Retrieval of ozone profiles from OMPS limb observations and merging satellite data sets to study long-term changes

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Seminar talk, 26 April 2019

Motivation and Introduction

CHAPMAN CYCLE

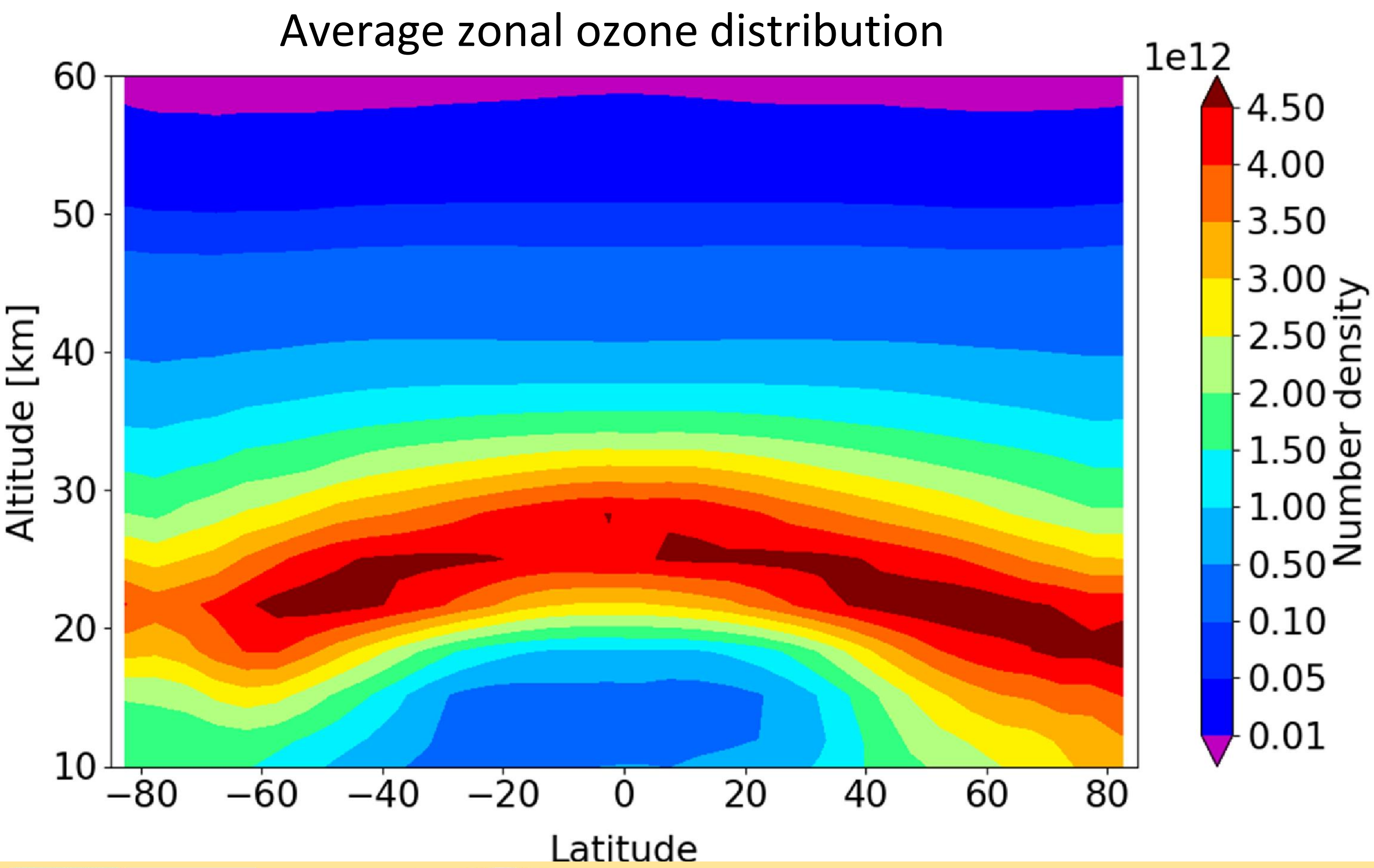
$$O_2 \xrightarrow[\lambda < 242\text{ nm}]{\text{light}} 2\,O$$

$$O + O_2 \underset{\substack{\text{Light} \\ \lambda<320\text{ nm}}}{\overset{\text{fast}}{\rightleftharpoons}} O_3$$

$$O_3 + O \xrightarrow{\text{slow}} 2\,O_2$$

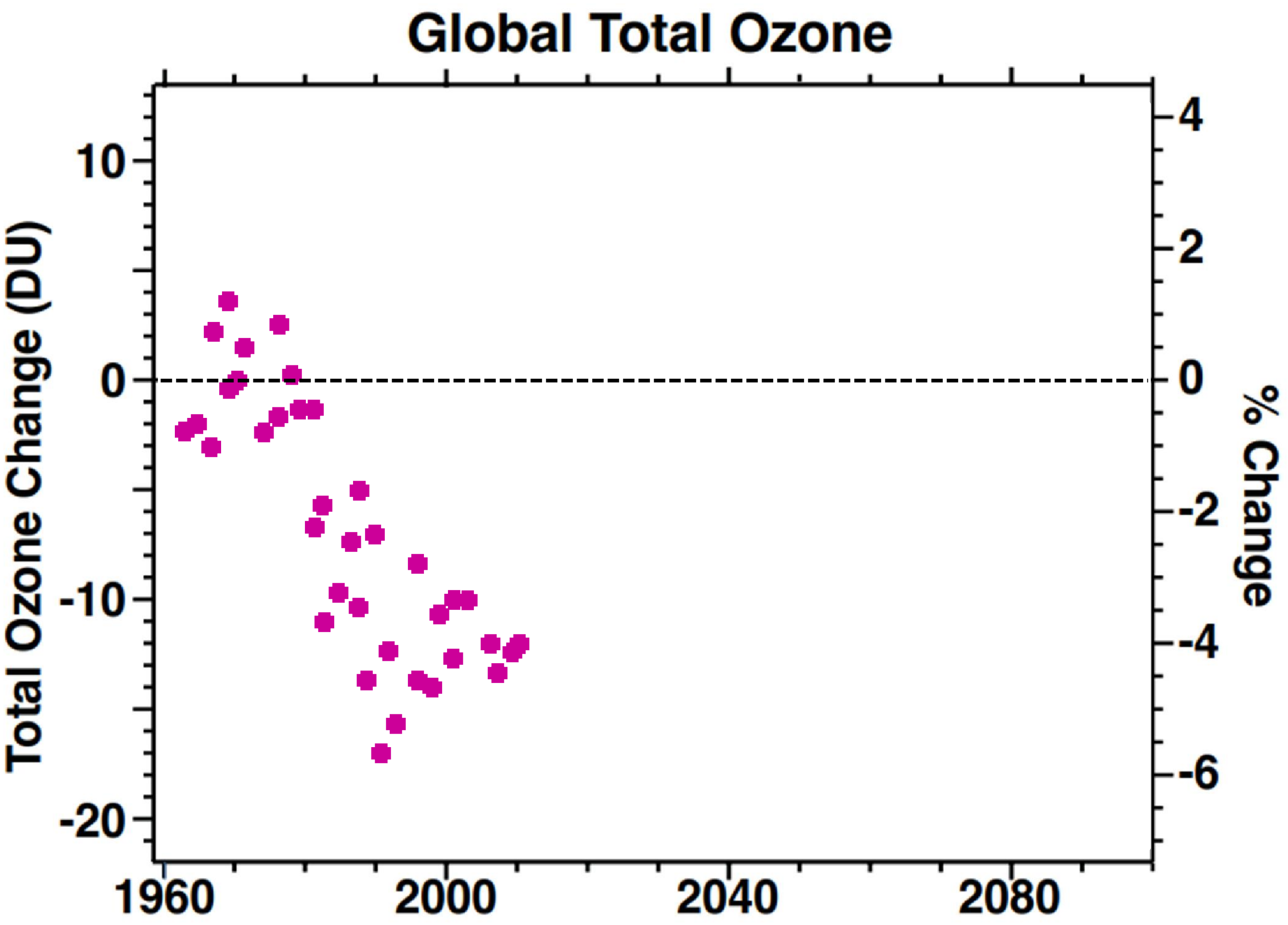
+ catalytic cycles

Stratospheric ozone layer: a balance between transport, photochemical production and loss.



Motivation and Introduction

A stratospheric ozone depletion was observed at the end of the last century due to the emission of chlorine-containing ozone-depleting substances (ODS)

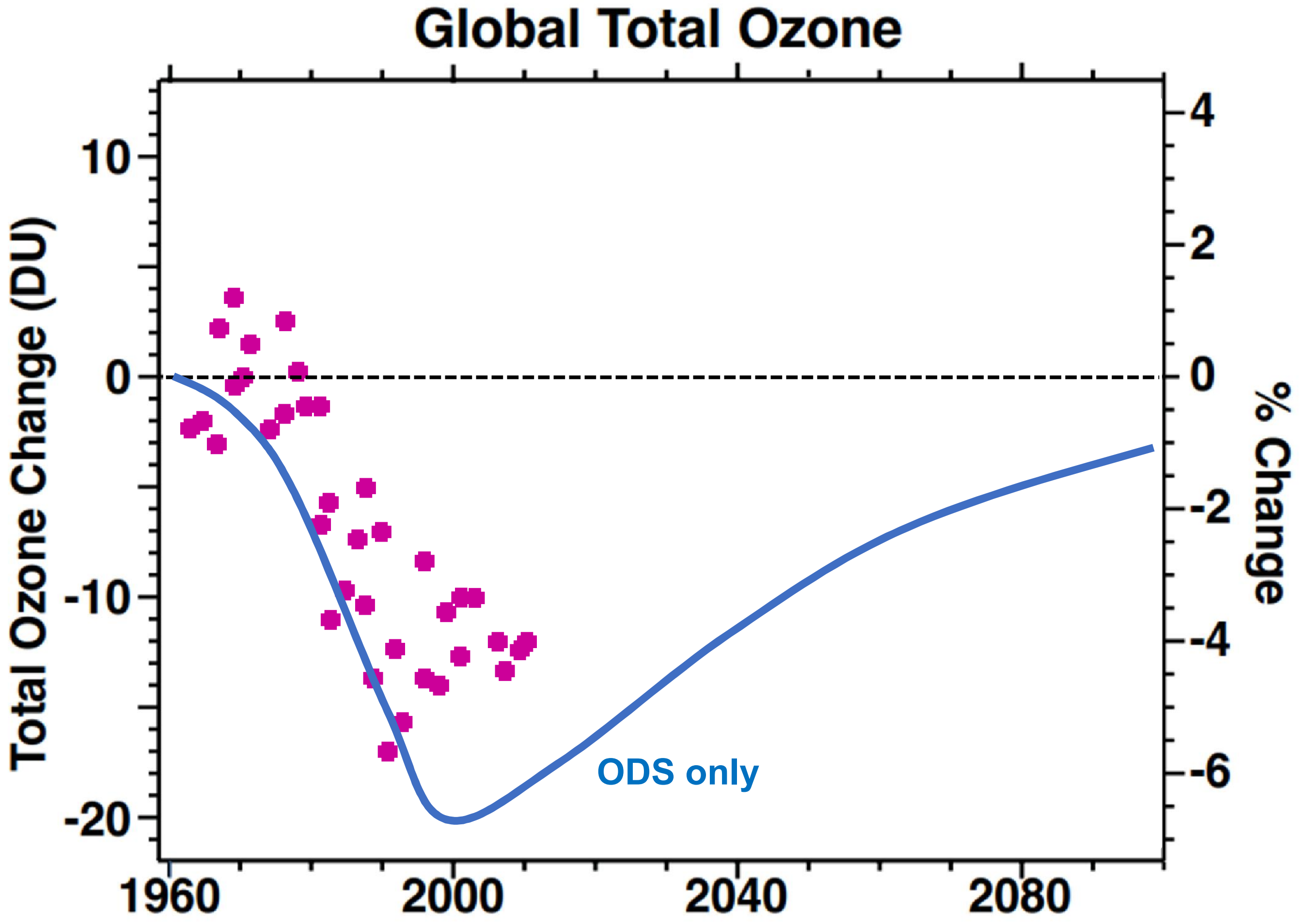


Adapted from WMO, 2014

Motivation and Introduction

What's expected in the 21st century?

- ODS have been banned with the Montreal Protocol and amendments, their concentration is steadily decreasing.



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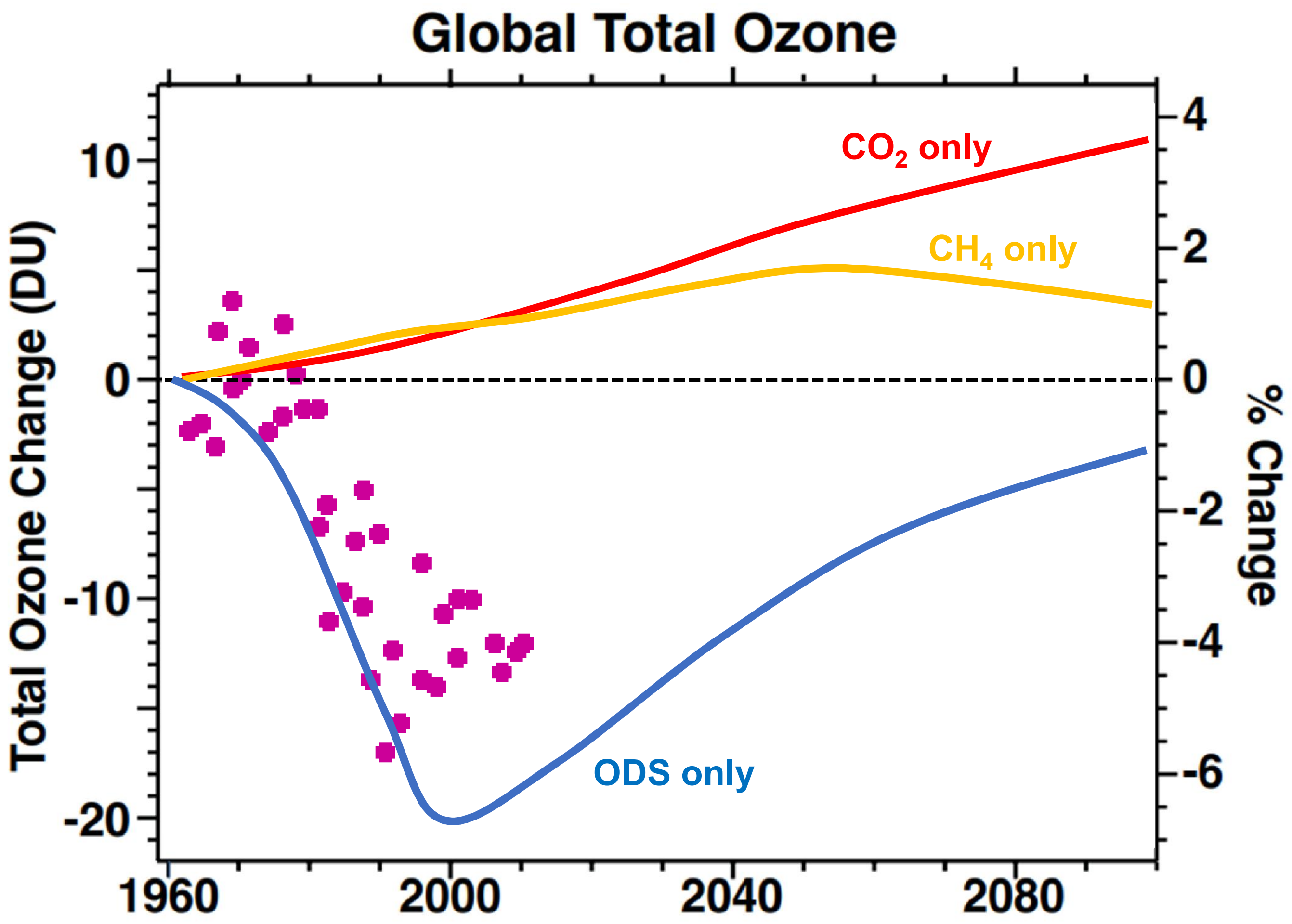

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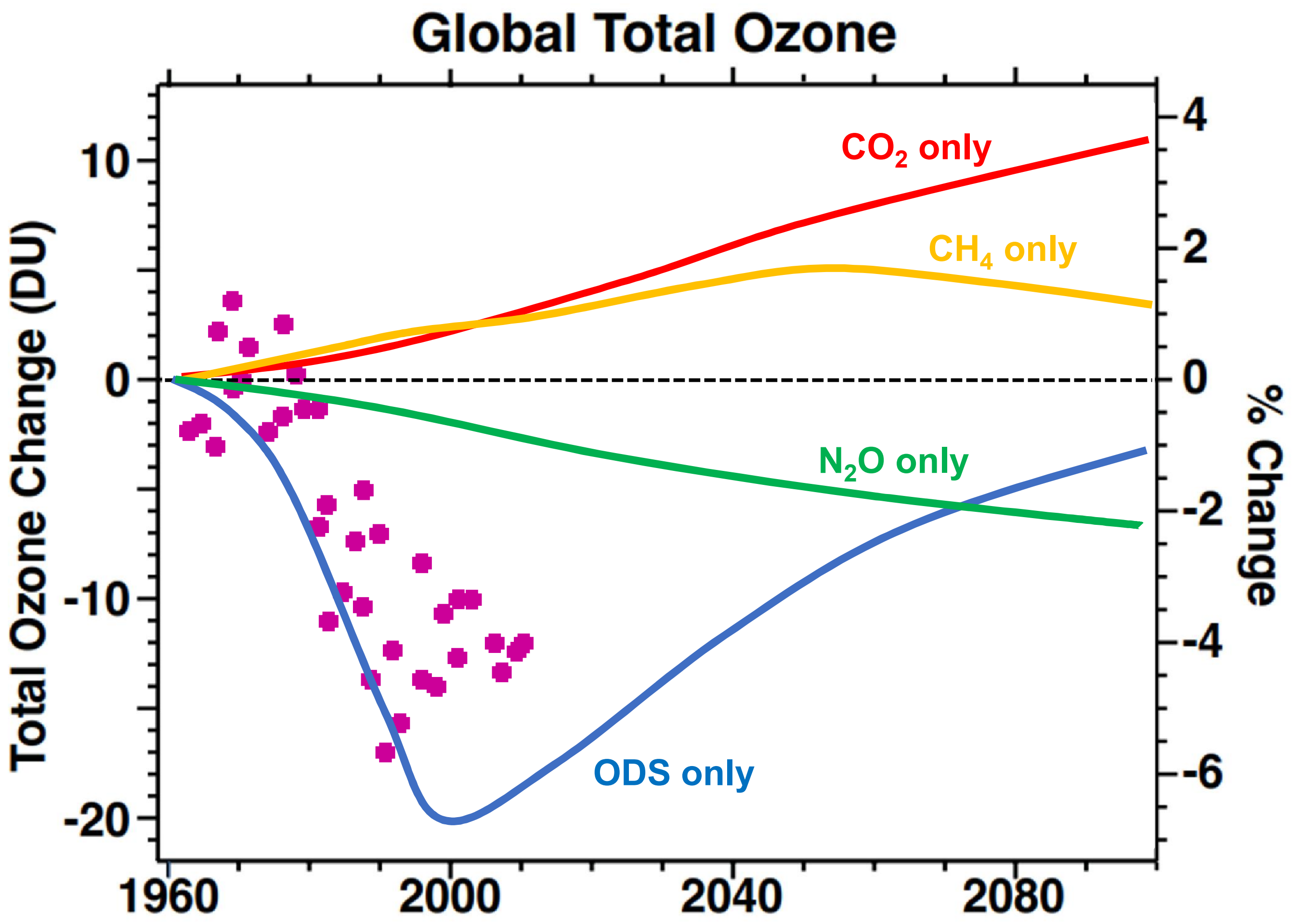
- Increasing N_2O emissions lead to a decrease in stratospheric ozone via NO_x catalytic cycles.



