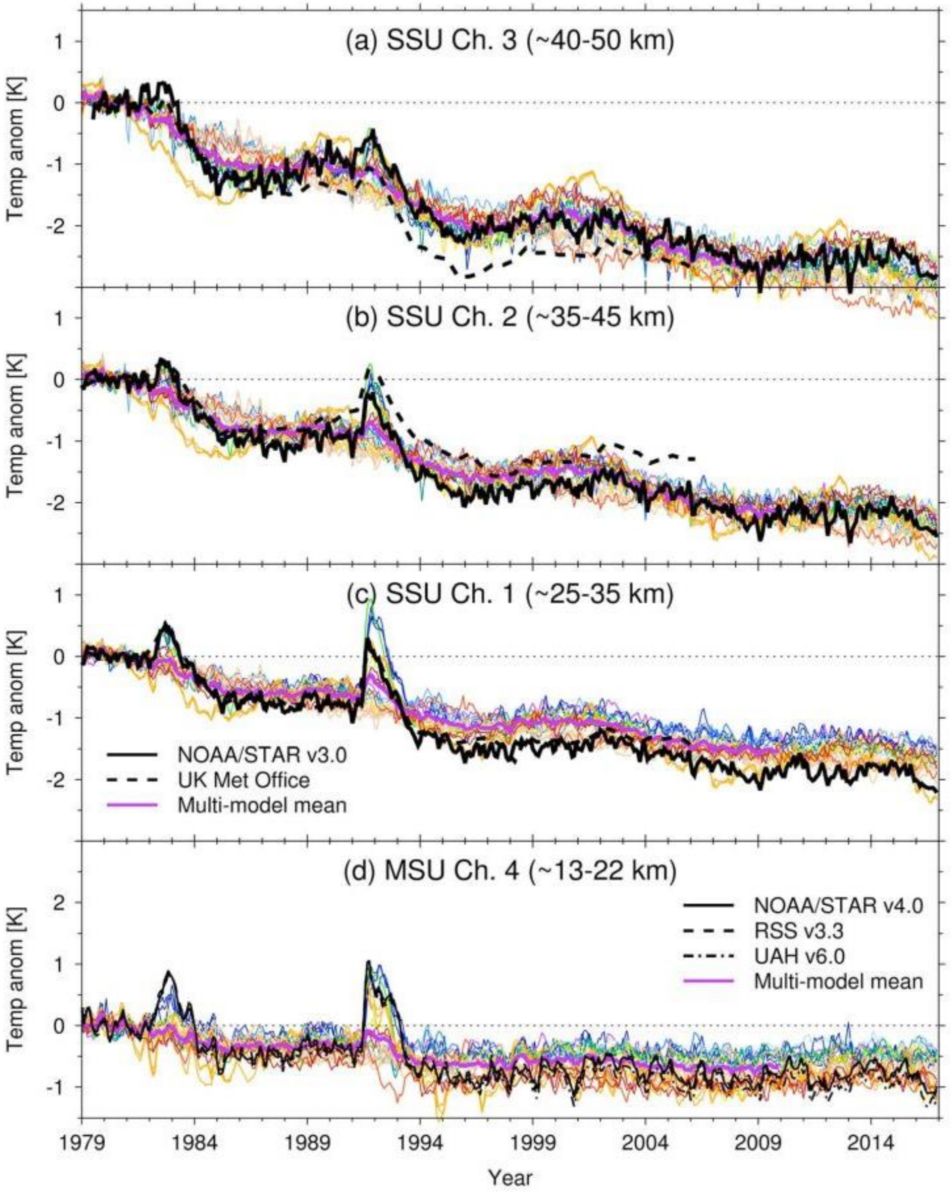
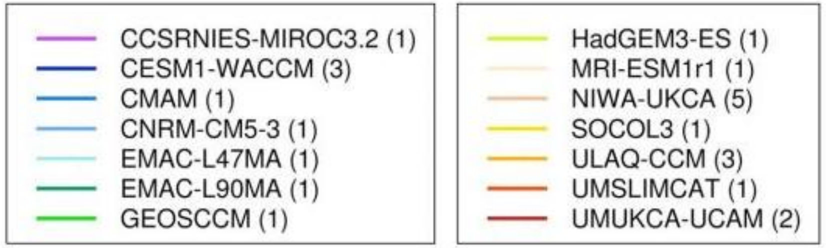
Recent stratospheric temperature changes



In the stratosphere, increased concentrations of greenhouse gases result in net cooling because they emit more infrared (IR) radiation into space than they absorb.



The emission of IR radiation increases with local temperature (σT^4). Therefore, the cooling effect increases with altitude, reaching a maximum at the stratopause where temperatures are highest.

Maycock et al., 2018

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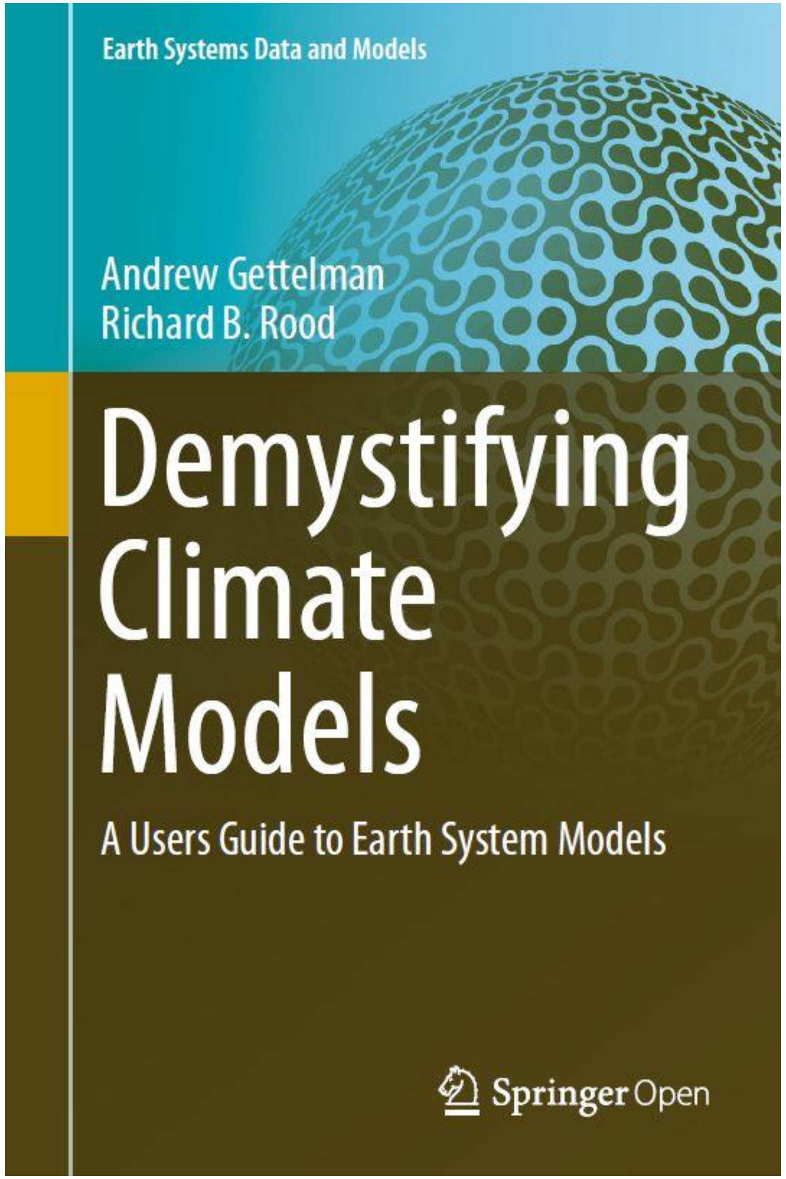
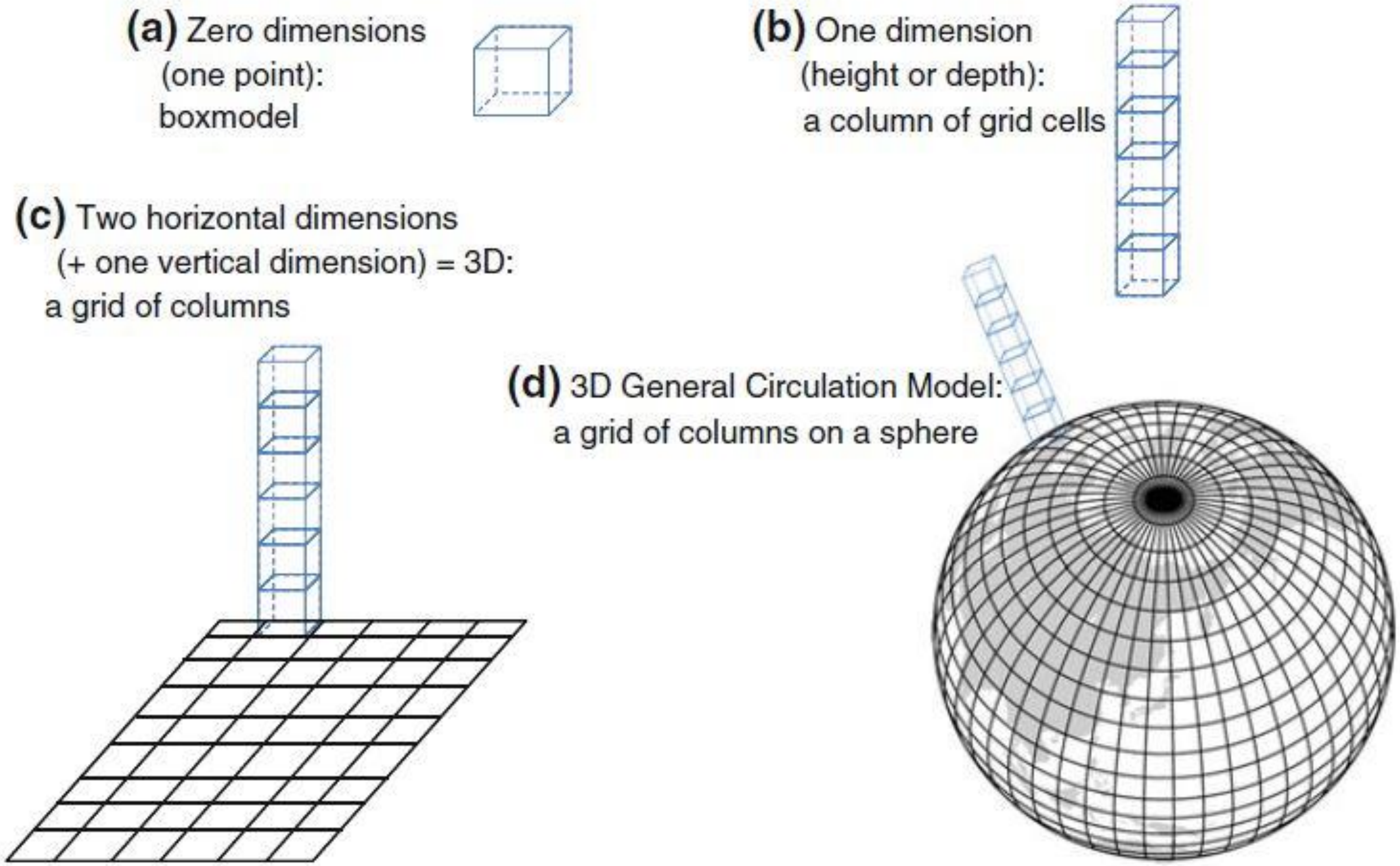


