SWIFT – Fast stratospheric ozone chemistry for climate models

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Introduction

Motivation

Importance of ozone-climate interactions has long been recognized

- E.g. Effect of changes in polar stratospheric vortex and ozone on surface temperature trends in Antarctica (Thompson and Solomon, Science, 296, 895, 2002)
- E.g. Changes in tropospheric wave driving and the Brewer-Dobson circulation (Rex et al., GRL, 33, doi:10.1029/2006GL026731, 2006)

But: Ozone is usually only prescribed in climate models, since a detailed calculation is computationally very expensive

- E.g. In the IPCC CMIP5 models (IPCC, 2013)

It is desirable to account for ozone-climate interactions on a decadal scale in climate models

Existing approaches

Chemistry Climate Models (CCMs): Coupling of a full stratospheric chemistry model to a GCM

- Slow: Not applicable to scenarios where long-term runs and multiple scenarios are needed

Existing fast extrapolar ozone schemes like the Cariolle scheme (e.g. Cariolle and Deque, JGR, 91, 10825, 1986) or Linoz (e.g. McLinden, JGR, 105, 14653, 2000) based on Taylor series expansion around mean state have disadvantages

- Do not model actual physical and chemical processes
- Can't cope well with non-linearities

The SWIFT model

SWIFT is a fast chemistry scheme for calculating the chemistry of stratospheric ozone in climate models which consists of two parts:

- The polar SWIFT model is based on a small set of differential equations, which simulate the time evolution of polar vortex averaged mixing ratios of ozone and key species
- Extrapolar SWIFT is based on evaluating a polynomial for the rate of change of ozone (lower stratosphere) or ozone itself (upper stratosphere), which is a function of 9 parameters (including latitude, temperature and chemical families like HOx or NOx).

SWIFT runs with three transport schemes:

- No transport and temperature-based transport parameterization (finished)
- Transport by the underlying GCM (in development)
- Lagrangian transport and mixing from the ATLAS CTM (in development)

SWIFT has been successfully coupled to two models, preliminary results are available, development is ongoing

- Coupling to ECHAM6.3 at AWI
- Coupling to EMAC at FU Berlin

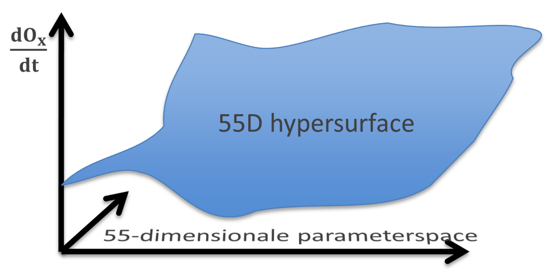
References

- First version: Rex et al., Atmos. Chem. Phys., 14, 6545–6555, 2014
- This version: Wohltmann et al./Kreyling et al., in preparation

Extrapolar SWIFT

Extrapolar SWIFT: Concept

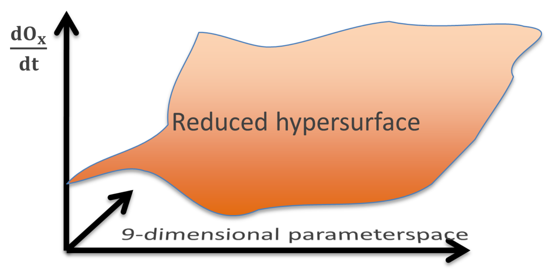
In a full stratospheric chemistry model (e.g. ATLAS CTM), the rate of change of ozone $\frac{dO_3}{dt}$ is calculated by a system of differential equations with **55 initial and boundary conditions**.



Using linear combinations of variables to reduce dimensionality (55D → 9D).

⇓

The 9D hypersurface is characterized by the numerical output of the ATLAS CTM (training data). Fitting hypersurface with one global polynomial of 4th degree.



Solving polynomial yields comparable results to full model → but much faster!