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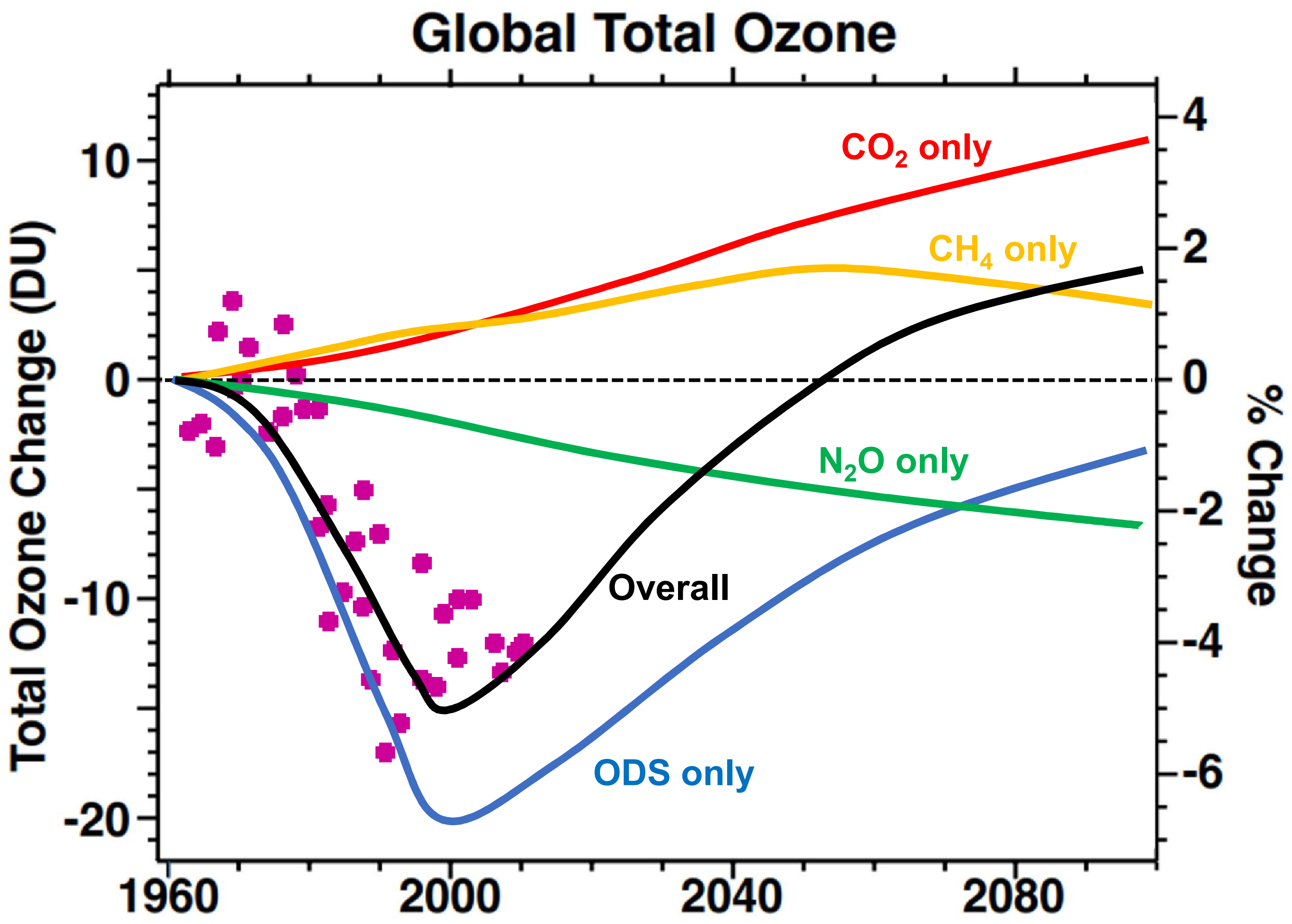
→ **A recovery is expected**



Adapted from WMO, 2014

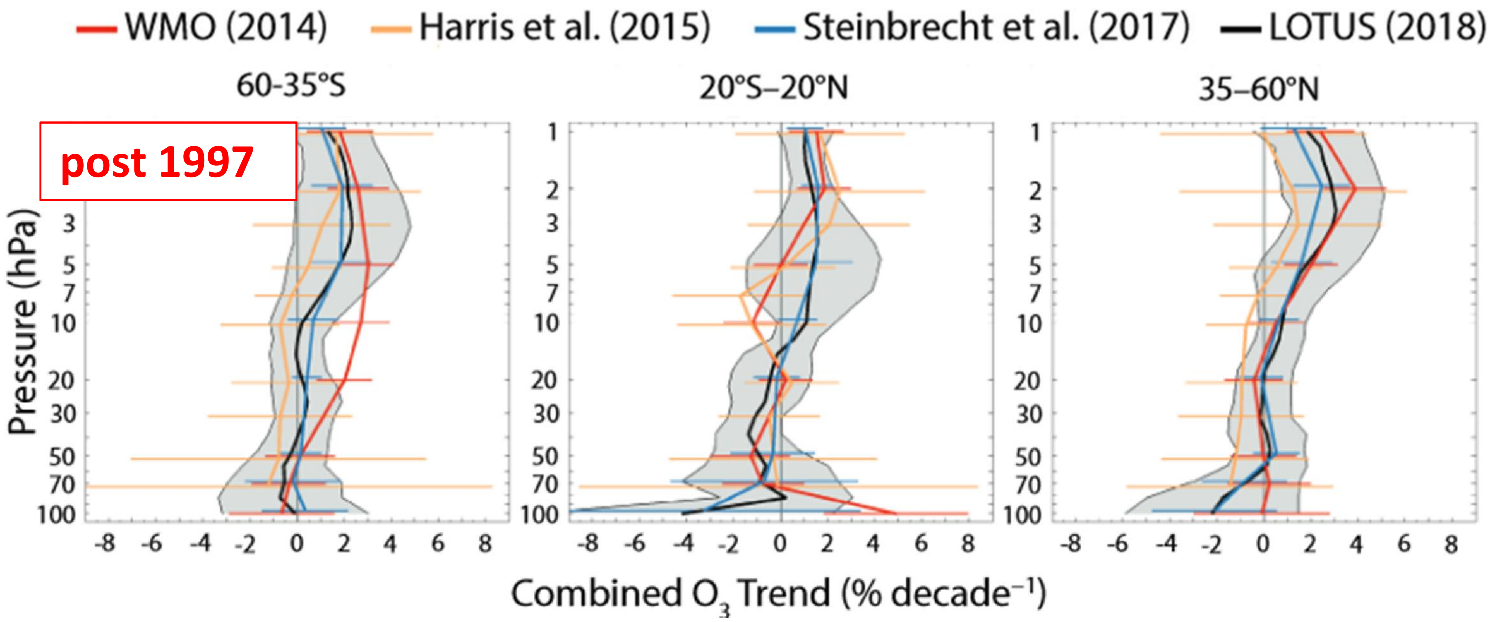
Motivation and Introduction

Has the recovery been detected? How is it as a function of altitude and latitude?

It has a complex structure as a function of altitude and latitude as it depends on dynamics and chemistry.

Need for:

- Stable and consistent single satellite measurements.
- Evaluation of uncertainties in single and merged data sets.
- Consistent methods to merge time series and compute trends.



WMO, 2018

Are there zonal asymmetries?

Overview

- **First part: ozone retrieval**
  - Limb geometry and satellite instruments
  - OMPS-LP ozone retrieval set-up and characterization
  - Comparison with NASA retrieved profiles
  - Validation using MLS, ozonesonde and lidar measurements
- **Second part: merging data sets**
  - Merging SCIAMACHY with OMPS-LP data set: method and results
  - Long-term ozone changes in the period 2003-2018
  - Merging with SAGE II data set

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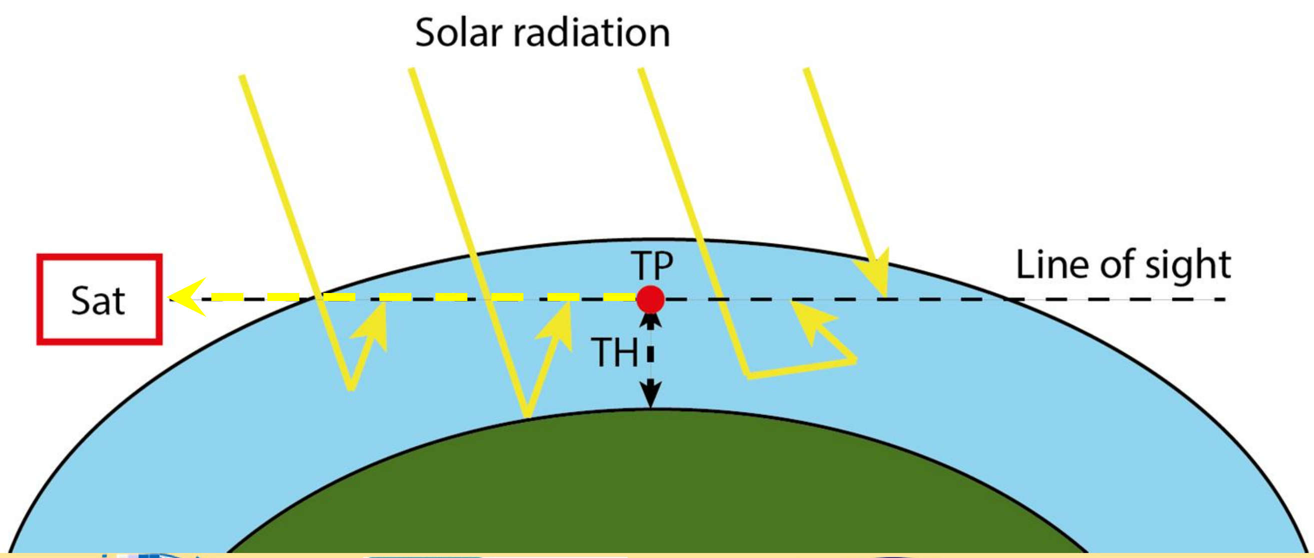
Limb observations from satellite

Instrument	SCIAMACHY	OMPS-LP	SAGE II	MLS
Technique	Limb scattering	Limb scattering	Solar occultation	Limb emission
Wavelengths	240-2300 nm	280-1000 nm	385-1020 nm	118 GHz – 2.5 THz
Spectral resolution	0.22-1.48 nm	1-40 nm (UV-NIR)	2-20 nm	-
Equatorial crossing t	10:00	13:30	-	13:45



TH: tangent height
TP: tangent point

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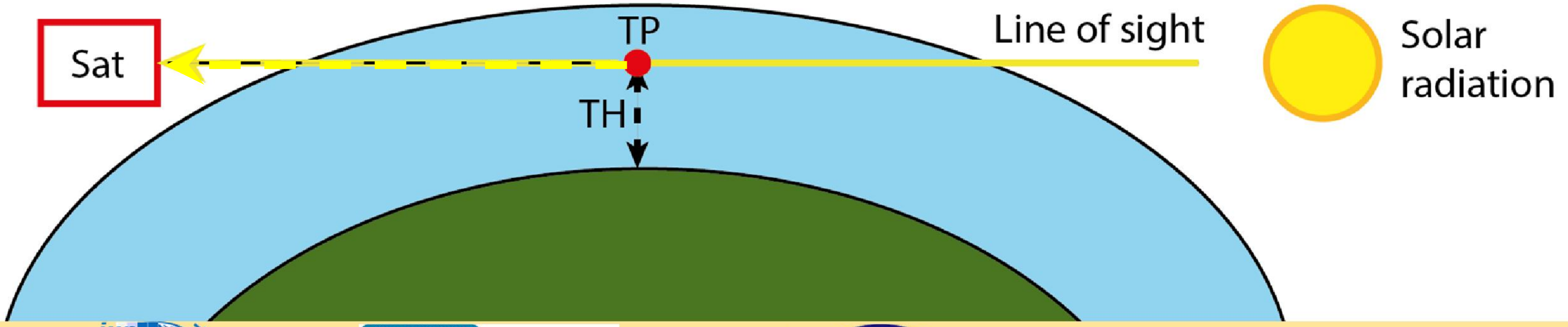

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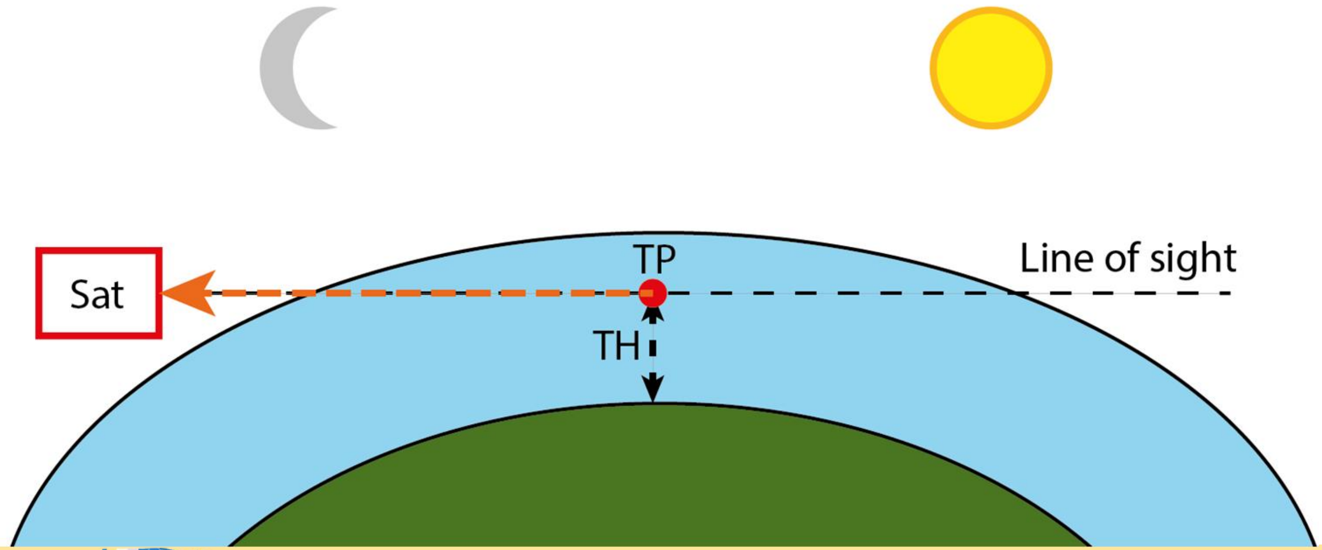

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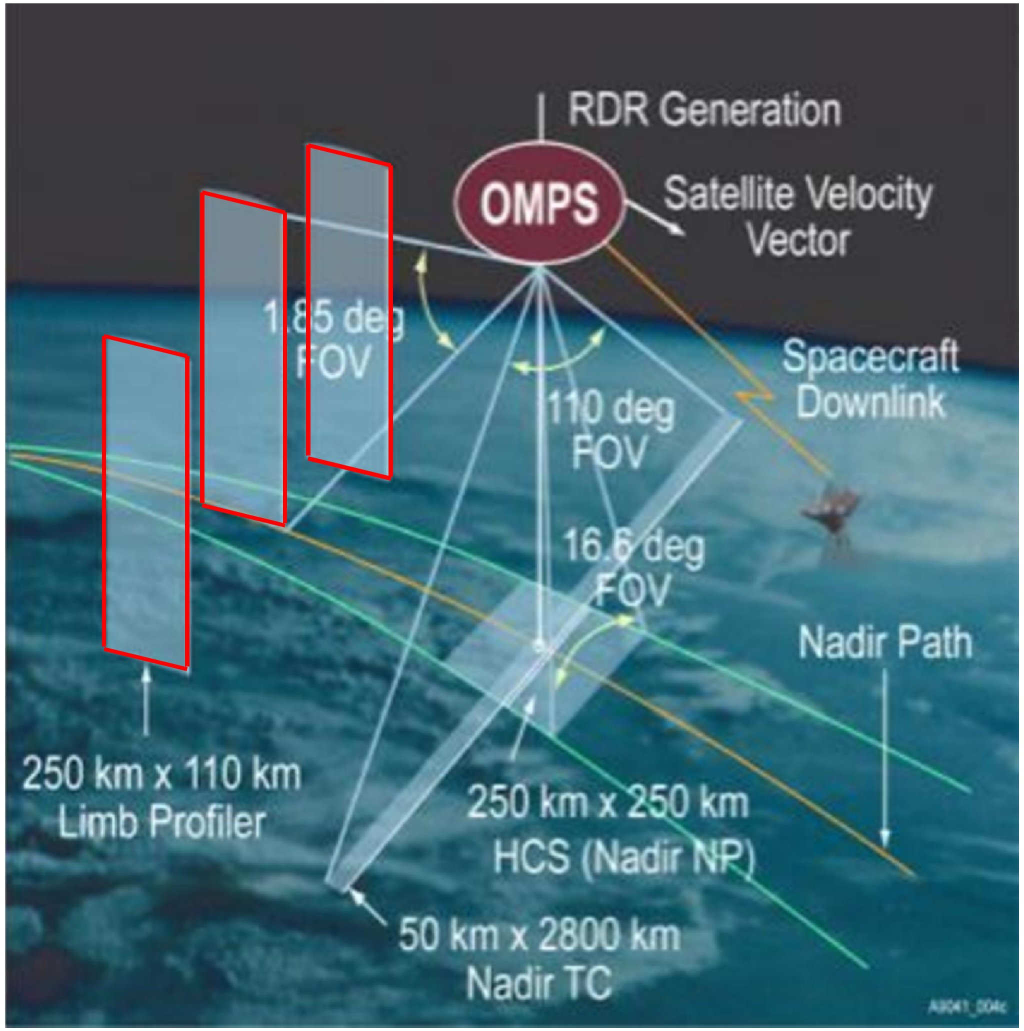
OMPS Limb Profiler



Adapted from Rault, 2013

Ozone Mapper and Profiler Suite - Limb Profiler (OMPS-LP)

- Started to collect data at the beginning of 2012;
- It observes the atmosphere through 3 vertical slits;
- It measures limb radiances simultaneously from the whole atmosphere;
- Spectral resolution: 1 - 40 nm;
- Spectral range: 280 - 1000 nm;
- Vertical sampling: 1.5 km.

OMPS-LP and SCIAMACHY limb share a similar geometry of observation in terms of solar scattering angles.