Freely
available

https://link.springer.com/book/10.1007/978-3-662-48959-8

Dimensions of atmospheric models



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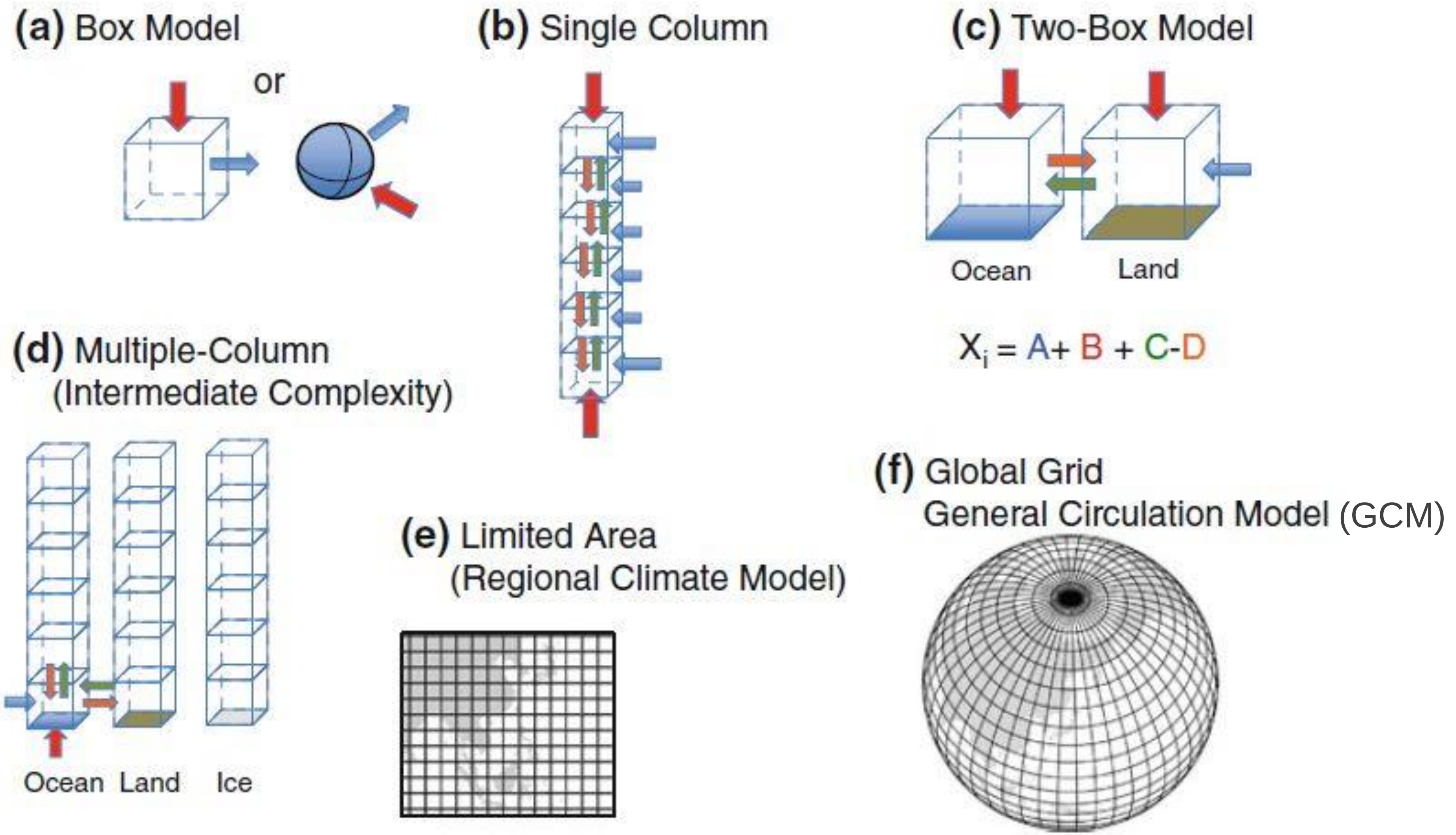
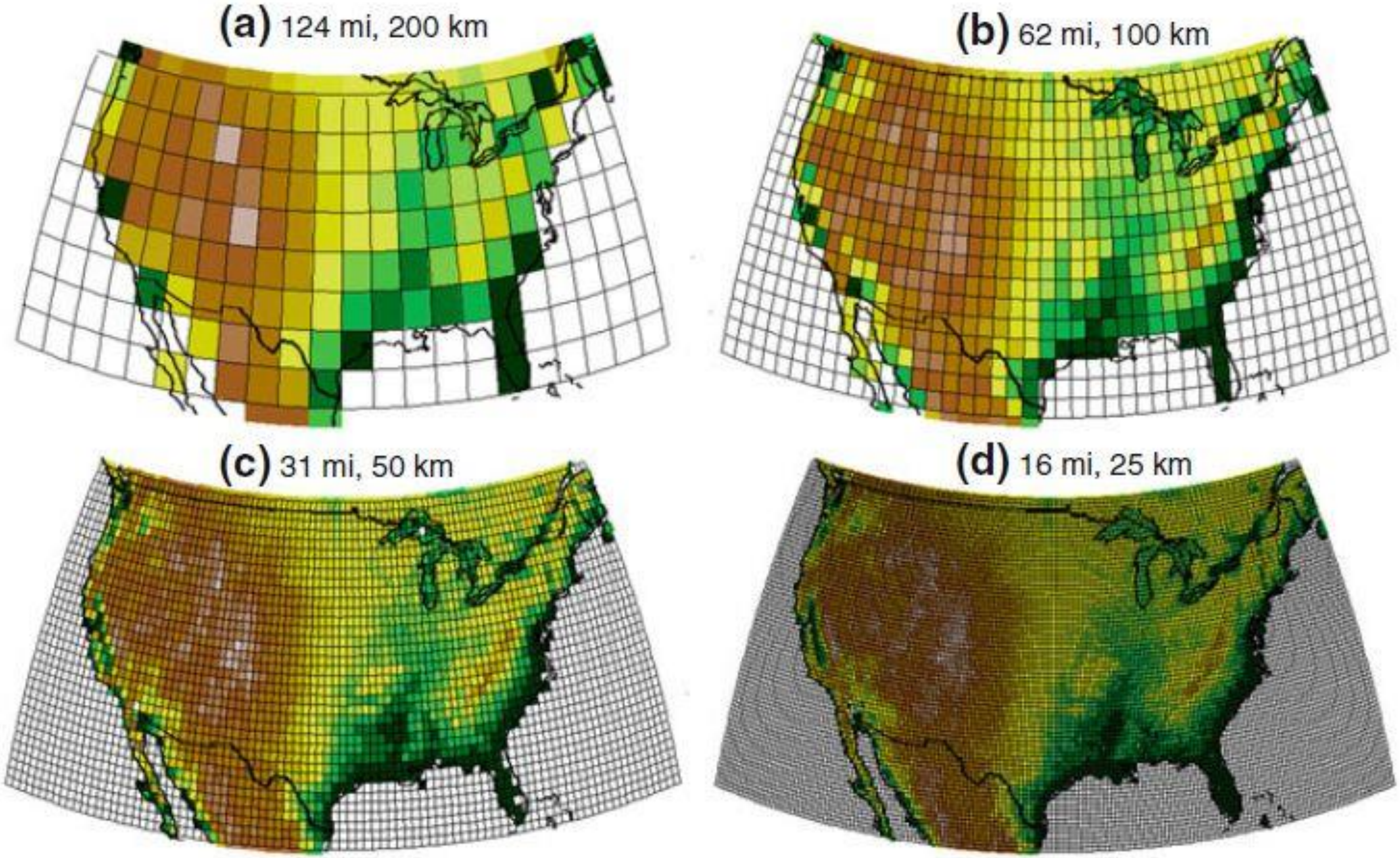
Hierarchy of atmospheric models