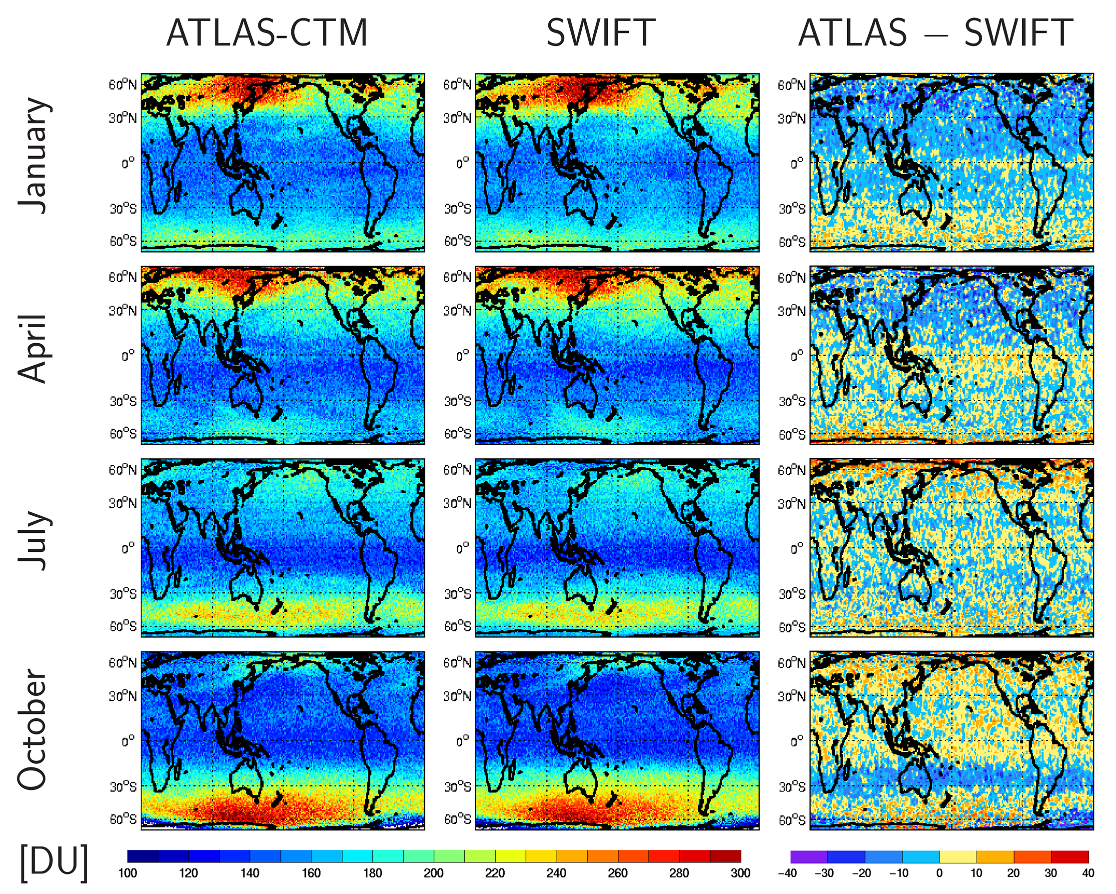
- **9 variables parameterize the physical and chemical properties of the rate of change of ozone $\frac{dO_3}{dt}$:**

Geographic and atmospheric variables:	Mixing ratios of chemical families:
Latitude	Chlorine family (Cl_y)
Altitude	Bromine family (Br_y)
Temperature	Nitrous-oxides family (NO_y)
Overhead ozone column	Water vapor (substitutes HO_y)
	Odd-oxygen family (O_x)

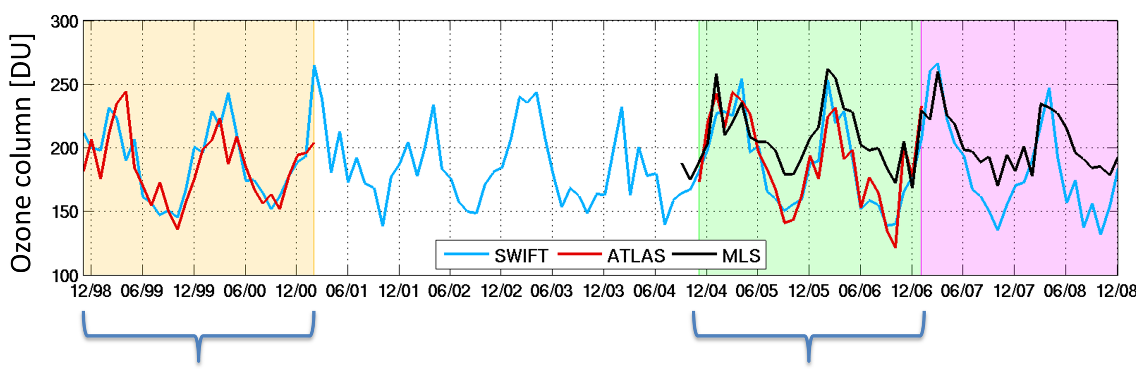
- So called **repro-modeling approach** has been successfully applied to chemical models, e.g. Turanyi, Computers and Chem., 18, 1, 45 (1994) or Lowe and Tomlin, Environmental Modelling & Software, 15, 6–7, 611 (2000)