Retrieval algorithm

SCIATRAN MODEL
Radiative transfer model + 1-D inversion scheme based on Tikhonov regularization, adapting SCIAMACHY algorithm

DATA
Radiance and reflectance from **L1 V2.5 OMPS-LP** gridded data, only the central slit considered

ANCILLARY
P and **T** profiles provided by NASA team (GMAO dataset).
O_3, O_4, NO_2 cross sections at OMPS' resolution

Adjust the ozone profile

no

Forward model: simulation of the radiation field, assuming a first guess ozone profile → Fit spectral ranges and compute residuals between model and observation → Are the differences below a threshold? → **yes** → Ozone profile from 12 to 60 km

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Measurement vector: $$\boldsymbol{y} = log\left(\frac{\boldsymbol{I}_{TH_i}}{\boldsymbol{I}_{TH_n}}\right) - \boldsymbol{P_n}$$

Altitude Range [km]	Spectral range [nm]	TH normalization [km]	Polynomial order
46-60	285-302	63	-
35-46	305-313	52	-
31-36	322-331	47	0
12-33	508-660	42	1

Retrieval algorithm

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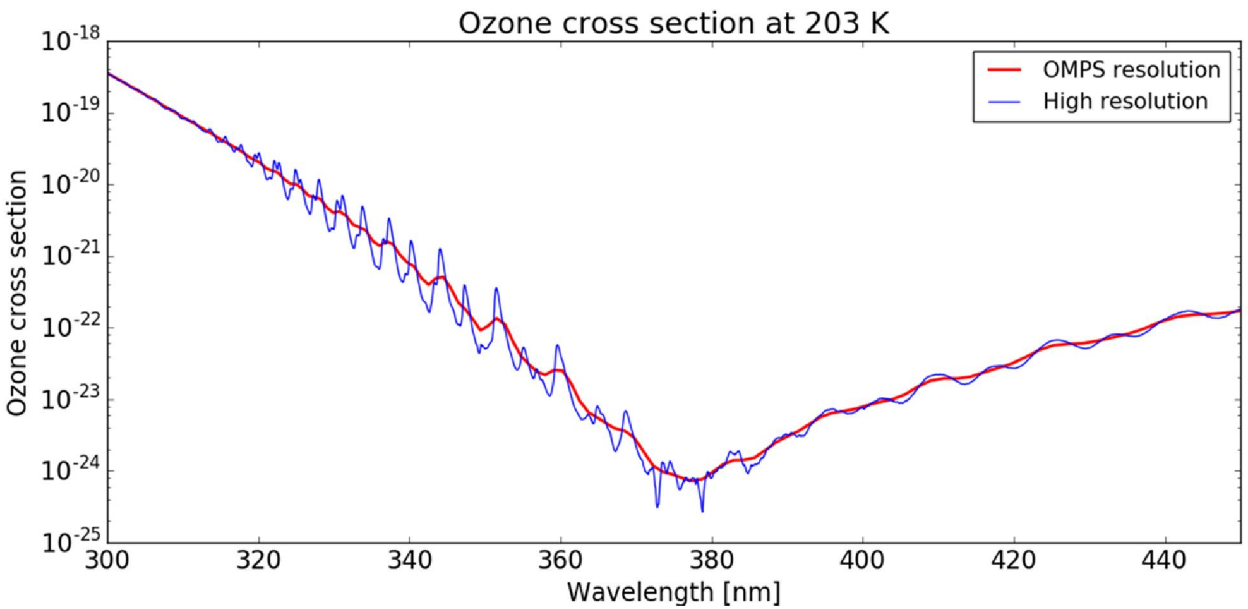
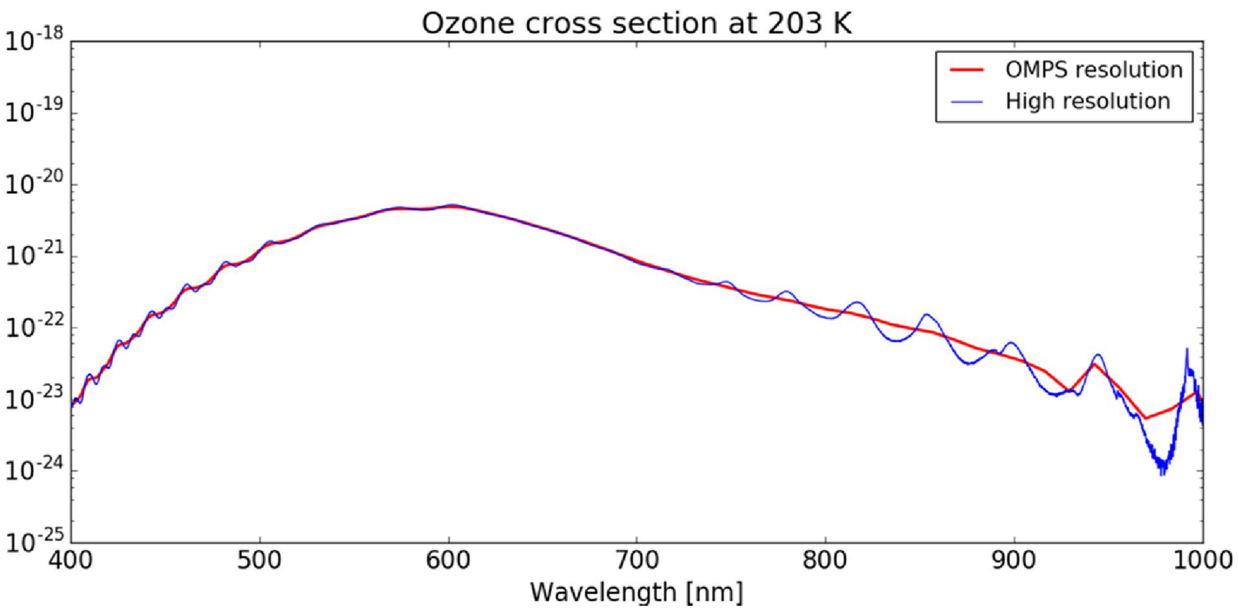
Same spectroscopic and climatologic databases as for SCIAMACHY



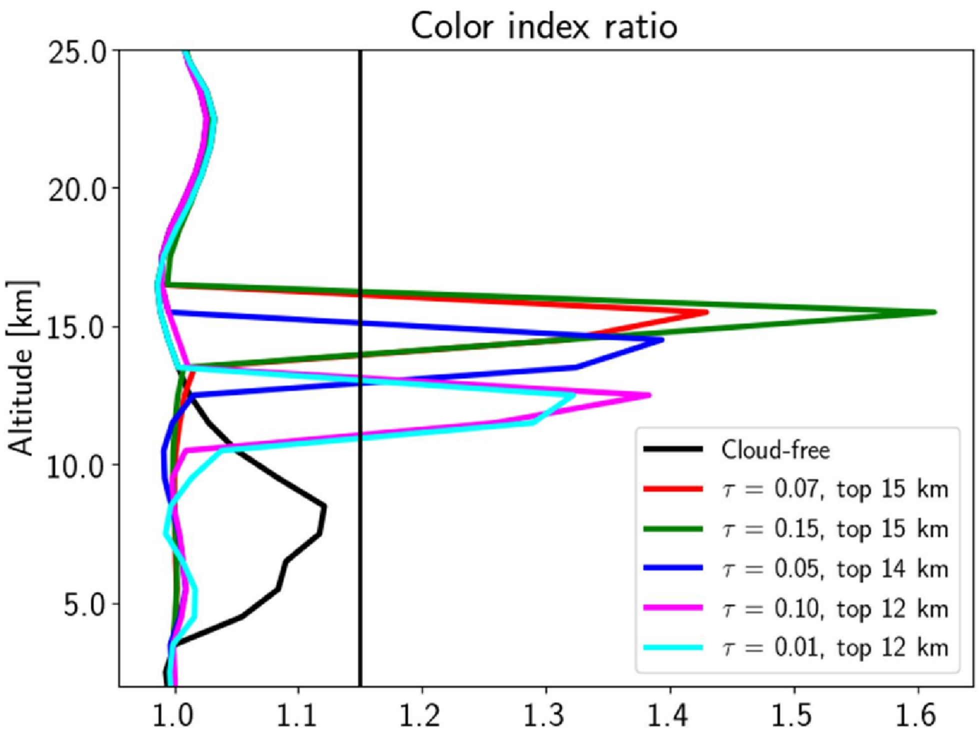


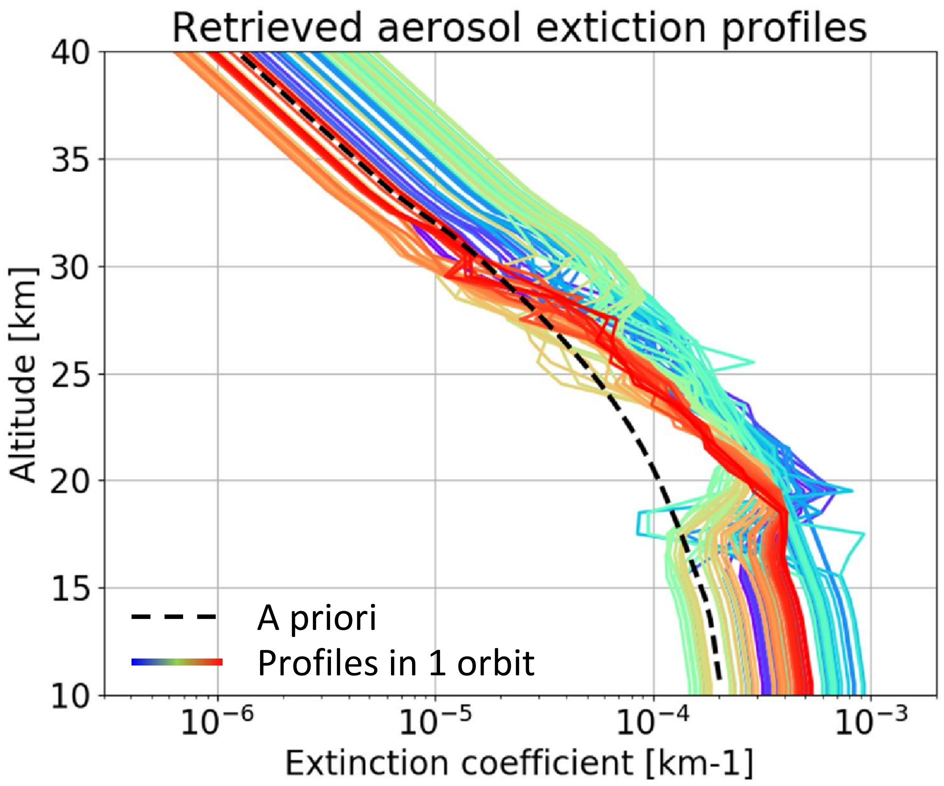
Retrieval algorithm: clouds and aerosol

Preliminary steps: **cloud filtering** and **aerosol extinction profile retrieval.**

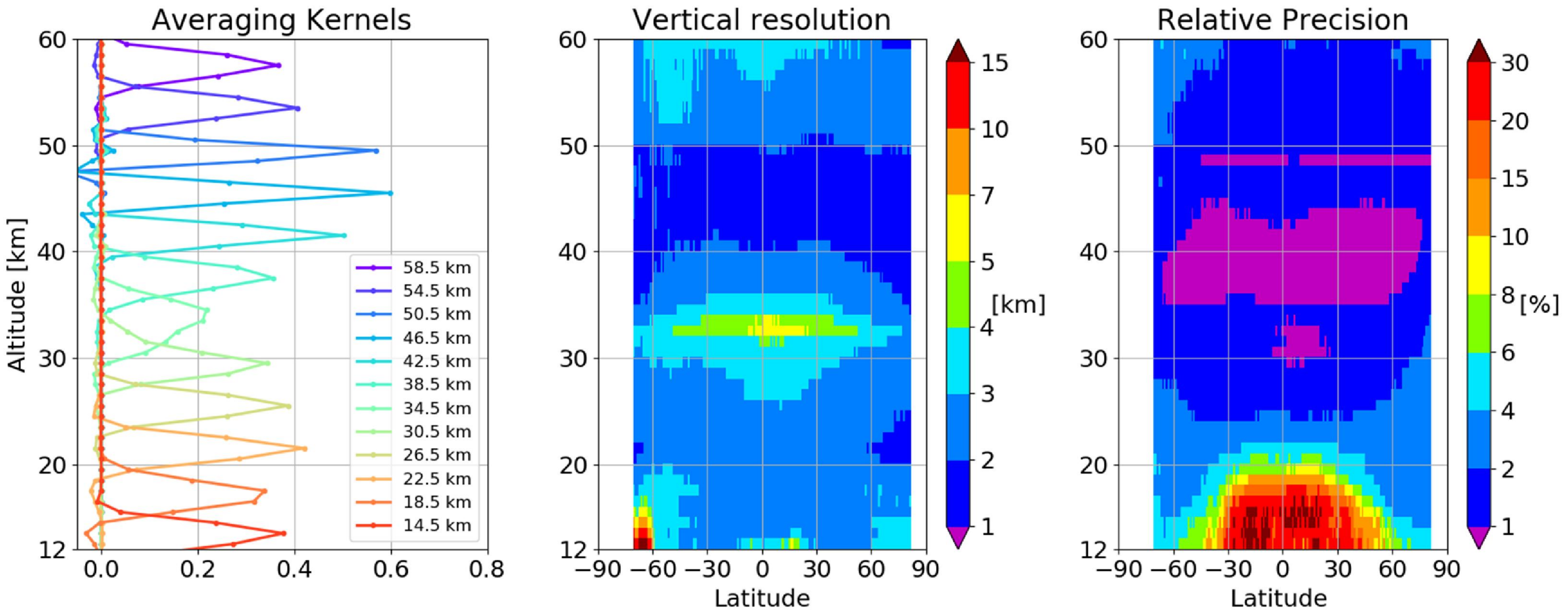
To detect the presence of **clouds**, a Color Index Ratio approach is followed, using the ratio of radiance at two wavelengths: 750 and 997 nm.

Aerosol extinction profiles retrieved for each OMPS-LP observation, exploiting radiance at 869 nm.





Retrieval algorithm: characterization



Averaging Kernels (AK) are plotted every 4 km;
Resolution calculated as the reciprocal of the diagonal elements of the AK matrix; lower resolution around 33 km (merging between Vis and UV spectral ranges) and above 50 km;
Precision drastically degrades in the lowermost stratosphere: low sensitivity.

Results: comparison with NASA profiles

NASA's retrieval algorithm: based on a Tikhonov regularization scheme, selected wavelengths are combined in pairs and triplets.

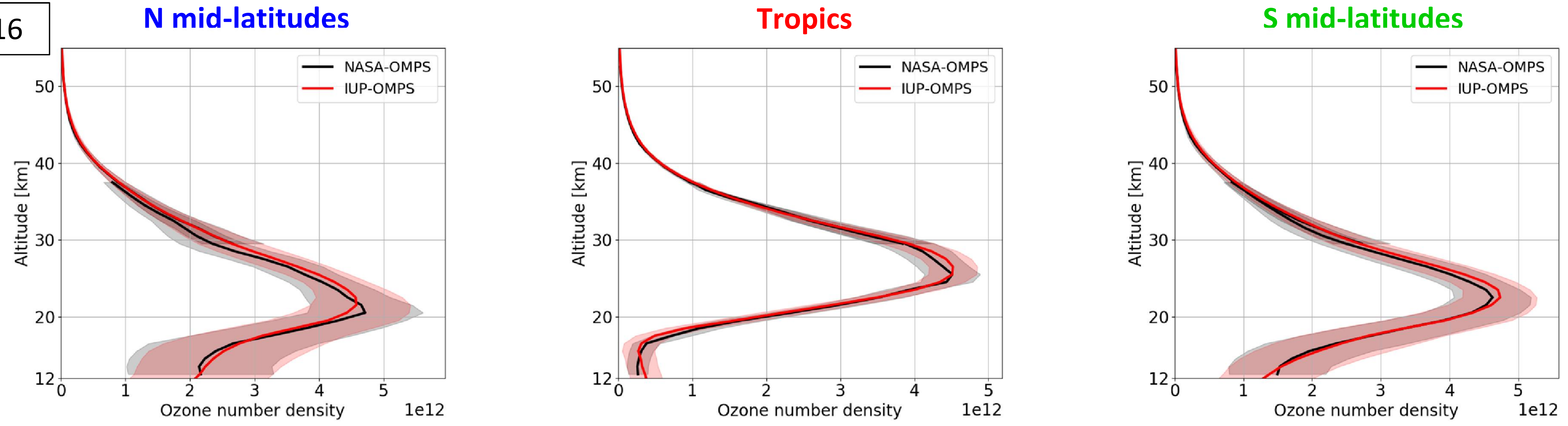
Five latitude bands used for the comparison:

- **northern mid-latitudes** [40°, 60°]
- **tropics** [-20°, 20°]
- **southern mid-latitudes** [-60°, -40°]

northern high-latitudes [60°, 80°]

southern high-latitudes [-80°, -60°]

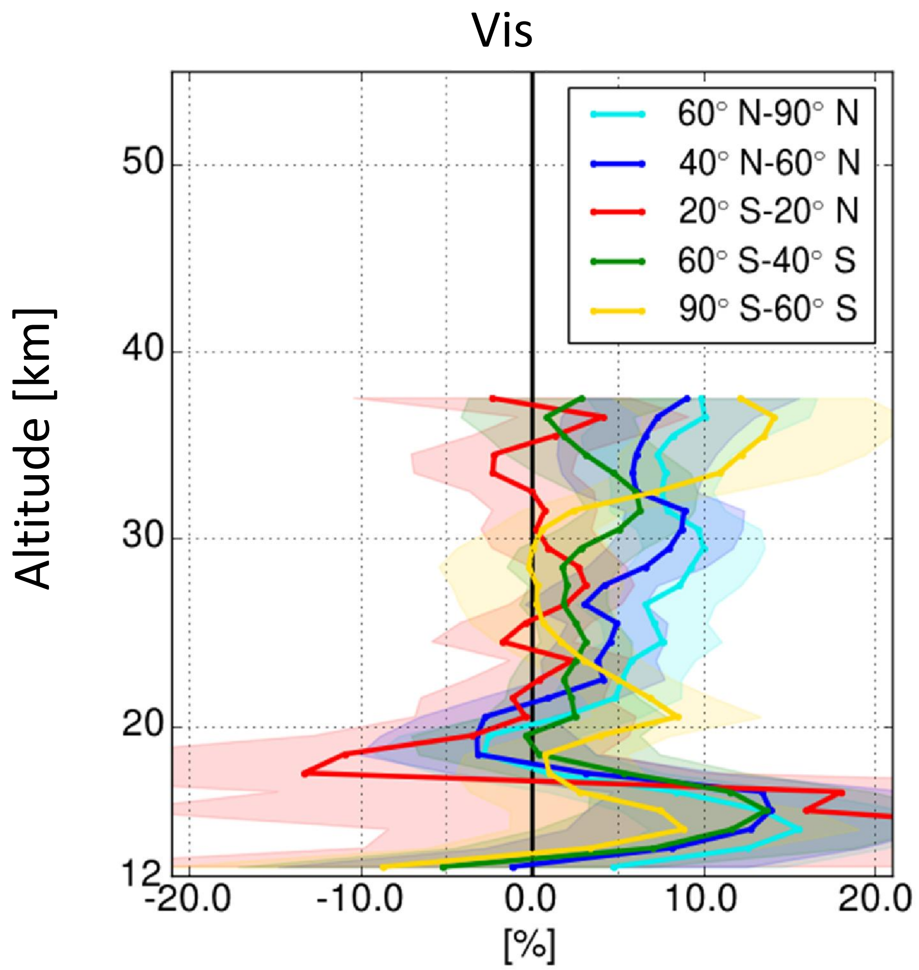
2016

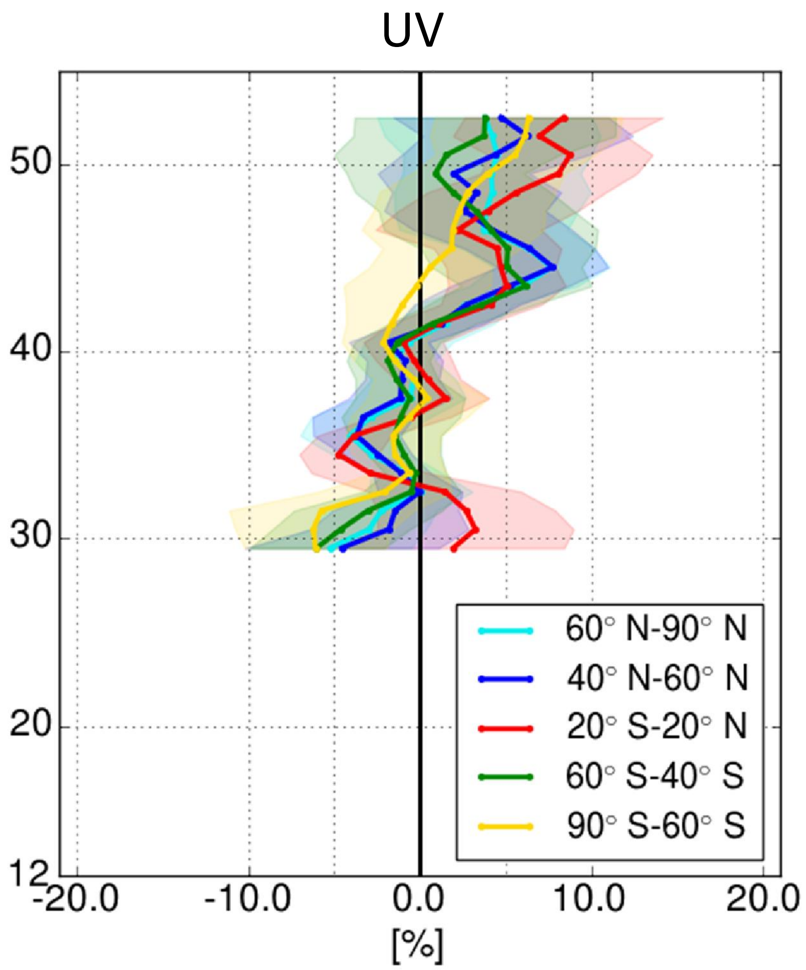


Results: comparison with NASA profiles

UV and Vis retrievals are kept separate in NASA L2 product.

