

First Results of Sentinel 5P water vapour retrieval using AMC DOAS



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Contents

- Introduction
- Methodology
- First Results and Validation
- Future plans



Greenhouse gases ...

CO_2
399.5 ppm

CH_4
1834 ppb

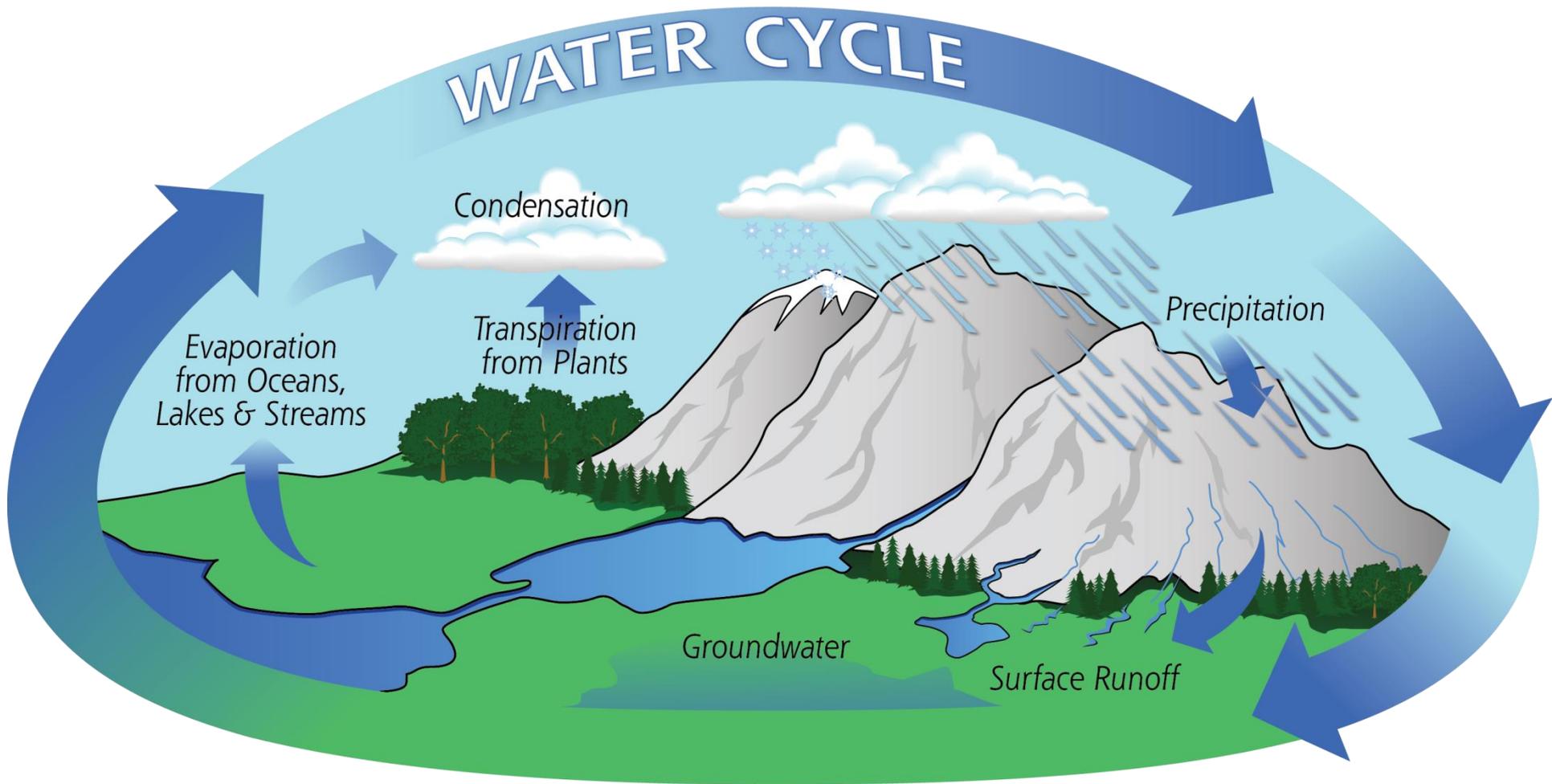
N_2O
328 ppb

H_2O
Until 40000 ppm



Values taken from: http://cdiac.ess-dive.lbl.gov/pns/current_ghg.html, 13.11.18

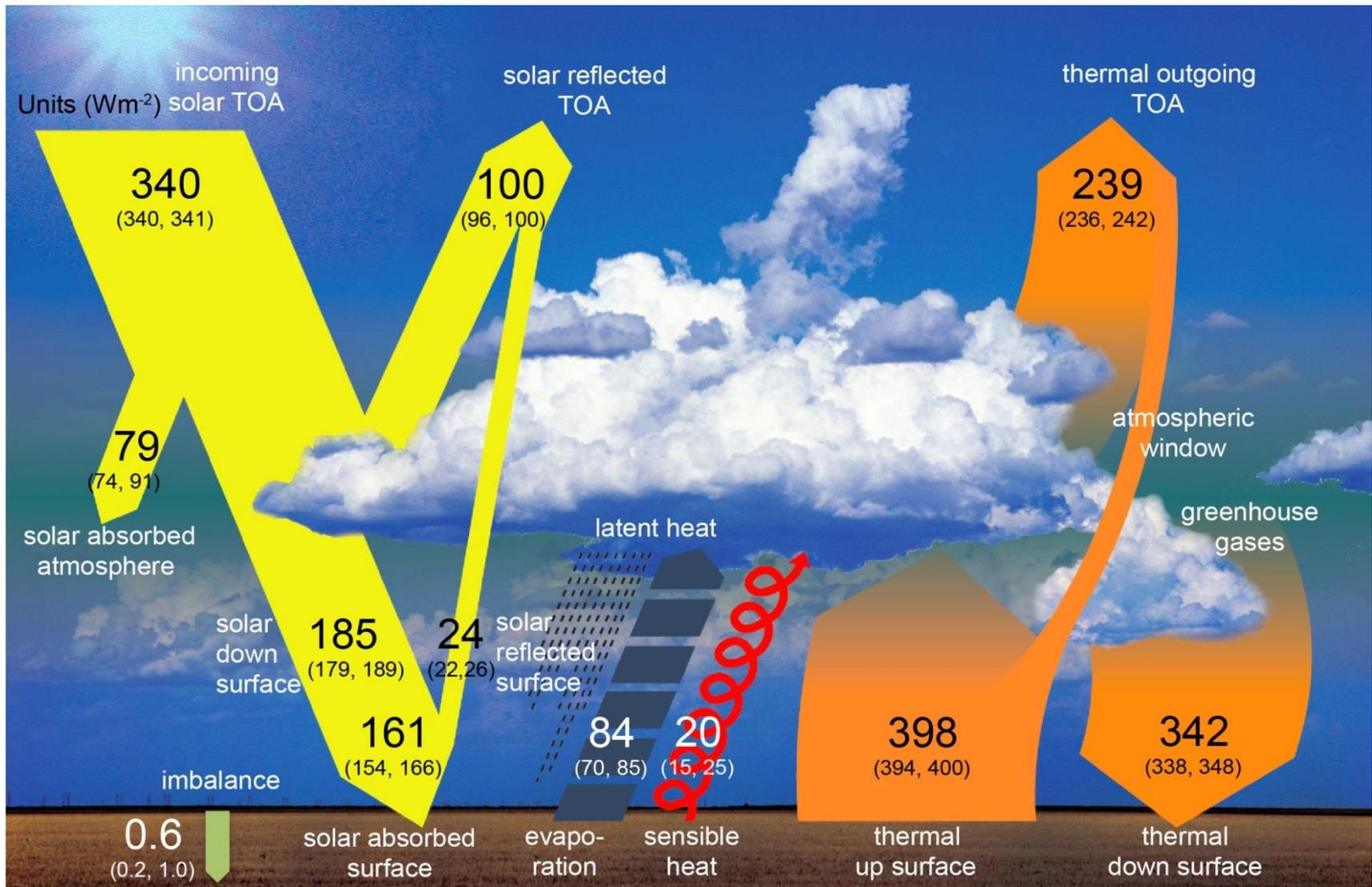
Water cycle



Courtesy: <https://pmm.nasa.gov/education/water-cycle>, 13.11.18



Radiation balance



Courtesy: Wild et al. (2013)



Water vapour

- In a warming climate:
 - Increase of absolute water vapour amount
 - Amplification of water cycle (e.g. Hall & Manabe (2002))
- Some other facts:
 - Atmosphere: 0.001 % of total water mass
 - Residence time around 9 - 10 days (Häckel, 2012)
- Additional impact on:
 - Stratospheric chemistry
 - Stratospheric cooling



How could we derive water vapour?

- Utilisation of microwave radiometry
 - absorption bands at 1.35 cm and 0.81 cm
 - Defense Satellite Meteorological Program (DSMP)
 - Special Sensor Microwave/Imager SSMI (July 1987)
 - SSMI/Sounder (SSMIS) (October 2003)
 - Measured emissivity (brightness temperature) combined with Radiative Transfer Model (statistical approach, Wentz (1997))