Horizontal resolution of regional and global models



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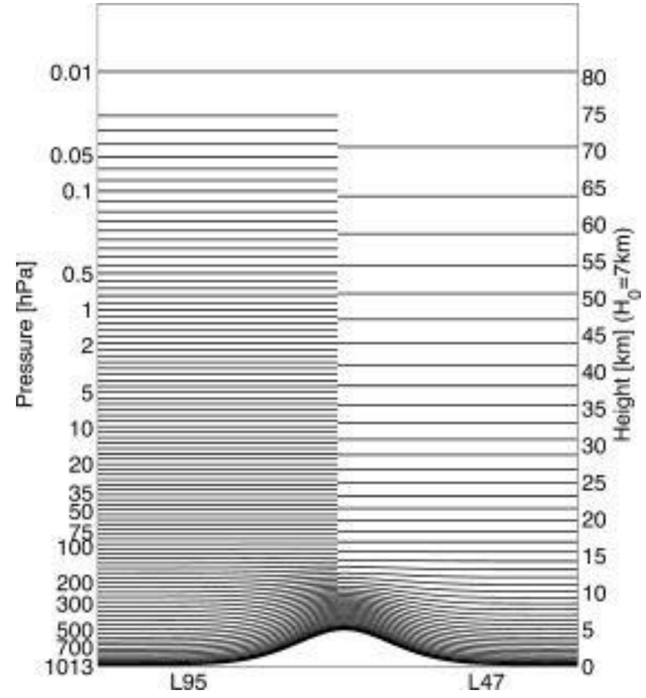
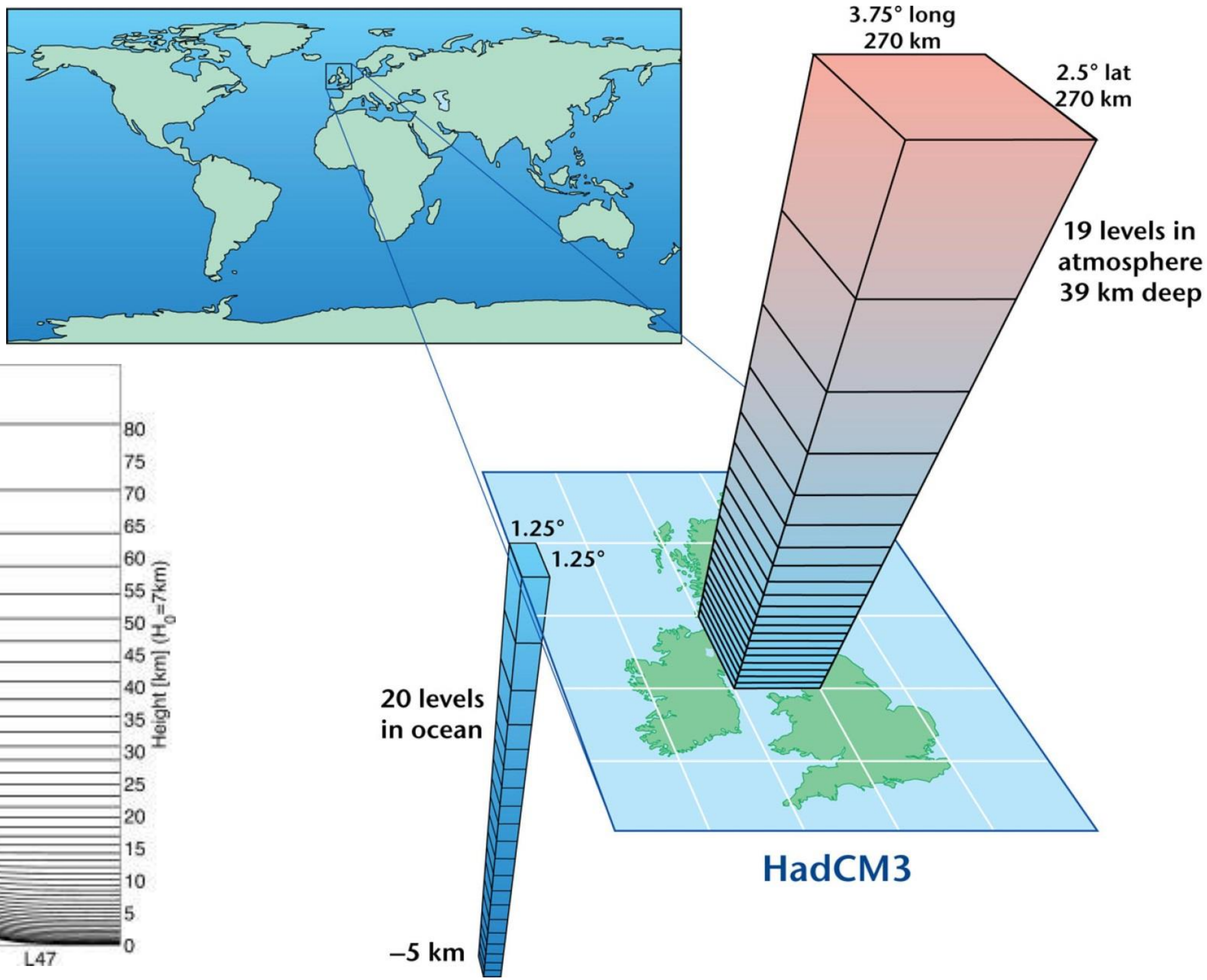
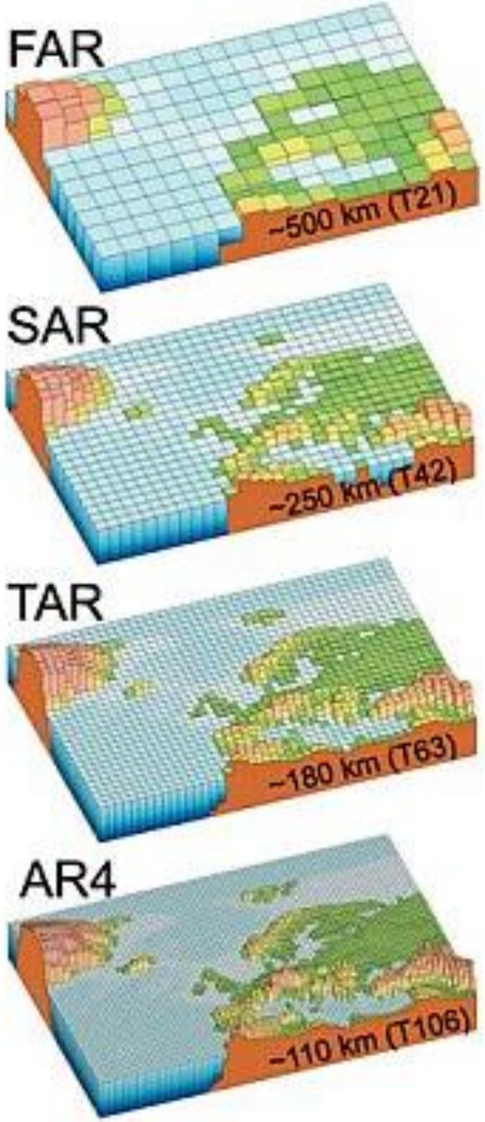
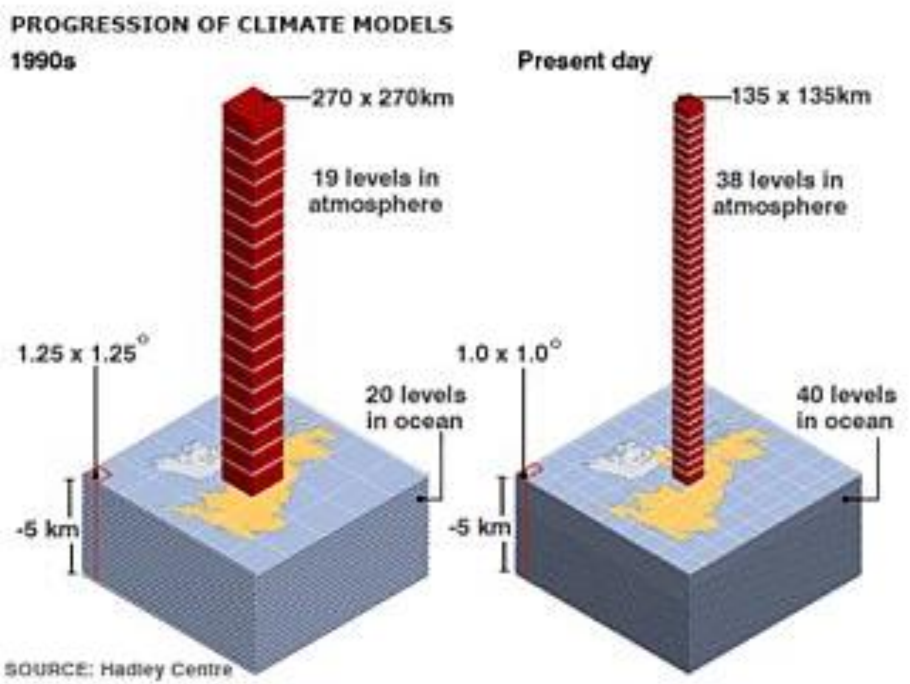
Vertical resolution of GCM and climate models





History of (global) climate models incl. GCM





AR5: ~70km maximum horizontal resolution; up to 90 layers in the atmosphere and over 60 in the ocean.

Definition

Atmospheric Model

Numerical models are useful for investigations of the composition and the thermal and dynamical structure of Earth's atmosphere. They allow evaluation of different processes and mechanisms as well as feedbacks. Scientific progress can be achieved by understanding the discrepancies between observations and results derived from model simulations. Assessments of the future development of atmospheric dynamics and chemistry are typically based on ***scenario simulations*** and ***sensitivity studies***.

Definition

Atmospheric General Circulation Model (AGCM)

Three-dimensional model of large-scale (spatial resolution of a few hundred km) physical, radiative, and dynamical processes in the atmosphere over years and decades.

An AGCM is used to study changes in natural variability of the atmosphere and for investigations of climate effects of radiatively active trace gases (greenhouse gases) and aerosols (natural and anthropogenic), along with their interactions and feedbacks.

Definition

Atmospheric General Circulation Model (AGCM)

Three-dimensional model of large-scale (spatial resolution of a few hundred km) physical, radiative, and dynamical processes in the atmosphere over years and decades.

Usually, AGCM calculations employ prescribed concentrations of radiatively active gases, e.g., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and ozone (O_3). Changes of water vapor (H_2O) concentrations due to the hydrological cycle are directly simulated by an AGCM. Sea surface temperatures (SSTs) are prescribed.

This means that neither a chemistry model nor an ocean model is interactively coupled to an AGCM.

Definition

Chemical Transport Model (CTM)

Simulation of chemical processes in the atmosphere employing meteorological analyses derived from observations or AGCMs.

A CTM is a *non-interactive* model that does not consider the feedback of chemistry to dynamical and radiative processes. It uses winds and temperatures from meteorological analyses or predictions to specify the atmospheric transport and temperatures and to calculate the abundances of chemical species in the troposphere and stratosphere. A CTM can be used to simulate the evolution of atmospheric composition and help interpret observations.

Definition

Climate Model

An AGCM interactively coupled to an ocean model, commonly referred to as an AOGCM or a climate model, is used for investigation of climate change. More recently, climate models may also include other feedback processes (e.g., carbon cycle, interaction with the biosphere). These are so-called ***Earth-System Models***.