$$\frac{(OMPS_{IUP} - OMPS_{NASA})}{(OMPS_{IUP} + OMPS_{NASA})} * 200$$





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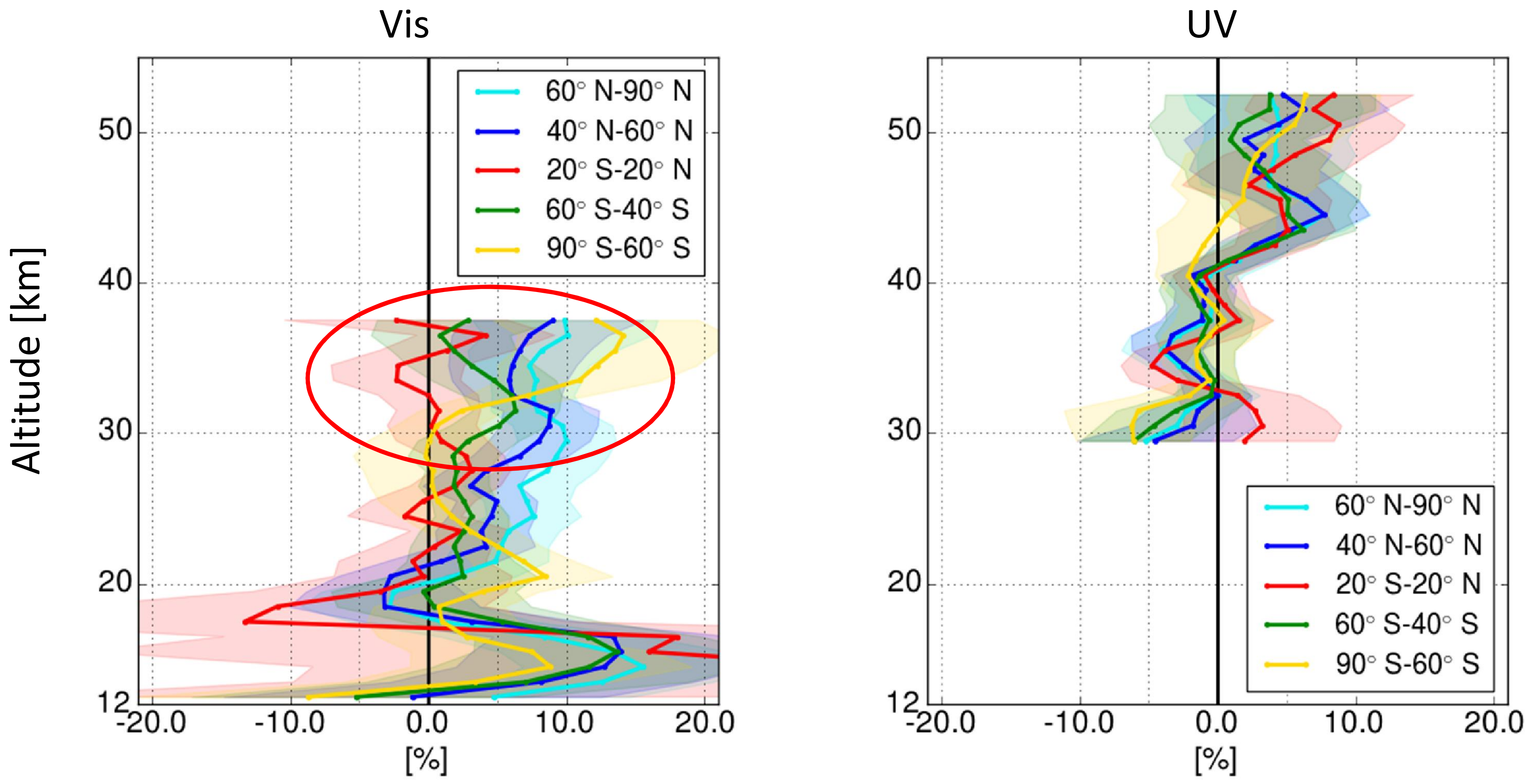


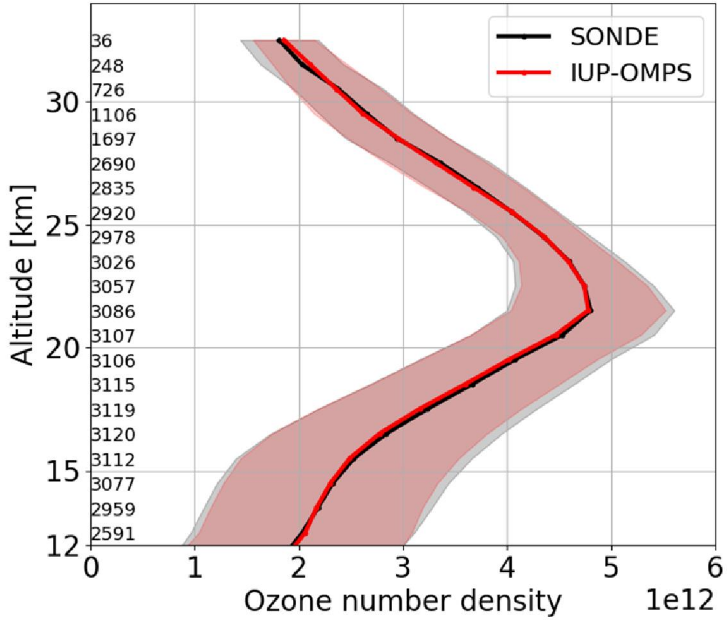
Results: validation with ozonesondes

Collocation criteria: **± 12 h, ± 5° lat, ± 10° lon**

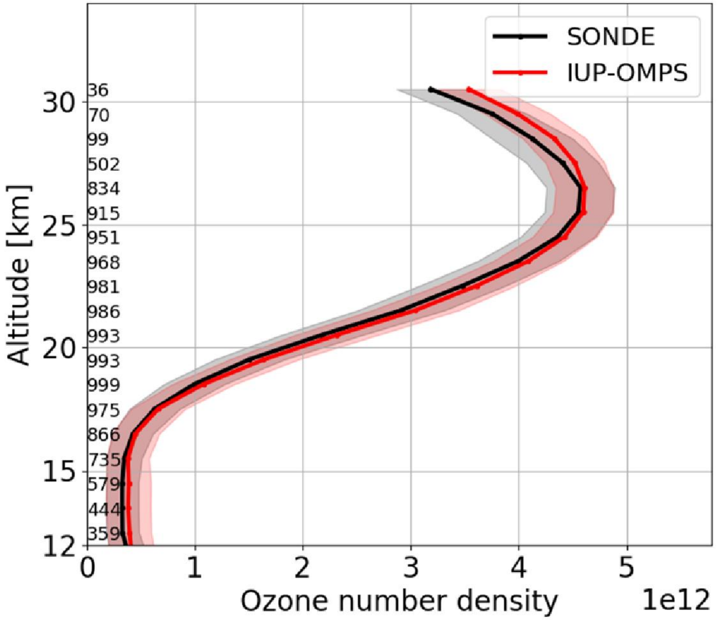
- After collocation all OMPS states around one ozonesonde are averaged;
- Sonde profiles are previously convolved at OMPS' resolution, using AKs of the retrieval;
- Data taken from WOUDC and SHADOZ databases respectively for tropics and mid-latitudes.

2012-2018

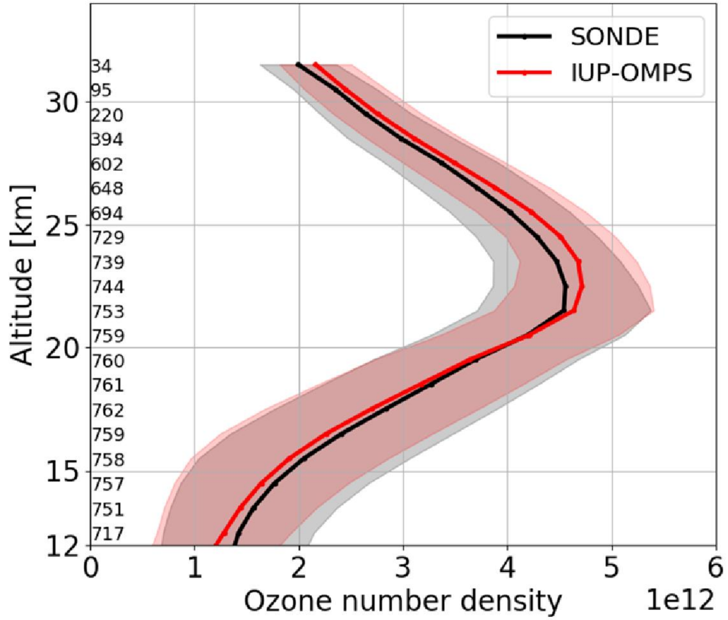
N mid-latitudes



Tropics

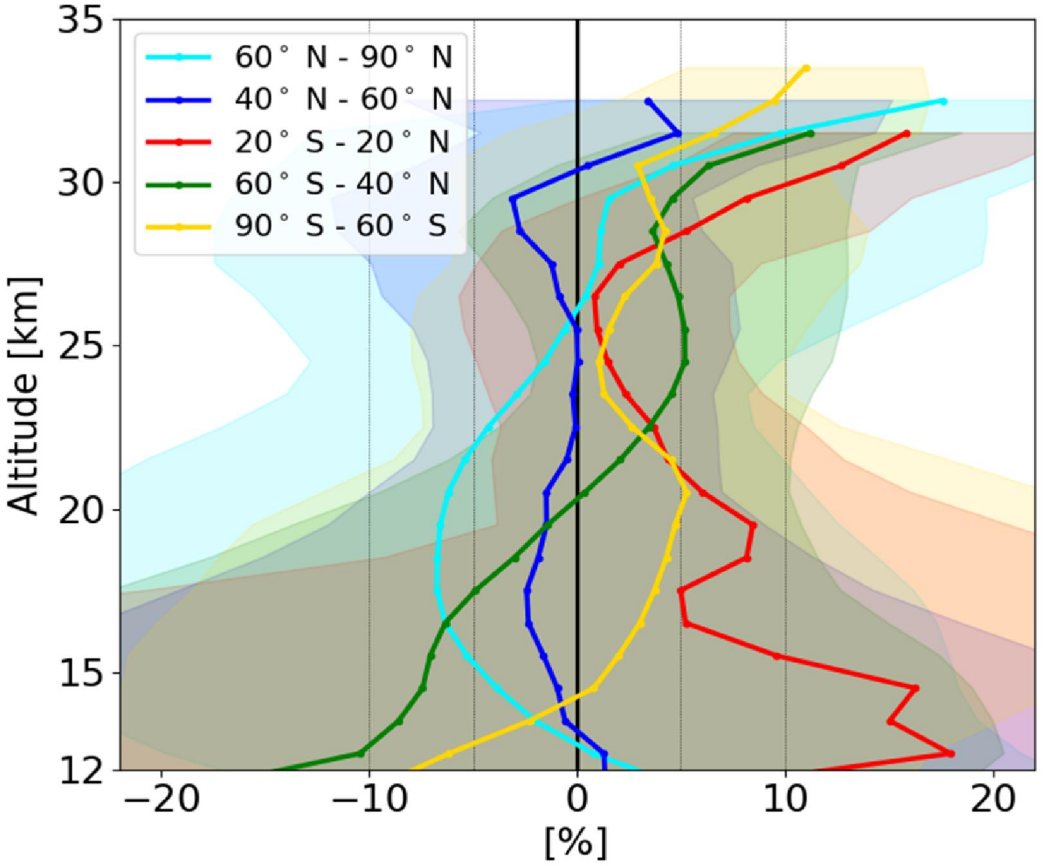


S mid-latitudes



Results: validation with ozonesondes

Northern mid-latitudes: agreement within ± 3% between 12 and 30 km;
Southern mid-latitudes: changing sign of the bias, within ± 7% between 15 and 30 km;
Tropics: positive differences, especially in the 12 - 21 km altitude range, where the ozone gradient is strong.



$$\frac{(OMPS_{IUP} - Sondes)}{(OMPS_{IUP} + Sondes)} * 200$$

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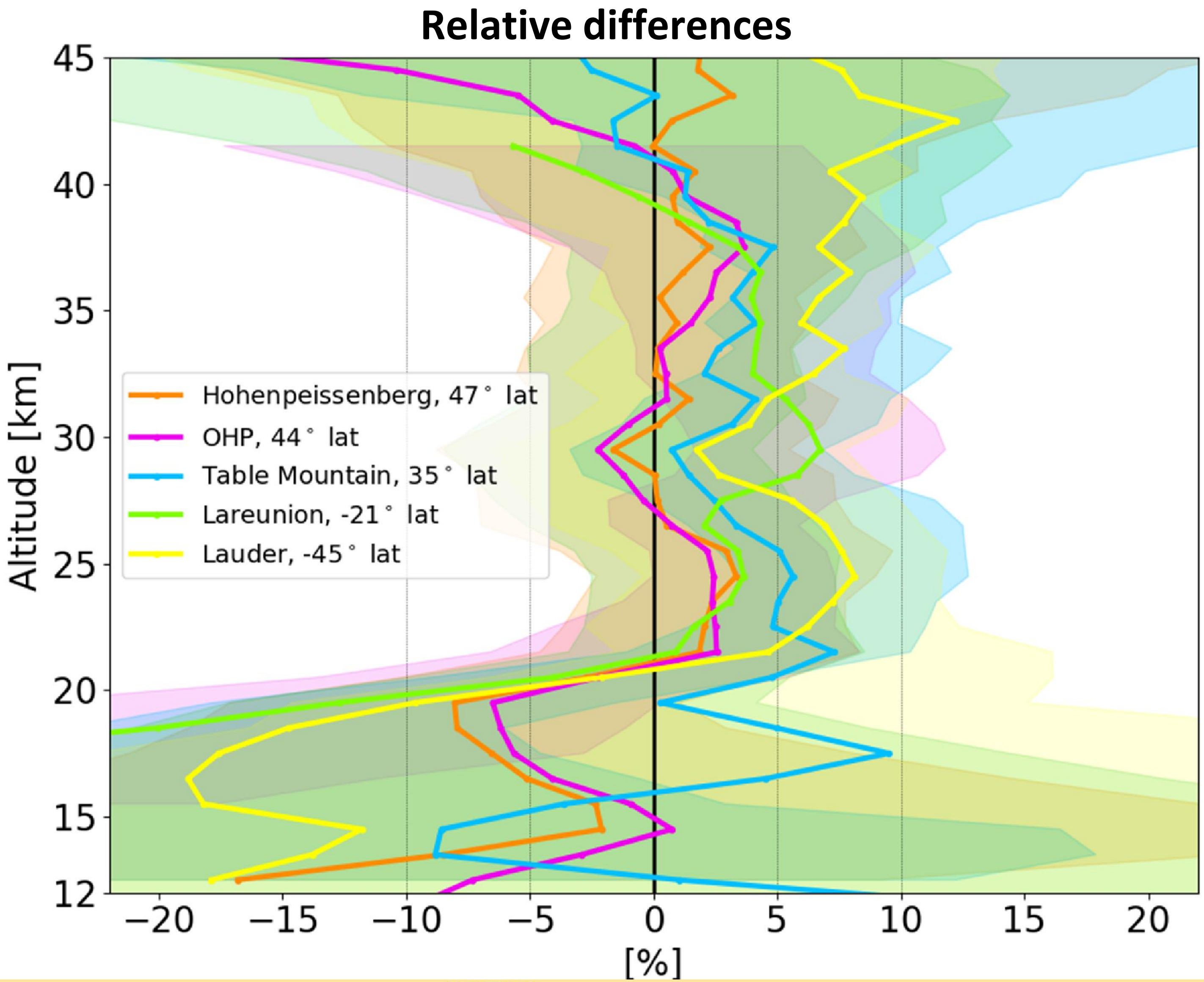
SCIAMACHY

Results: validation with lidar



<u>5 lidar stations used</u>

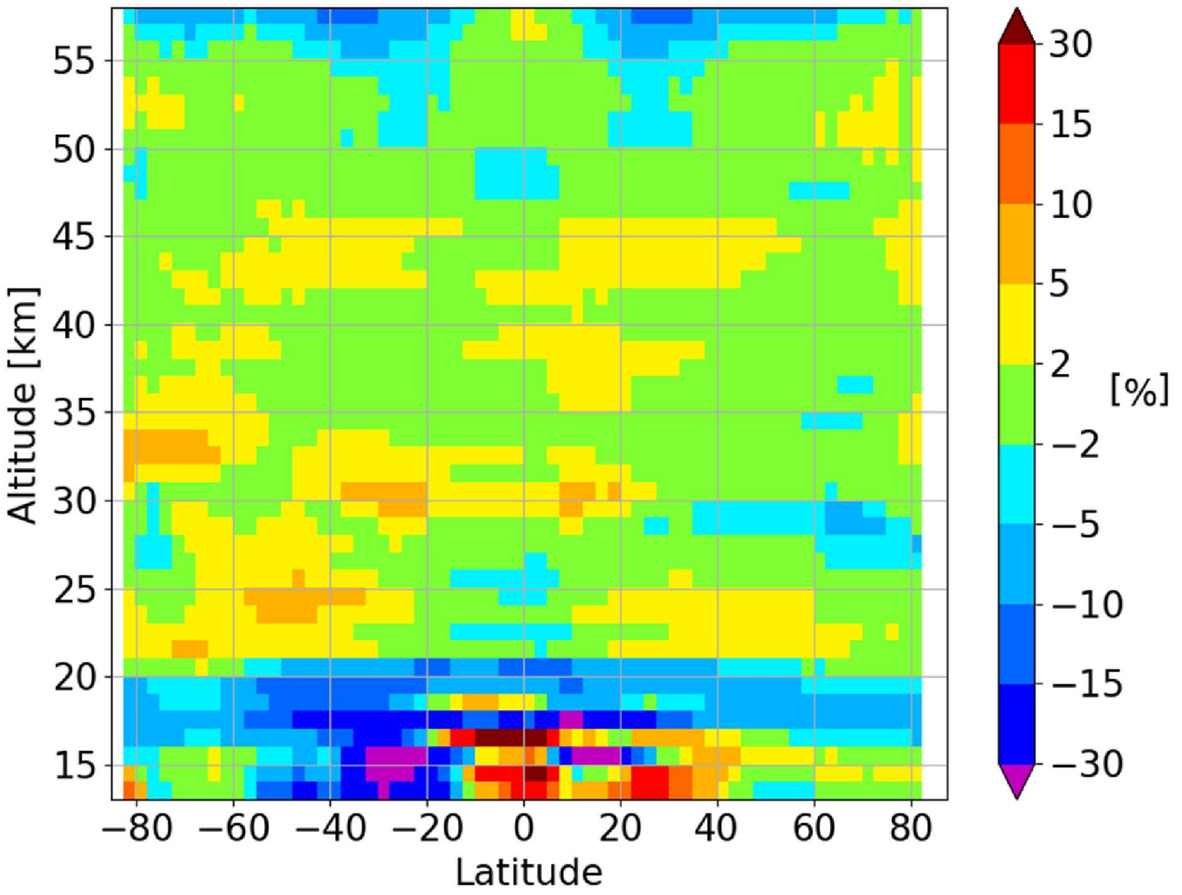
- Collocated profiles, smoothed at OMPS' resolution.
- Generally positive discrepancies, but between 20 and 40 km values are within 7% for all stations.

$$\frac{(OMPS_{IUP} - Lidar)}{(OMPS_{IUP} + Lidar)} * 200$$

Results: validation with MLS

Collocation criteria: **± 6 h, ± 1° lat, ± 1° lon**

Relative differences: $\frac{(OMPS_{IUP}-MLS)}{(OMPS_{IUP}+MLS)} * 200$

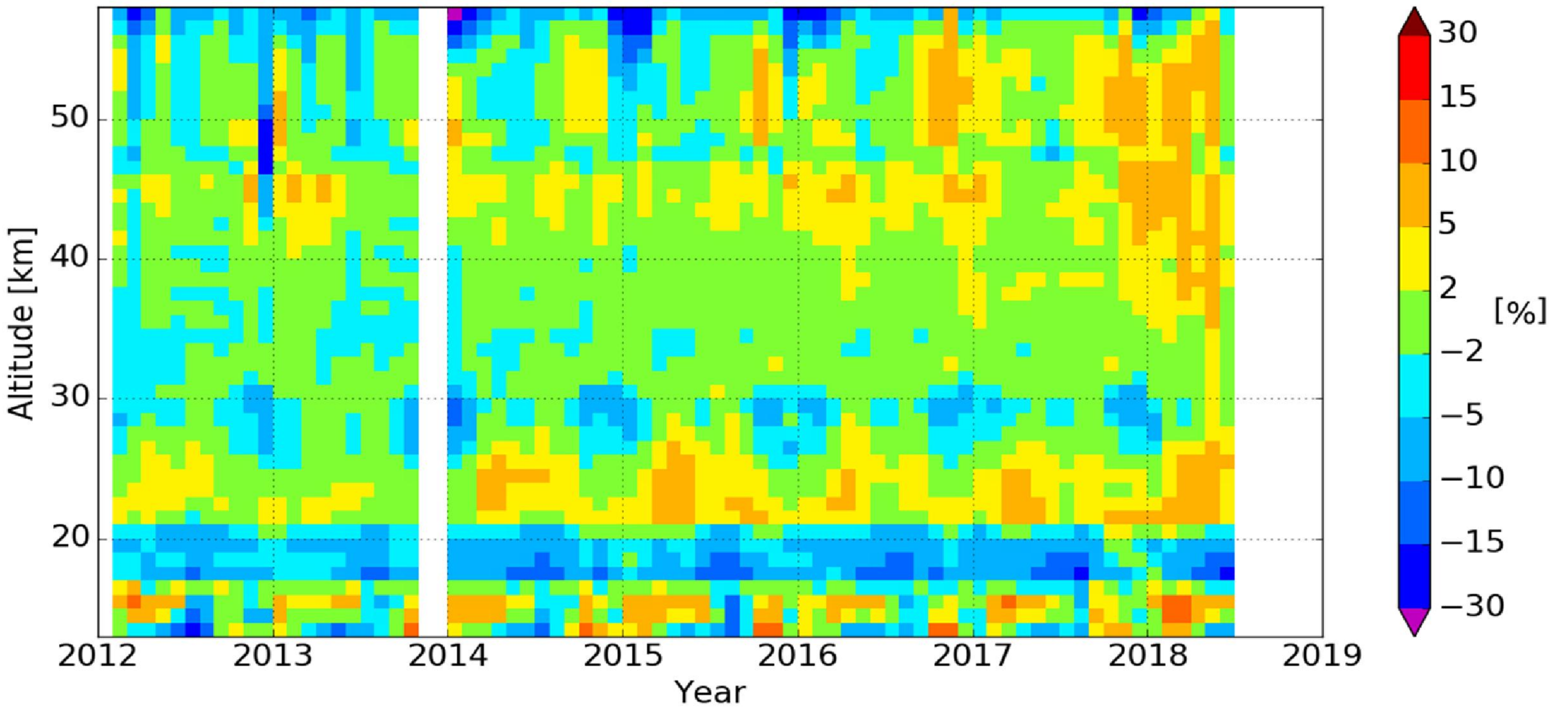


Main discrepancies

- Overall differences within ±10 % between 20 and 57 km at all latitudes.
- Discrepancies below 20 km in the tropics: *low sensitivity to ozone and vertical resolution issues; low values of ozone concentration.*
- Lower number density around 30 km towards northern high latitudes, especially during winter.

