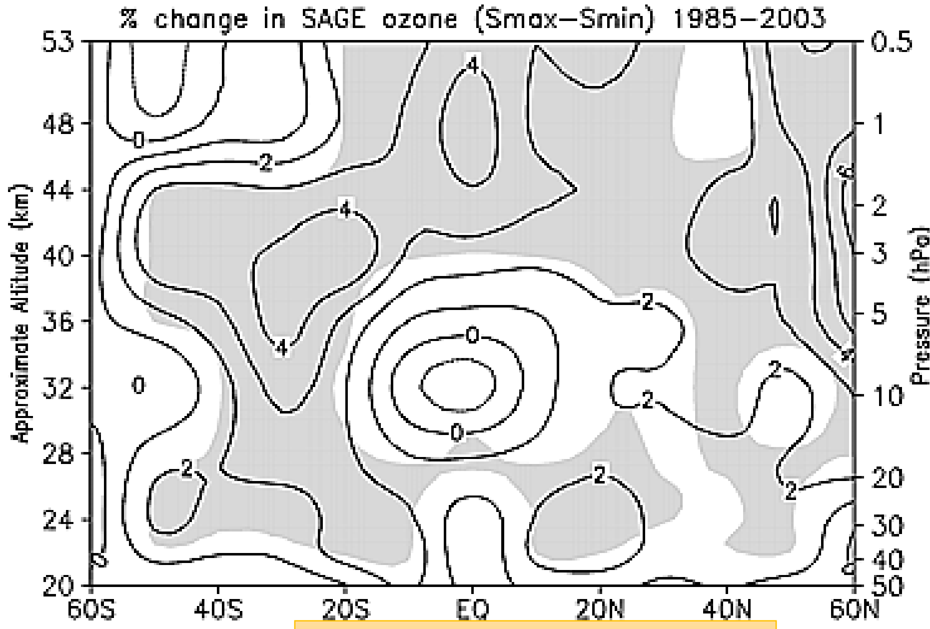
Anonymous nature of Solar Cycle Signal in the Stratospheric Ozone

<u>Sandip Dhomse</u>, Yajuan Li, Martyn Chipperfield, Wuhu Feng (Uni-Leeds), Michelle Santee (JPL), Mark Weber (Uni-Bremen)

- Stratosphere exists → O_3 is produced/destroyed by UV
- **Recent Understanding → "Double-Peak" structure**
- Improvements in satellite data, new instruments (MLS)
- Improved chemistry models → Here we use TOMCAT CTM

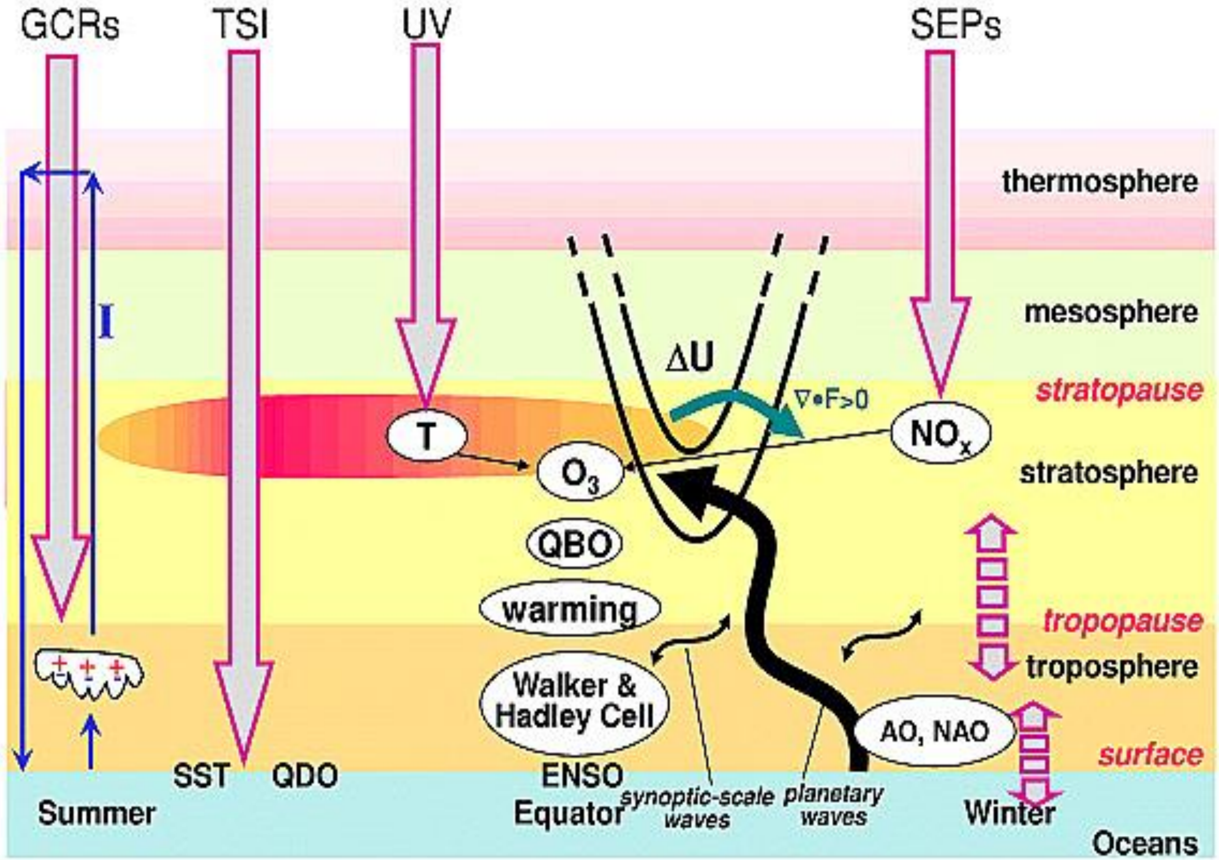
- Here we show how ozone solar cycle signal (SCS) estimates vary with quality of ozone & atmospheric data sets used to quantify the signal

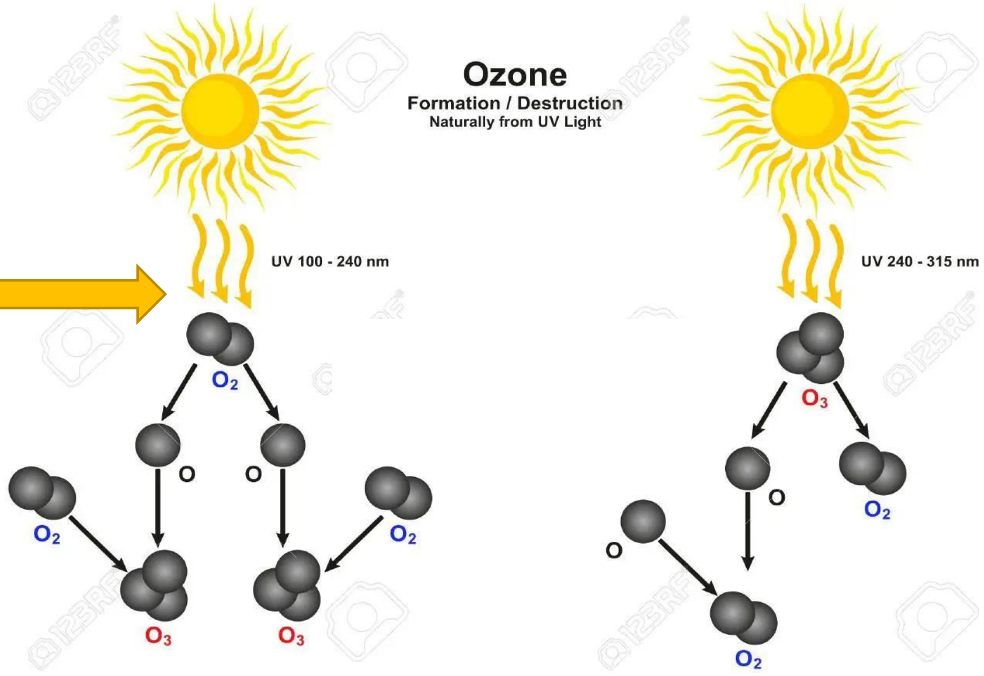


Soukharev & Hood, 2006

Top Down Mechanism (Gray et al., 2010)

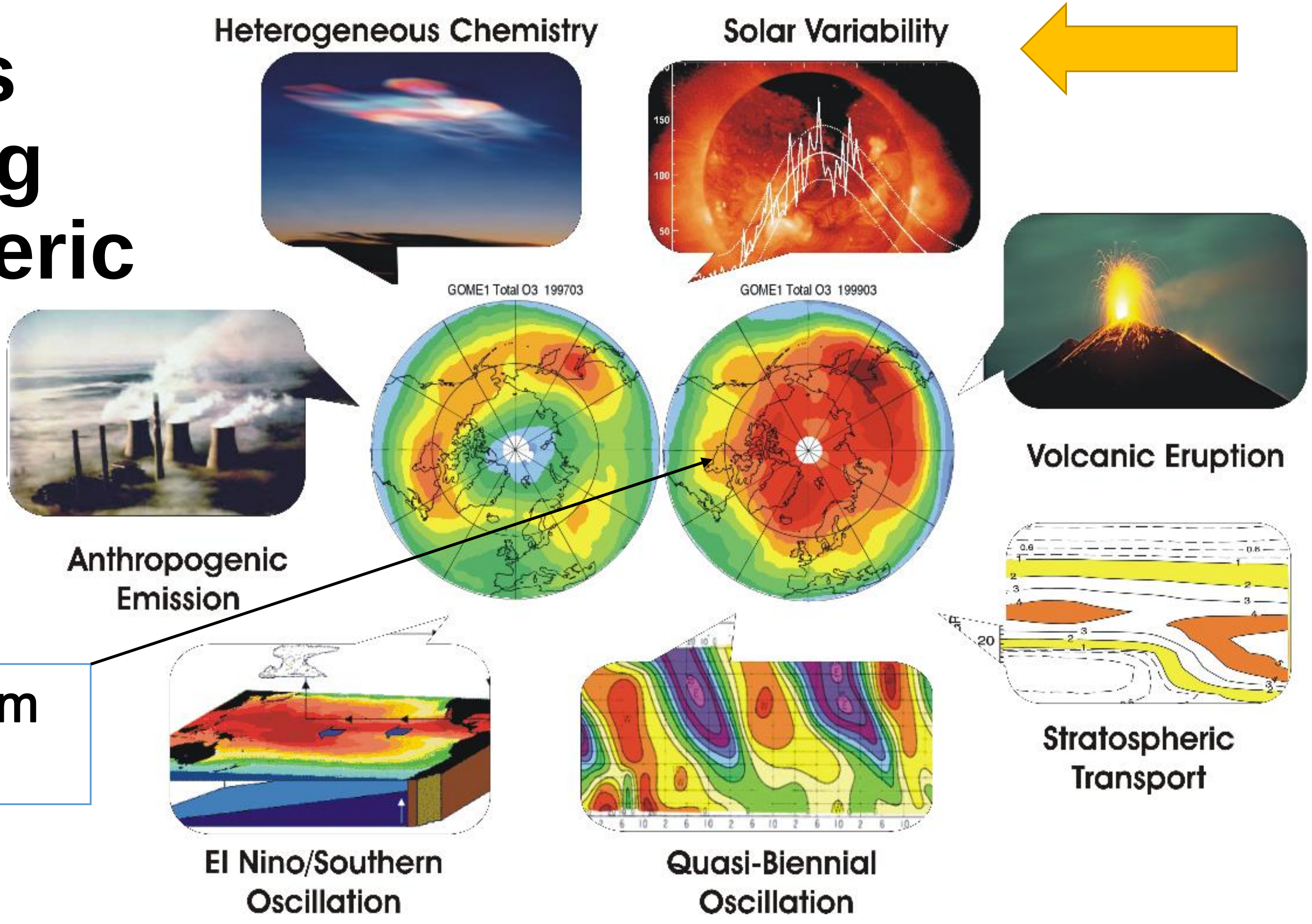
Key-> changes in UV – 240 nm





Self-healing effect

Processes Controlling Stratospheric Ozone



Large short-term variability

TOMCAT/SLIMCAT CTM

Off-line 3-D global chemical transport model with many different options.

Key points here:

- Extends from surface to ~60km using hybrid σ-θ (SLIMCAT), σ-p (TOMCAT) levels.
- Horizontal winds and temperatures from analyses (e.g. ECMWF ERA-40, ERA-Int).
- Vertical motion from diagnosed heating rates (SLIMCAT)
- Tropospheric physics: convection, PBL mixing etc
- Chemistry: ‘Full’ stratospheric chemistry scheme (64 species, 160 reactions)
- More than 300 published papers

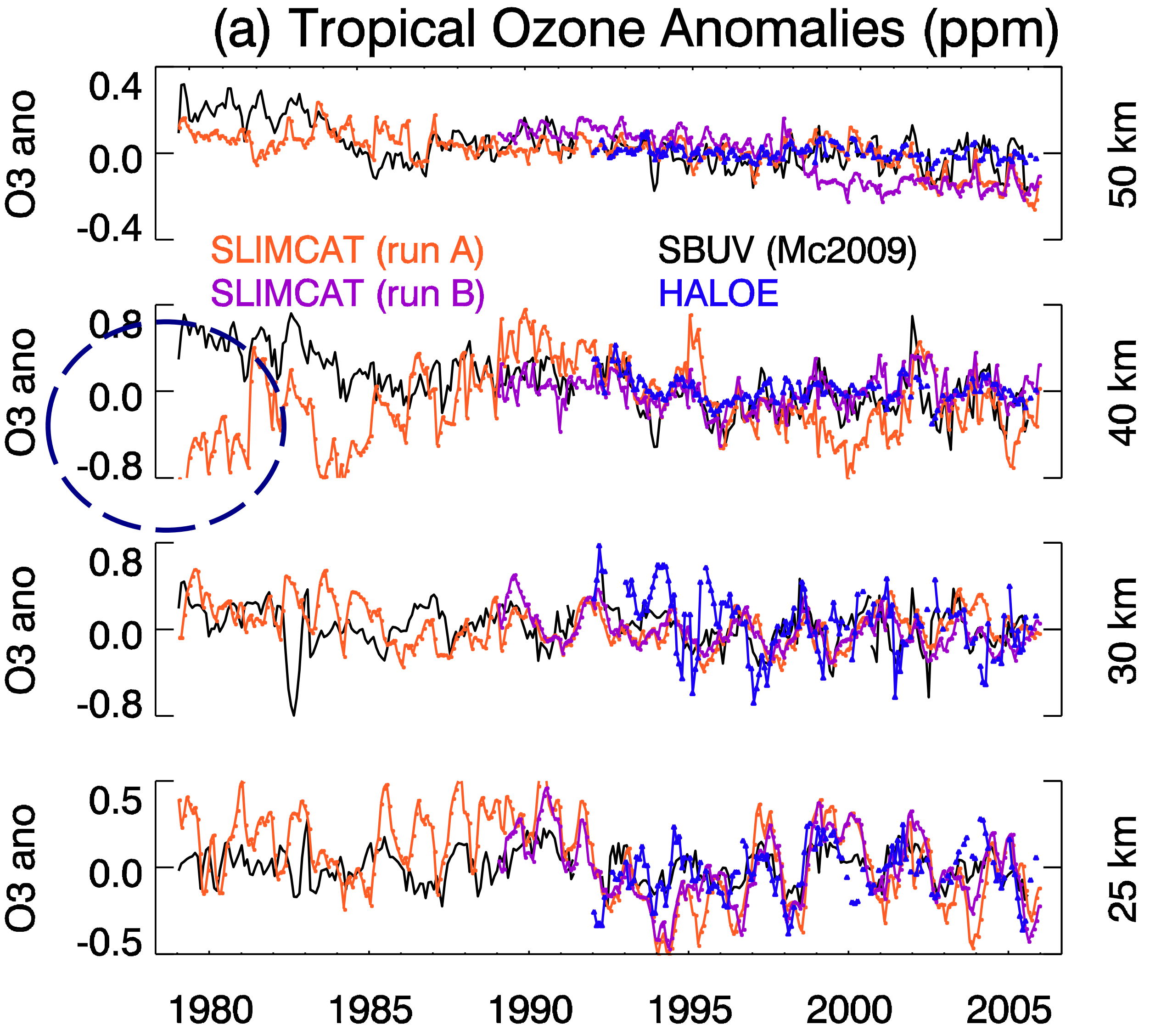
Model Set up and Observational Data (Dhomse et al, 2011)