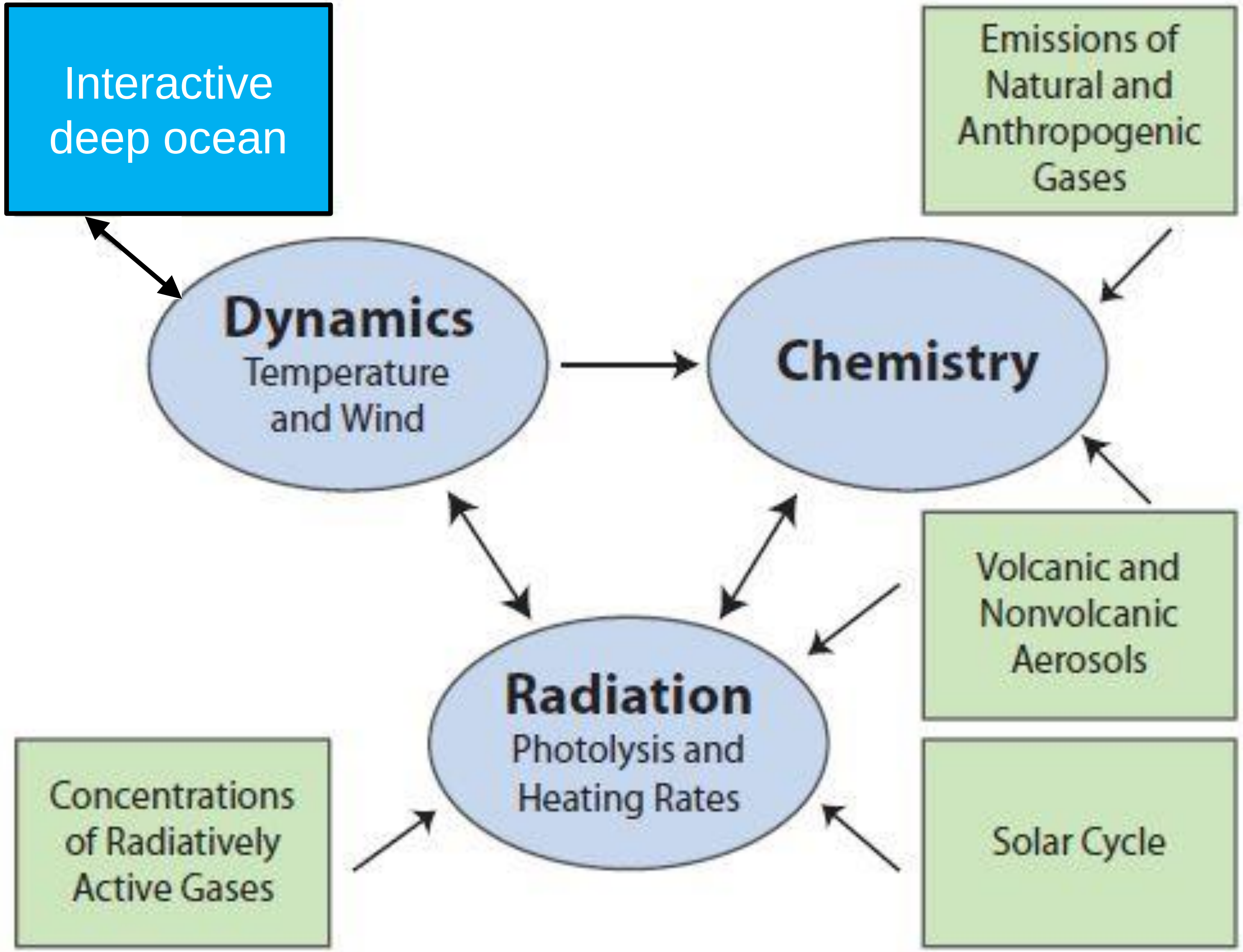
Definition

Chemistry-Climate Model (CCM)

An AGCM or climate model that is interactively coupled to a detailed chemistry module.

In a CCM, 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. This gives rise to a dynamical-chemical coupling in which the chemistry influences the dynamics (via radiative heating) and vice versa (via temperature and advection).

Schematic of a CCM



Strategy of climate modelling

So-called ***transient* simulations** consider observed or predicted gradual changes in concentrations of radiatively active gases and other boundary conditions (e.g., emissions). The temporal development of source gas emissions are prescribed for a specific episode (years to decades).

In so-called ***time-slice* simulations**, the internal variability of a CCM can be investigated under fixed conditions, e.g., for greenhouse gas (GHG) concentrations and SSTs, to estimate the significance of specific changes.

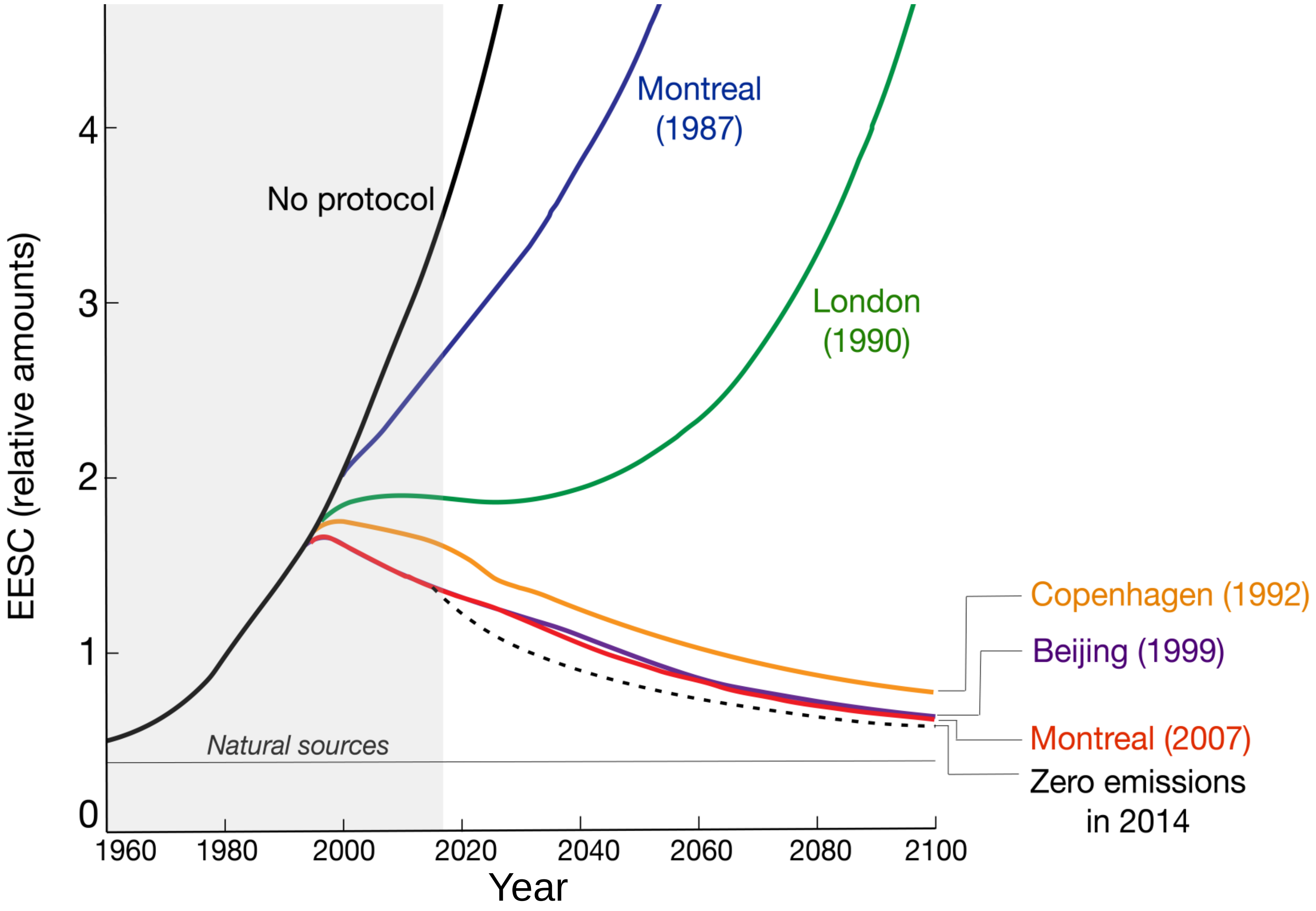
Strategy for CCM simulations for IPCC and WMO

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

(1) A hindcast simulation with specified dynamics, i.e. nudged to observed meteorology from 1979 to 2017 (referred to REF-C1SD),
(2) a free-running hindcast simulation representing the past (from 1950 to 2017; referred to REF-C1), and
(3) a combined hindcast and forecast simulation (from 1950 until 2100; referred to REF-C2 (RCP6.0) either with fixed ocean temperature (SST) and sea-ice cover (SIC) or with an interactively coupled ocean).

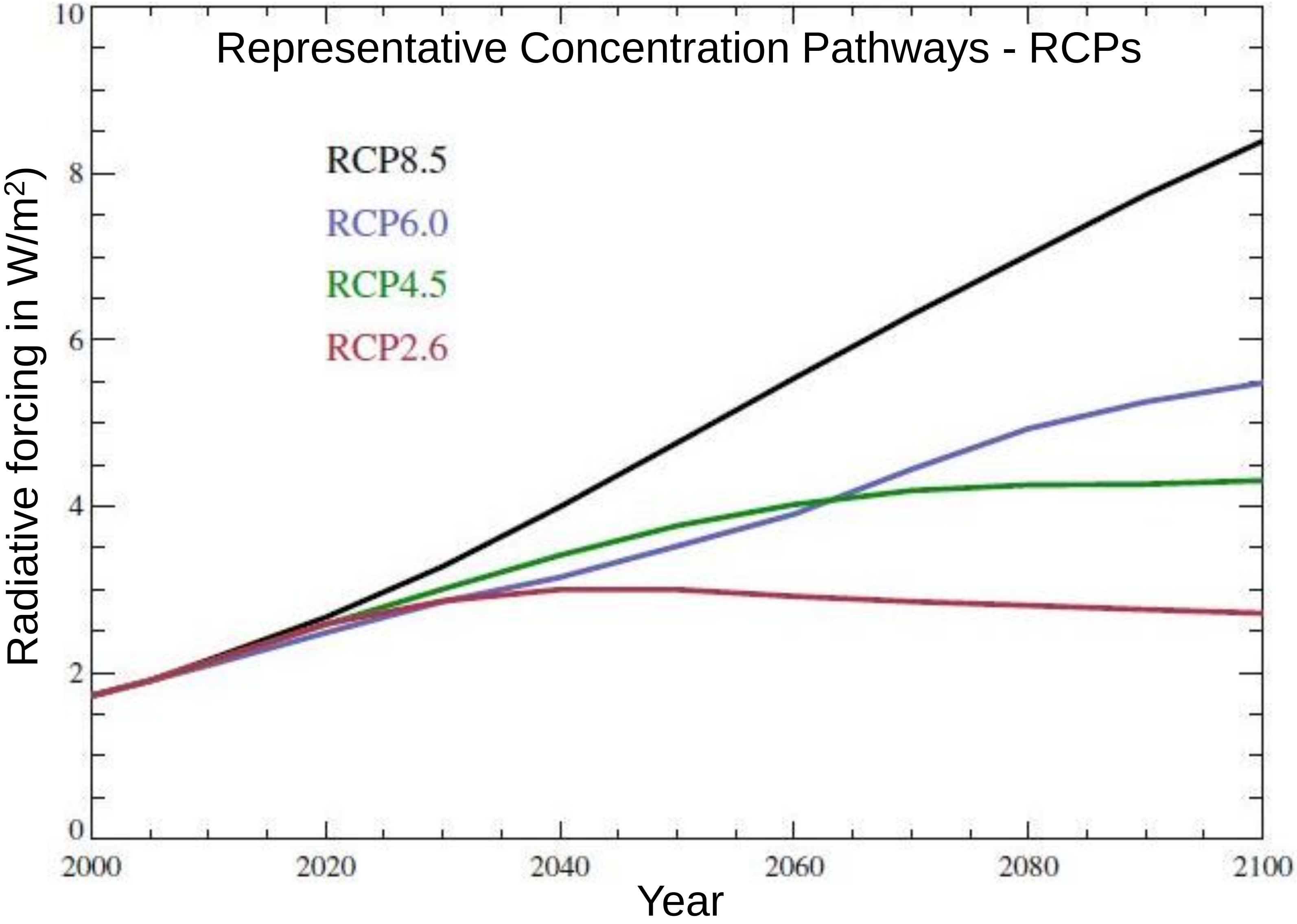
In addition, several sensitivity simulations (SEN) have been carried out, for instance with fixed boundary conditions regarding ozone depleting substances (ODSs) and greenhouse gases (GHGs).