Results: validation with MLS

Relative difference time series

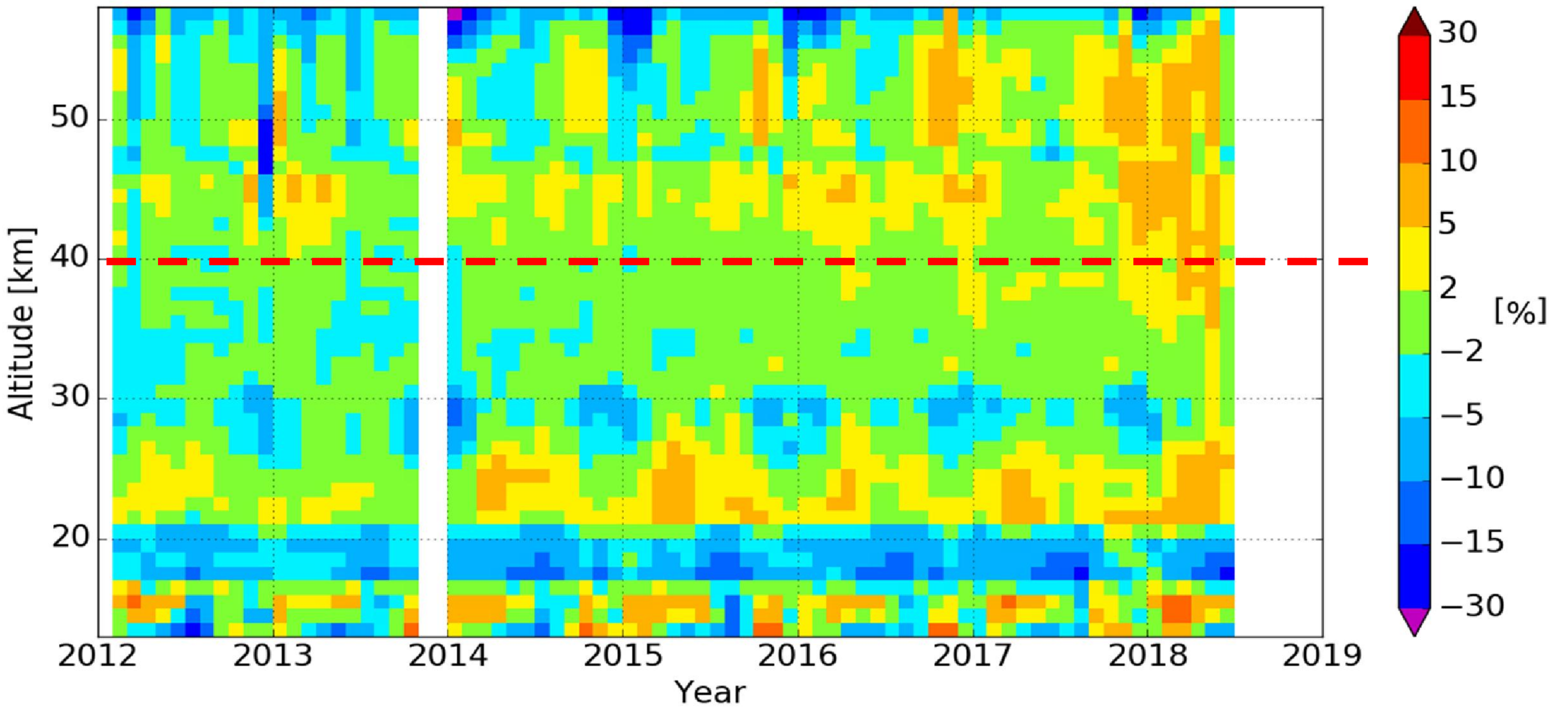


[40° N – 60° N]

$$\frac{(OMPS_{IUP} - MLS)}{(OMPS_{IUP} + MLS)} * 200$$

Results: validation with MLS

Relative difference time series



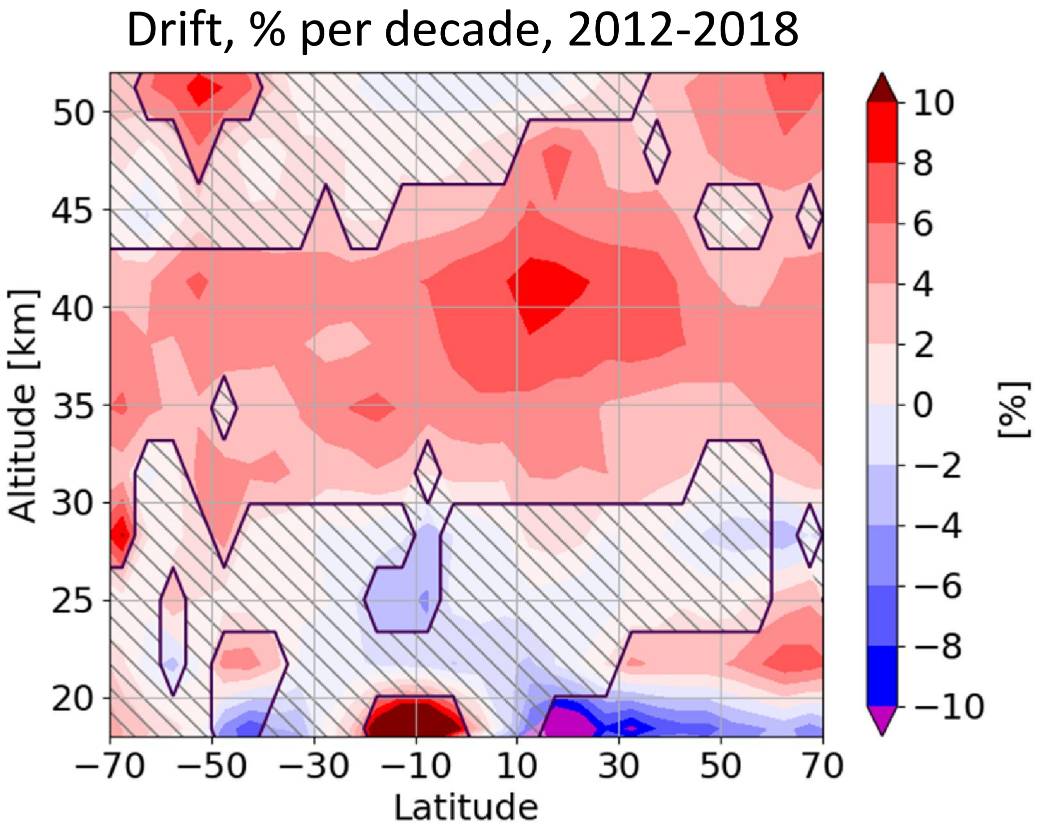
[40° N – 60° N]

$$\frac{(OMPS_{IUP} - MLS)}{(OMPS_{IUP} + MLS)} * 200$$

Is there a drift w.r.t. MLS?

OMPS drift?

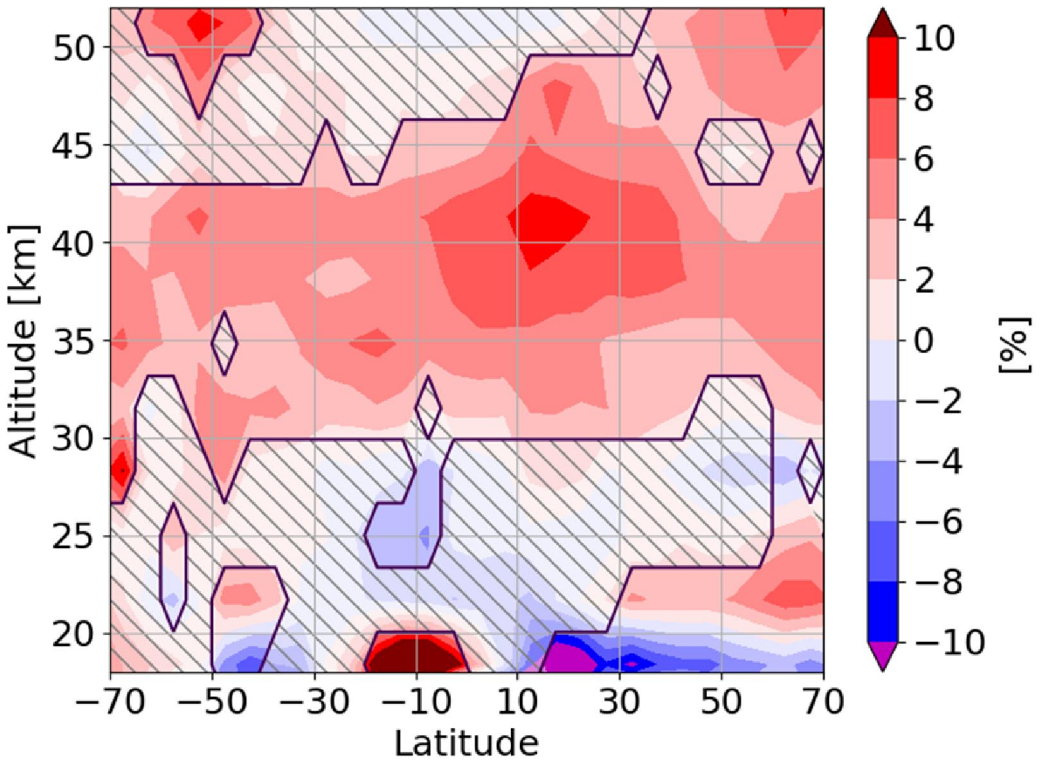
Linear trend of: $$\frac{(OMPS_{IUP} - MLS)}{(OMPS_{IUP} + MLS)} * 200$$



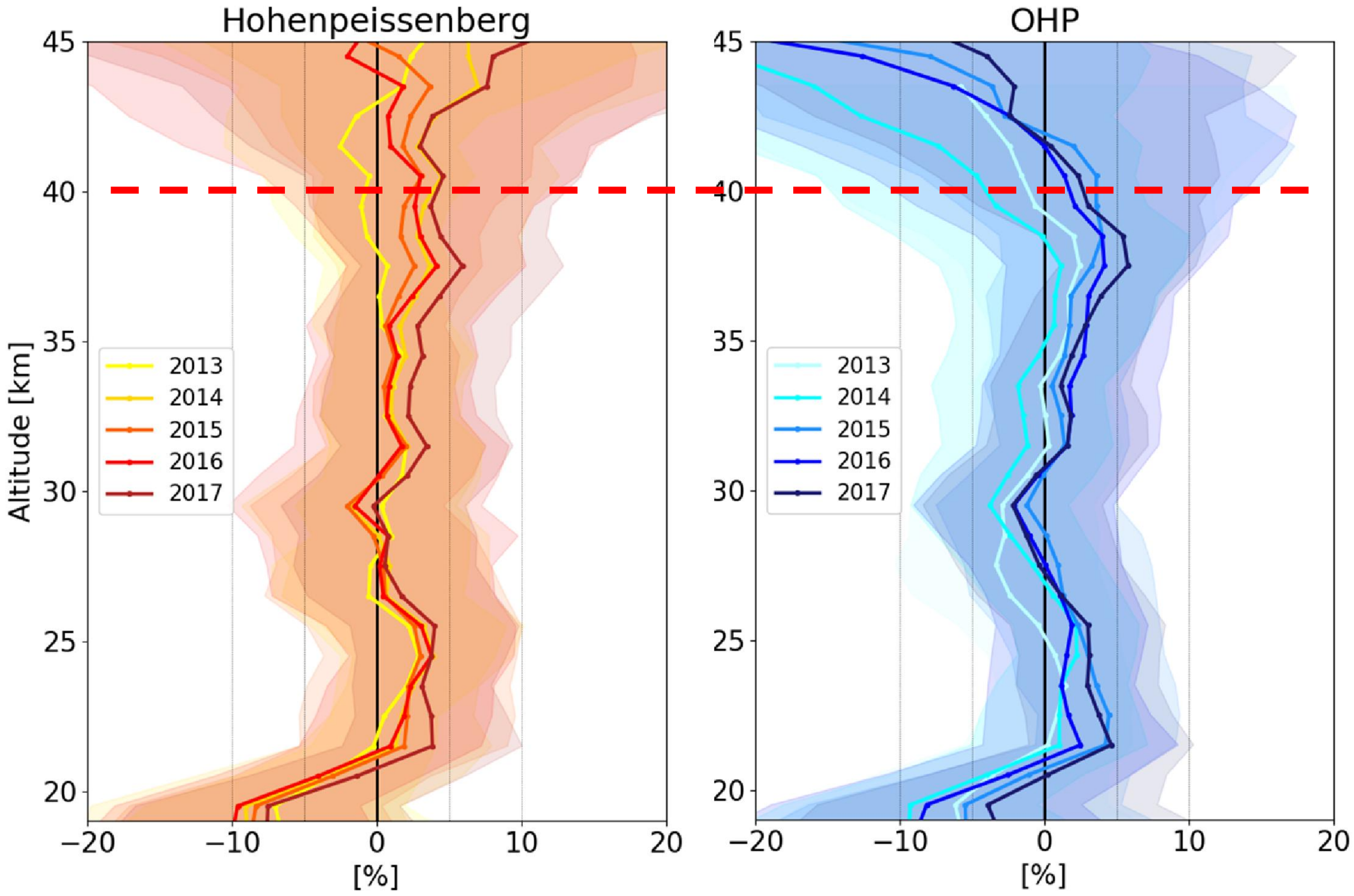
OMPS drift?

Linear trend of: $$\frac{(OMPS_{IUP} - MLS)}{(OMPS_{IUP} + MLS)} * 200$$

Drift, % per decade, 2012-2017



$$\frac{(OMPS_{IUP} - Lidar)}{(OMPS_{IUP} + Lidar)} * 200$$ Every year



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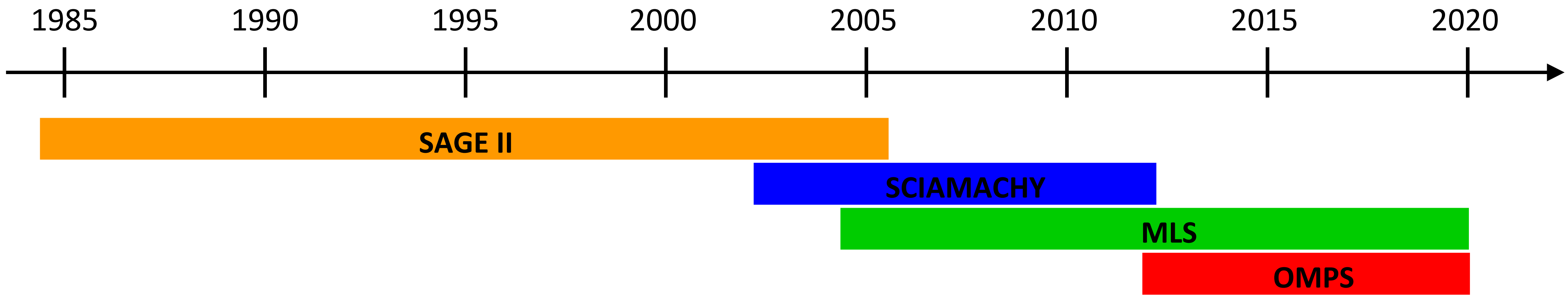
Satellite time series



Used **limb sounders** time series:

SAGE II:	10.1984 – 08.2005,	2 observations per orbit
SCIAMACHY:	08.2002 – 04.2012,	100 observations per orbit
OMPS-LP:	02.2012 – present,	140 observations per orbit (per slit)
MLS:	08.2004 – present,	120 observations per orbit (daylight)

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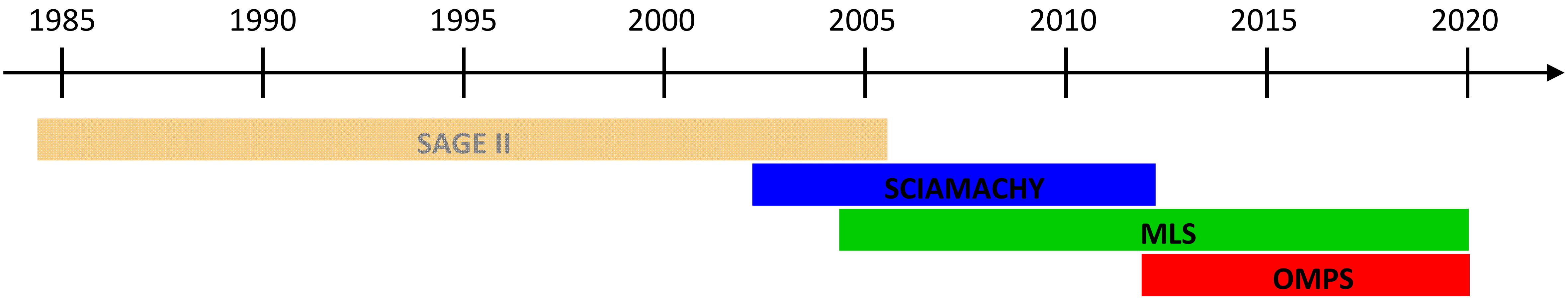