Experiments	Solar fluxes (NRL V1)	Dynamics
Run A	time-varying	time-varying (ERA-40)
Run B	time-varying	time-varying (ERA-Int)
Run C	time-varying	fixed (year 2004)

Satellite Data Sets

- Stratospheric Aerosol and Gas Experiment (SAGE I+II, 1979-2005)
- Solar Backscatter Ultraviolet Radiometer (SBUV, 1979-2005)
- Halogen Occultation Experiment (HALOE, 1992-2005)
- Total Ozone Mapping Spectrometer (TOMS)

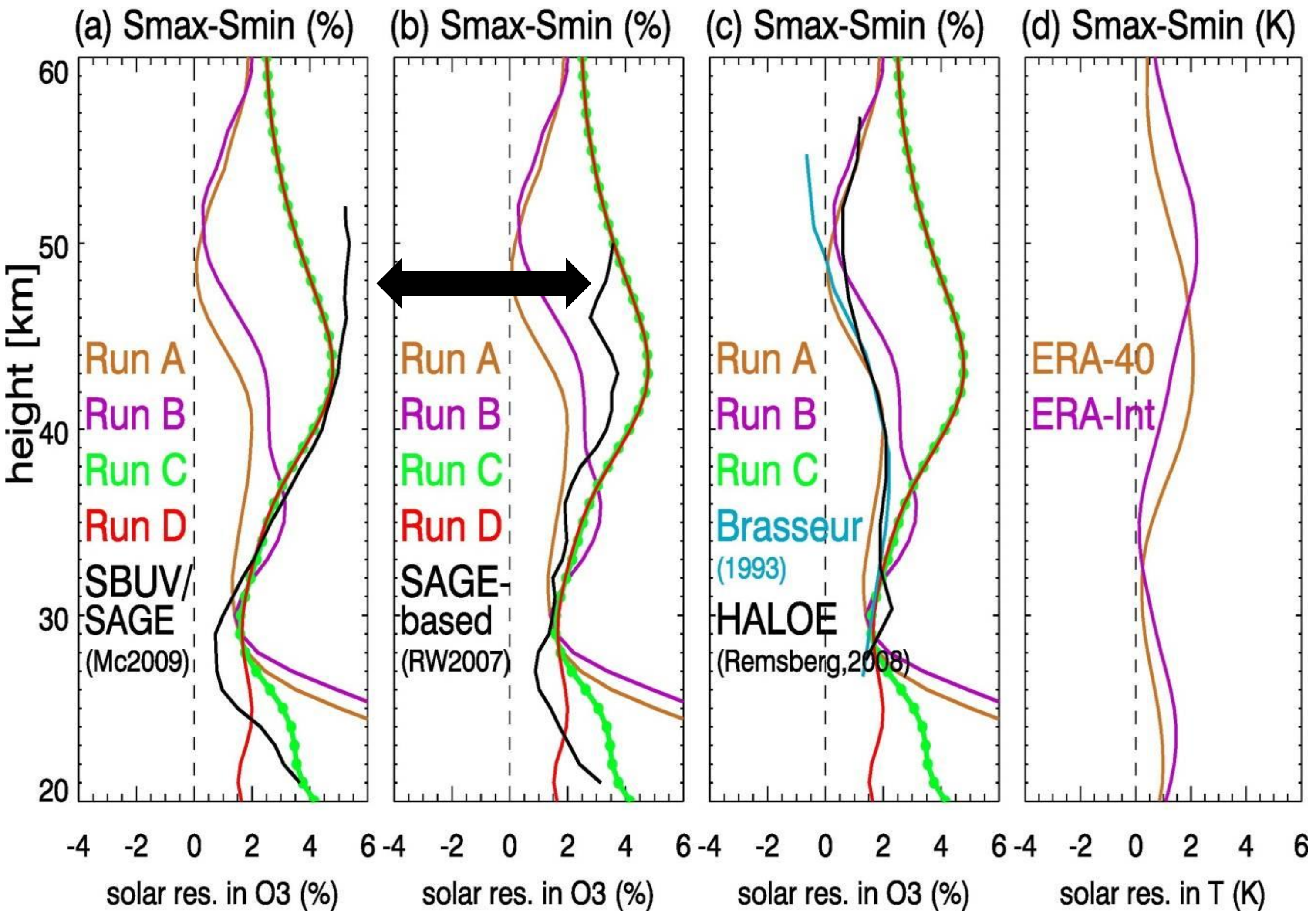
Comparison with satellite data



Run A ERA40, **Run B ERA-Int**

Some inhomogeneities in ECMWF reanalysis data sets
→ Corrected using step function in a regression model

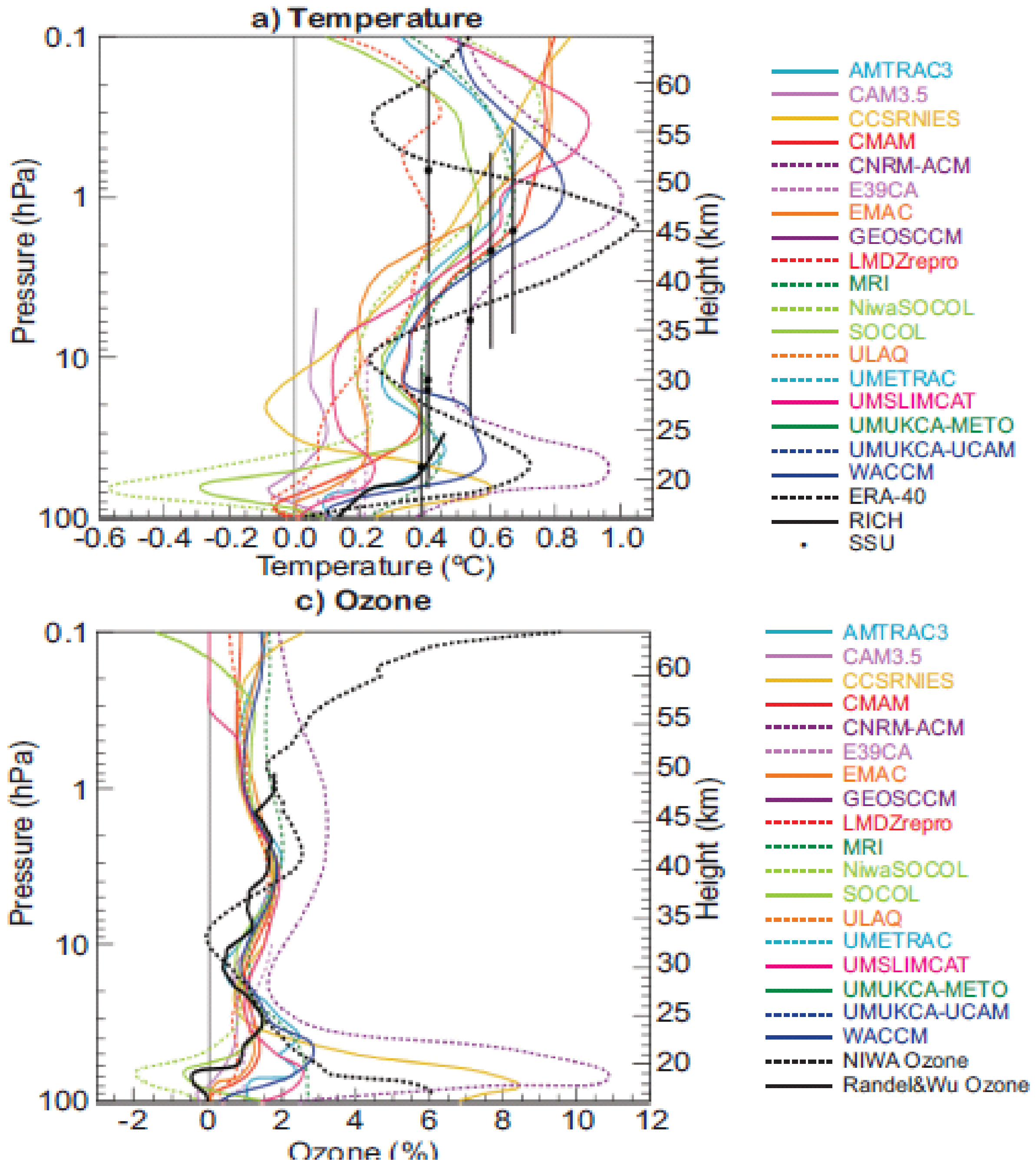
Solar response in tropical stratospheric O_3



Dhomse et al, ACP, 2011

- ➢SAGE and SBUV type estimates → only if there are no dynamical variability
- ➢Positive solar response in ECMWF temp.
- ➢HALOE/Model peak – 30 to 40 km

Solar response in CCMVal-2



1. UMSLIMCAT simulates large solar response in upper stratospheric temp

2. Ozone response in lower and middle stratosphere is well simulated

3. None of the models could reproduce upper stratospheric ozone response →

Models missing something?

SPARC - CCMVAL-2 report 2010

SORCE data & O_3 response – a 2D model

Haigh et al., Nature, 2010

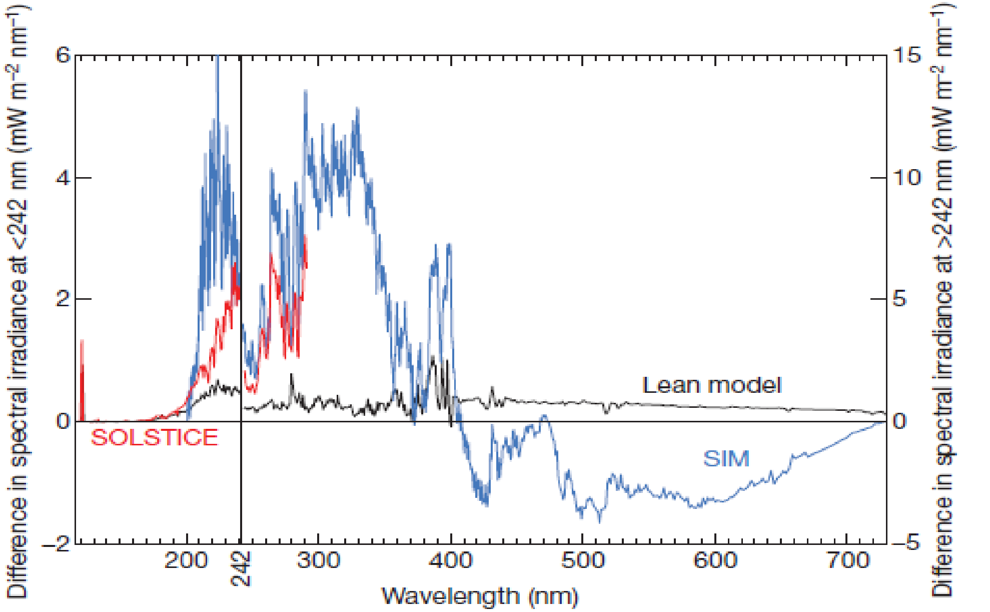


Figure 1 | Difference in solar spectrum between April 2004 and November 2007. The difference (2004–2007) in solar spectral irradiance (W m^{-2} nm^{-1}) derived from SIM data[4] (in blue), SOLSTICE data[8] (in red) and from the Lean model[5] (in black). Different scales are used for values at wavelengths less and more than 242 nm (see left and right axes respectively).

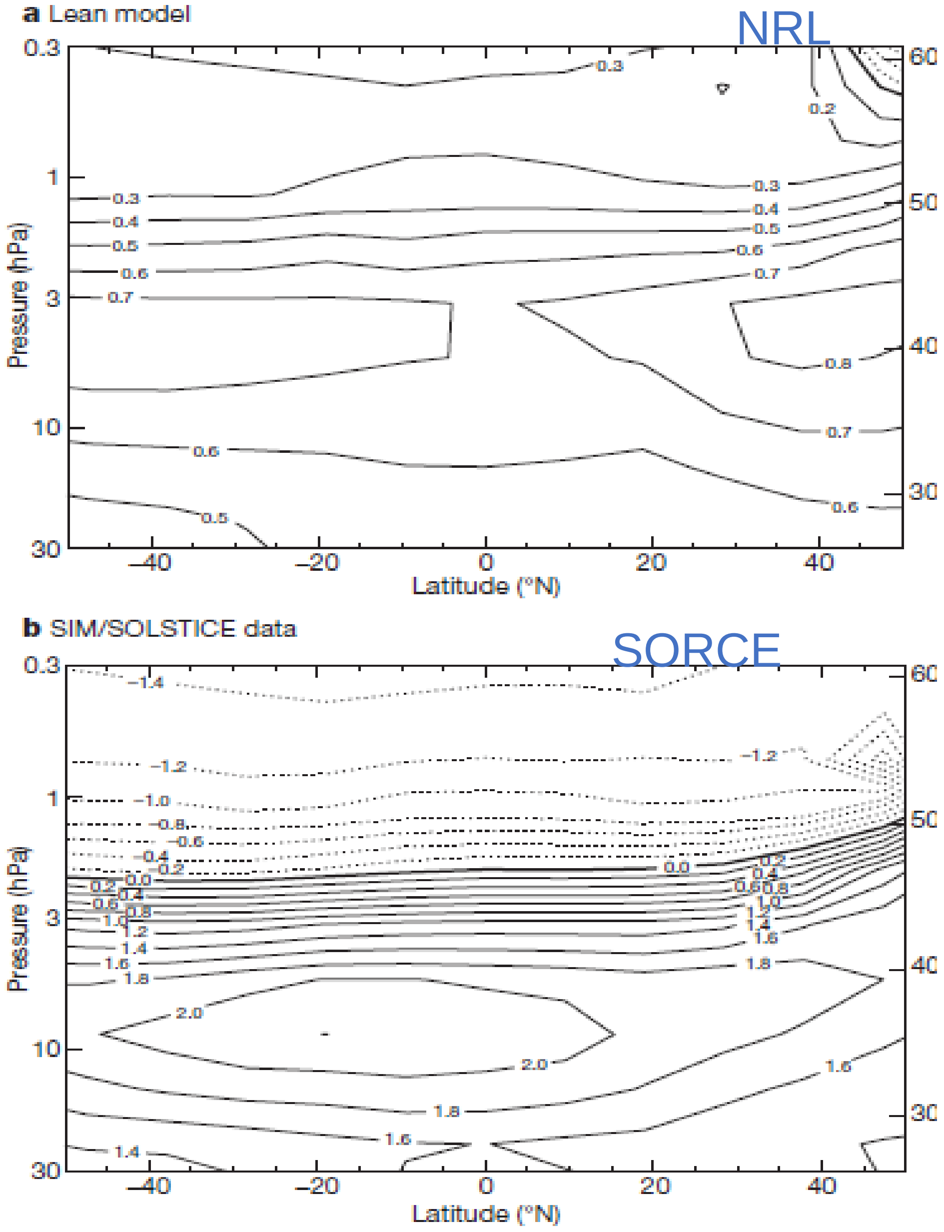


Figure 2 | Modelled difference in ozone between December 2004 and December 2007. Estimates of the percentage difference (2004–2007) in zo