Equivalent Effective Stratospheric Chlorine (EESC)

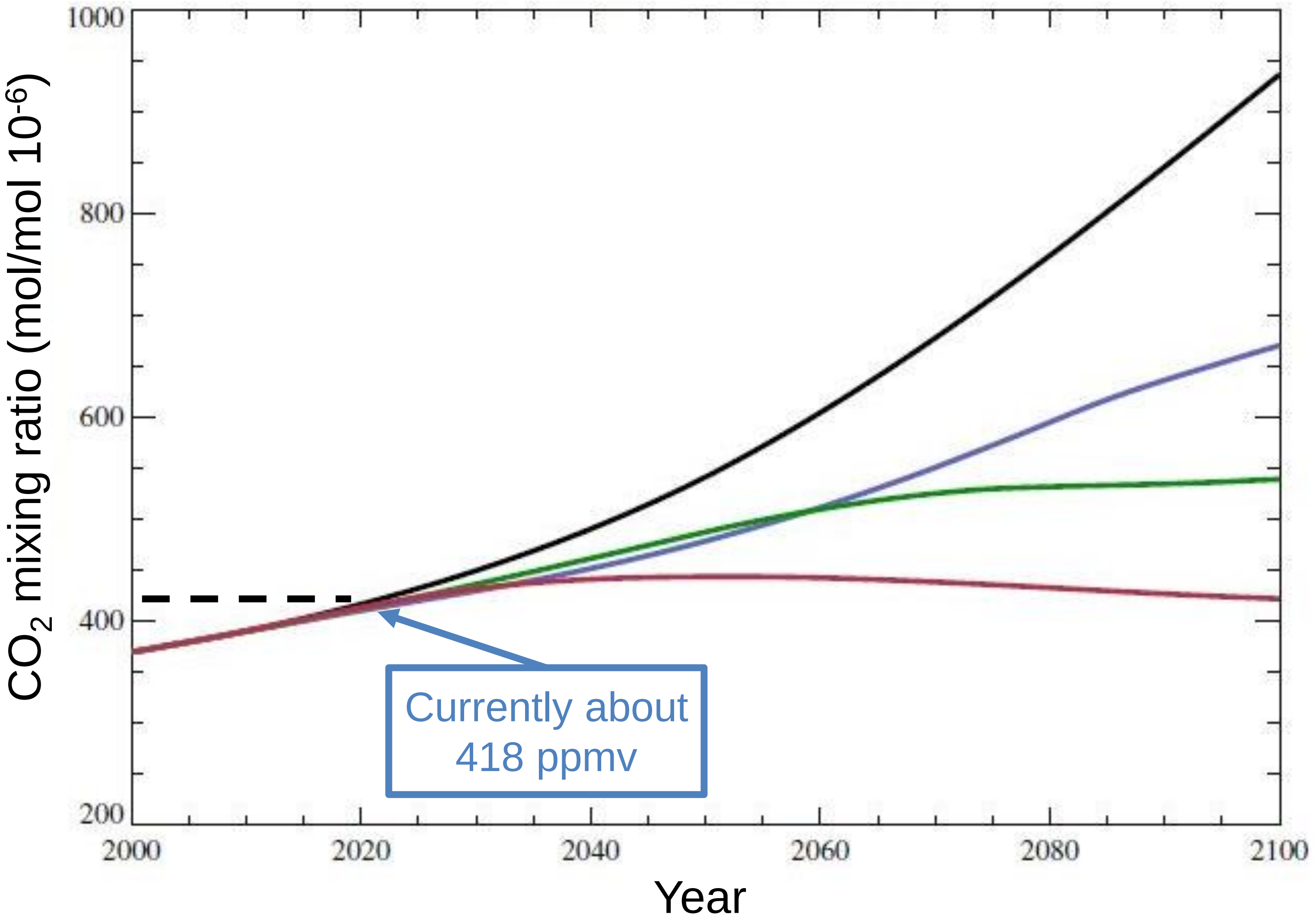


Source: Montreal Protocol Scientific Assessment Panel (2014). Twenty Questions and Answers About the Ozone Layer.
The data visualization is available at OurWorldinData.org. There you will find more on this topic.

Future scenarios of radiative forcing (W/m²)

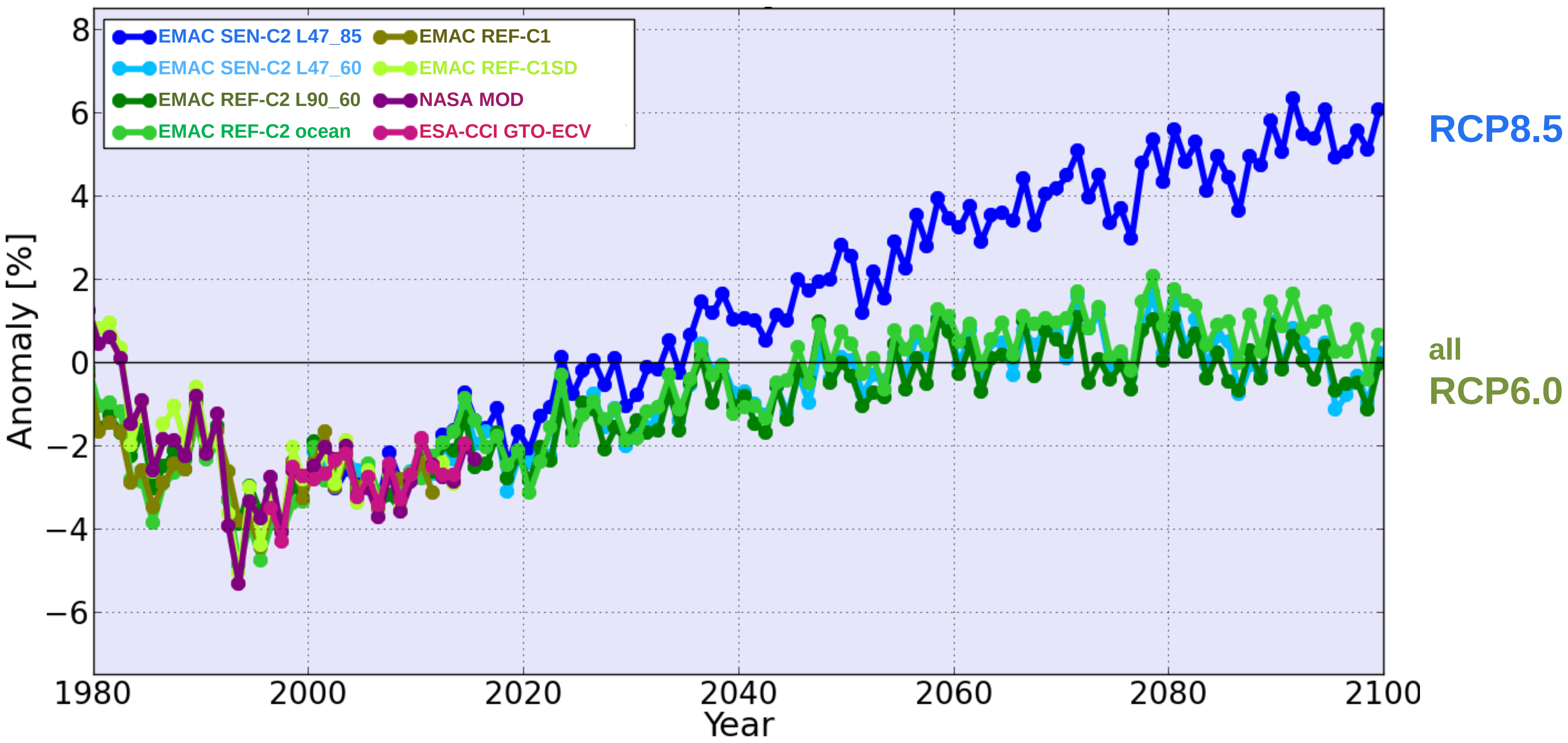


Scenarios for future CO_2 mixing ratio (mol/mol 10^{-6})