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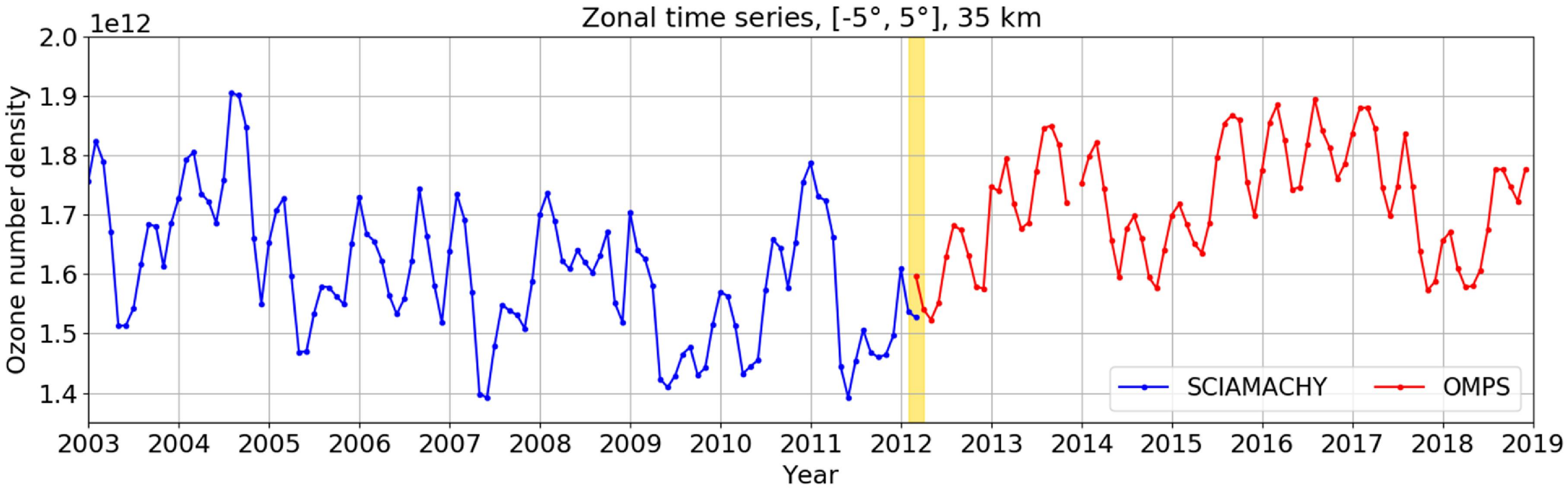
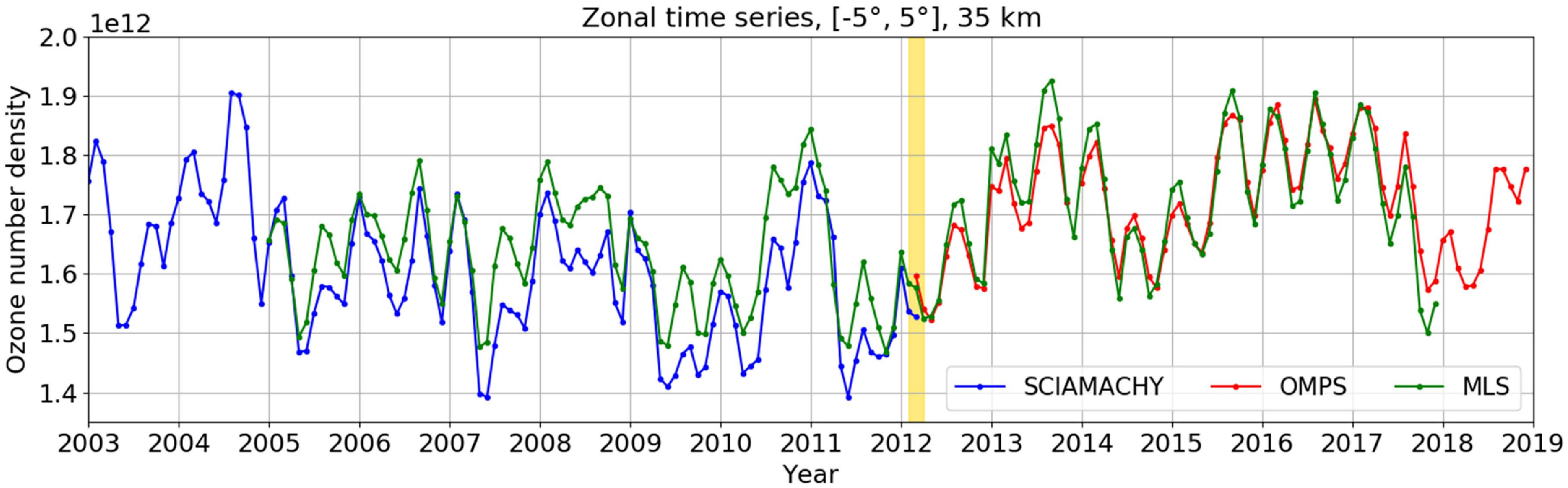
Used as a **transfer function** to merge SCIAMACHY and OMPS-LP time series

Merging SCIAMACHY and OMPS-LP profiles



OMPS-LP and **SCIAMACHY** have an overlap of only 2.5 months.
A tranfer function is needed to overcome calibration issues: **MLS** was chosen

Merging SCIAMACHY and OMPS-LP profiles



- **MLS** used as a transfer function for the merging.
- **Monthly averaged** ozone profiles on a **5˚ latitude x 20˚ longitude** regular grid. Number density ozone profiles interpolated on a vertical grid with 3.3 km steps.

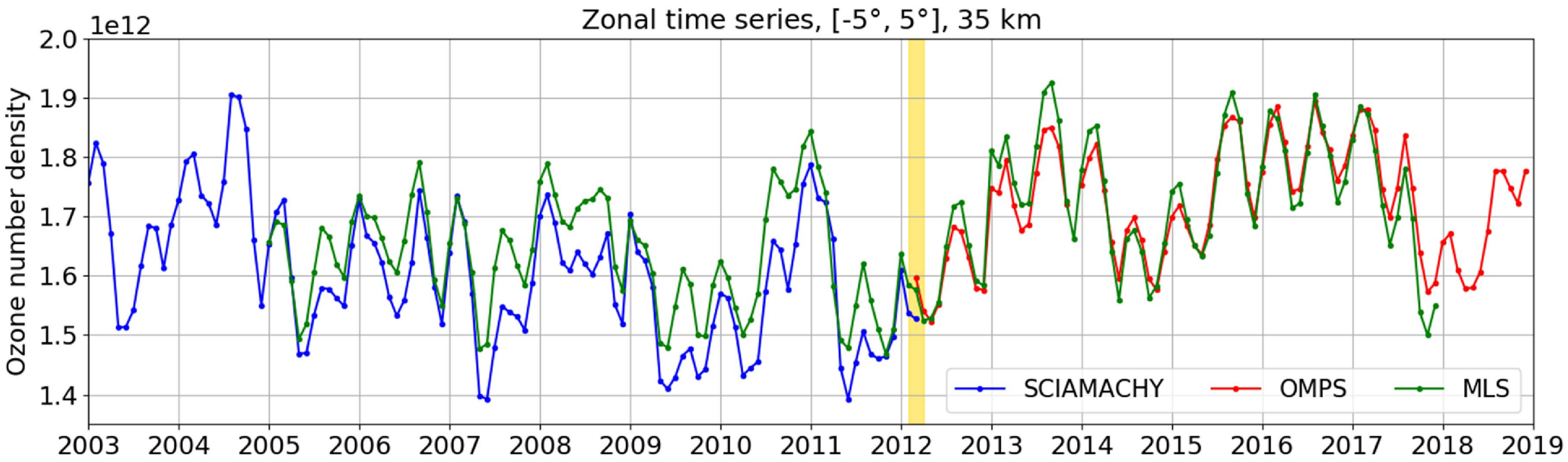
Merging SCIAMACHY and OMPS-LP profiles

Merging approach: plain debiasing

Subtract the average bias between OMPS and MLS (2012-2017) and between SCIAMACHY and MLS (2005-2012). For example, for each latitude, longitude and altitude:

$$Bias_{OMPS} = mean\left(OMPS_{(2012-2017)} - mean(MLS_{(2012-2017)})\right)$$

$$Bias_{SCIA} = mean\left(SCIA_{(2005-2012)} - mean(MLS_{(2005-2013)})\right)$$



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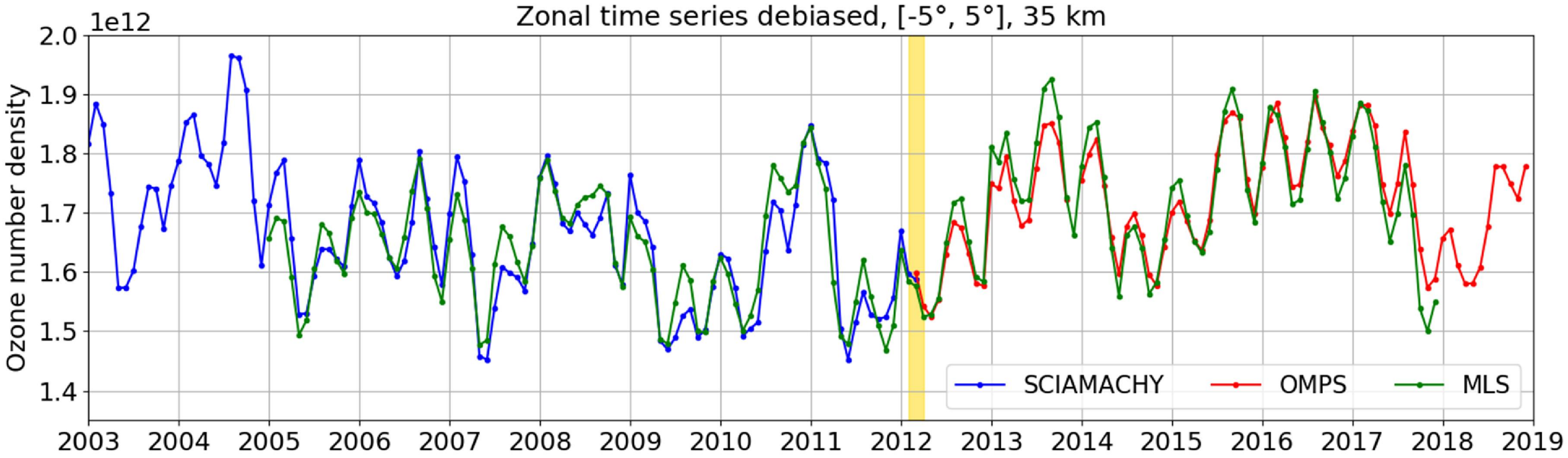
$$\textbf{SCIA deb} = SCIA_{(2003-2012)} - Bias_{SCIA} \qquad \textbf{OMPS deb} = OMPS_{(2012-2018)} - Bias_{OMPS}$$



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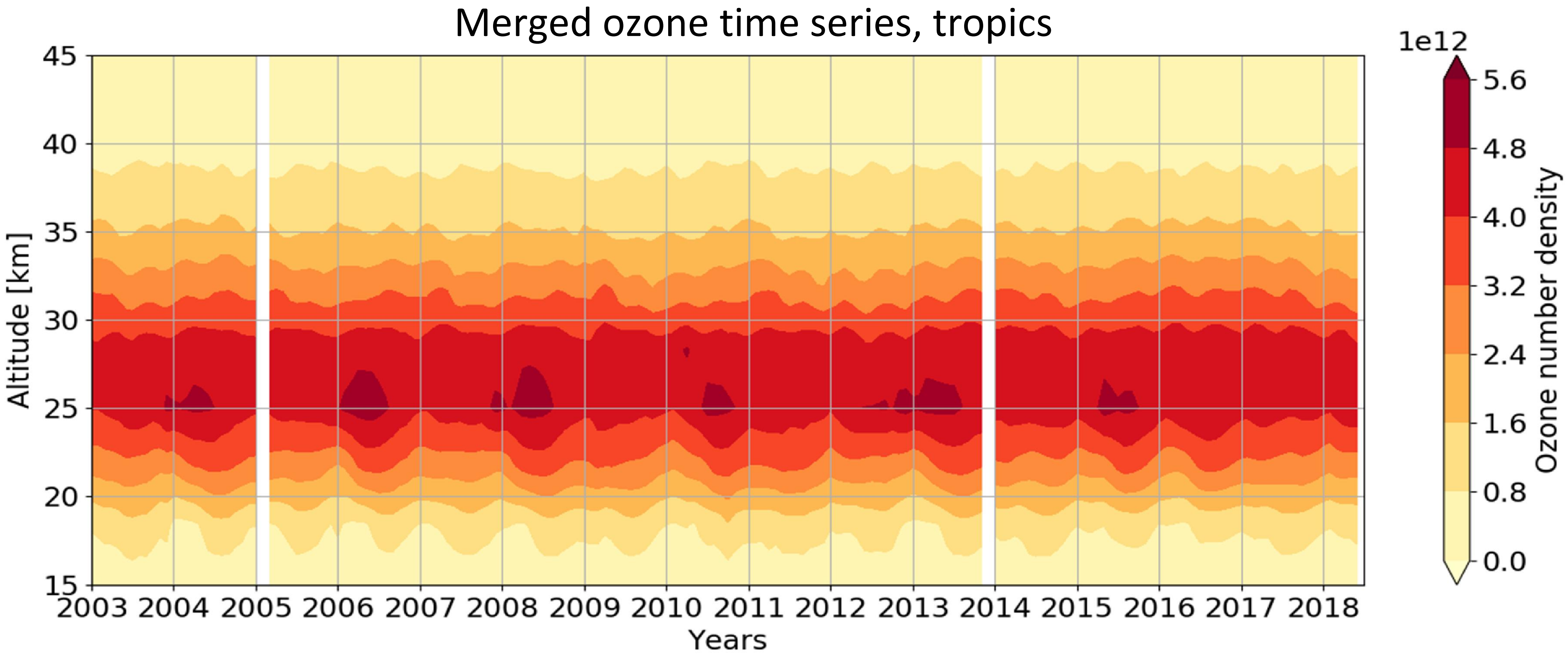
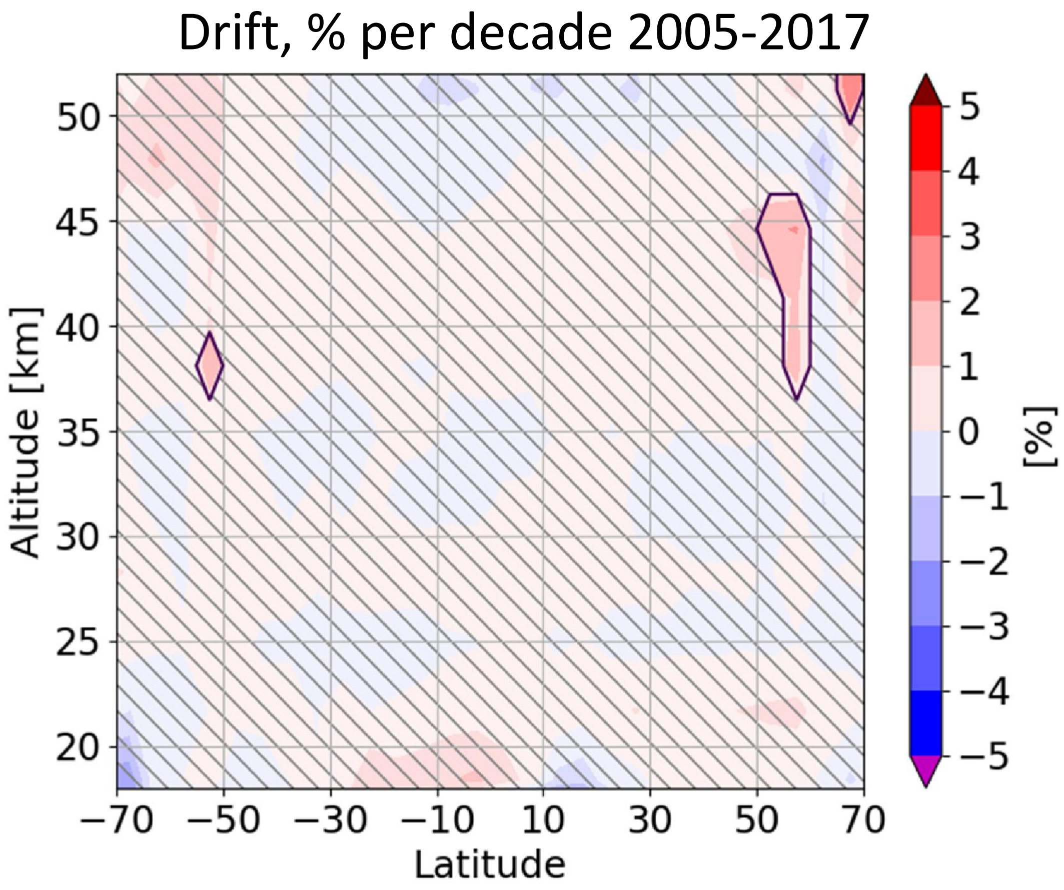
SCIAMACHY

Merging SCIAMACHY and OMPS-LP profiles



Study long-term ozone changes in the $O_3(t)$ over the last 15 years

Merging SCIAMACHY and OMPS-LP profiles



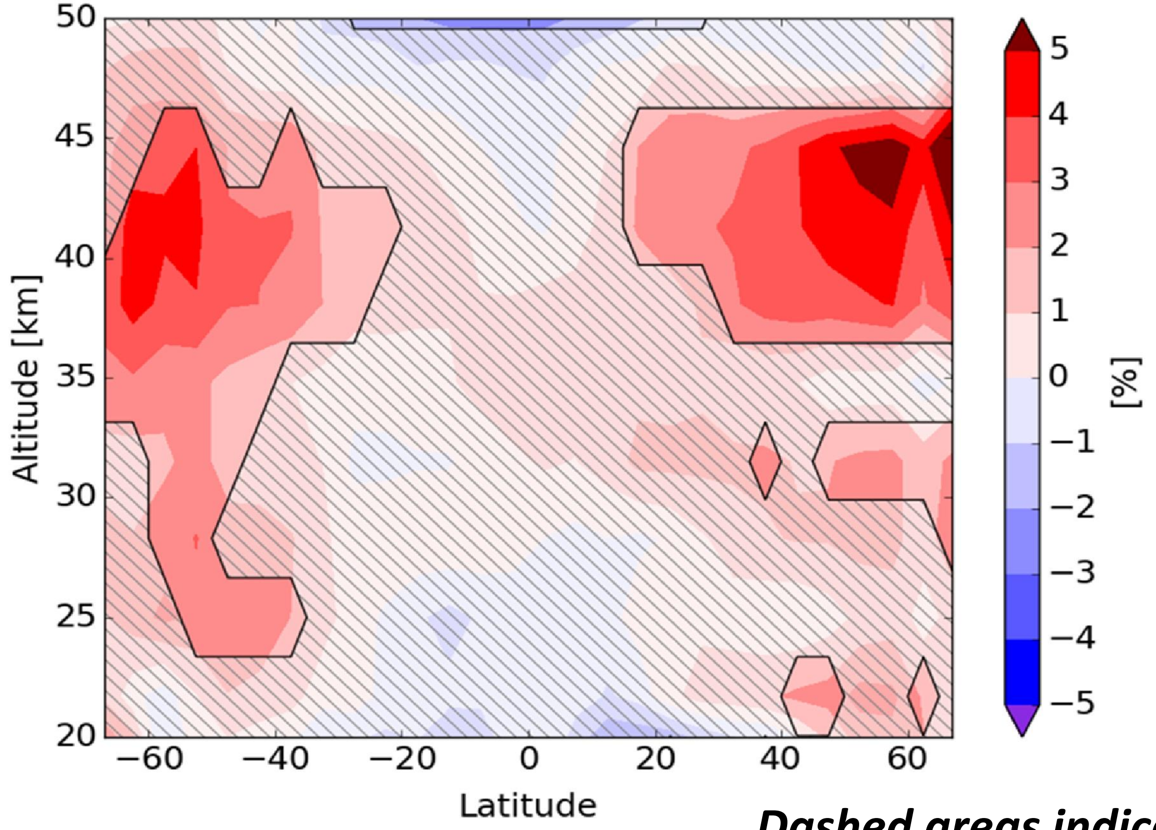
- No significant drift detected with respect to MLS;
- Range of validity: 20-50 km and within 60° latitude.