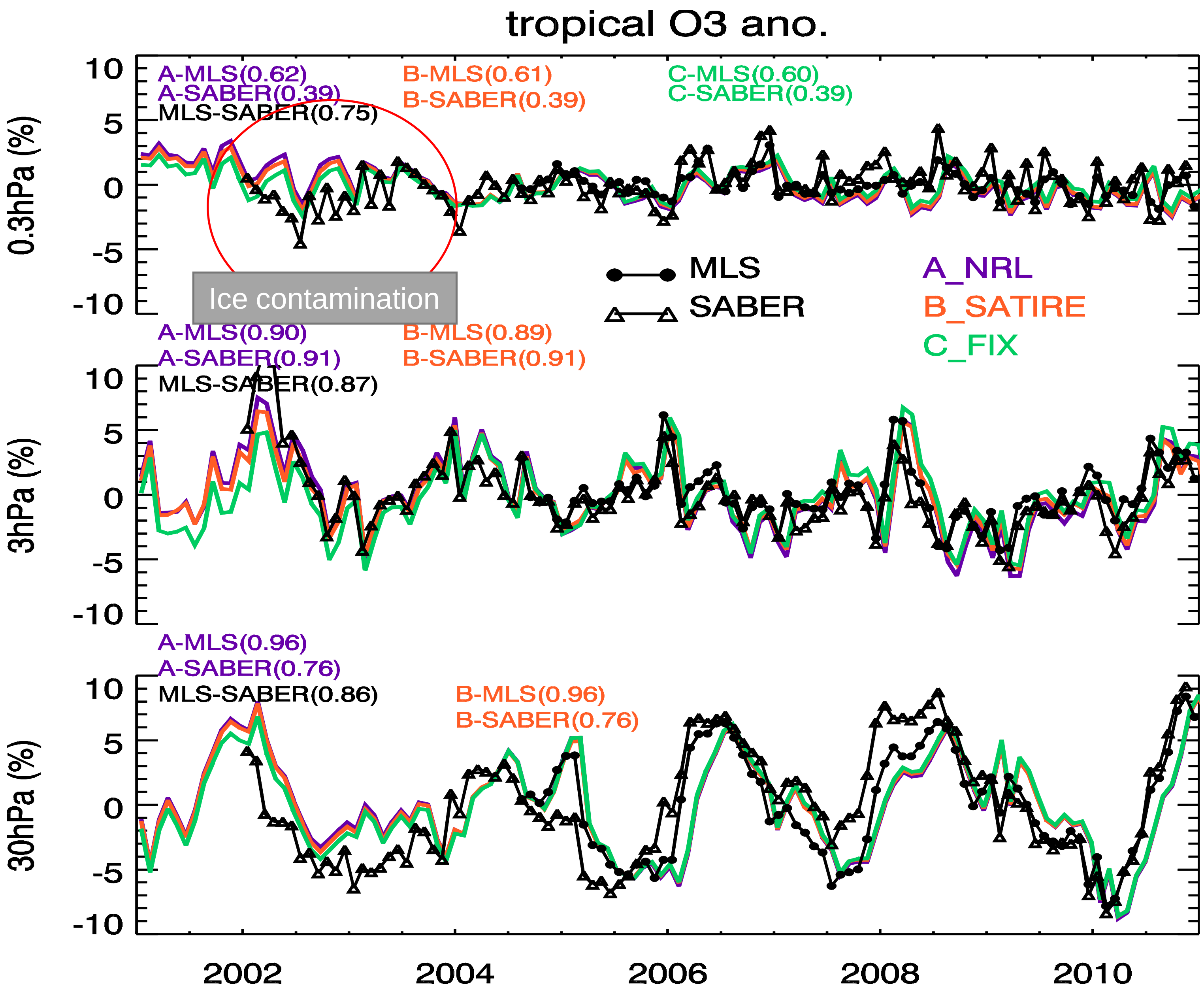
Day time ozone

Model Set up & Observational Data (Dhomse et al., 2013)

Experiments	Solar fluxes	Dynamics
Run A_NRL	time-varying (NRL)	time-varying (ERA-Int)
Run B_SAT	time-varying (SATIRE)	Same as Run A_NRL
Run C_FIX	Fixed (mean 2001-2010)	Same as Run A_NRL
Run D_S2004	SORCE (2004)	Same as Run A_NRL
Run E_S2007	SORCE (2007)	Same as Run A_NRL

Ozone Data (Satellite)

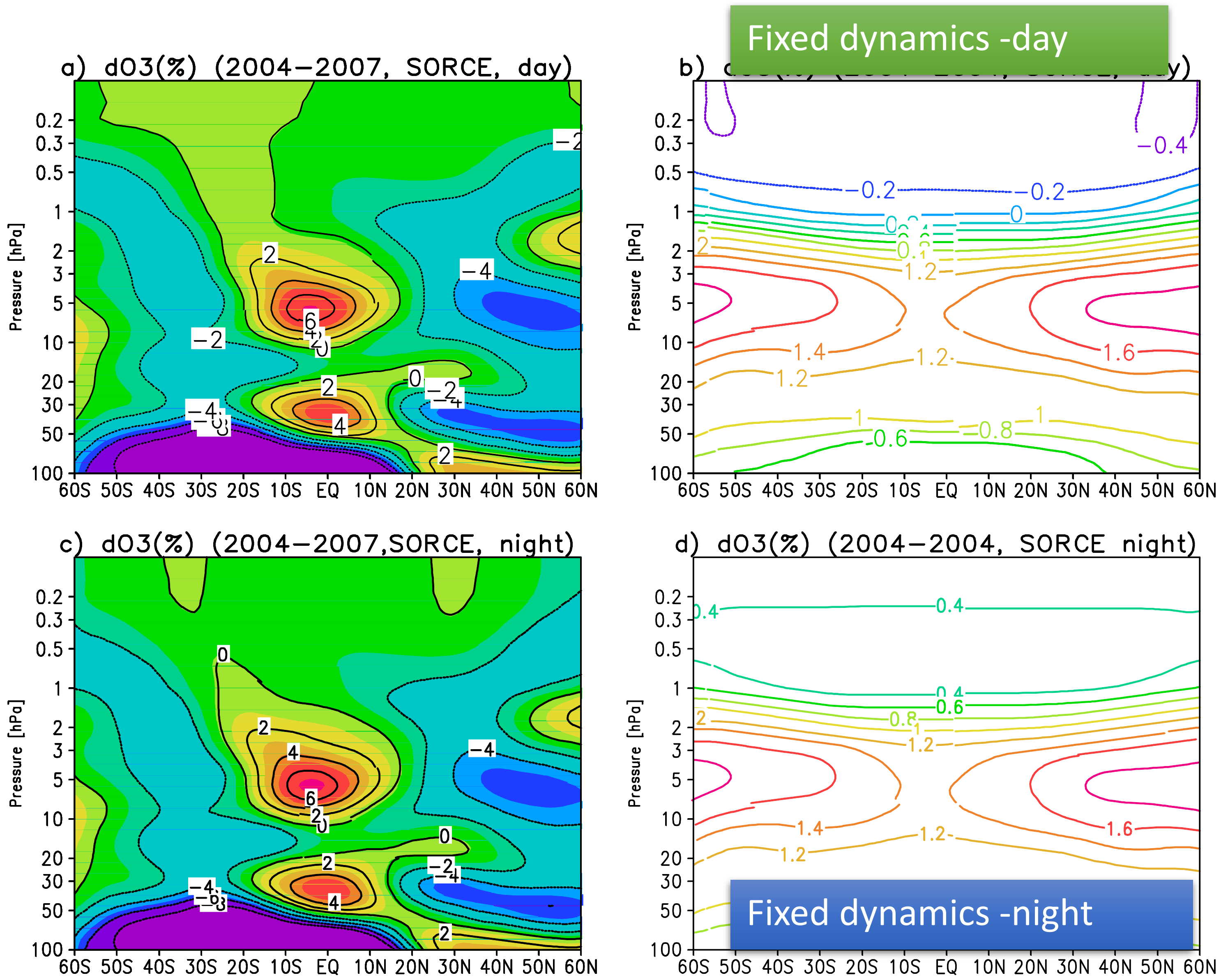
- Sounding of the Atmosphere using Broadband Emission Radiometry (SABER, 2002-2010)
- Microwave Limb Sounder (MLS, 2004-2010)



TOMCAT, MLS & SABER

Good agreement with MLS
→ realistic dynamics is the key

ΔO3 (%) 2004 minus 2007

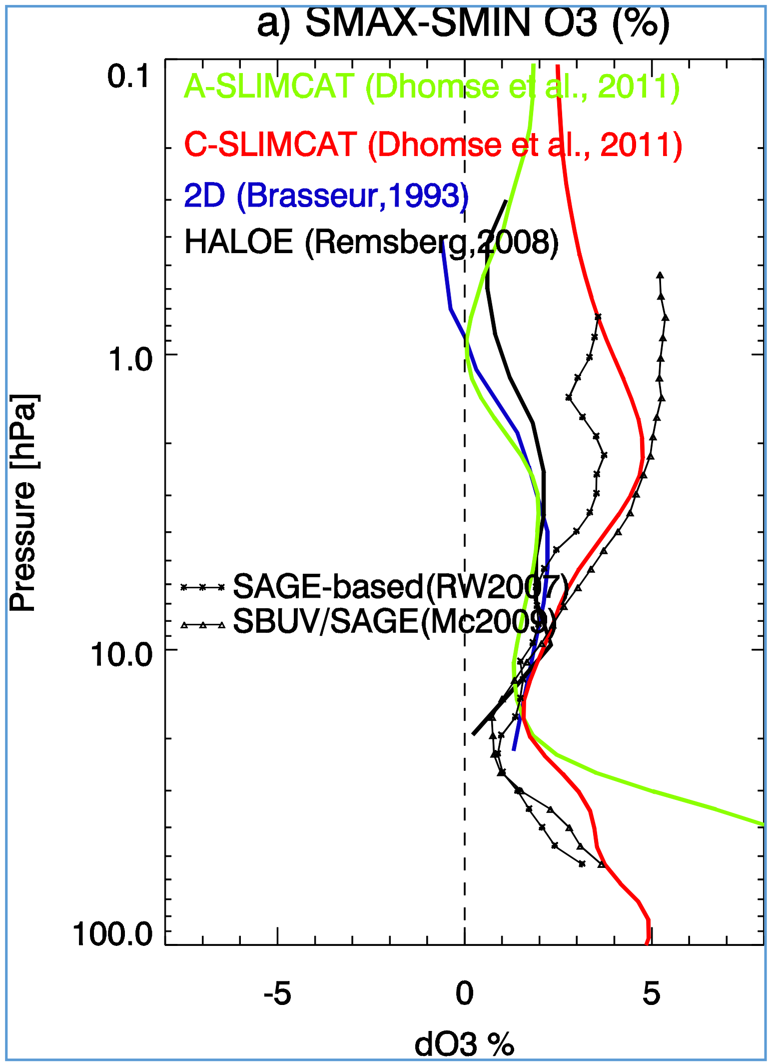


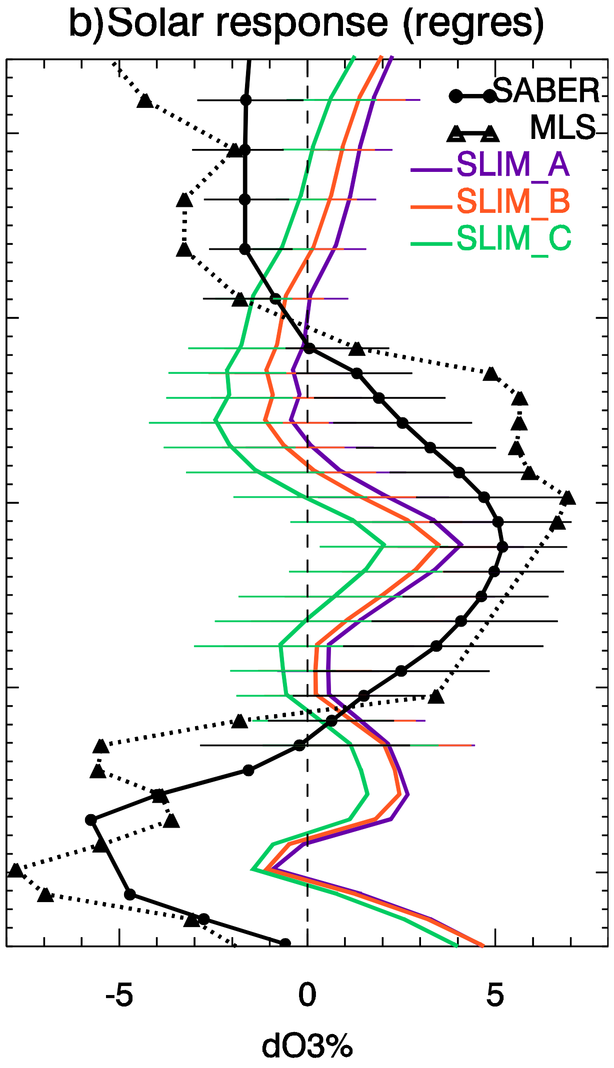
SORCE, as in Haigh et al., 2010)

Slight differences in day & night time solar signal

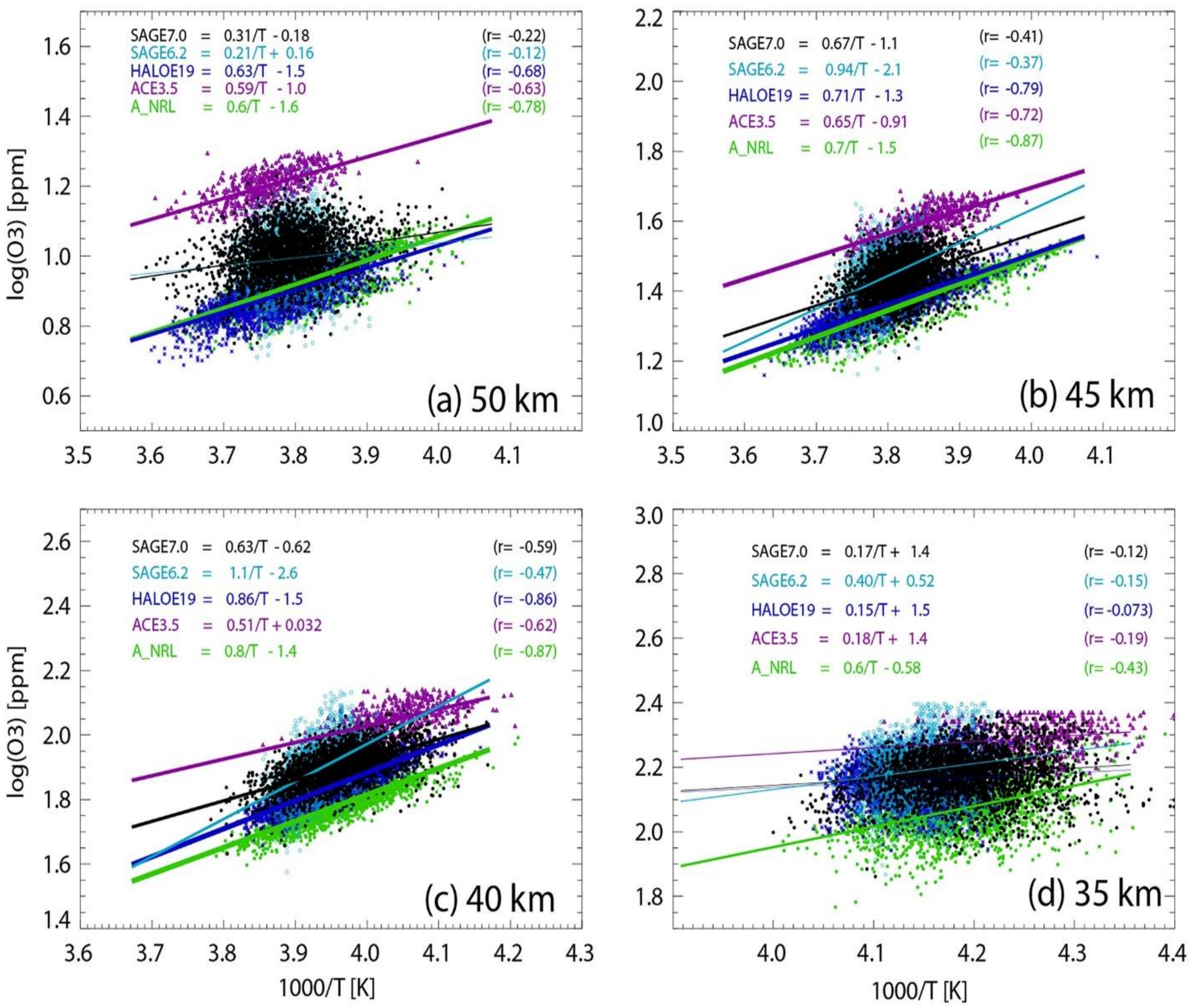
(Dhomse et al., 2013)