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

Comparison of satellite- and CCM-data (EMAC) incl. projections



update of Jöckel et al., 2016

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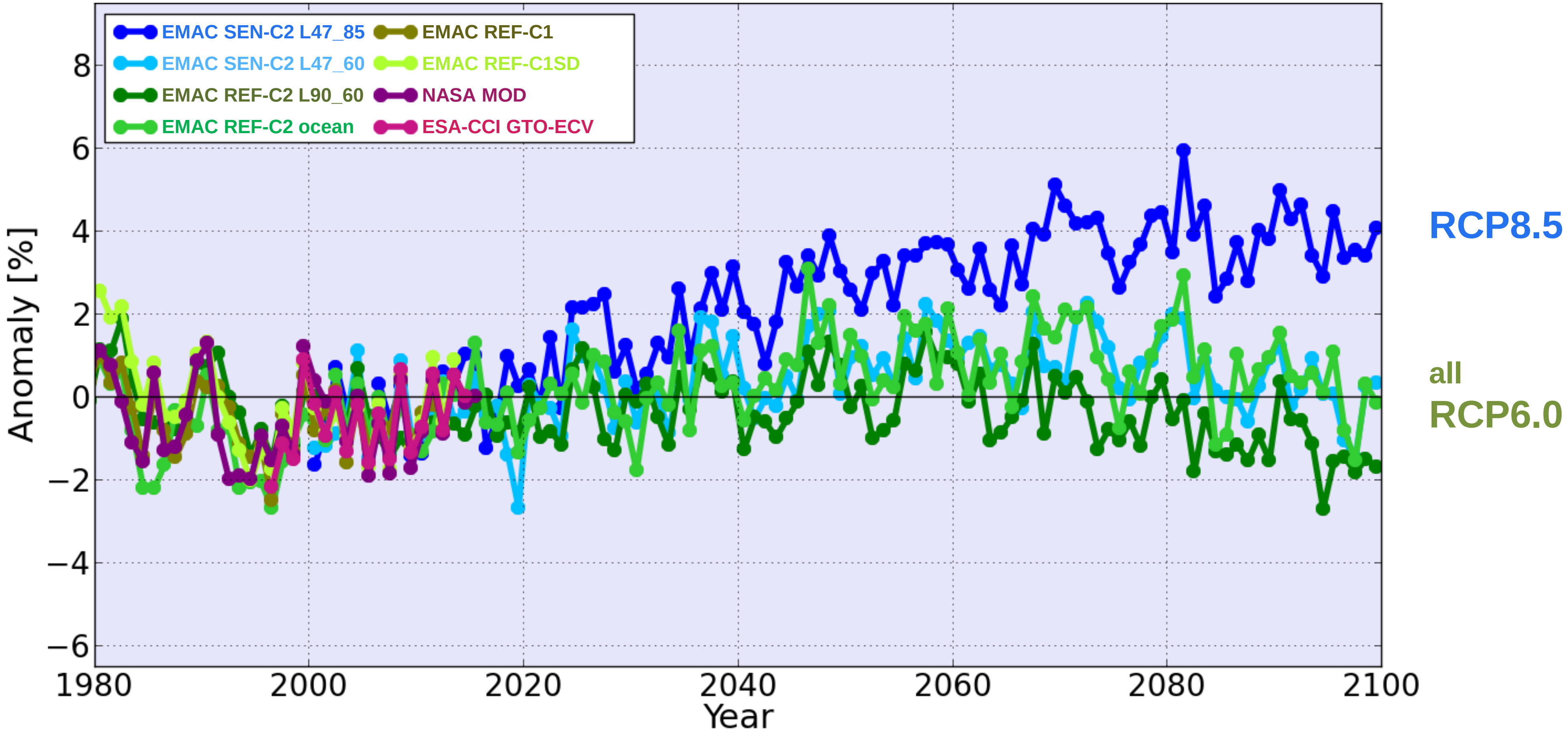
Ozone anomalies (1960-2100): 20°S - 20°N

Comparison of satellite- and CCM-data (EMAC) incl. projections



update of Jöckel et al., 2016

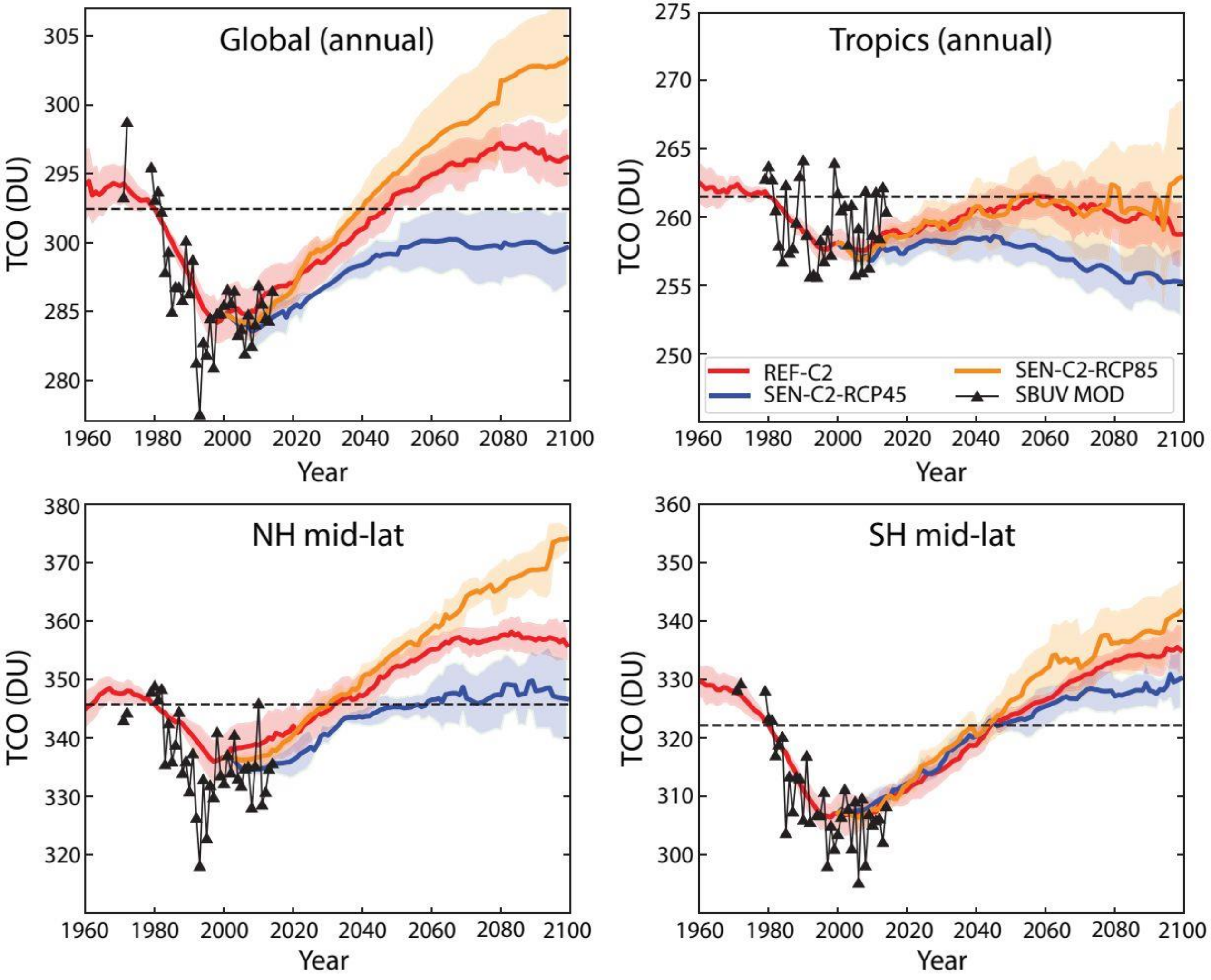
Ozone projections under different climate change scenarios at middle latitudes, the tropics and the near global mean (Total Column Ozone, TCO)

60°S-60°N

20°S-20°N

30°N-60°N

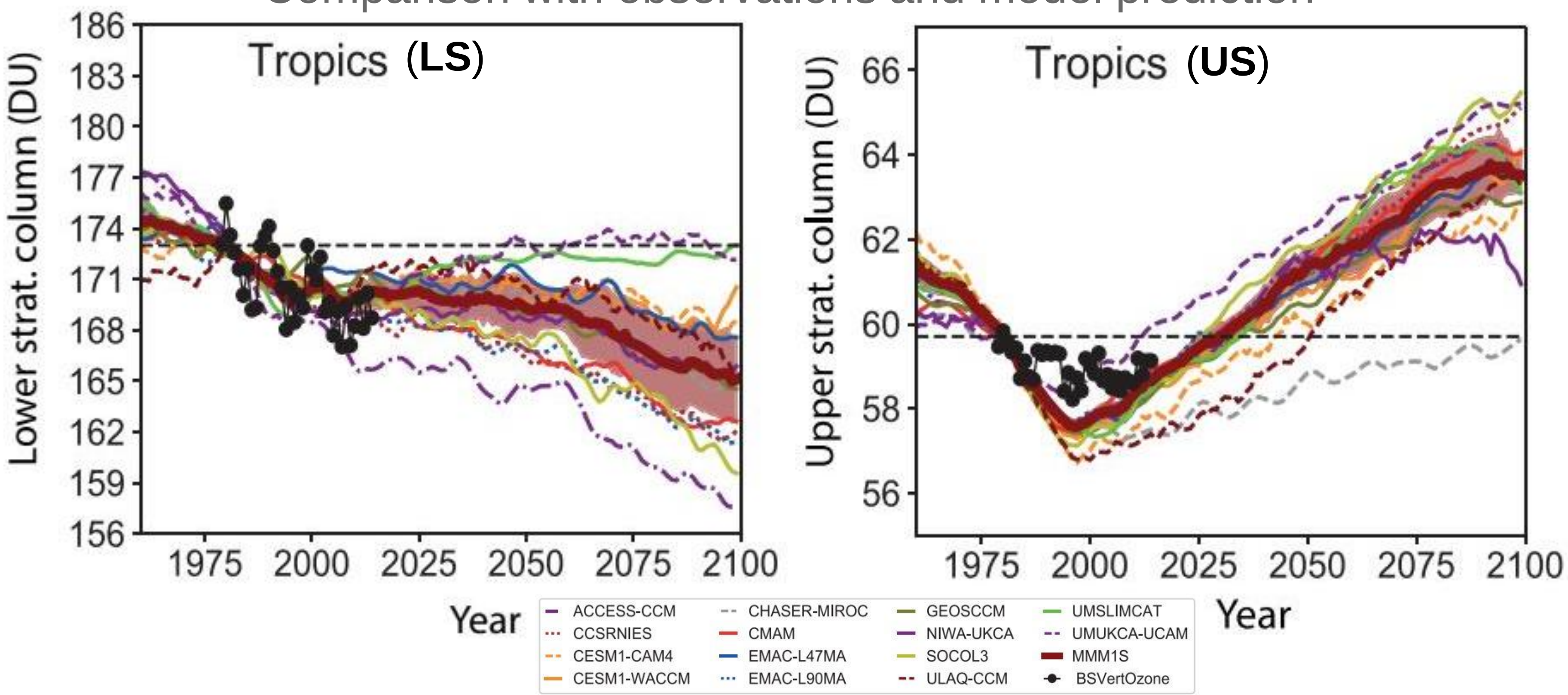
30°S-60°S



WMO, 2019

Ozone anomalies (1960-2100): 20°S - 20°N

Comparison with observations and model prediction



Evolution of partial column ozone (DU) (left) for the **lower stratosphere** (**LS**: tropopause – 10 hPa) and (right) for the **upper stratosphere** (**US**: ≥ 10 h Pa) from the REF-C2 (= RCP6.0) simulations from 14 individual models (different colors), along with the MMM (thick red line). Also shown are estimates of the partial column from the Bodeker Scientific Vertical Ozone (BSVertOzone) database (black dots) (*Bodeker et al*., 2013).