Extrapolar SWIFT: Results

Monthly means (2005) of simulated ozone columns (15 km–32 km)



Monthly mean ozone columns above Potsdam from a 10 year simulation



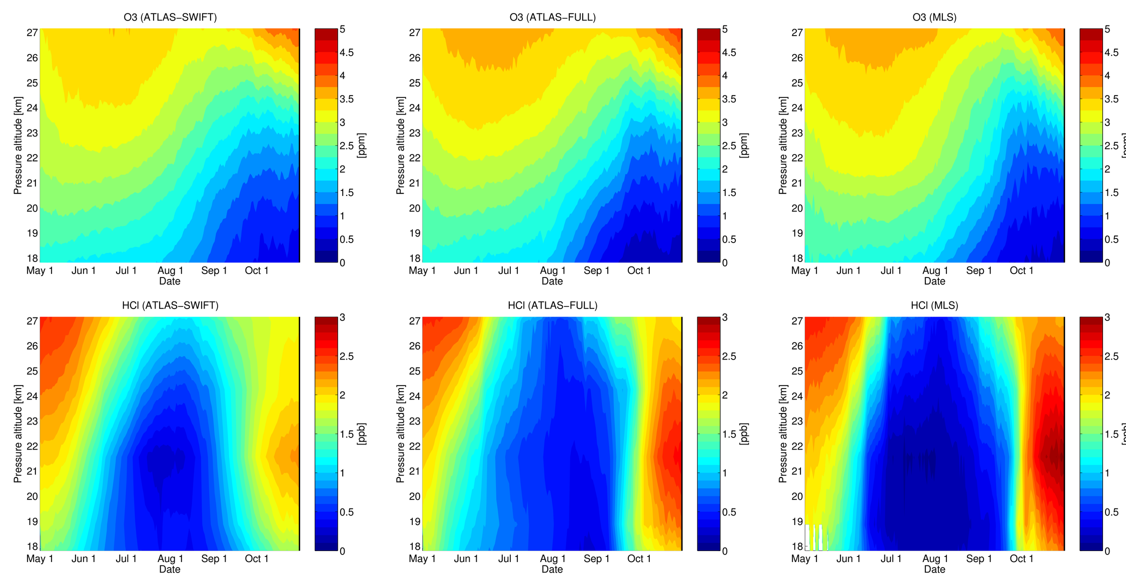
- Interactive ozone layer:
  - Two-way feedback with model dynamics (e.g. planetary waves)
  - Interannual variability
- Stable simulations: No error accumulation.
- Average relative error of ozone columns < 10%.

Polar SWIFT

Polar SWIFT: Overview

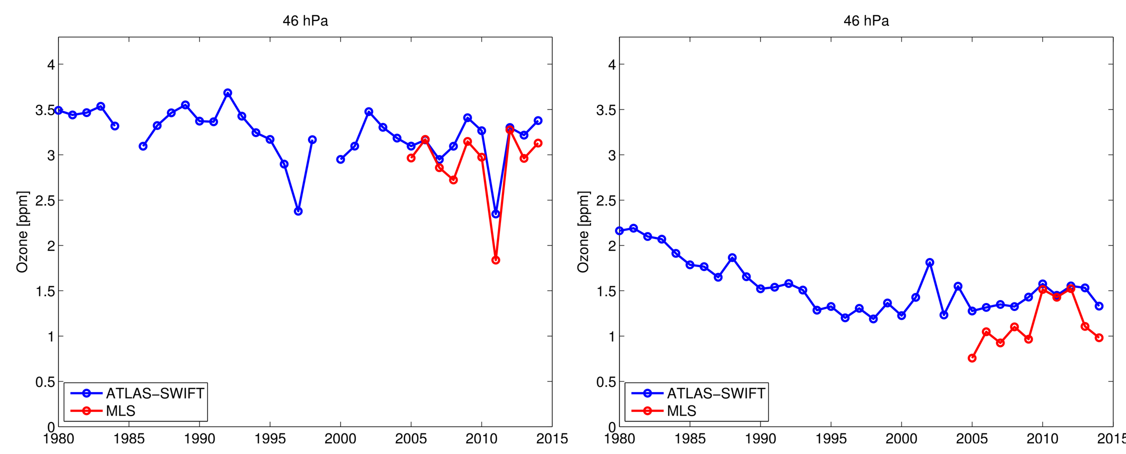
- Model for vortex averaged polar ozone loss
- Only 4 prognostic equations per altitude (vortex means)
- Large time step possible (1 day)
- Fast: seconds per model year on 1 processor
- Solves system of differential equations for key species
  - O_3
  - HNO_3 (total)
  - HNO_3 (gas phase)
  - HCl
  - $ClONO_2$
  - ClO_x
- Includes terms for the overall net effect of chemical and physical mechanisms rather than one term for each reaction. Equations are physically justified (no Taylor expansions etc.). Terms include e.g.
  - Chlorine activation by heterogeneous reaction HCl + $ClONO_2$
  - Ozone loss by ClO dimer cycle
  - Denitrification by sedimenting particles
  - Deactivation of chlorine in the southern hemisphere by Cl + CH_4
  - ...
- Proportionality constants of the individual terms are empirical parameters trained on chemical reaction rates from a Chemistry Transport Model (ATLAS CTM) for two Arctic and two Antarctic winters
- Driven by only 2 time series: FAP (fraction of vortex where polar stratospheric clouds can form) and FAS (fraction of vortex exposed to sunlight)