Regression analysis (Dhomse et al., 2013)





- MLS & SABER show middle strat. signal that is larger than SAGE, SBUV or HALOE
- Negligible signal in the upper stratosphere
- Large error bars in upper strat./ lower mesosphere, but look close to HALOE

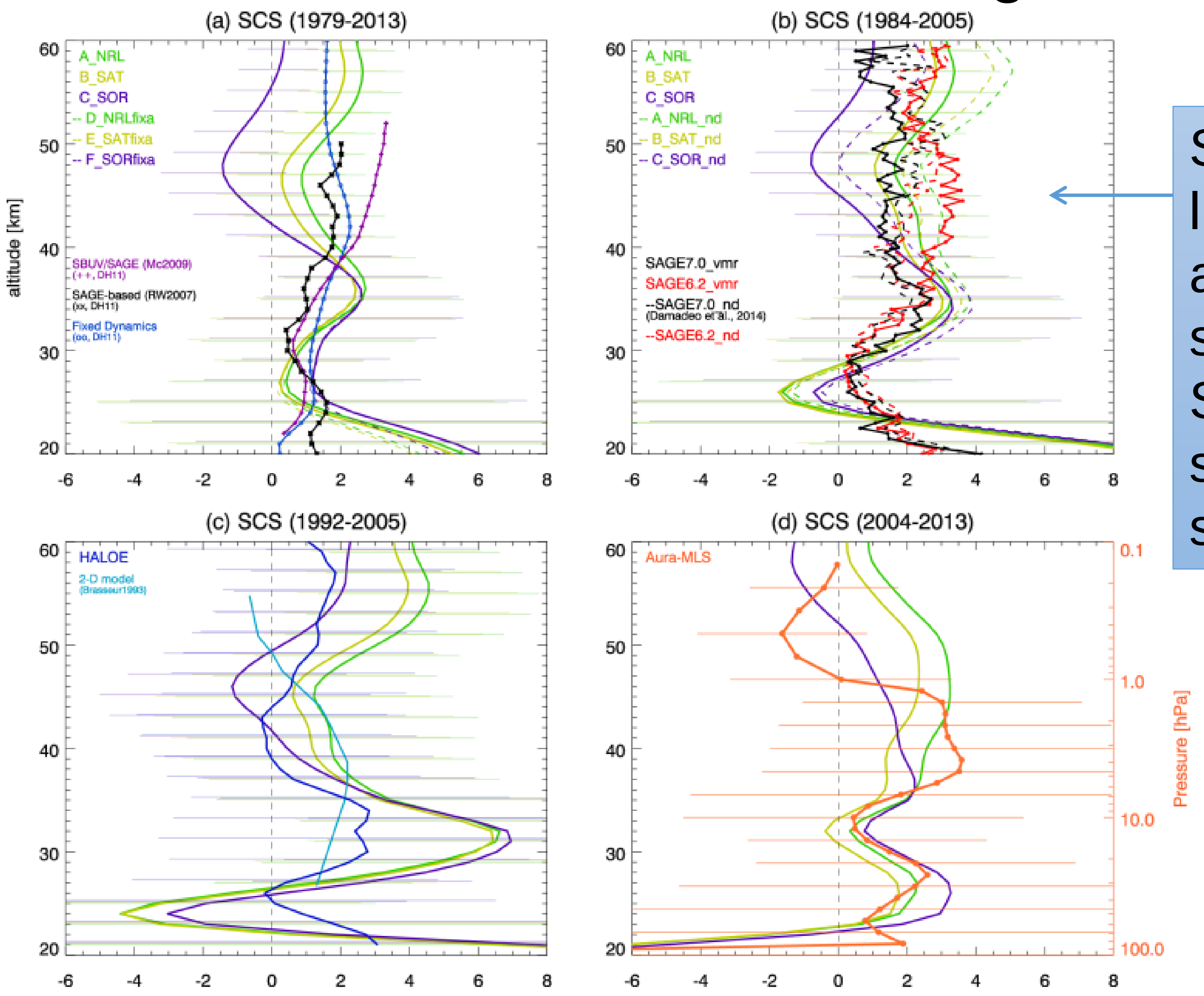


New SAGE V7 data was released in 2014

O_3 /Temp relationship improved in SAGE V7 data

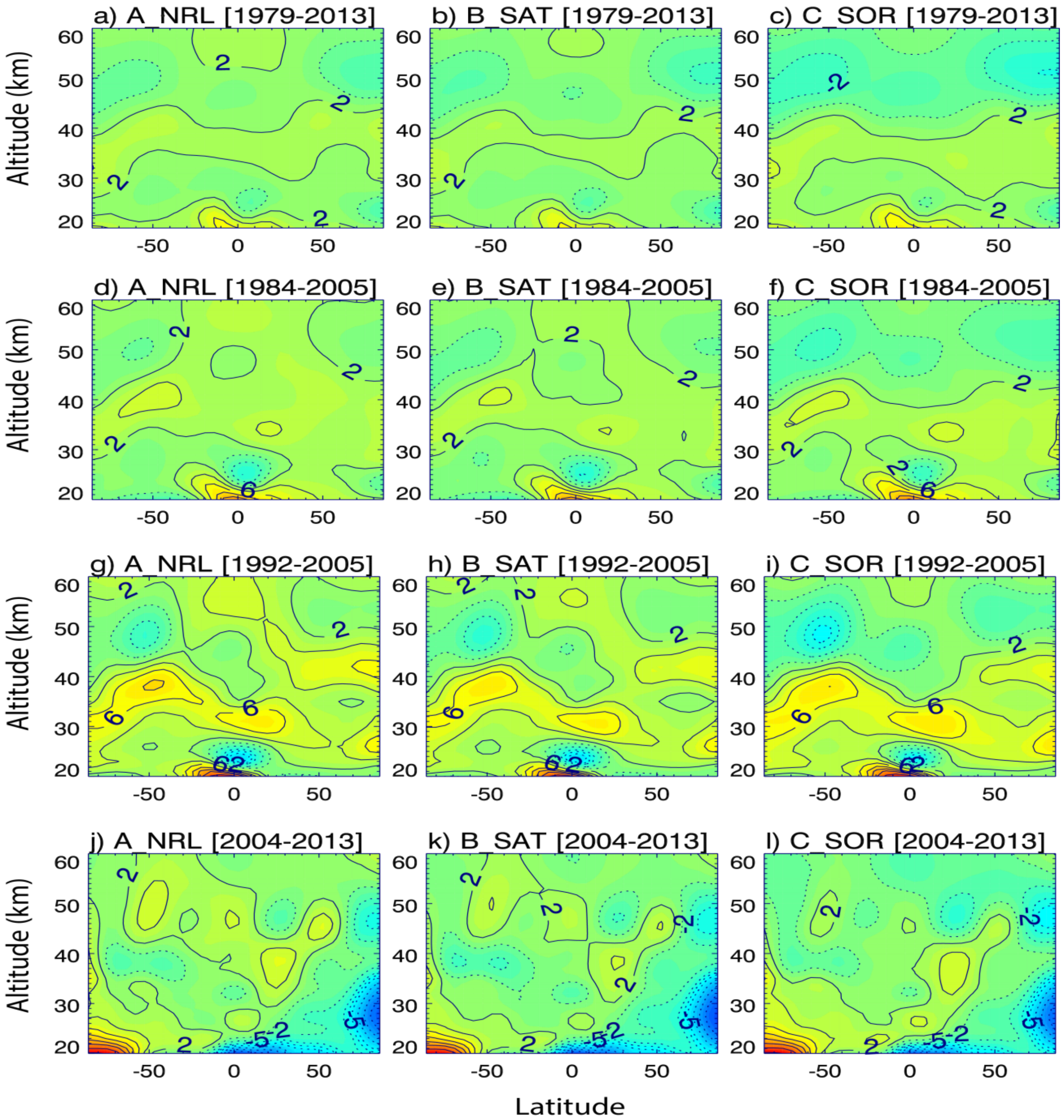
Dhomse et al., 2016

Solar signal in tropical O_3 (Dhomse et al., 2016)



SAGE 7 (vmr-black solid line) shows good agreement with model simulated SCS (NRL or SATIRE) → Reduced signal in the upper stratosphere

Key diffs. between SAGE 7 and SAGE 6.2 data are discussed in Damadeo et. al, 2014

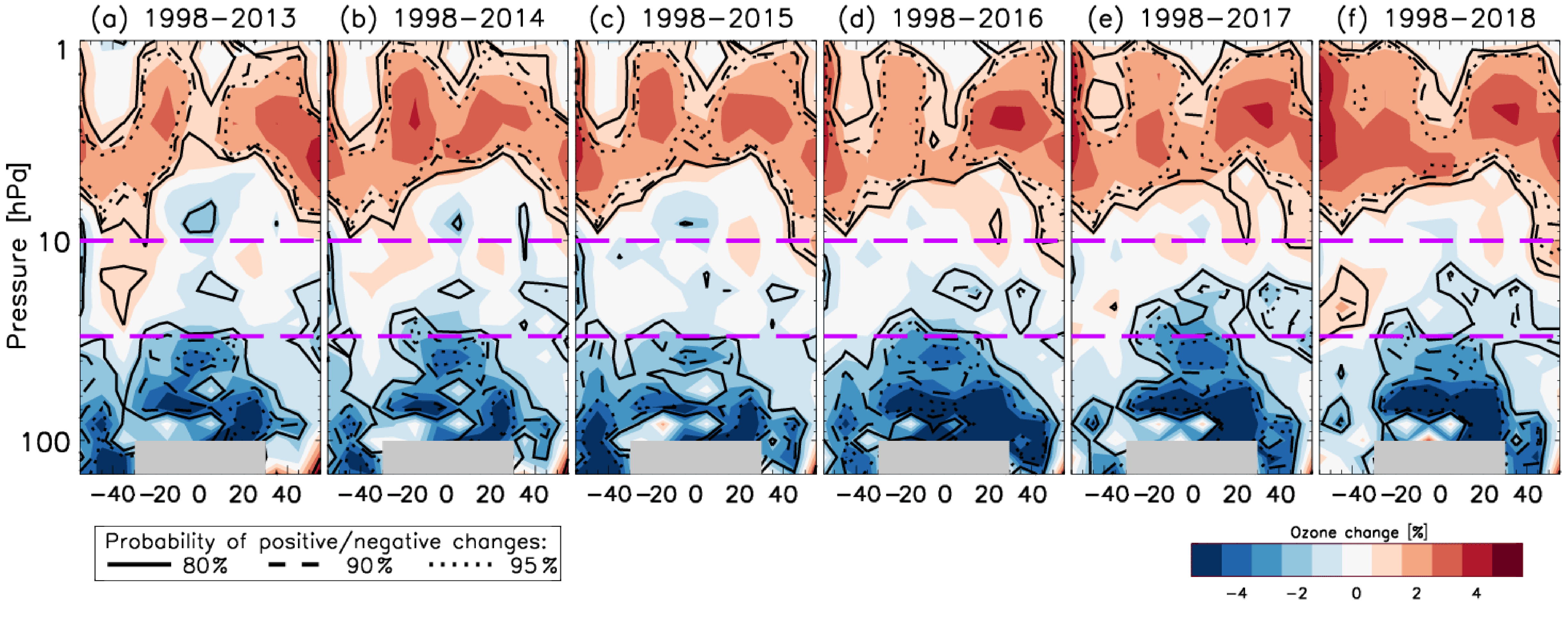


Temporal variation in solar signal

Dhomse et al., 2016

- ❑ SORCE-type SCS model simulates negative SCS in the upper strat
- ❑ If model simulations are correct, then analysing it over different time period gives different SCS
- ❑ Significant inter-hemispheric differences in SCS over MLS period (2004-2013) due to changes in stratospheric circulation (Mahieu et al., 2014): Internal variability or solar induced?