Ozone long-term changes 2003-2018

Multi-Linear Regression model:

$$O_3(t) = c_0 + c_1 t + Seasonal\ terms + QBO(t) + Solar(t) + ENSO(t) + N(t)$$

Zonal trends, % per decade, 2003-2018



Dashed areas indicate non significant trends

Universität Bremen

iup

ozone cci

SCIAMACHY

Ozone long-term changes 2003-2018

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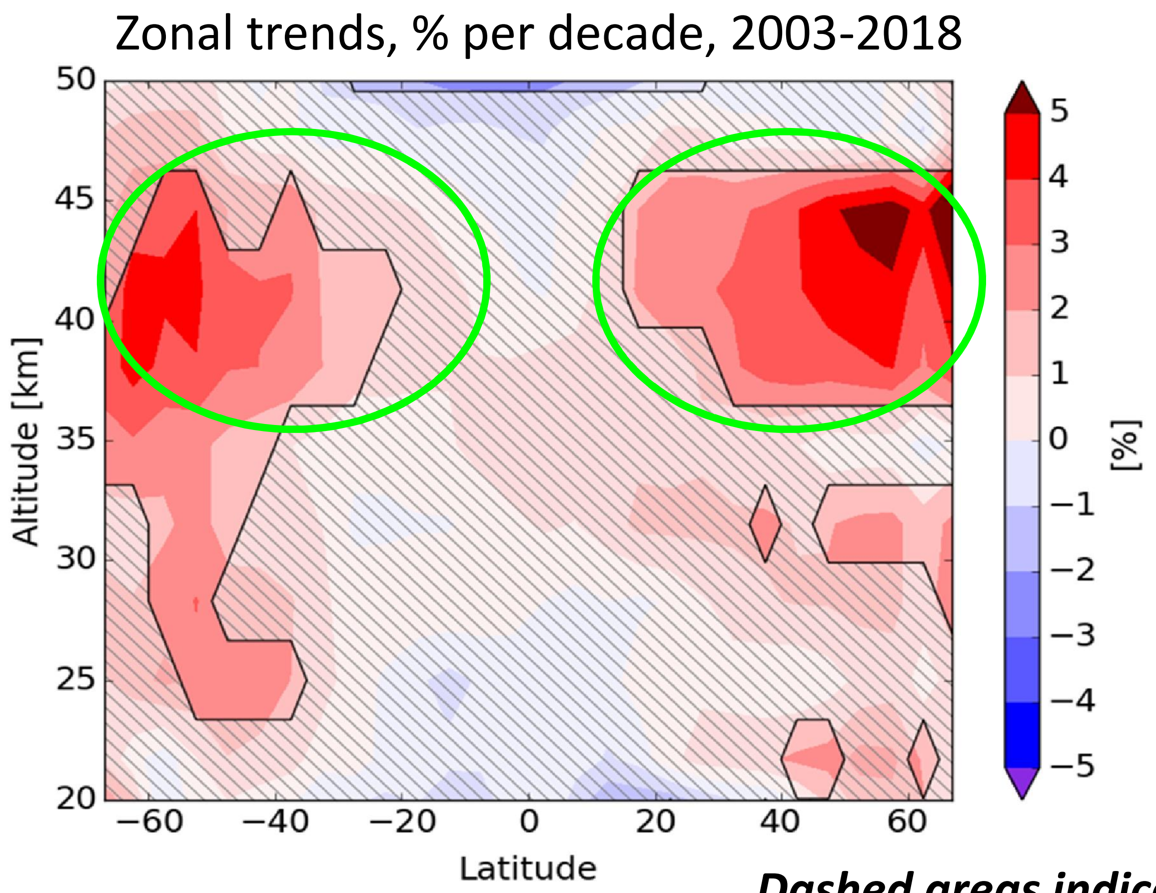

Main features:

- Recovery in the upper stratosphere, particularly at mid-latitudes

Dashed areas indicate non significant trends

Ozone long-term changes 2003-2018

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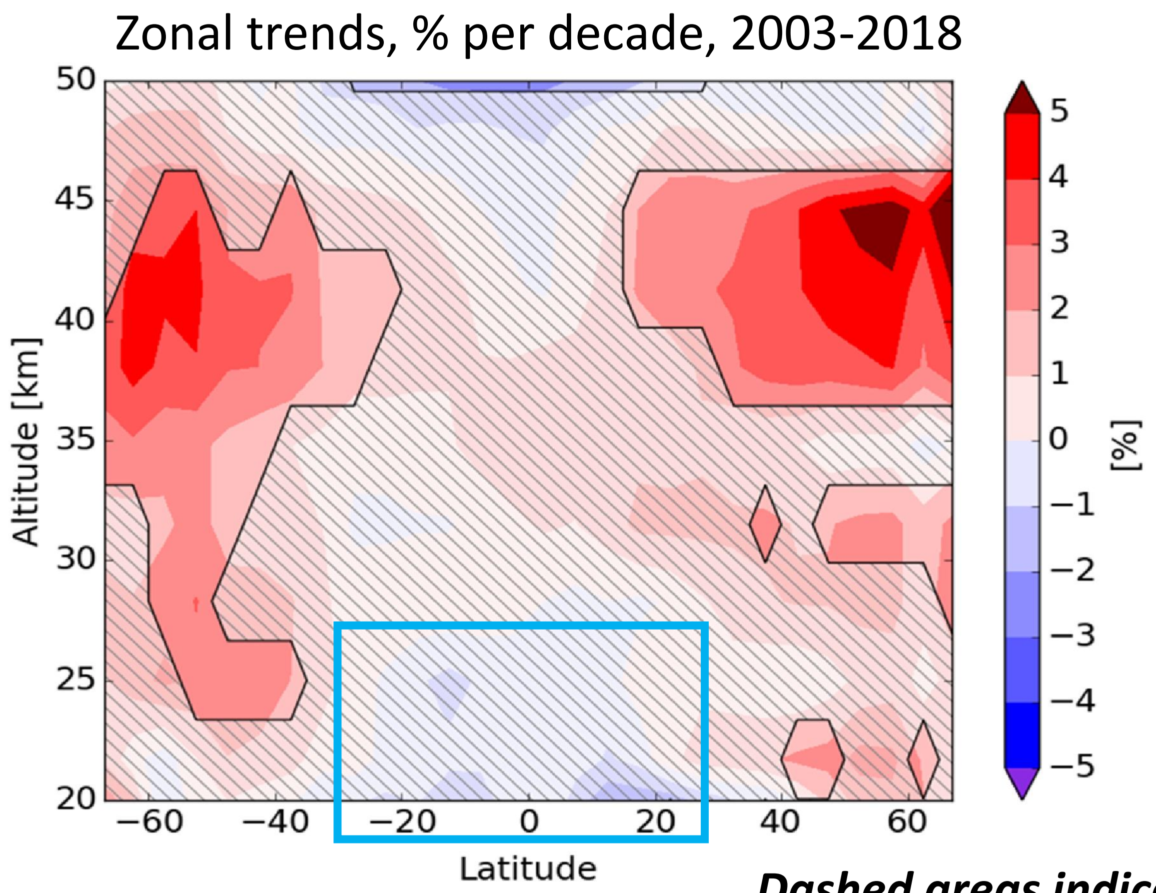


Main features:

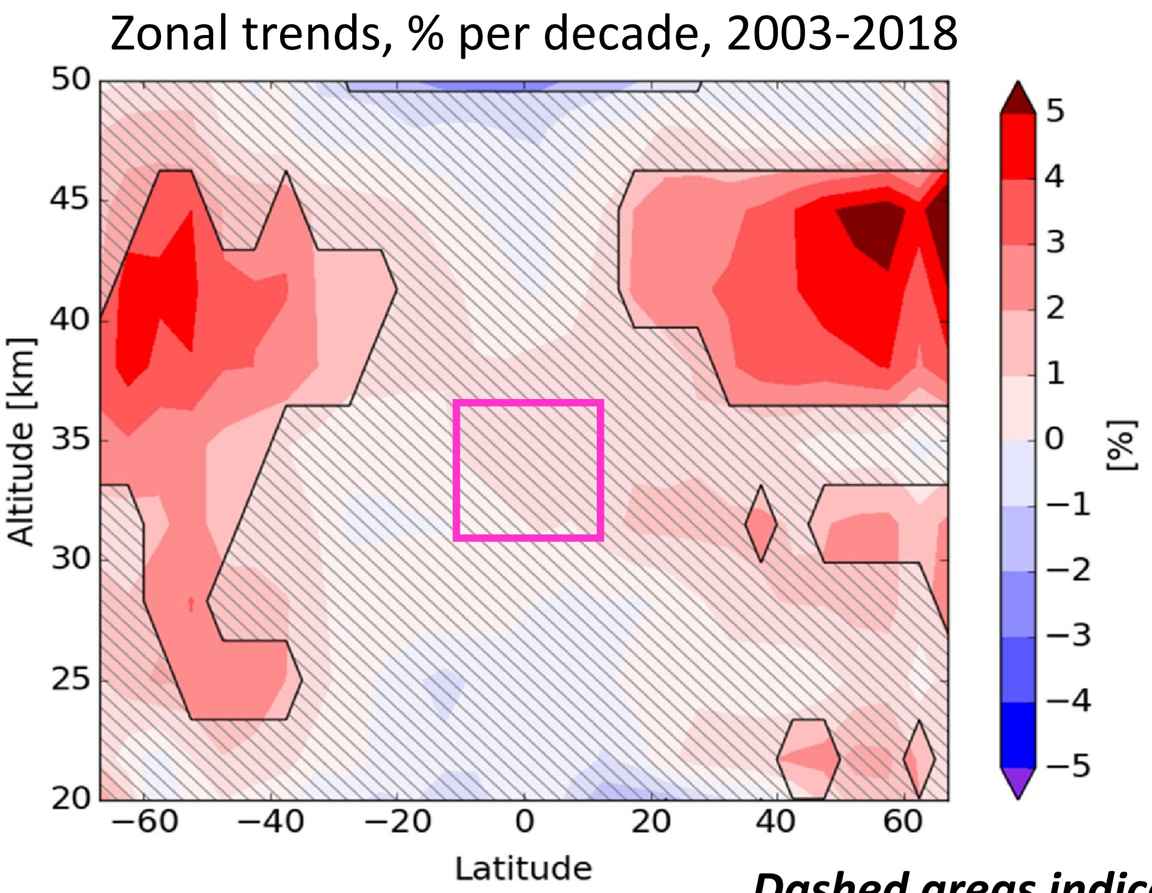
- Recovery in the upper stratosphere, particularly at mid-latitudes
- Negative non-significant trends in the lower tropical stratosphere

Dashed areas indicate non significant trends

Ozone long-term changes 2003-2018

Multi-Linear Regression model:

$$O_3(t) = c_0 + c_1 t + Seasonal\ terms + QBO(t) + Solar(t) + ENSO(t) + N(t)$$



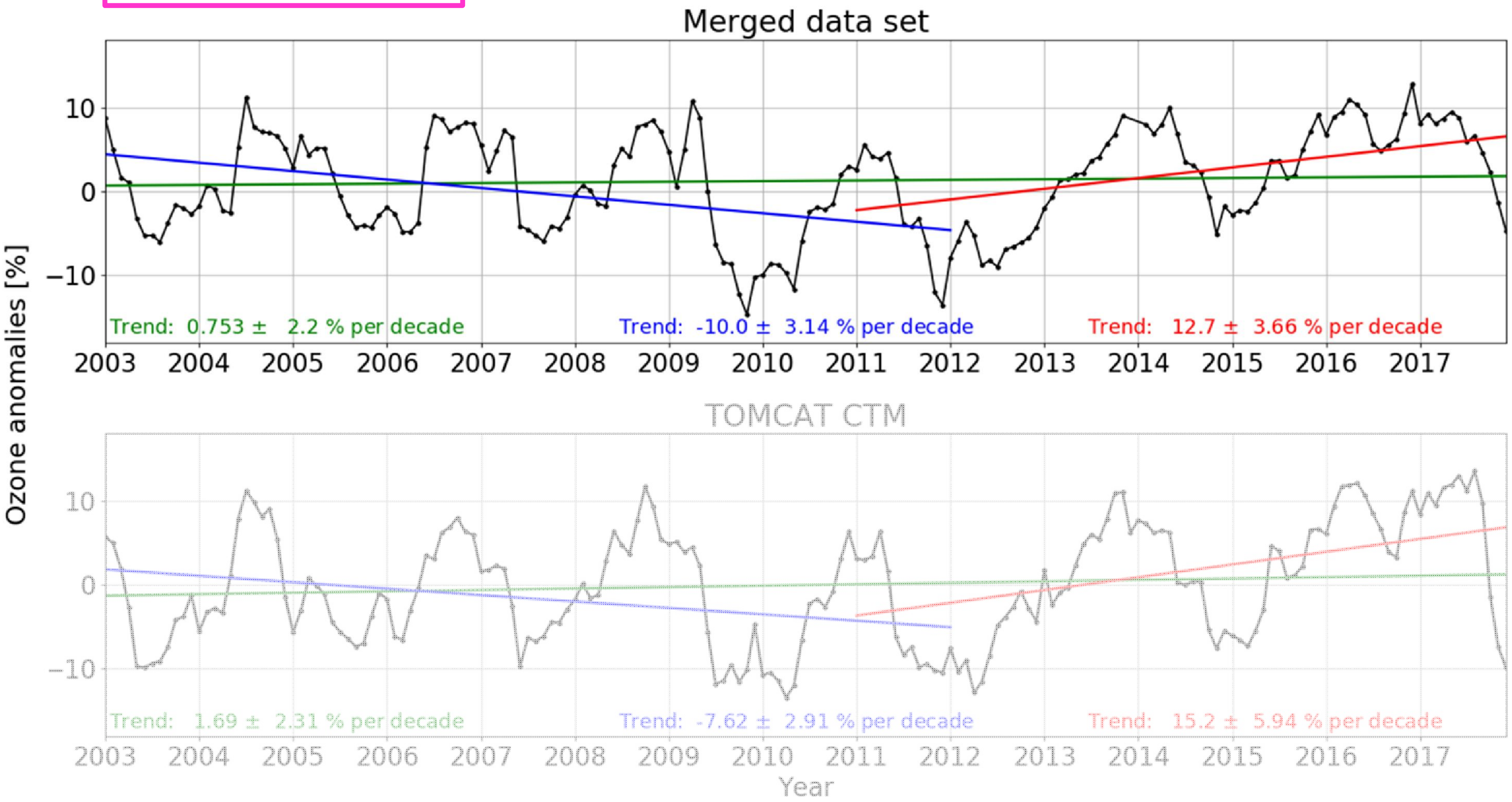
<u>Main features:</u>

- Recovery in the upper stratosphere, particularly at mid-latitudes
- Negative non-significant trends in the lower tropical stratosphere
- Small positive but non-significant trends in the middle tropical stratosphere...but different behaviour over SCIAMACHY and OMPS time series

Dashed areas indicate non significant trends

Ozone long-term changes 2003-2018

32 km, tropics



TOMCAT is a chemistry transport model (CTM, *Chipperfield et al., 2006*)

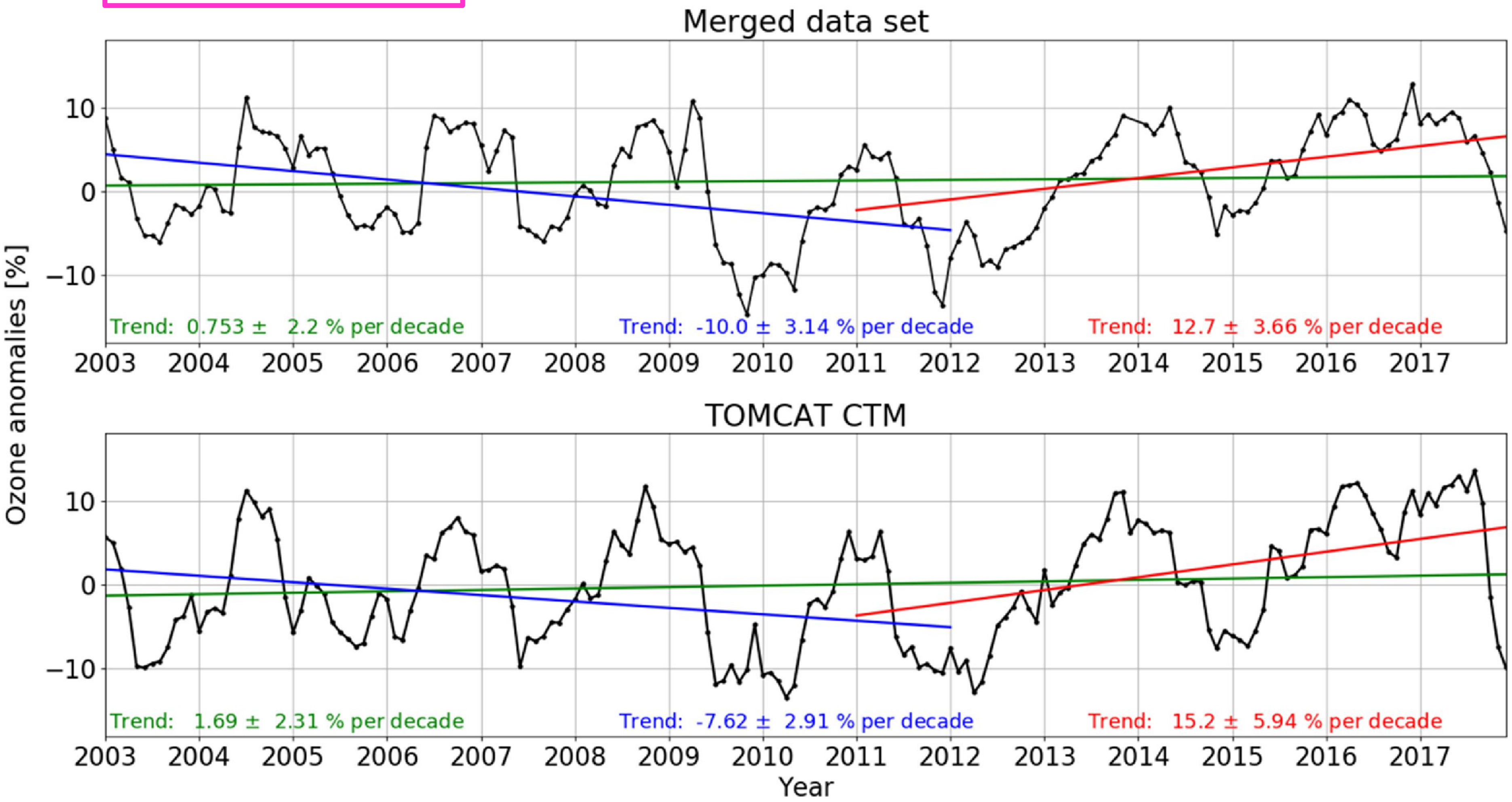
Good agreement between the merged data set and TOMCAT

Overall positive non-significant ozone changes but:

- Negative trend over SCIAMACHY lifetime
- Positive trend over OMPS-LP period

Ozone long-term changes 2003-2018

32 km, tropics



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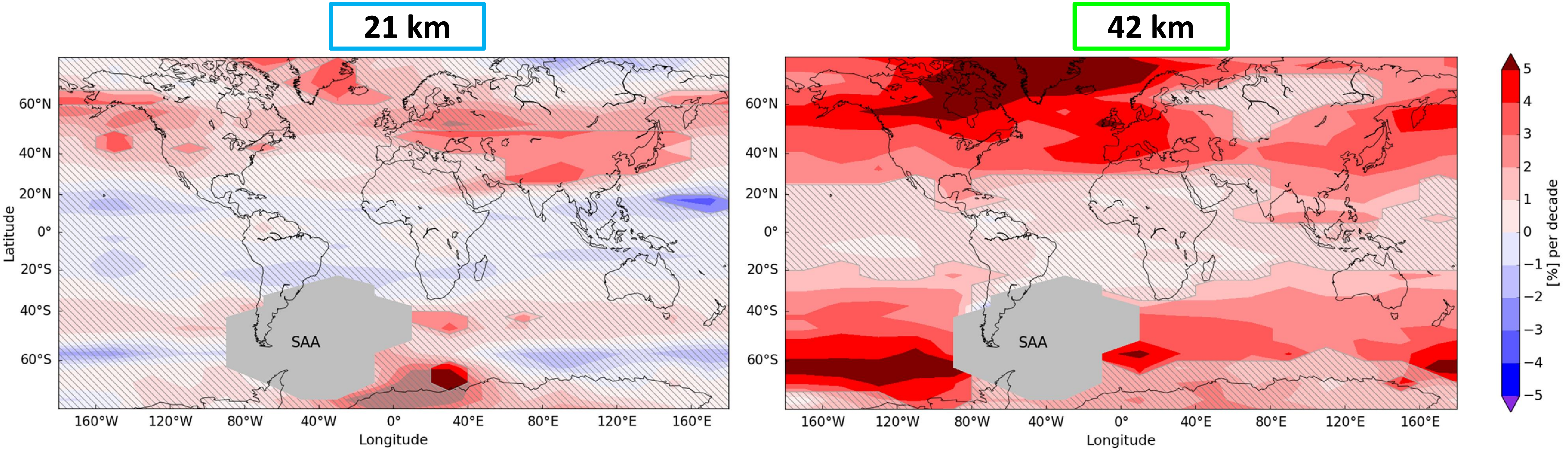
Ozone long-term changes 2003-2018

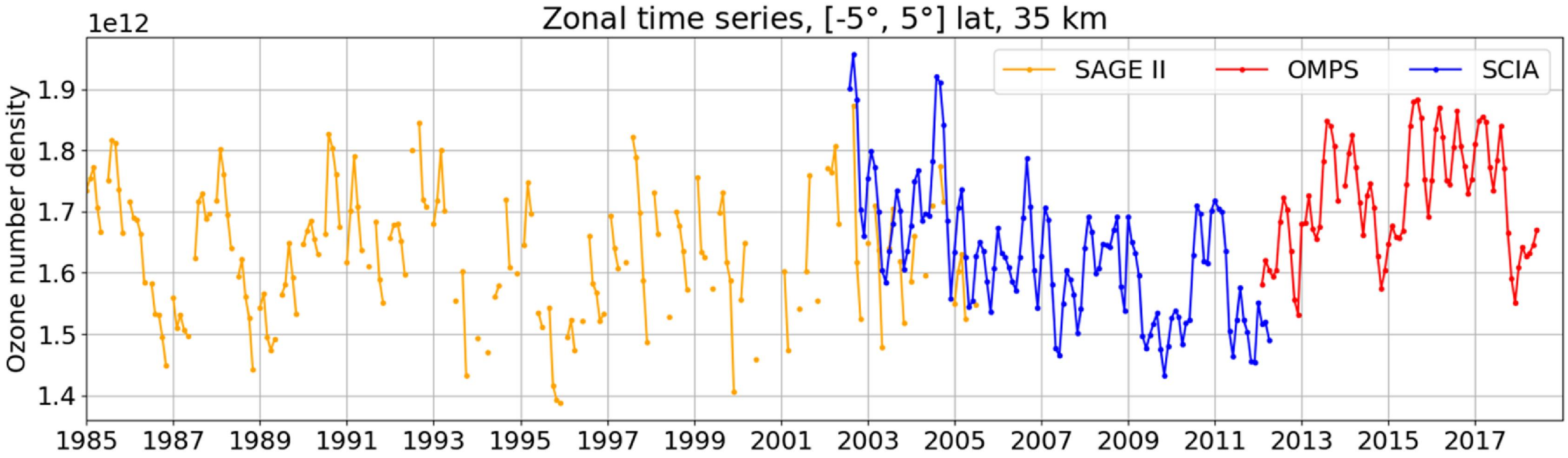
Longitudinally resolved trends, % per decade, 2003-2018



The longitudinal structure of the trends shows a large variability not only in the lower stratosphere but also in the middle-upper stratosphere, where the maximum recovery has been found.