Polar SWIFT validation: Evolution during winter



Validation of Polar SWIFT. Time evolution of vortex means for the southern hemisphere winter 2006 as a function of altitude. Left: SWIFT implemented as a chemistry module in the ATLAS CTM driven by ECMWF ERA Interim reanalysis data. Middle: Same for the ATLAS CTM using its own full chemistry model. Right: MLS satellite measurements. Top: Ozone volume mixing ratios. Bottom: HCl volume mixing ratios.

Polar SWIFT validation: Interannual variability



Left: Interannual variability of vortex averaged ozone mixing ratios in early spring shortly before vortex breakup in the northern hemisphere at 46 hPa. Ozone mixing ratios simulated by Polar SWIFT as a chemistry module in the ATLAS CTM driven by ECMWF ERA Interim reanalysis data (blue) and observed mixing ratios by the MLS satellite instrument (red). Dates in different years differ due to the different breakup dates of the vortex and availability of satellite data. Chlorine loading changes according to EESC. Right: Same for southern hemisphere and 1 October.

SWIFT in ECHAM6.3

Implementation of SWIFT into the ECHAM6.3 climate model

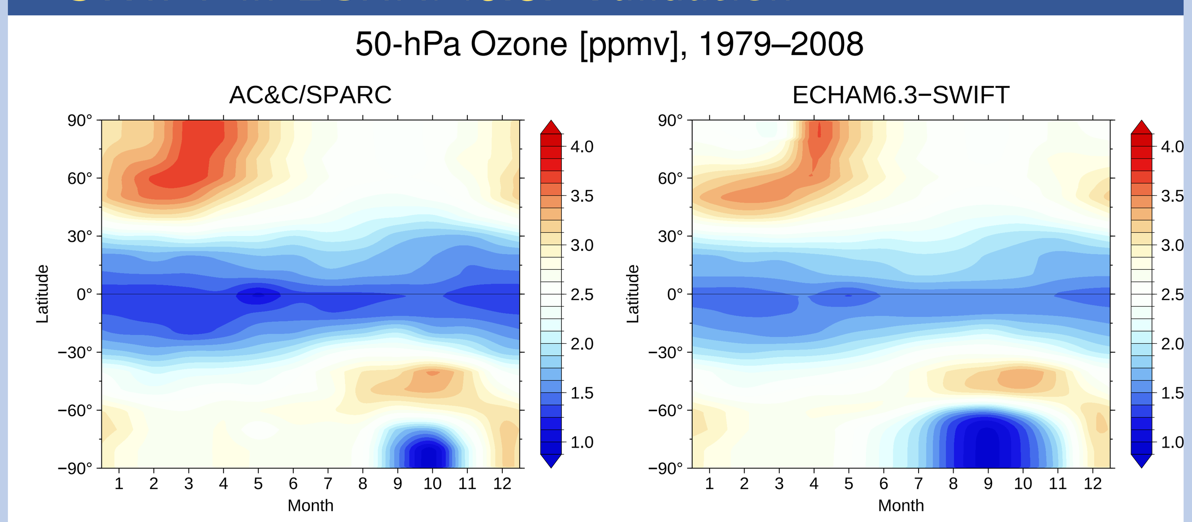
Preliminary results from SWIFT implemented in ECHAM6.3