Lower stratospheric ozone still declining → Ball et al. (2018)



Data and methodology

- Data : MLS level 2 (daily profile data) v5 data (2005-2020) from

  https://search.earthdata.nasa.gov/search?q=ML2O3_005

- MLS L2 data is binned onto TOMCAT latitude bins (2.8^{o})

- Calculate zonal mean monthly mean percentage anomalies 2005-2020 (model and MLS)

- Multivariate regression model is modified version of that used in Dhomse et al., (2016)

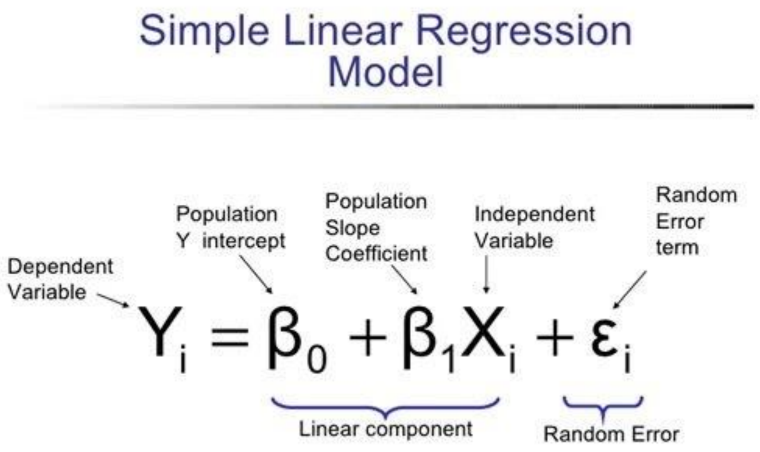
dOzone = linear trends (12) + QBO terms (Q30 and Q50, 24) + Age of Air (12) +

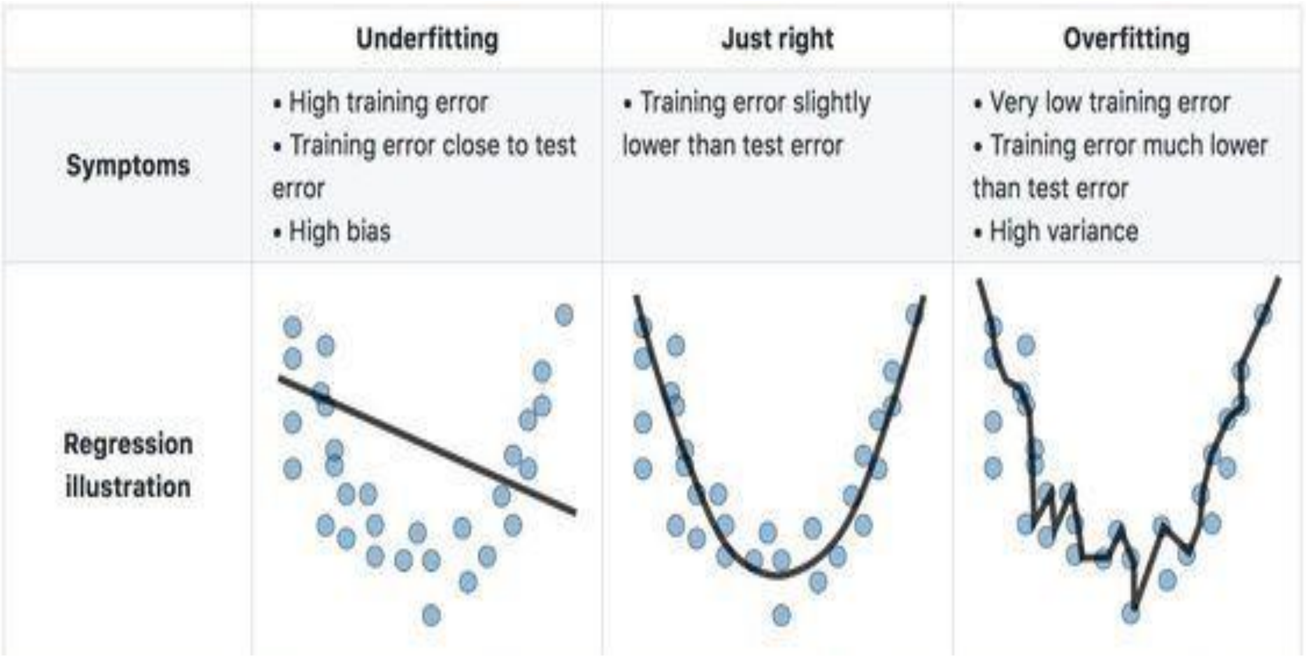
+ Solar + SOI + AO + AAO   (total 52 terms)

- QBO, Southern Oscillation, AO and AAO indices from Climate Prediction Center, Solar (Mg ii index) from IUP Bremen, Age-of-Air is from TOMCAT simulation

Dhomse et al., 2022

Historically Multivariate Regression Models with Ordinary Least Square Fit (OLS) method are used to estimate solar cycle signal



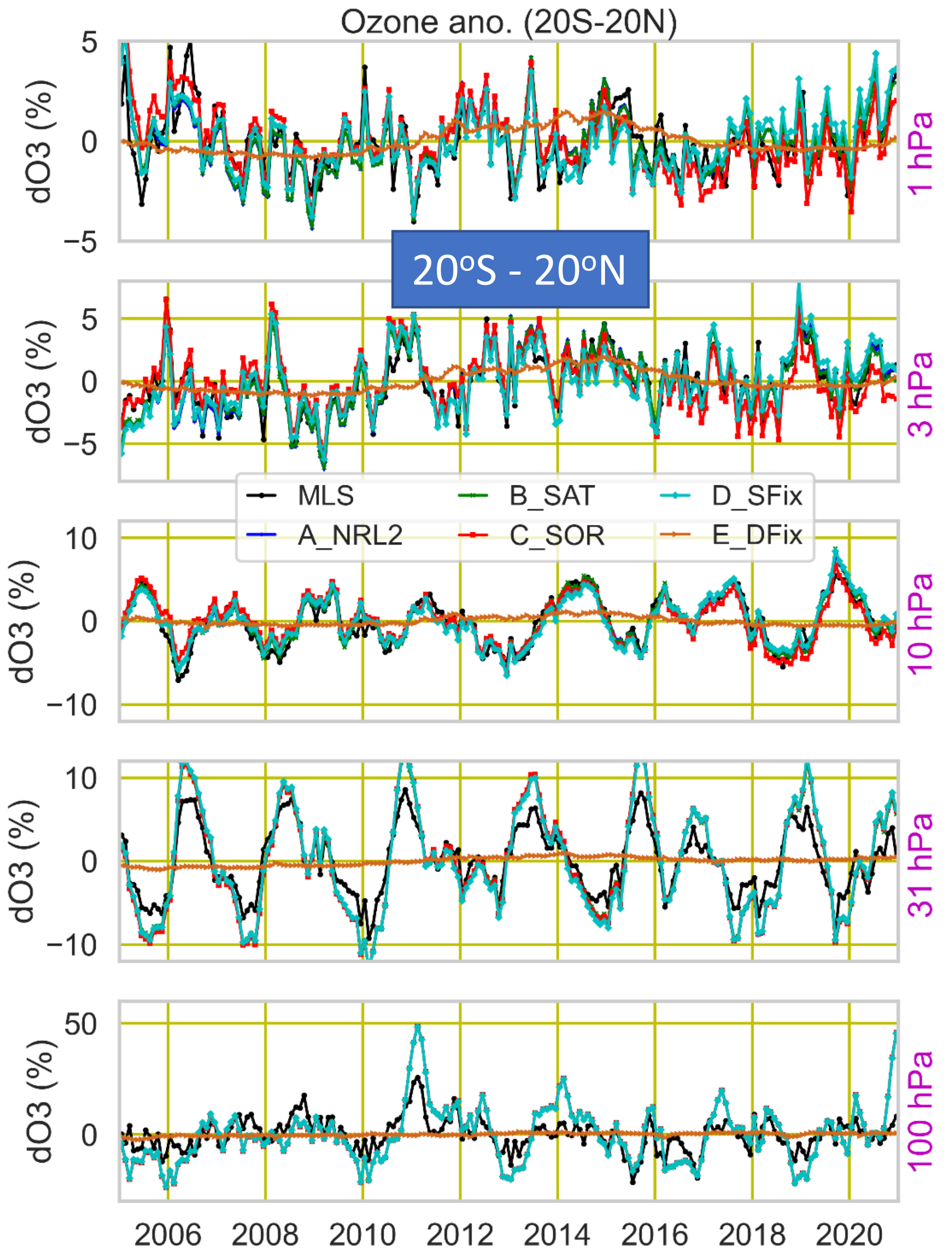


- Complicated to find suitable proxies that control ozone variations at all the levels
- Hence, here we use regularised multivariate regression models (Lasso, Ridge, ElasticNet)

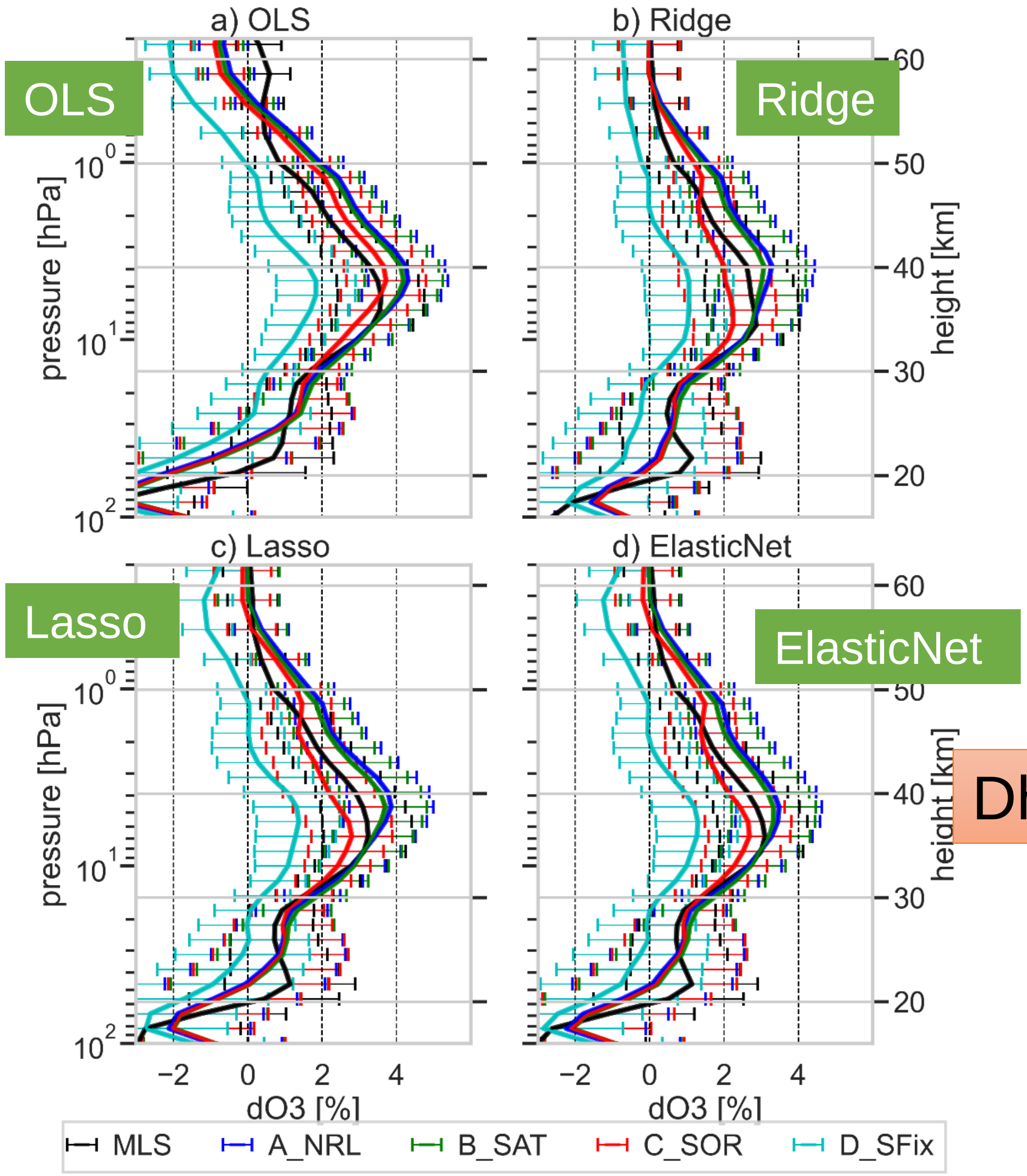
TOMCAT CTM Simulations: good agreement with MLS data

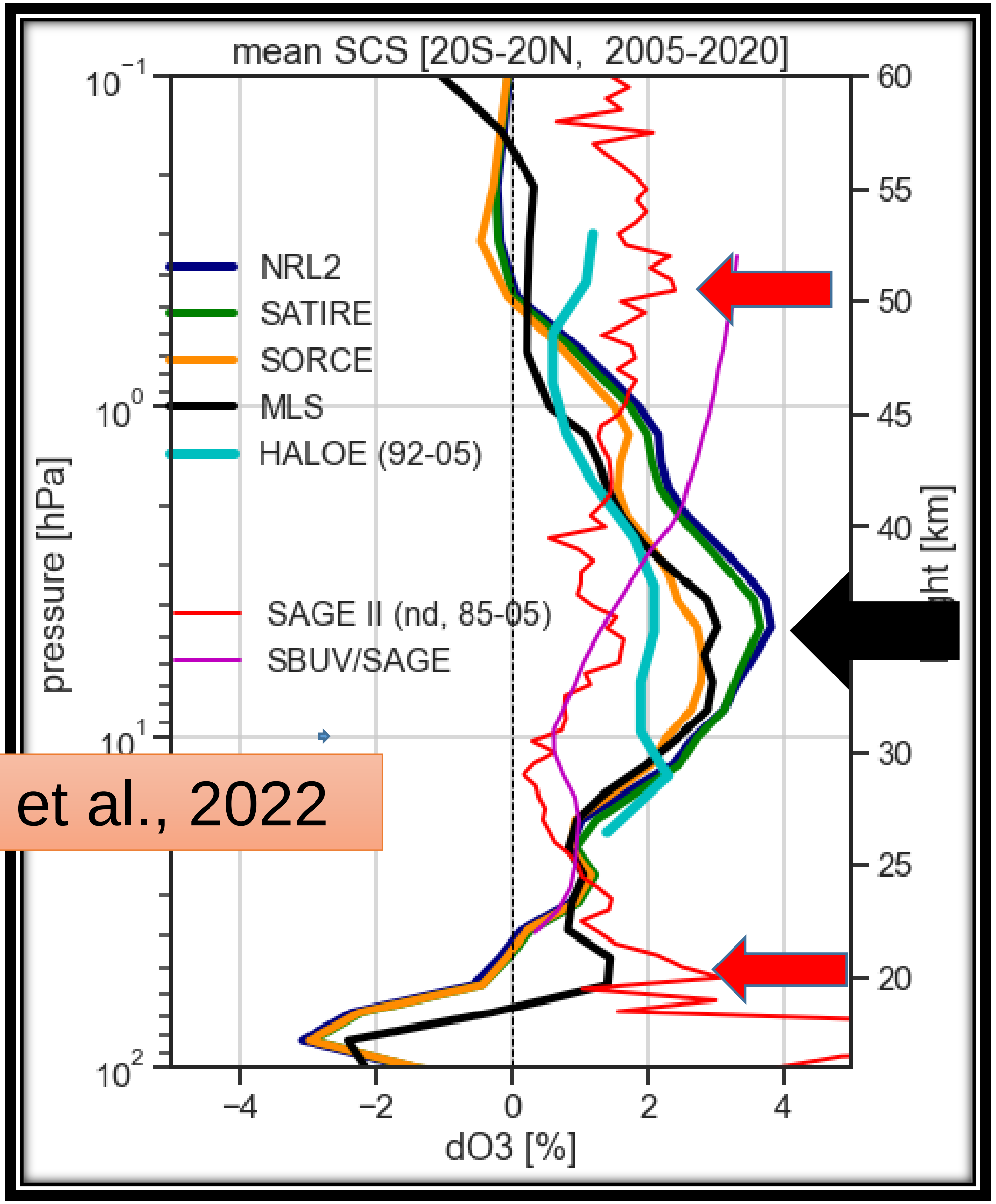
Setup is similar to:
Feng et al., (GRL, 2021),
Weber et al., (JGR, 2021)
Bognar et al., (JGR, 2021)

Simulation	Solar Irradiance data
A_NRL2	NRL v2
B_SATIRE	SATIRE
C_SORCE	SORCE satellite (SIM/SOLSTICE)
D_SFix	Fixed (year 2004)
E_DFix	Same as A_NRL2 but annually repeating dynamics



SCS in the tropical strat. - different than earlier estimates





Dhomse et al., 2022

Current Status:

- New data: newer version of homogenized data sets

SWOOSH (NOAA, Davies et al., 2016),
MLTOMCAT (Dhomse et al., 2021)

- Lower stratospheric ozone not recovering??