Dhomse et al., 2018

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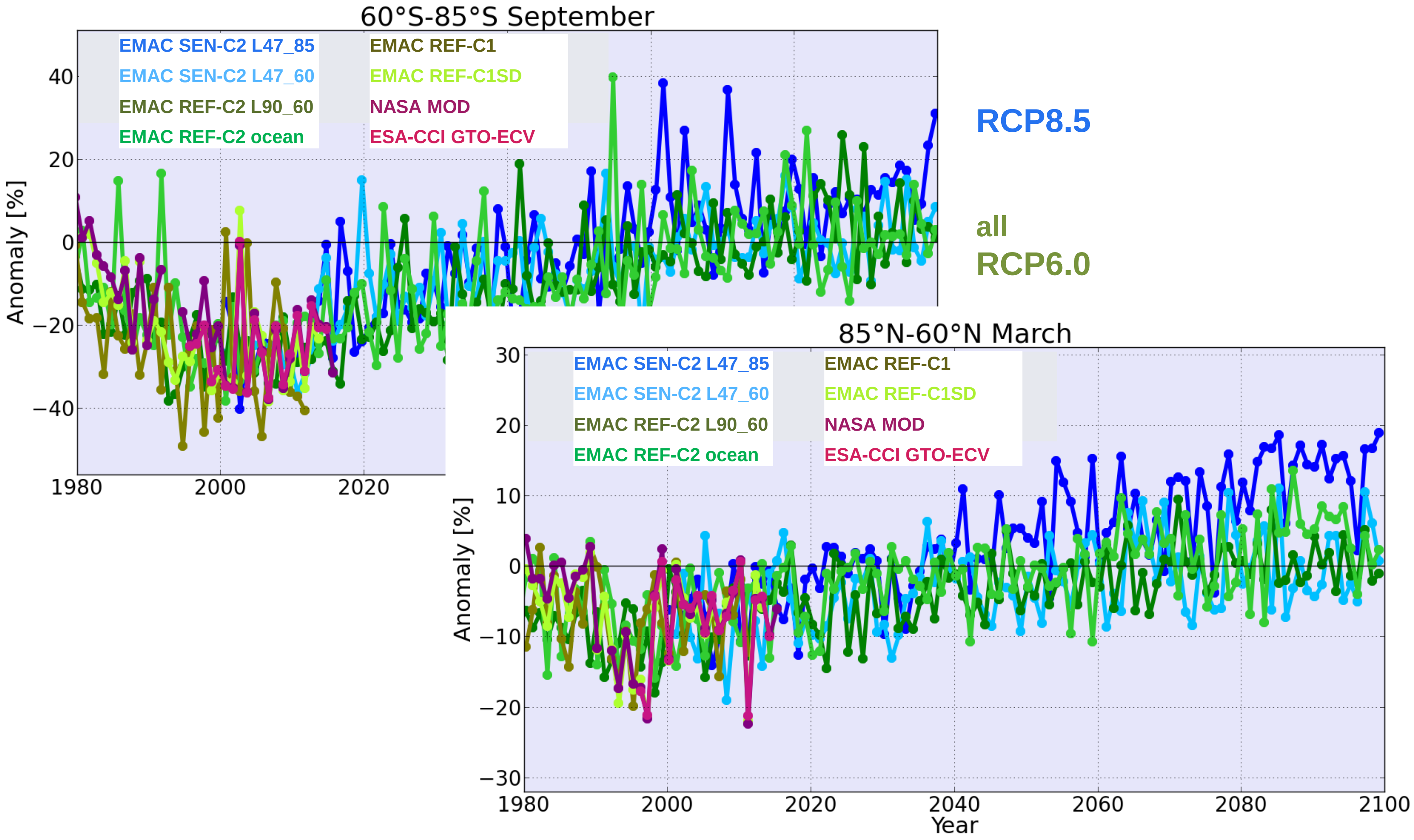
Ozone anomalies (1960-2100): polar regions

Comparison of satellite- and CCM-data (EMAC) incl. projections



RCP8.5

all RCP6.0

RCP8.5

all RCP6.0

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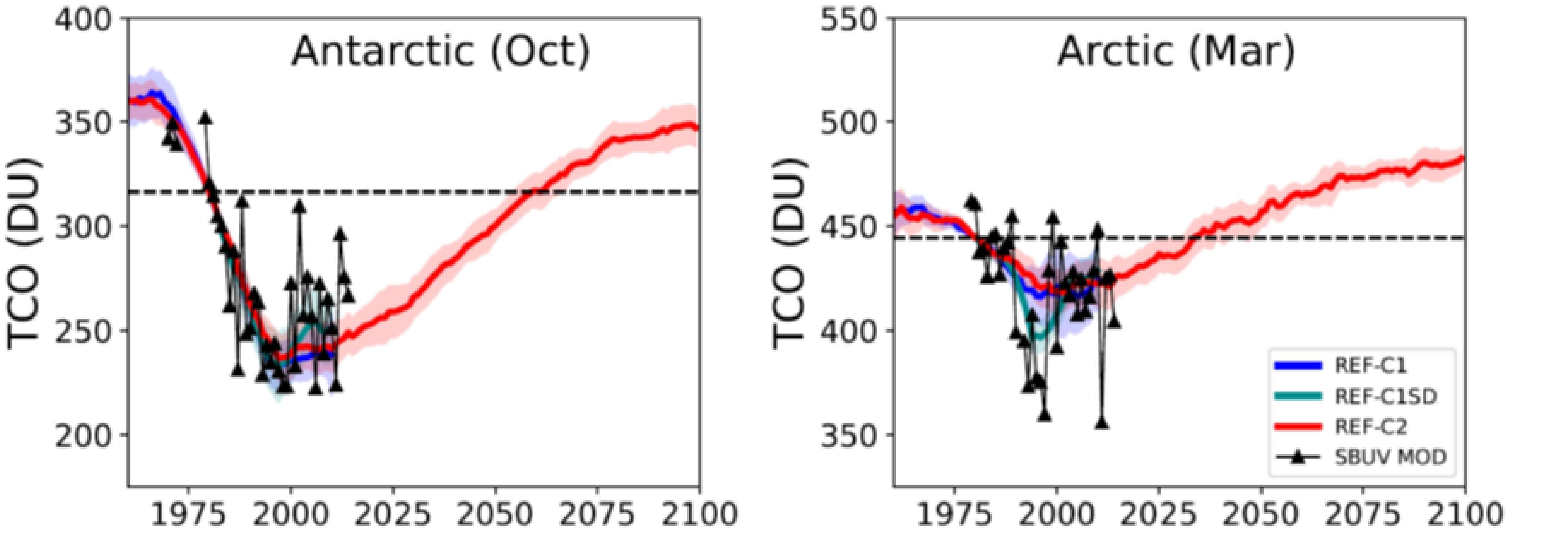
Ozone anomalies (1960-2100): polar regions

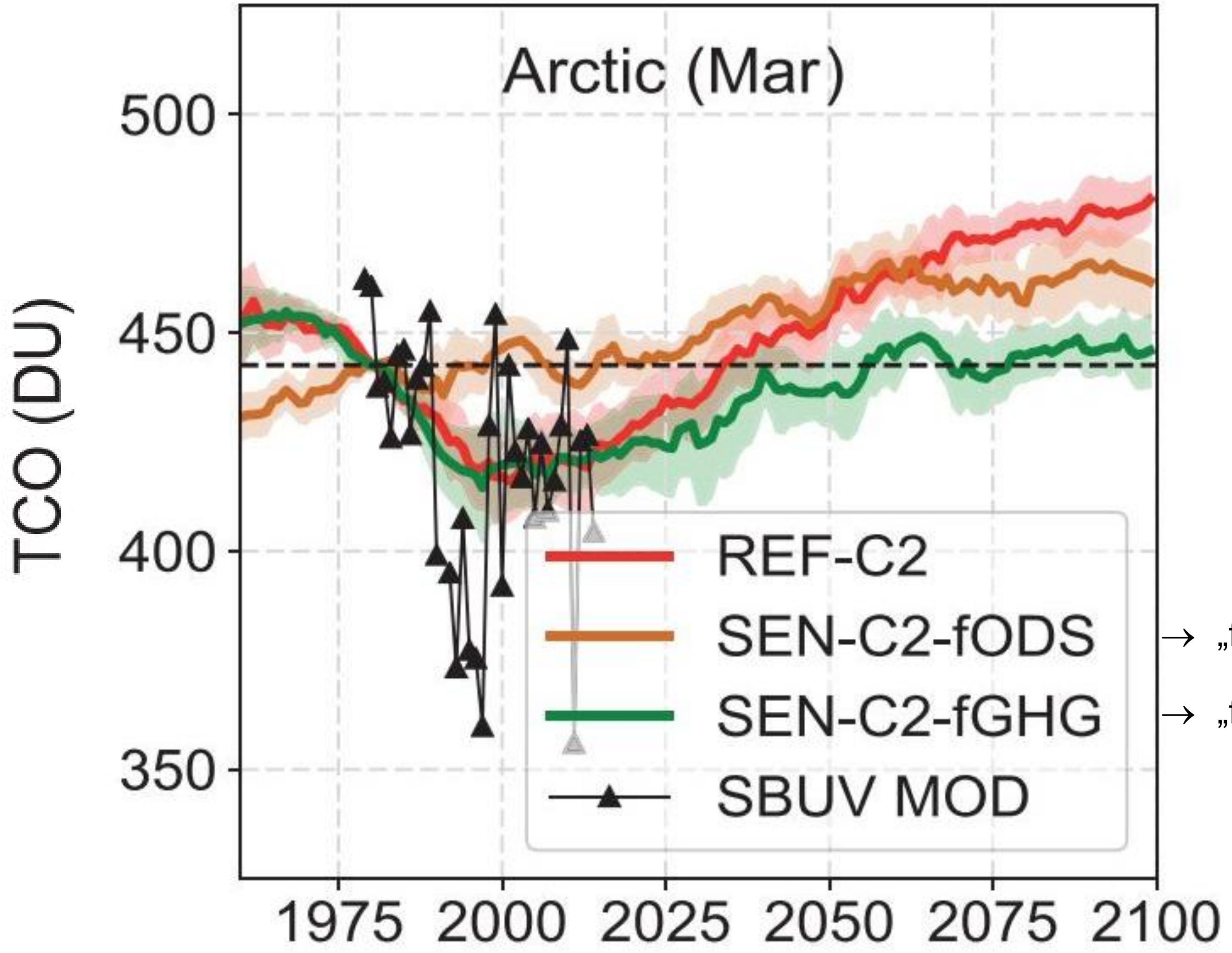
Comparison with satellite data and model (MMM) prediction



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, 2019; adopted from Dhomse et al., 2018).