- ECHAM6.3 (AMIP configuration) without coupled ocean
- Low resolution model (LR) T63L47
- Chlorine scaled to observed chlorine with EESC
- Reference run: Ozone climatology AC&C SPARC (CMIP5)
- SWIFT run: Polar SWIFT + Extrapolar climatology, temperature-based transport parameterization for ozone

Findings

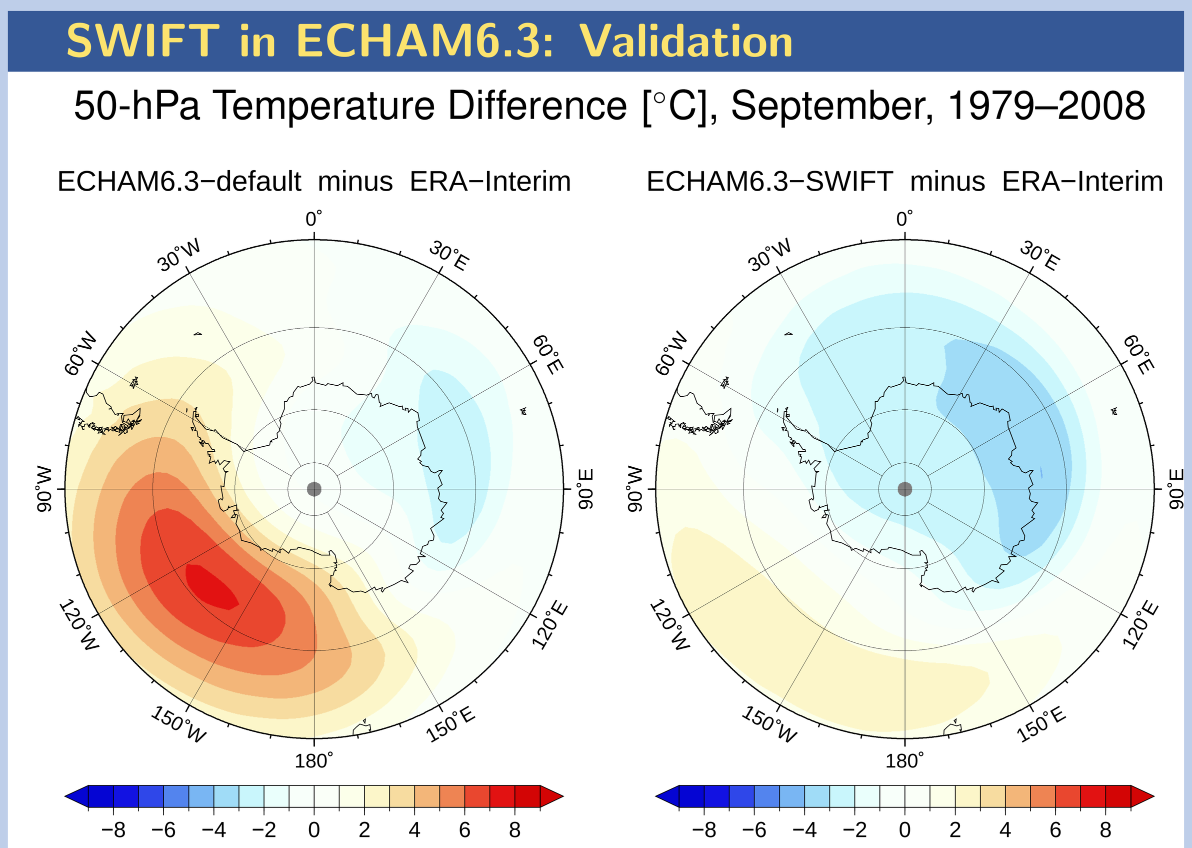
- SWIFT reduces temperature difference at 50 hPa to observations (ERA Interim) in September in southern hemisphere, but performance of SWIFT varies with month and hemisphere
- SWIFT simulates less ozone than climatology in both hemispheres. Reasons may be overestimation of polar vortex size in ECHAM6.3 and cold temperature bias

SWIFT in ECHAM6.3: Validation



Ozone climatological means (1979–2008) at 50 hPa as a function of latitude and month. Left: AC&C SPARC ozone climatology. Right: Run with interactive ozone from SWIFT.

SWIFT in ECHAM6.3: Validation



Temperature difference (1979–2008) between ECHAM6.3 and ERA Interim. Left: Reference run with ozone climatology. Right: Run with interactive ozone from SWIFT.

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