Multivariate regression models (1984-2020)

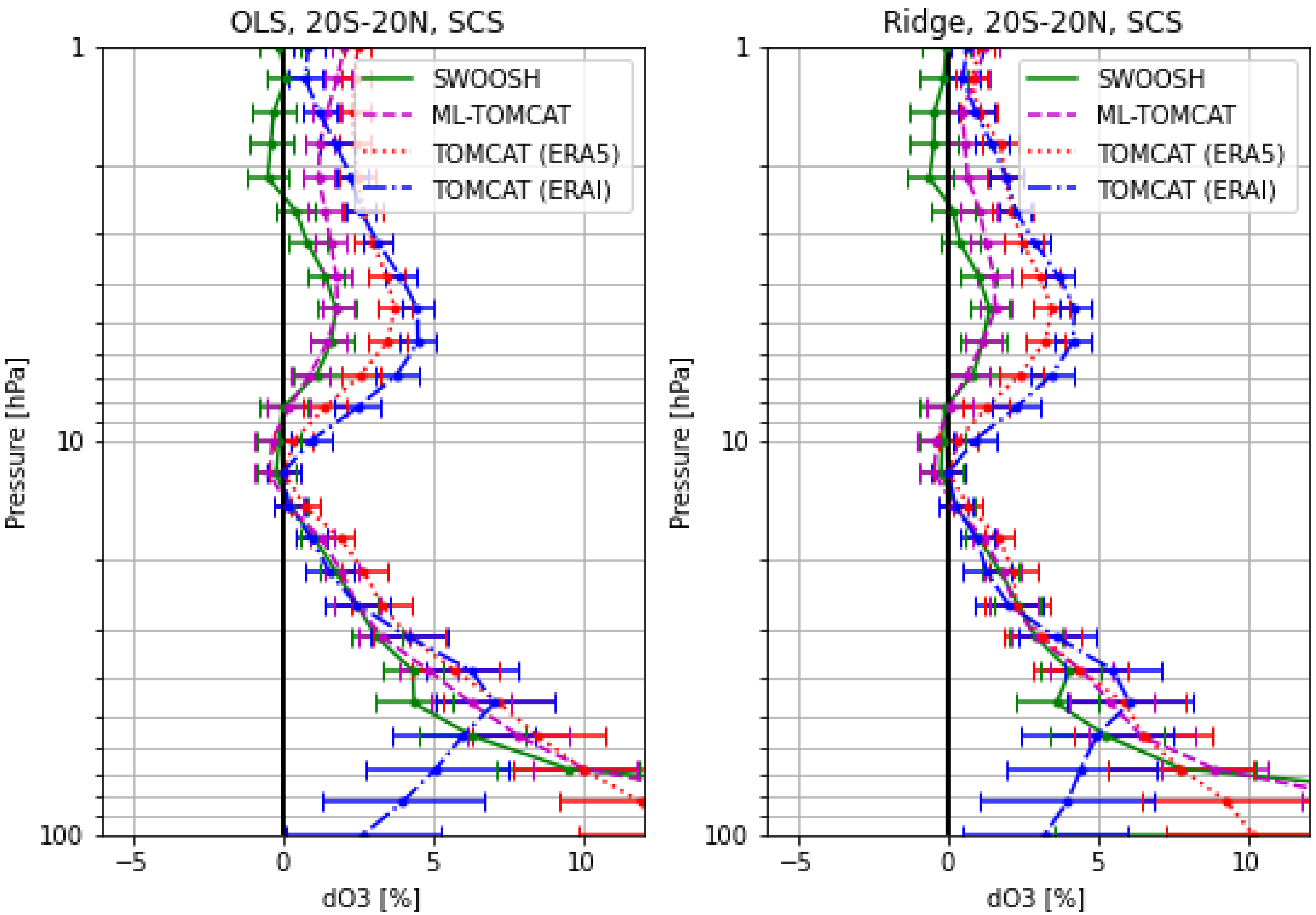
- Transport differences between two versions of ECWMF reanalyses
- Fz, vertical component of Eliassen-Palm Flux that drives stratospheric circulation (2-month average)
- Data during 1991-1992 are removed (Mt. Pinatubo eruption)

Solar cycle signals in the tropical stratosphere:

- 1984-2020/18, Fz at 50hPa

- Upper stratospheric signal still small

- Lower stratospheric signal is back



Li et al., *in preparation*

Solar cycle signals in the tropical stratosphere:

- 2005-2020/18, Fz at 50hPa

- Upper stratospheric signal bit larger

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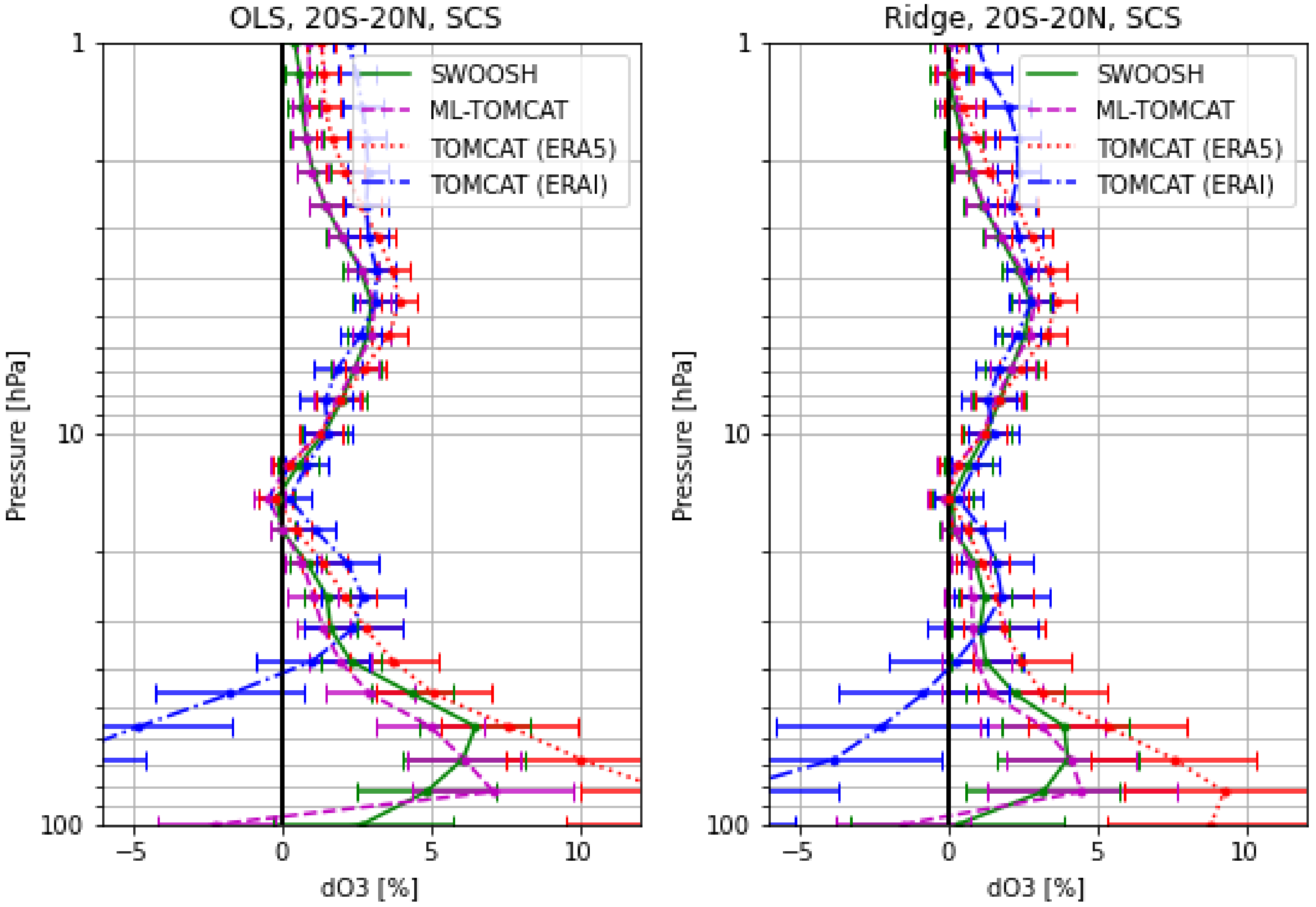


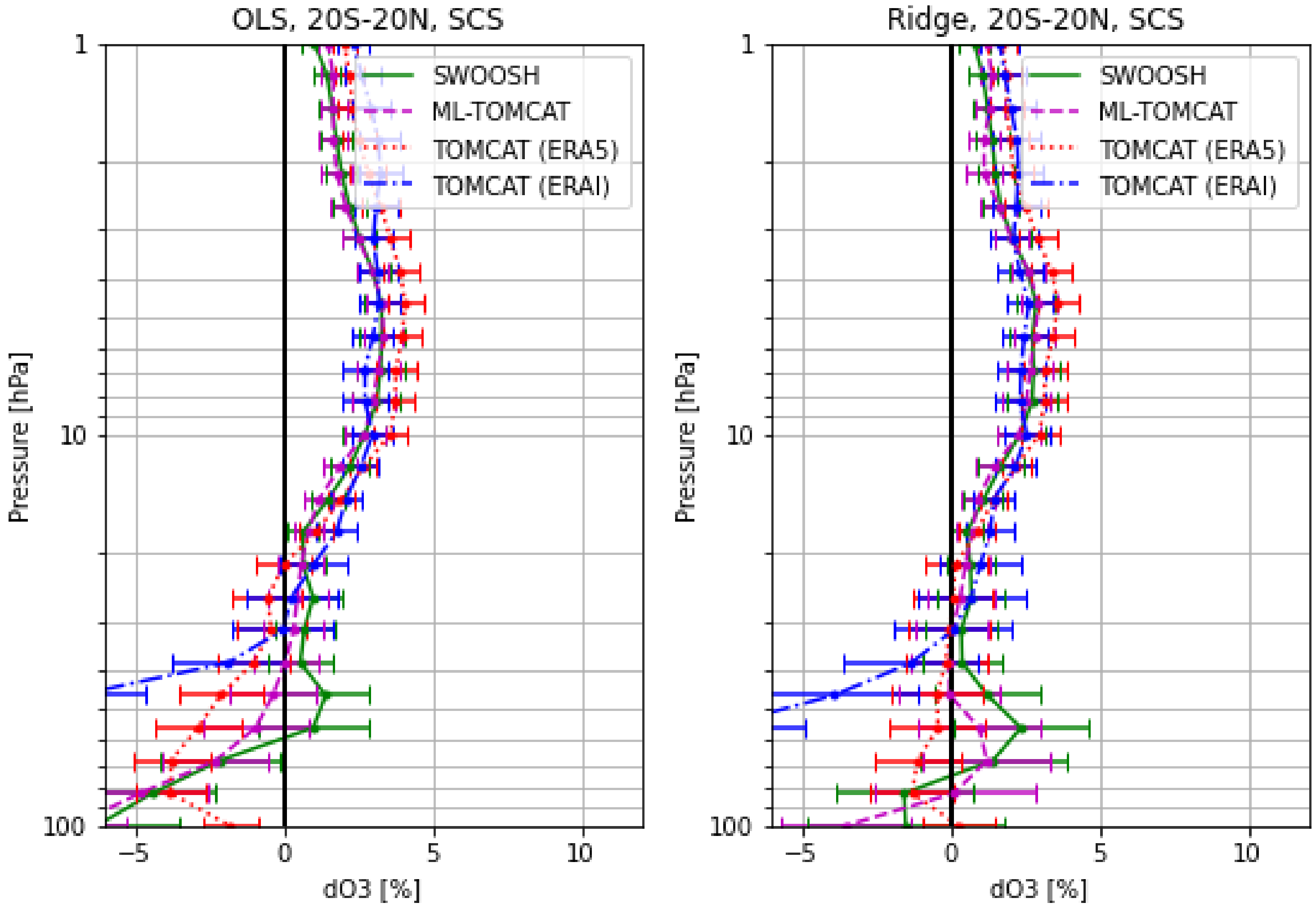
Dynamical proxy -> age of air Vs Fz

- 2005-2020/18, AoA from ERA5

- Upper stratospheric signal bit larger

- Lower stratospheric signal is gone

Li et al., *in preparation*

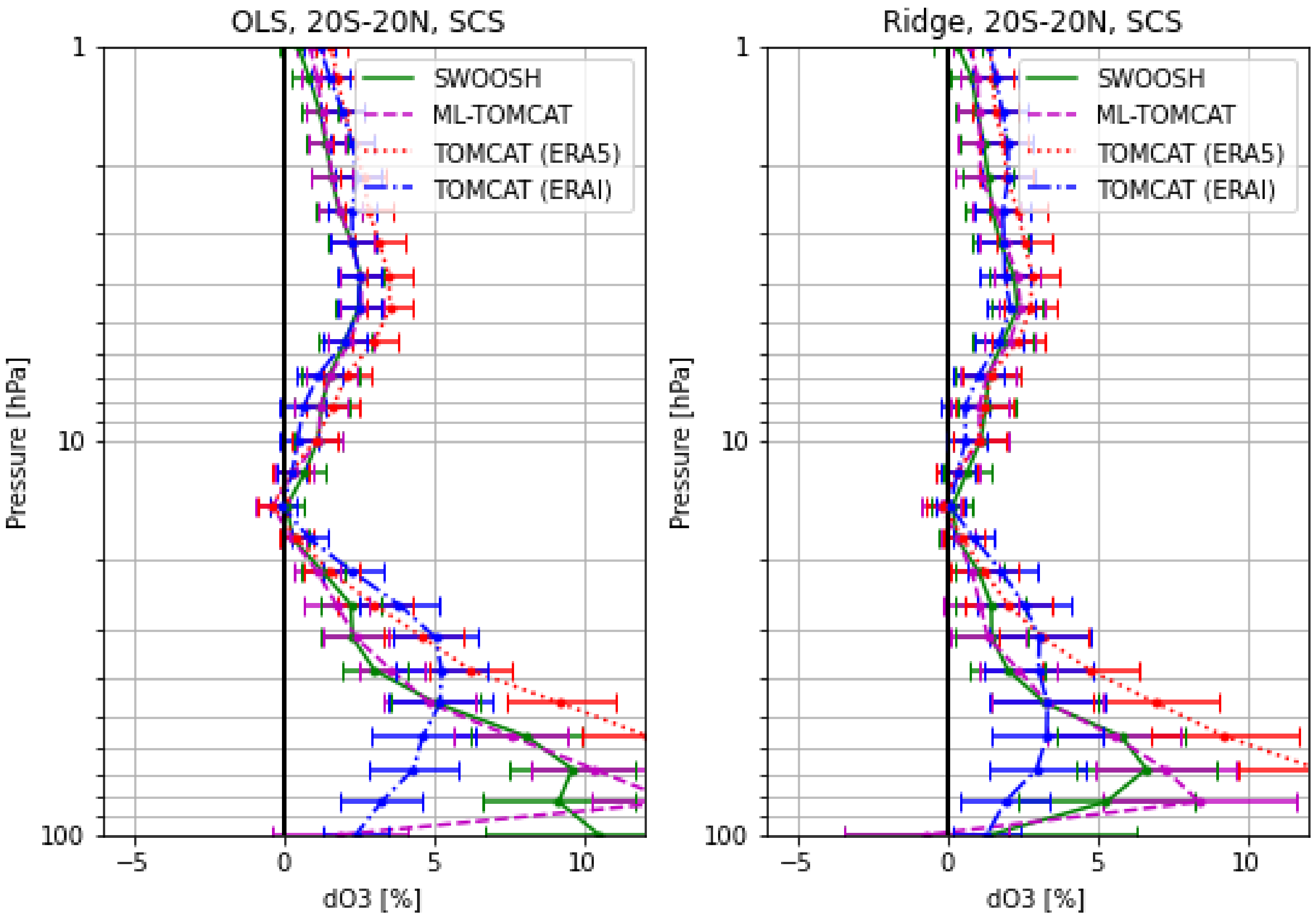


Dynamical proxy -> age of air Vs Fz

- 2005-2018, AoA from ERA-int

- Upper stratospheric signal bit larger

- Lower stratospheric signal is back



Relevant Publications

Effects of reanalysis forcing fields on ozone trends and age of air from a chemical transport model

Yajuan Li[1], Sandip S. Dhomse[2,3], Martyn P. Chipperfield[2,3], Wuhu Feng[2,4], Andreas Chrysanthou[2], Yuan Xia[1], and Dong Guo[5]