Ozone anomalies (1960-2100): polar regions

Comparison with satellite data and model (MMM) prediction



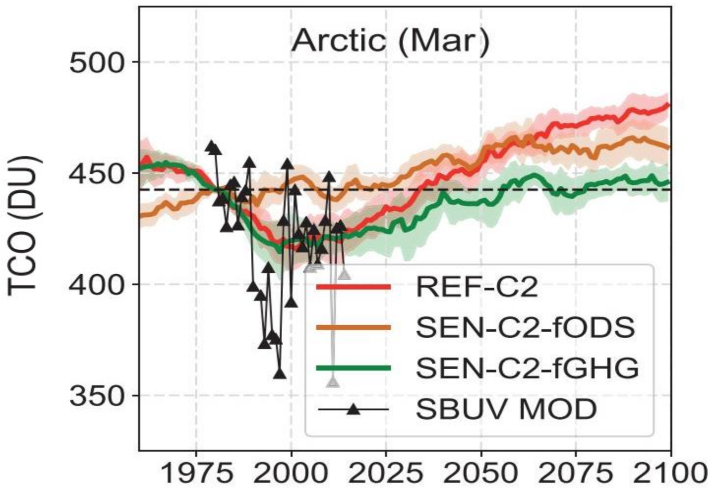
→ „fixed ozone depleting substances“

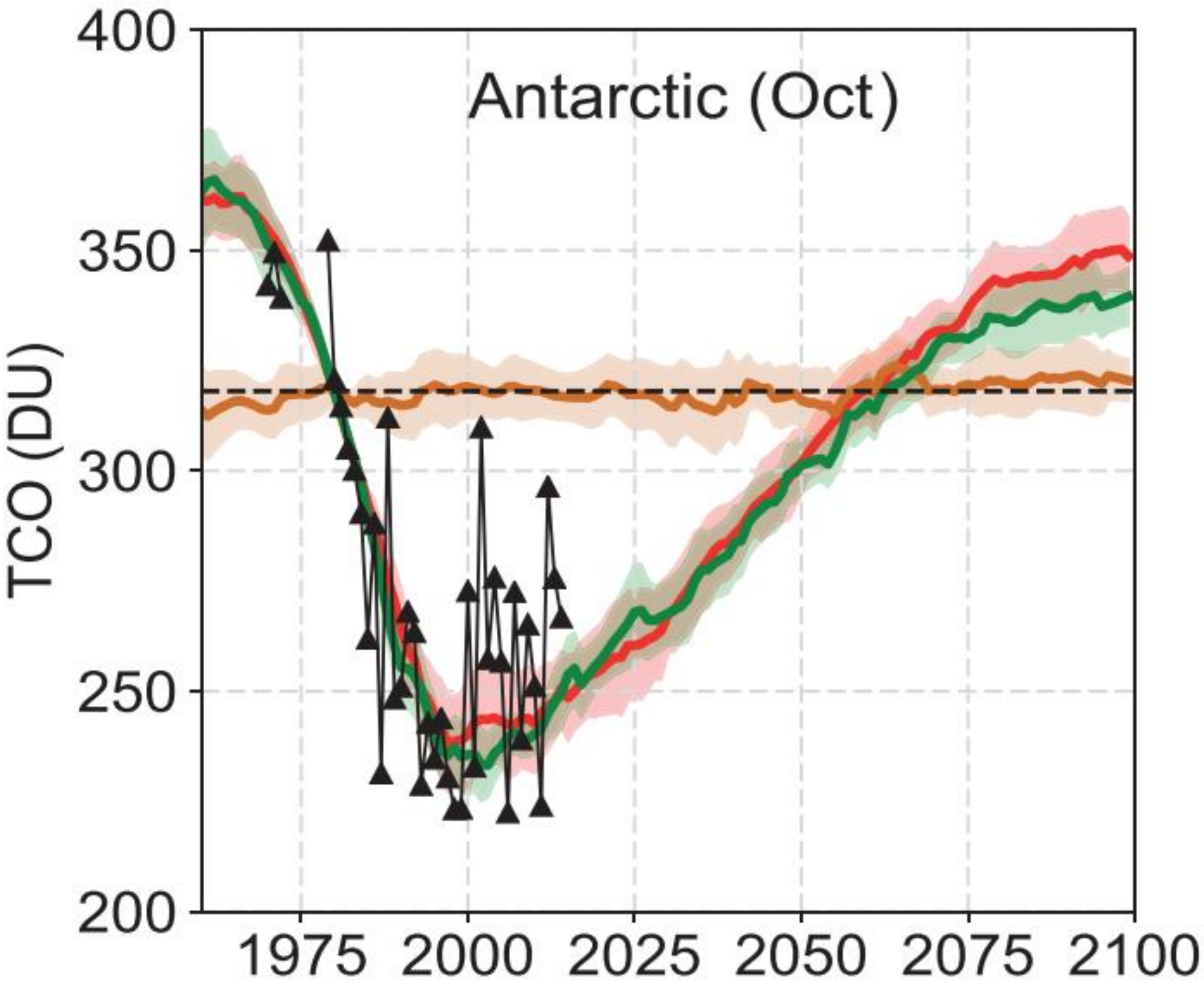
→ „fixed greenhouse gas concentrations“

(Fig. 4-19 in WMO, 2019; adopted from Dhomse et al., 2018)

Ozone anomalies (1960-2100): polar regions

Comparison with satellite data and model (MMM) prediction

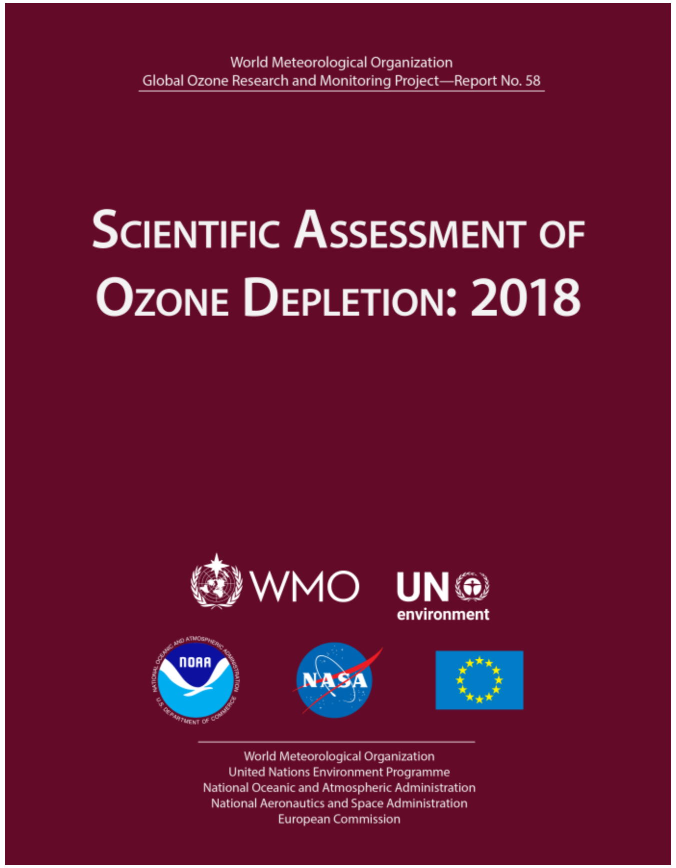




(Fig. 4-19 in WMO, 2019; adopted from Dhomse et al., 2018)

Concluding remarks (see also in WMO, 2019)

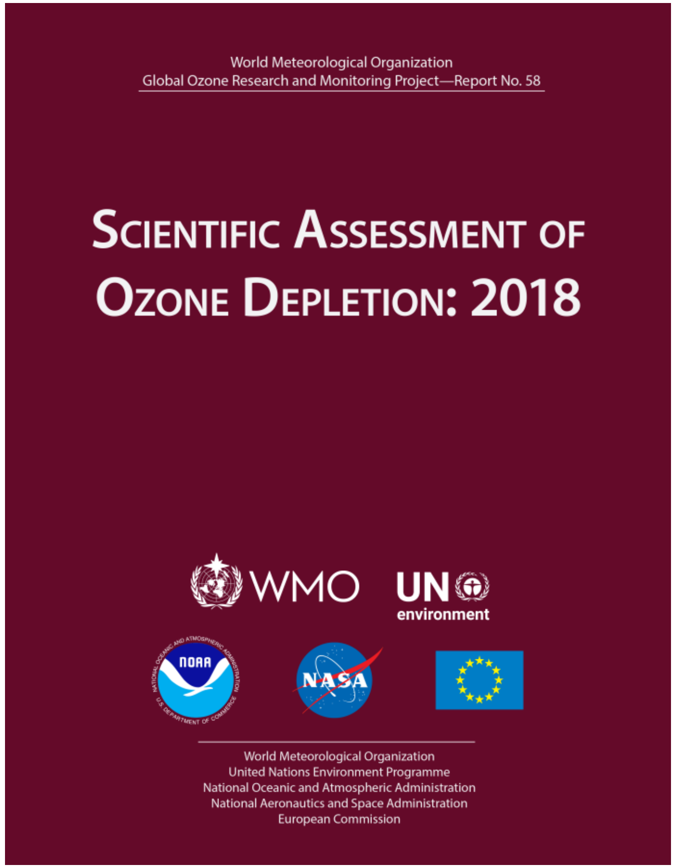
- There are emerging indications that the Antarctic ozone hole has diminished in size and depth since the year 2000, with the clearest changes occurring during early spring (especially in September).
- In the Arctic, year-to-year variability in total column ozone is much larger than in the Antarctic, precluding identification of a statistically significant increase in Arctic ozone over the 2000-2018 period.



https://www.esrl.noaa.gov/csd/assessments/ozone/2018/

Concluding remarks (see also in WMO, 2019)

- 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 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 CO_2, CH_4, and N_2O will be the dominant drivers of Arctic ozone changes, assuming full compliance with the Montreal Protocol.



https://www.esrl.noaa.gov/csd/assessments/ozone/2018/

General and final remarks

- The stratosphere plays an important role in the Earth-Climate system. It contains the ozone layer.
- The stratosphere and the troposphere are affecting each other.
- There are strong indications that climate change affects the stratosphere (e.g. the cooling of the stratosphere).
- In recent years modelling of the stratosphere achieved major progress. Comprehensive CCMs are established.
- CCMs are able to simulate the dynamic state and variability of the stratosphere as well as the chemical behavior and composition in accordance with observations. Chemistry-climate connections can be investigated in an adequate manner, for instance the evolution of the stratospheric ozone layer in a changing climate.
- CCMs can be used for climate research including the consideration of chemistry feedback processes, e.g. for investigations of chemistry-climate connections. Evaluated CCMs can be used for projections.