Merging with SAGE II

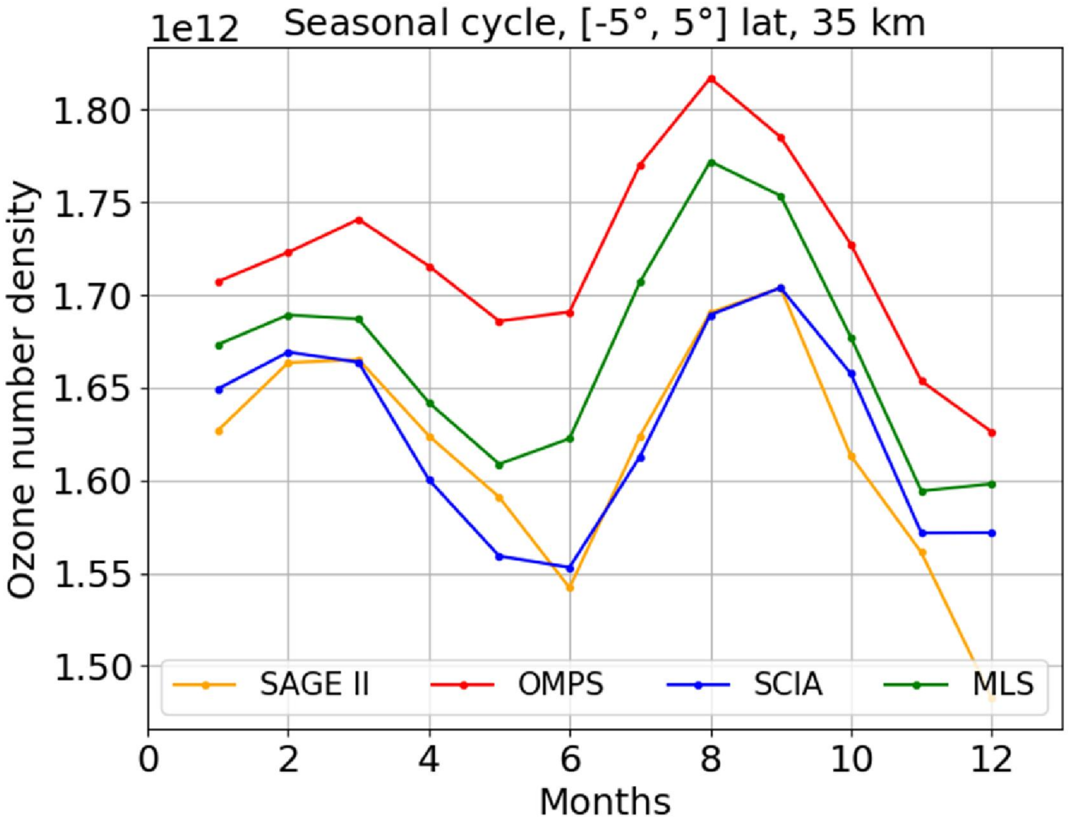
SAGE II: 01.1985 – 08.2005. **Zonal monthly mean values**, gridded every 10° latitude.



Merging with SAGE II

SAGE II: 01.1985 – 08.2005. **Zonal monthly mean values**, gridded every 10° latitude.
Merging approach: deseasonalized anomalies.

1. Compute the seasonal cycle (SC) for each instrument



Merging with SAGE II

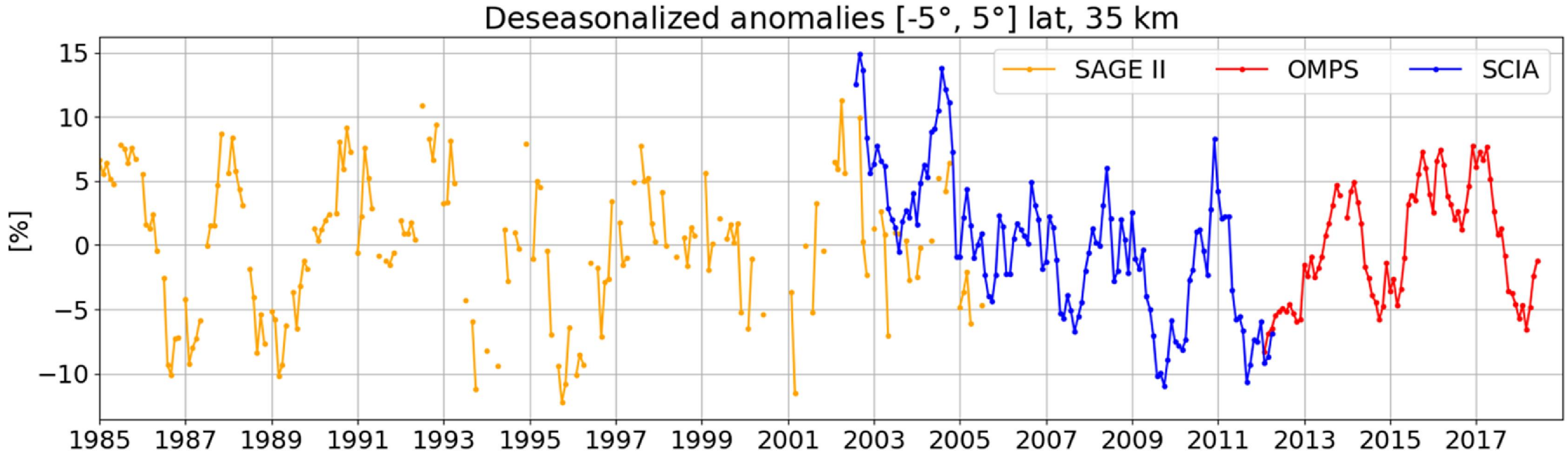
SAGE II: 01.1985 – 08.2005. **Zonal monthly mean values**, gridded every 10° latitude.

Merging approach: deseasonalized anomalies.

2. Subtract the SC for each latitude and altitude: relative anomalies are computed

$$\boldsymbol{SAGE\ II\ Anomaly} = \frac{SAGE_{(1985-2005)} - SC}{SC} * 100, \qquad \boldsymbol{SCIA\ Anomaly} = \frac{SCIA_{(2002-2012)} - SC}{SC} * 100$$

$$\boldsymbol{OMPS\ Anomaly} = \frac{OMPS_{(2012-2018)} - SC}{SC} * 100$$



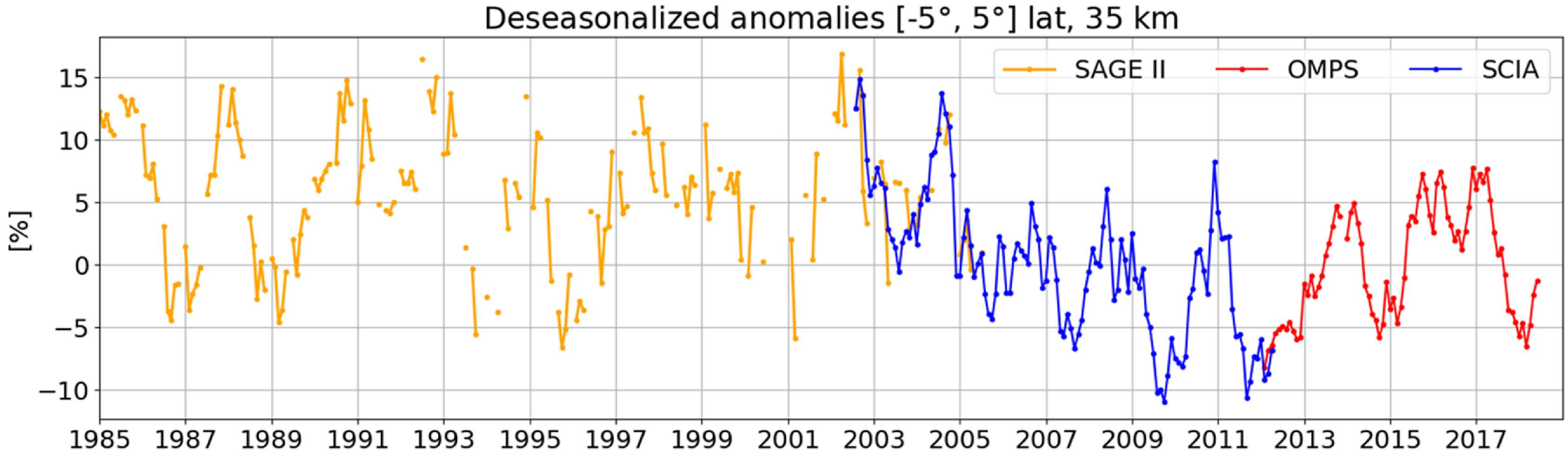
Merging with SAGE II

SAGE II: 01.1985 – 08.2005. **Zonal monthly mean values**, gridded every 10° latitude.
Merging approach: deseasonalized anomalies.

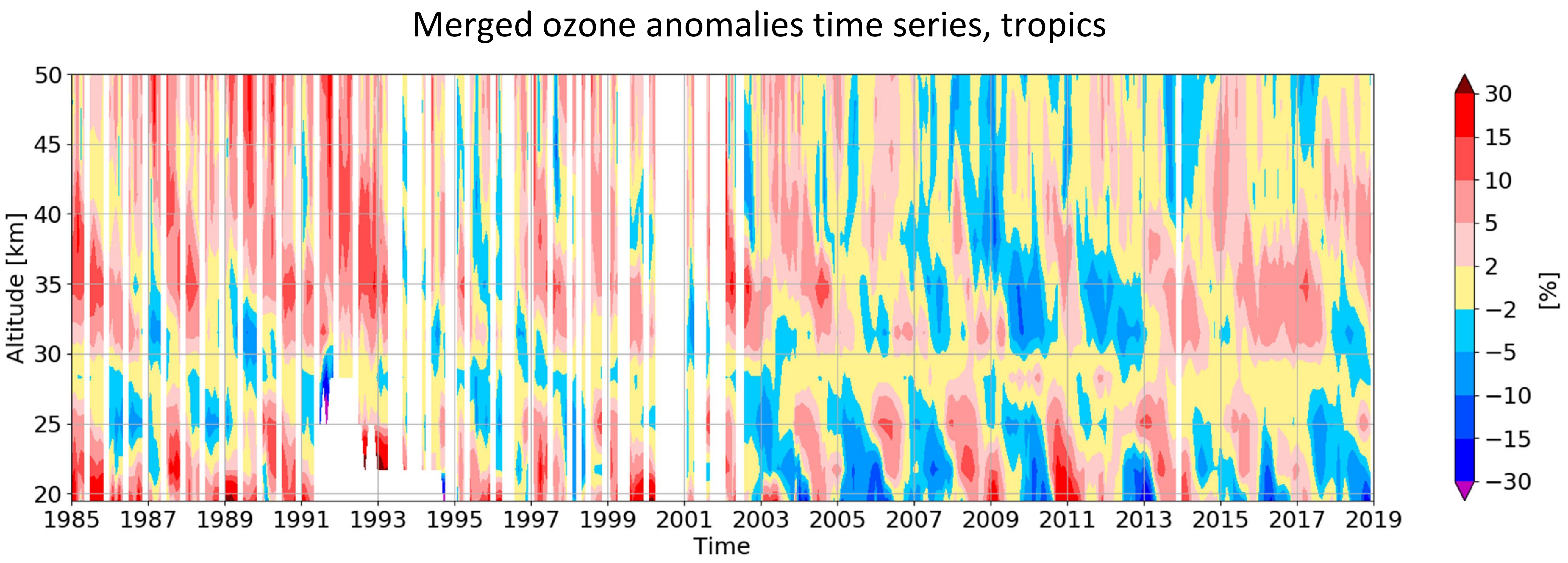
2. Subtract the SC for each latitude and altitude: relative anomalies are computed and debiased

$$\textbf{\textit{SAGE II Anomaly}} = \frac{SAGE_{(1985-2005)} - SC}{SC} * 100, \qquad \textbf{\textit{SCIA Anomaly}} = \frac{SCIA_{(2002-2012)} - SC}{SC} * 100$$

$$\textbf{\textit{OMPS Anomaly}} = \frac{OMPS_{(2012-2018)} - SC}{SC} * 100$$



Merging with SAGE II

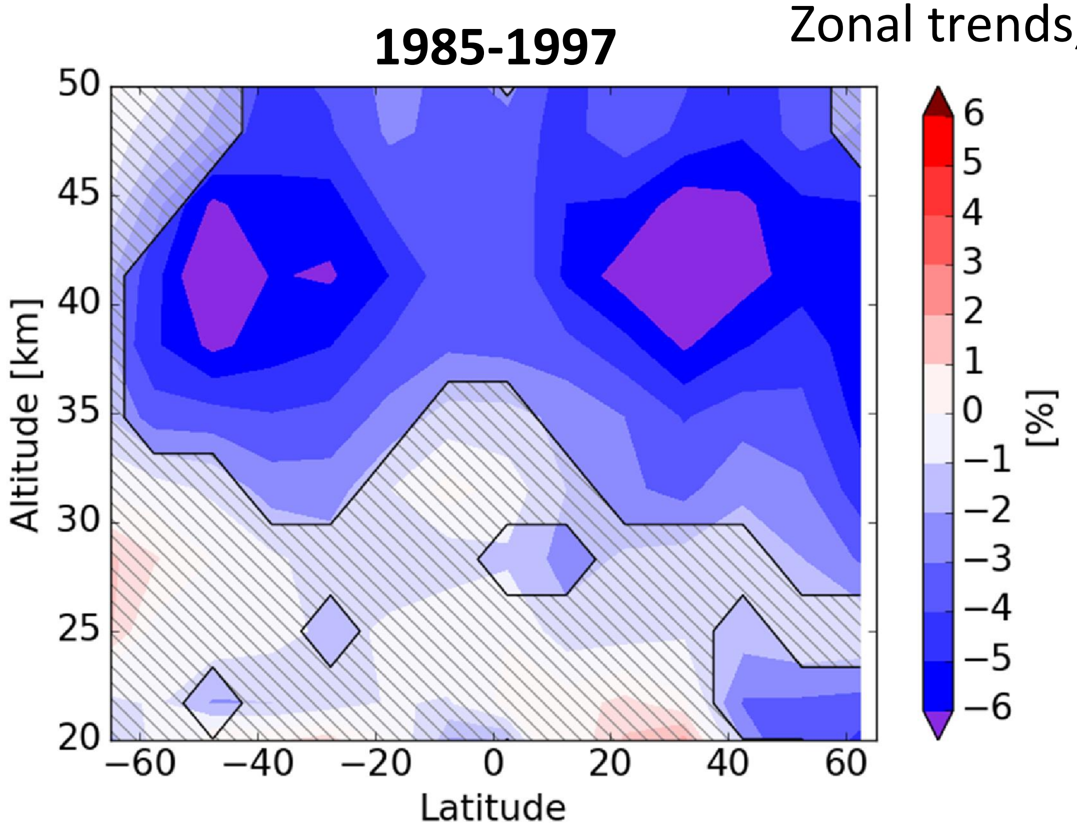


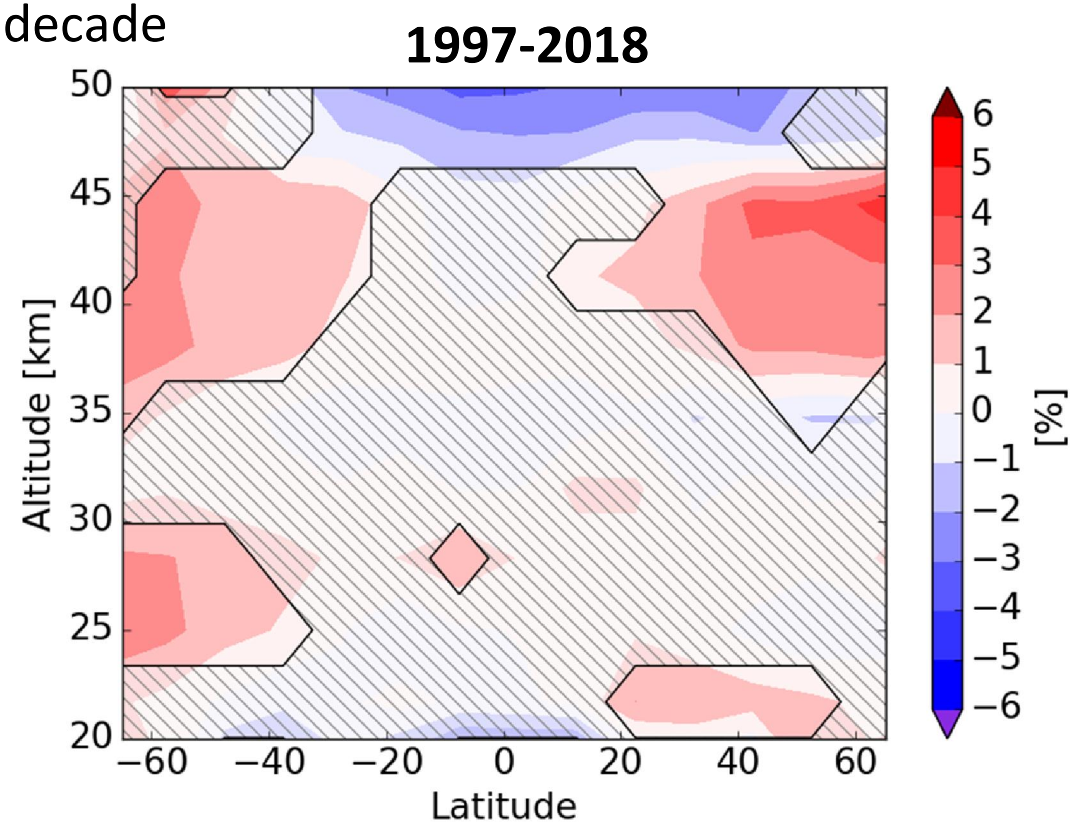
Study long-term ozone changes in the $O_3(t)$ over the last 33 years

Ozone long-term changes 1985-2018

- The same MLR model has been applied, considering 2 periods;
- Negative trends **before 1997**, when ODS reached the peak of concentration;
- Positive trends in the upper stratosphere at mid-latitudes **after 1997**;
- General agreement with previous studies.

Zonal trends, % per decade





Conclusions and outlook

Ozone retrieval from OMPS-LP observations :

- The comparison and validation against MLS and ozonesonde observations showed a general good agreement between 20 and 50 km, with discrepancies within 7 % at most latitudes.
- Possible drift of IUP-OMPS w.r.t MLS time series, to be studied in more details.
- Merging of SCIAMACHY and OMPS-LP limb profiles using MLS as a transfer function, to get a longitudinally resolved long-term ozone data set. The merging with SAGE II extends the zonal time series back to 1985.

Has the recovery been detected? How is it as a function of altitude and latitude?

- An ozone recovery was detected in the upper stratosphere at mid-latitudes and negative but non-significant trends in the lower tropical stratosphere. A run of TOMCAT CTM confirmed the changing trends in the middle tropical stratosphere.

Are there zonal asymmetries?

- Significant zonal asymmetries found especially at northern high latitudes.

Conclusions and outlook

Outlook:

- Extend the uncertainty budget of the retrieved ozone profiles to assess also the uncertainties on the merged data set.
- Investigate the robustness of the longitudinally resolved trend patterns, e.g. by validating OMPS-LP ozone profiles using ozonesondes as a function of longitude.
- Investigate the atmospheric processes behind the change of sign in the trend in the middle tropical stratosphere during the last 15 years with the help of TOMCAT.
- Study the impact on the computed trends of a possible OMPS-LP drift.
- Investigate the trends in the tropical lower stratosphere and in the polar regions, by using apposite methodologies and longer time series.