[1]School of Electronic Engineering, Nanjing Xiaozhuang University, Nanjing, China
[2]School of Earth and Environment, University of Leeds, Leeds, UK
[3]National Centre for Earth Observation, University of Leeds, Leeds, UK
[4]National Centre for Atmospheric Science, University of Leeds, Leeds, UK
[5]Key Laboratory of Meteorological Disaster, Ministry of Education/Joint International Research Laboratory of Climate and Environment Change/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, China

Correspondence: Yajuan Li (yajuanli@njxzc.edu.cn) and Sandip S. Dhomse (s.s.dhomse@leeds.ac.uk)

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Revised: 28 July 2022 – Accepted: 2 August 2022 – Published: 23 August 2022

A single-peak-structured solar cycle signal in stratospheric ozone based on Microwave Limb Sounder observations and model simulations

Sandip S. Dhomse[1,2], Martyn P. Chipperfield[1,2], Wuhu Feng[1,3], Ryan Hossaini[4], Graham W. Mann[1], Michelle L. Santee[5], and Mark Weber[6]

[1]School of Earth and Environment, University of Leeds, Leeds, UK
[2]National Centre for Earth Observation, University of Leeds, Leeds, UK
[3]National Centre for Atmospheric Science, University of Leeds, Leeds, UK
[4]Lancaster Environment Centre, Lancaster University, Lancaster, UK
[5]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[6]Institute of Environmental Physics, University of Bremen, P.O. Box 330 440, 28334 Bremen, Germany

Correspondence: Sandip S. Dhomse (s.s.dhomse@leeds.ac.uk)

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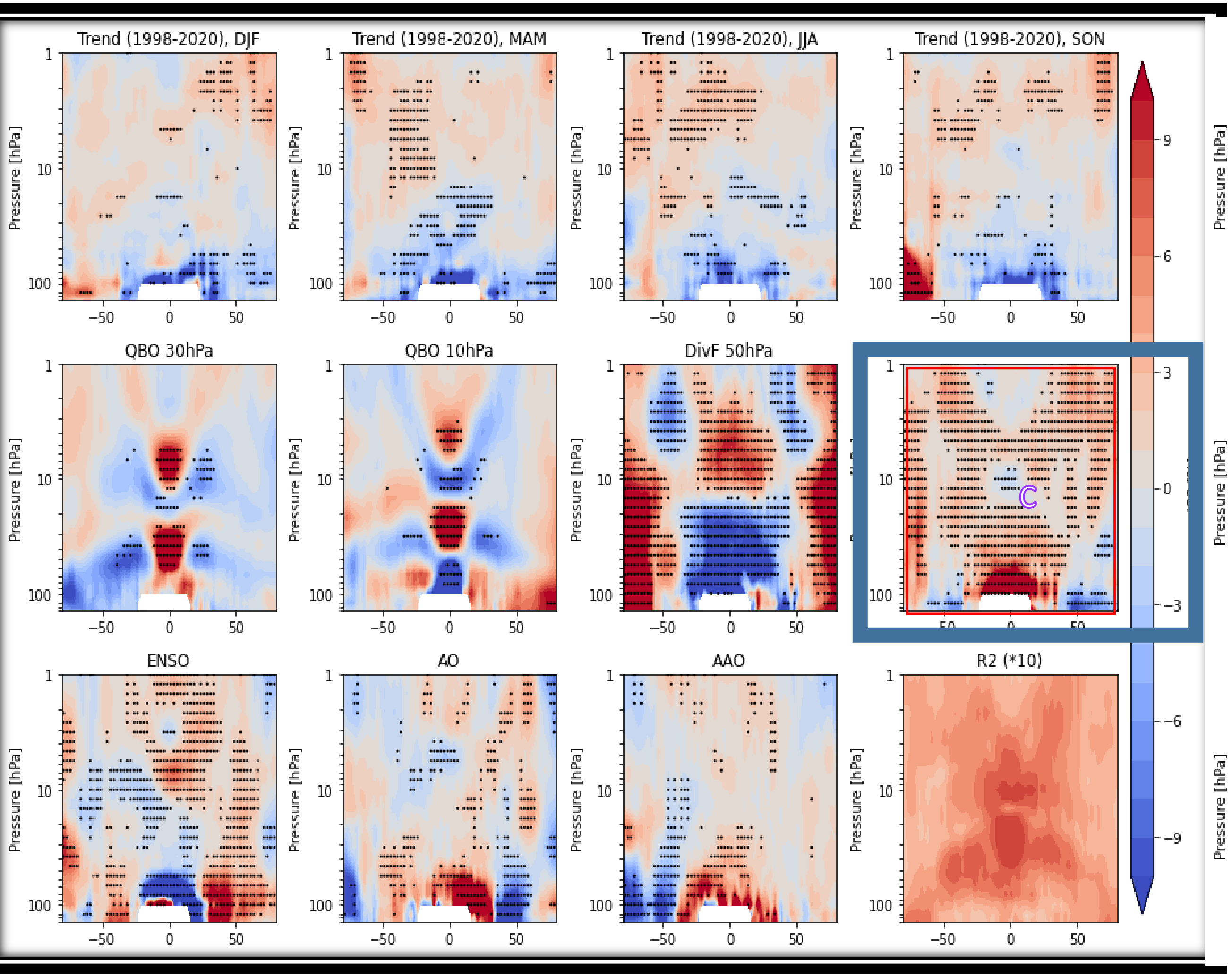
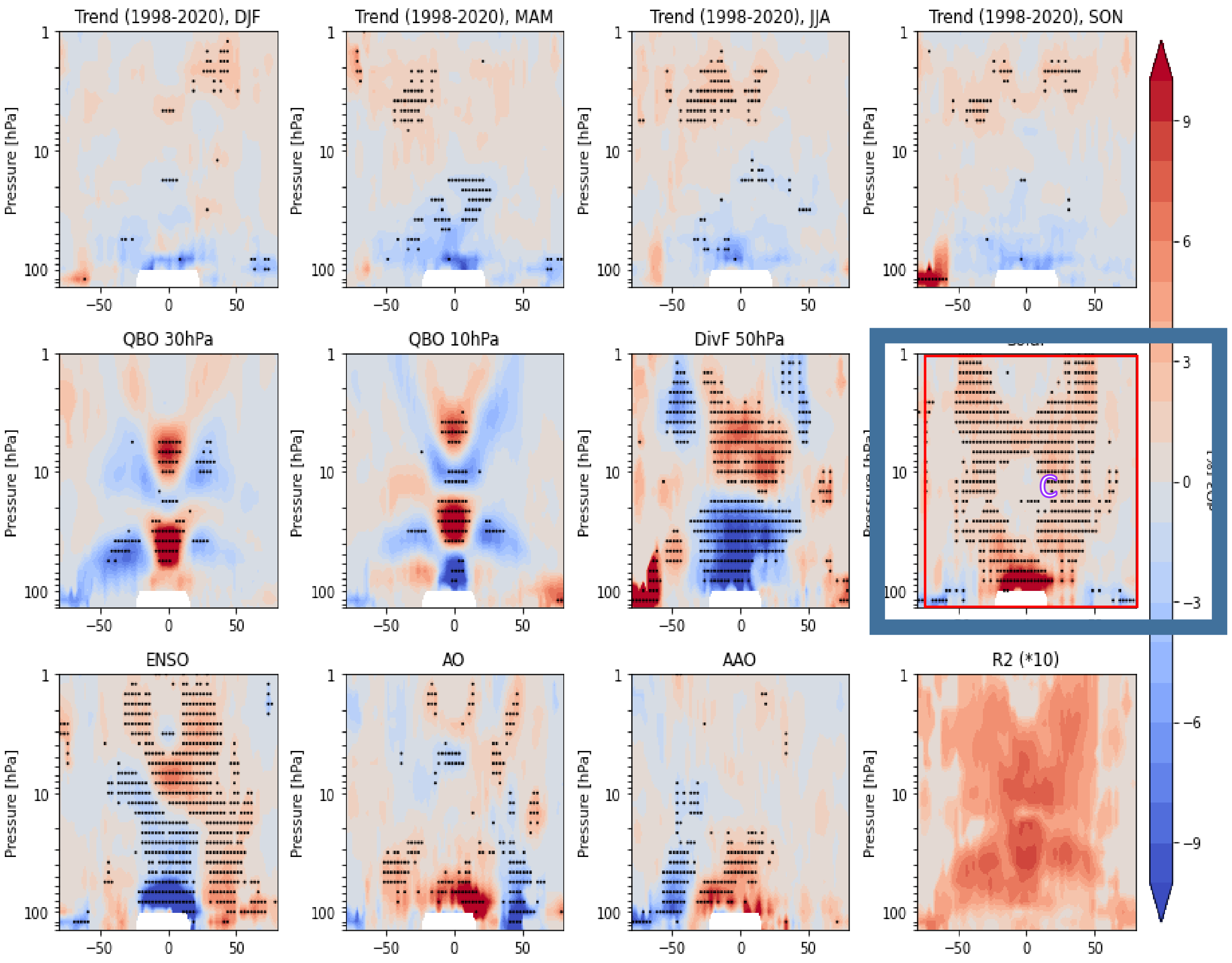
Summary & Outlook

- ❑ Used various satellite data sets & TOMCAT CTM simulations with different solar fluxes & dynamical forcings to estimate SCS
- ❑ “Double-Peak”-structured signal still there – analysis period matters
- ❑ SAGE V7 → Upper stratospheric signal moved from 50 km to 35 km
- ❑ Still large uncertainty in the lowermost stratospheric signal
- ❑ Ongoing search for constraining lower stratospheric ozone variability using different dynamical proxies → Careful with observation-based SCS estimates (they are reanalysis data dependent)

OLS regression-SWOOSH

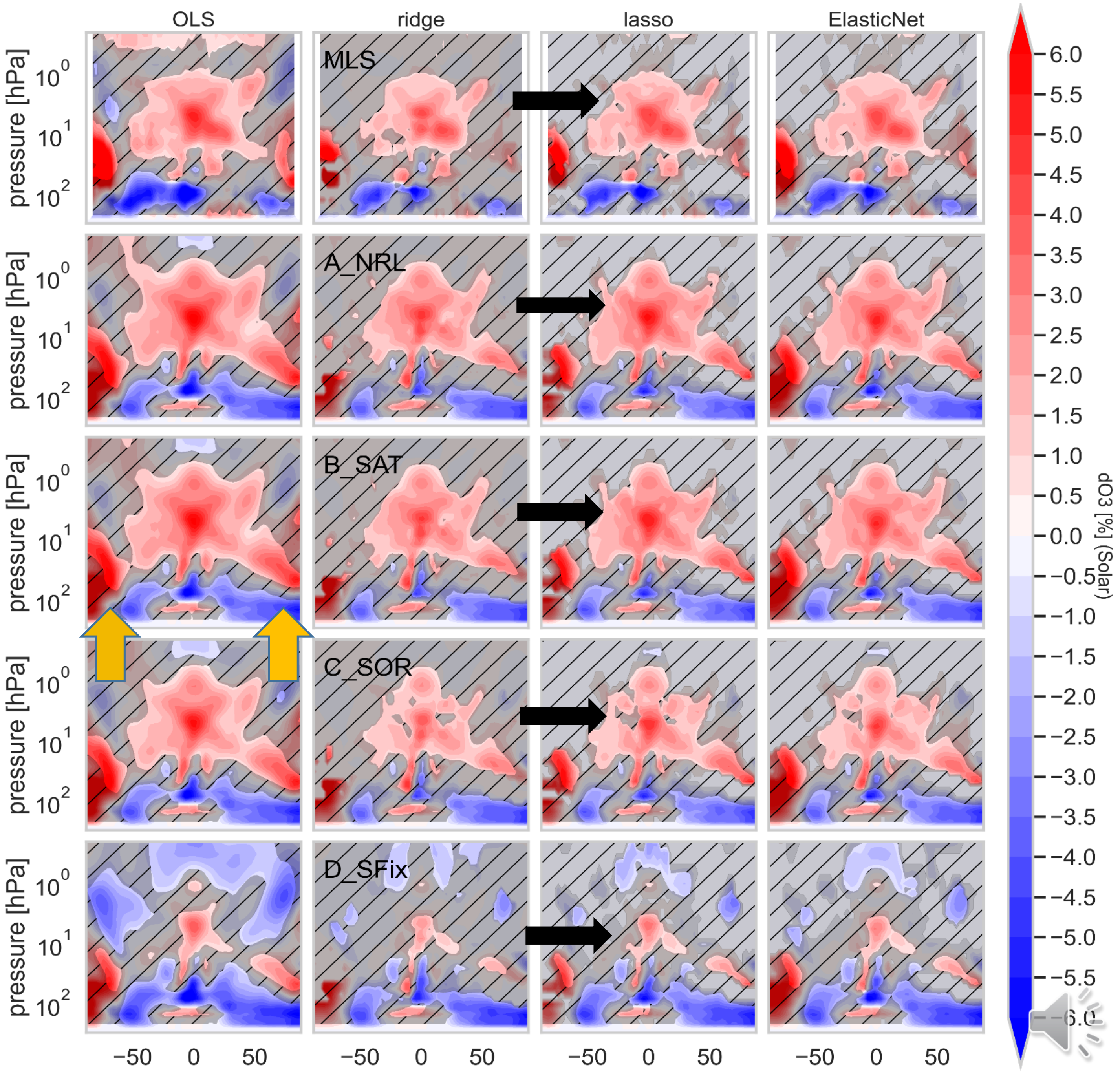


Ridge regression-SWOOSH



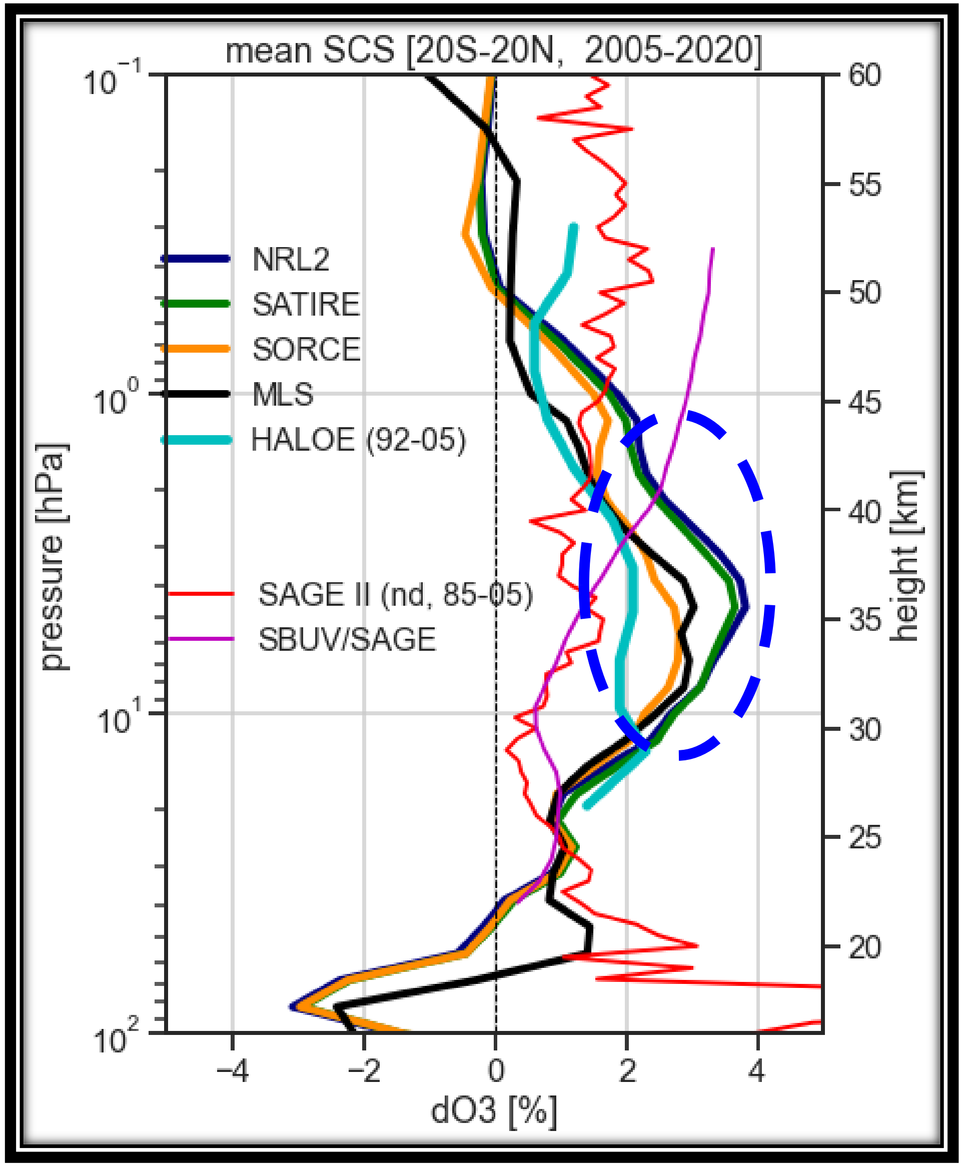
SCS using Multivariate linear regression models : OLS/Ridge/Lasso/ElasticNet

- Consistent SCS between MLS and modelled ozone
- Large region with positive SCS in the tropical mid-upper stratosphere
- Simulation with fixed solar variations show much smaller SCS
- Negative SCS in the Arctic lower strat.
- Positive SCS in the Antarctic lower stra.

