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
Schematic of the stratospheric system

- **Ozone**
  - Ozone (O$_3$)
  - O$_2$ photolysis
  - Chemistry
    - NO$_x$ (Nitric Oxide)
    - HO$_x$ (Hydroxy Radicals)
    - ClO$_x$ (Chlorine Oxides)
    - BrO$_x$ (Bromine Oxides)
  - Transportation
  - Heating
  - T-depending chemistry

- **Temperature**
  - Energy transport (heat, momentum)

- **Dynamics**
  - Propagation of waves
  - Deposition (rain-out, HCl, HNO$_3$)
  - Emissions (CH$_4$, N$_2$O, CFCs, HCFCs, Halons)

- **Sun**
  - Energy transport (heat, momentum)

- **Energy transport** (solar UV)

**Chemistry**

**Transport**
The stratospheric Northern Hemisphere polar vortex in winter

Air pressure and winds around the Arctic switch between these two phases (Arctic Oscillation) and contribute to winter weather patterns.
The meridional circulation of the stratosphere

- Winter pole                    Equator              Summer pole
- Pressure (hPa)
- Height (km)
- 50
- 10
- 300
- 0.01
- 1
- 10
- 100
- 300
- 1000
- Polar cell
- Ferrel cell
- Hadley cell
- Tropopause
- Mesopause
- Stratopause
Transport of stratospheric ozone

Shaw and Shepherd, 2007
Total ozone distribution for the four seasons

Example: 2009
Variability of stratospheric dynamics

90°S Mean Temperature
50 hPa  MERRA2

South Pole, about 20 km

HNO$_3$ = 6 ppbv, H$_2$O = 4.5 ppmv

Type I PSC
Type II PSC

P. Newman (NASA), E. Nash (SSAI), S. Pawson (NASA)

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Variability of stratospheric dynamics

90°S Mean Temperature
50 hPa  MERRA2

South Pole, about 20 km

P. Newman (NASA), E. Nash (SSAI), S. Pawson (NASA)

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Variability of stratospheric dynamics

90°N Mean Temperature
50 hPa  MERRA2

North Pole, about 20 km

HNO₃ = 6 ppbv, H₂O = 4.5 ppmv

Type I PSC
Type II PSC

1978/1979–2017/2018
2009/2010

P. Newman (NASA), E. Nash (SSAI), S. Pawson (NASA)
Variability of stratospheric dynamics

90°N Mean Temperature
50 hPa  MERRA2

North Pole, about 20 km

P. Newman (NASA), E. Nash (SSAI), S. Pawson (NASA)

Variability of polar ozone: Impact of stratospheric dynamics

WMO, 2019
Recent stratospheric temperature changes

Maycock et al., 2018
Recent stratospheric temperature changes

- **Linear trend**
  - Trend + solar cycle + volcanoes

- **11-year solar cycle**

- **Volcanic eruptions**
  - \( \Rightarrow \) "step-like" cooling of the stratosphere
Freely available

Dimensions of atmospheric models

(a) Zero dimensions (one point): boxmodel

(b) One dimension (height or depth): a column of grid cells

(c) Two horizontal dimensions (+ one vertical dimension) = 3D: a grid of columns

(d) 3D General Circulation Model: a grid of columns on a sphere
Hierarchy of atmospheric models

(a) Box Model
(b) Single Column
(c) Two-Box Model
(d) Multiple-Column
   (Intermediate Complexity)
(e) Limited Area
   (Regional Model)
(f) Global Grid
   General Circulation Model
   (“GCM”)
Horizontal resolution of regional and global models

(a) 124 mi, 200 km

(b) 62 mi, 100 km

(c) 31 mi, 50 km

(d) 16 mi, 25 km
Vertical resolution of GCM and climate models
History of (global) climate models incl. GCM

AR5: ~70 km 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.
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$_2$O), chlorofluorocarbons (CFCs), and ozone (O$_3$). Changes of water vapor (H$_2$O) 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.
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.
**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

Interactive deep ocean

Dynamics
Temperature and Wind

Chemistry

Emissions of Natural and Anthropogenic Gases

Volcanic and Nonvolcanic Aerosols

Solar Cycle

Radiation
Photolysis and Heating Rates

Concentrations of Radiatively Active Gases
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 (RCP-6.0) either with fixed ocean temperature (SST) and sea-ice cover (SIC) or with an interactively coupled ocean).

In addition, several sensitivity simulations 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)

Representative Concentration Pathways - RCPs

- RCP8.5
- RCP6.0
- RCP4.5
- RCP2.6

Radiative forcing in W/m² vs Year

Year:
- 2000
- 2020
- 2040
- 2060
- 2080
- 2100

DLR
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
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

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 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
Ozone anomalies (1960-2100): polarregions
Comparison of satellite- and CCM-data (EMAC) incl. projections
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

(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 CO₂, CH₄, and N₂O will be the dominant drivers of Arctic ozone changes, assuming full compliance with the Montreal Protocol.
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. 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.