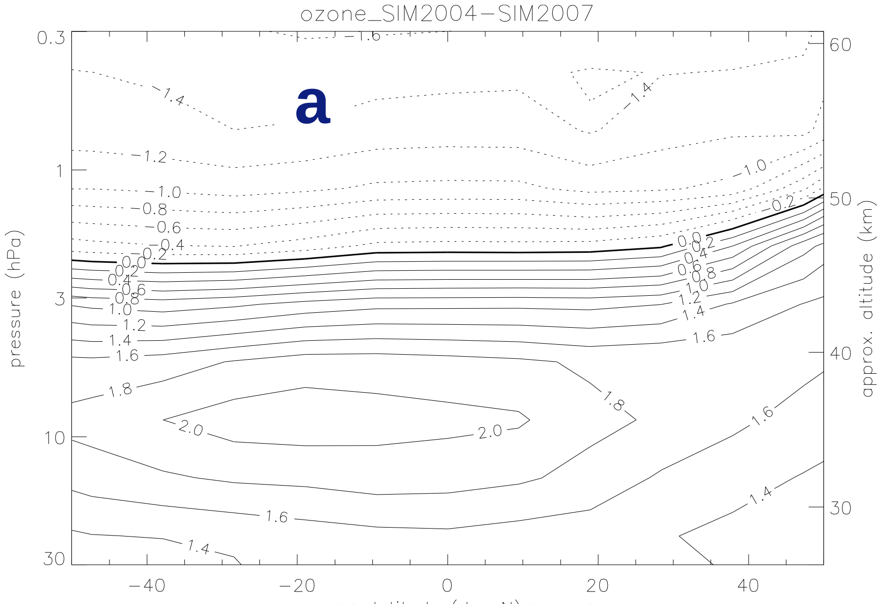


Summary & Conclusions: A Single-peak structured SCS

- We have used four types of linear regression models (OLS, Ridge, Lasso, ElasNet) to estimate SCS from MLS satellite data and TOMCAT CTM simulations and all of them show consistent SCS
- Updated analysis shows significantly different (single peak structured) SCS compared earlier(double-peak structured) SCS estimates.
- Simulation with fixed solar fluxes suggest much smaller implicit SCS in ERA5 dynamical fields.
- Lack of secondary peak in the lower stratosphere might be due to a) almost linear changes in Cl, b) no volcanic eruptions, …



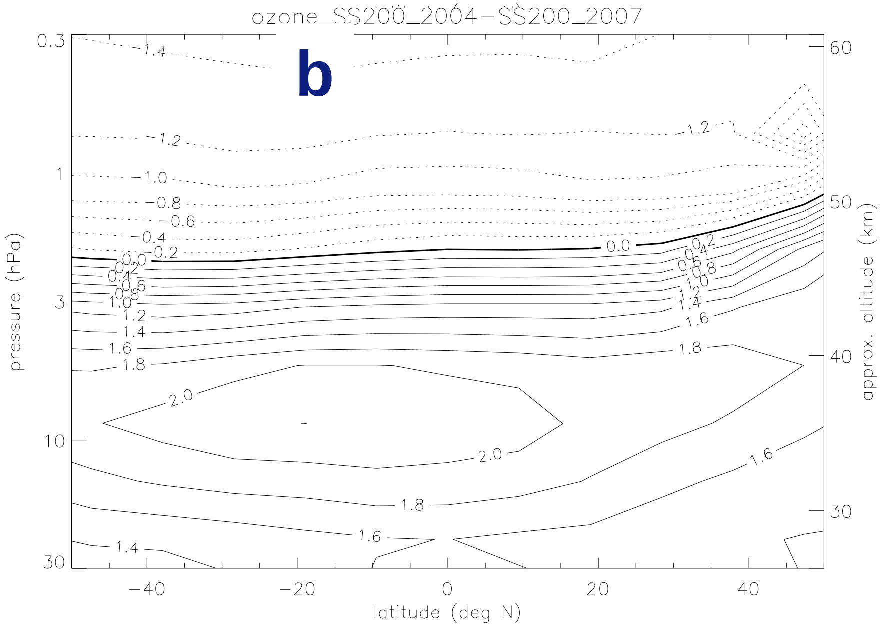
SORCE Fluxes - Haigh et al, 2010

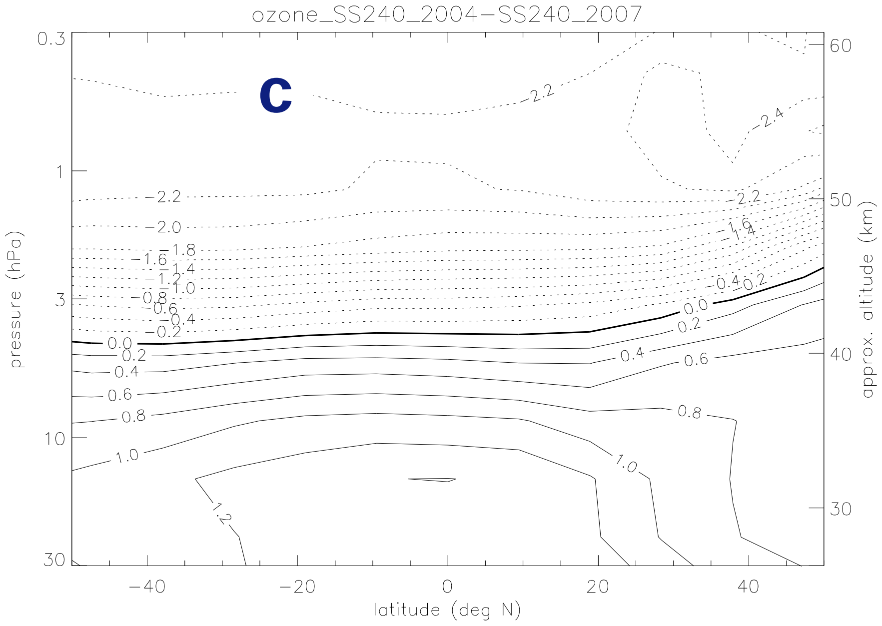


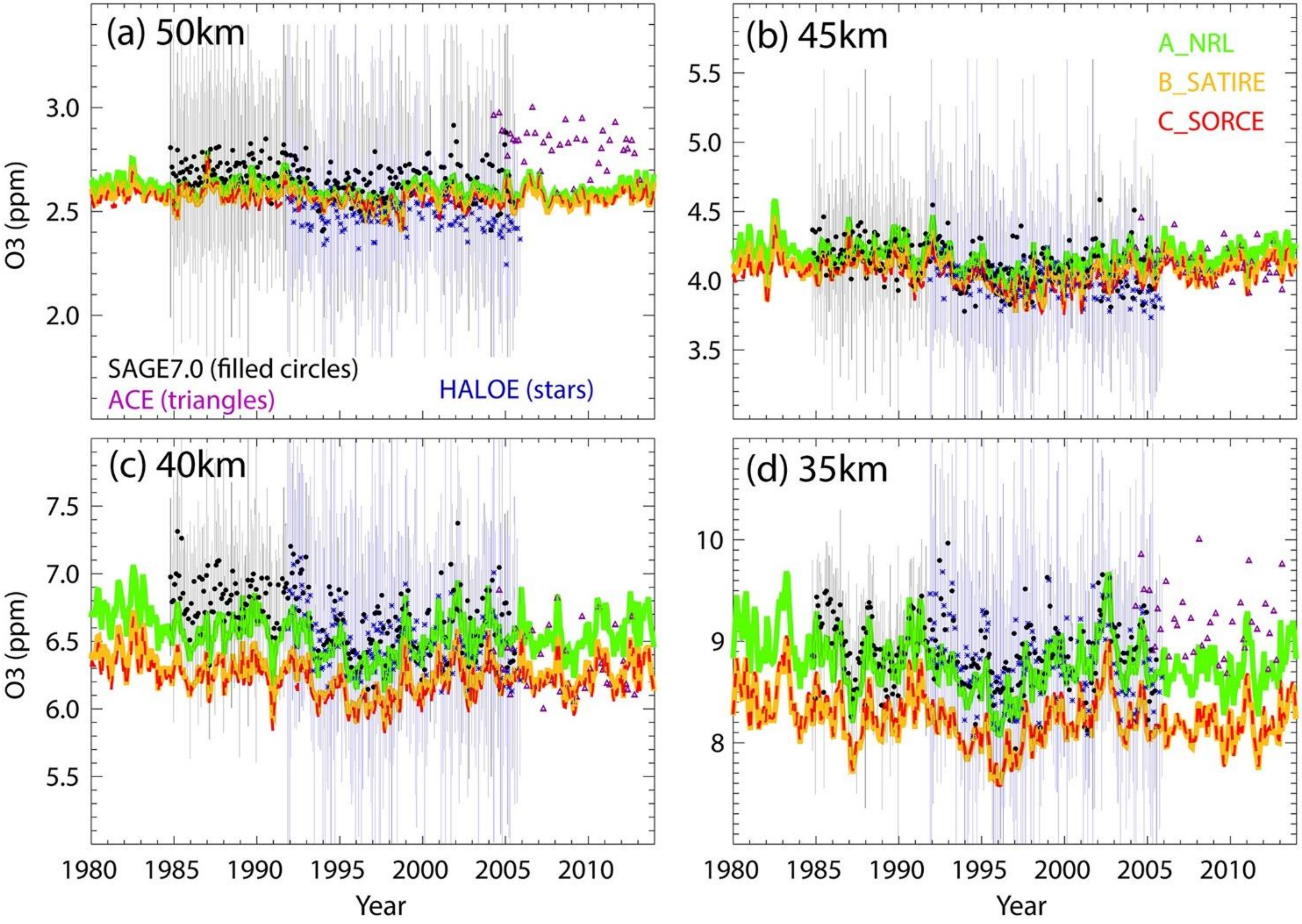
Choice of spectra $\lambda < 240$ nm

	$\lambda < 200$	$200 < \lambda < 240$	$\lambda > 240$
a	Lean	SIM	SIM
b	SOLSTICE	SIM	SIM
c	SOLSTICE	SOLSTICE	SIM

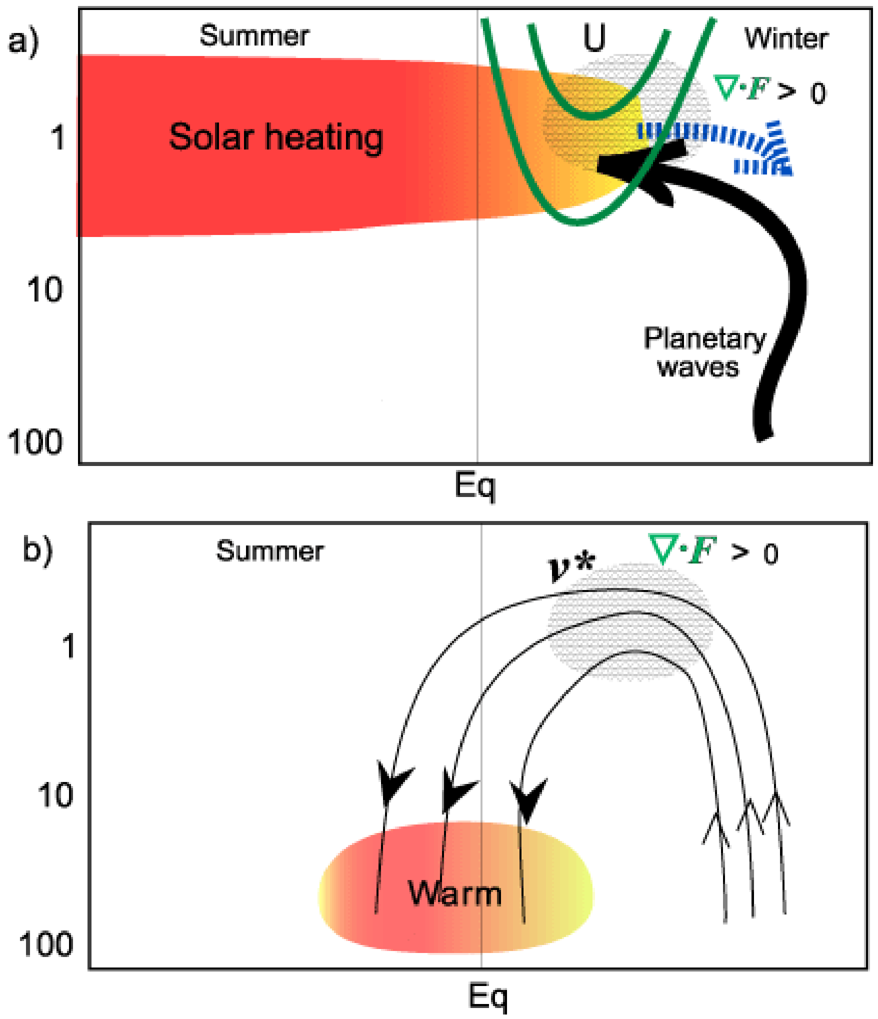
Ozone difference (%) 2004-2007






(a) 50km
(b) 45km
(c) 40km
(d) 35km
O3 (ppm)
Year
SAGE7.0 (filled circles)
ACE (triangles)
HALOE (stars)
A_NRL
B_SATIRE
C_SORCE
1980
1985
1990
1995
2000
2005
2010

Solar coupling & planetary waves



Kodera and Kuroda (2002)

•extra solar heating during solar max strengthens subtropical stratopause jet (SJ) in early winter

- **radiative response**

•Strengthening of westerlies (SJ) means reduced wave progation and reduced BD circulation /warming of tropical tropopause region in early winter

- **dynamical response**
- **weak BD circulation in early winter**

•Deflection of planetary waves away from subtropics (towards pole) while SJ descends downwards and polewards leading to weakening of polar night jet (polar vortex) in mid- to late winter

- **strong BD circulation**

•warmer polar stratospheric temperatures with reduced polar ozone loss in late winter

- **chemical response**