 - Limitation: restricted to oceans
 - Absorption at 1.6 mm
 - Advanced Microwave Sounding Unit on NOAA satellites
 - See Melsheimer & Heygster (2008)



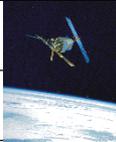
How could we derive water vapour?

- Usage of GPS signals
 - Atmosphere → time delay
 - Time delay dependent on pressure, temperature and water vapour
 - Ground receiver needed

But we want to gain water vapour amount
from visible spectra...



Overview of past satellites

	GOME		SCIAMACHY		GOME-2
Launch date	21 Apr 1995		1 Mar 2002		19 Oct 2006
Platform	ERS-2	<small>Graphics: ESA</small>	ENVISAT	<small>Graphics: ESA</small>	MetOp
Orbit	sun-synchronous 10:30 LT @ equator		sun-synchronous 10:00 LT @ equator		sun-synchronous 09:30 LT @ equator
Spatial resolution	320 km x 40 km		typically 60 km x 30 km (depending on orbital position and wavelength)		80 km x 40 km
Swath	960 km		960 km		1920 km
Spectral range	ca. 240 – 790 nm		ca. 220 – 2380 nm		ca. 240 – 790 nm
Measurement geometry	Nadir		Nadir (, Limb, Occultation)		Nadir
Mission duration	June 1995 – July 2011		August 2002 – April 2012		March 2007 – now

→ Successfully application of the so called Air Mass Corrected DOAS (Noël et al. (1999), Noël et al. (2004), Noël et al. (2008))

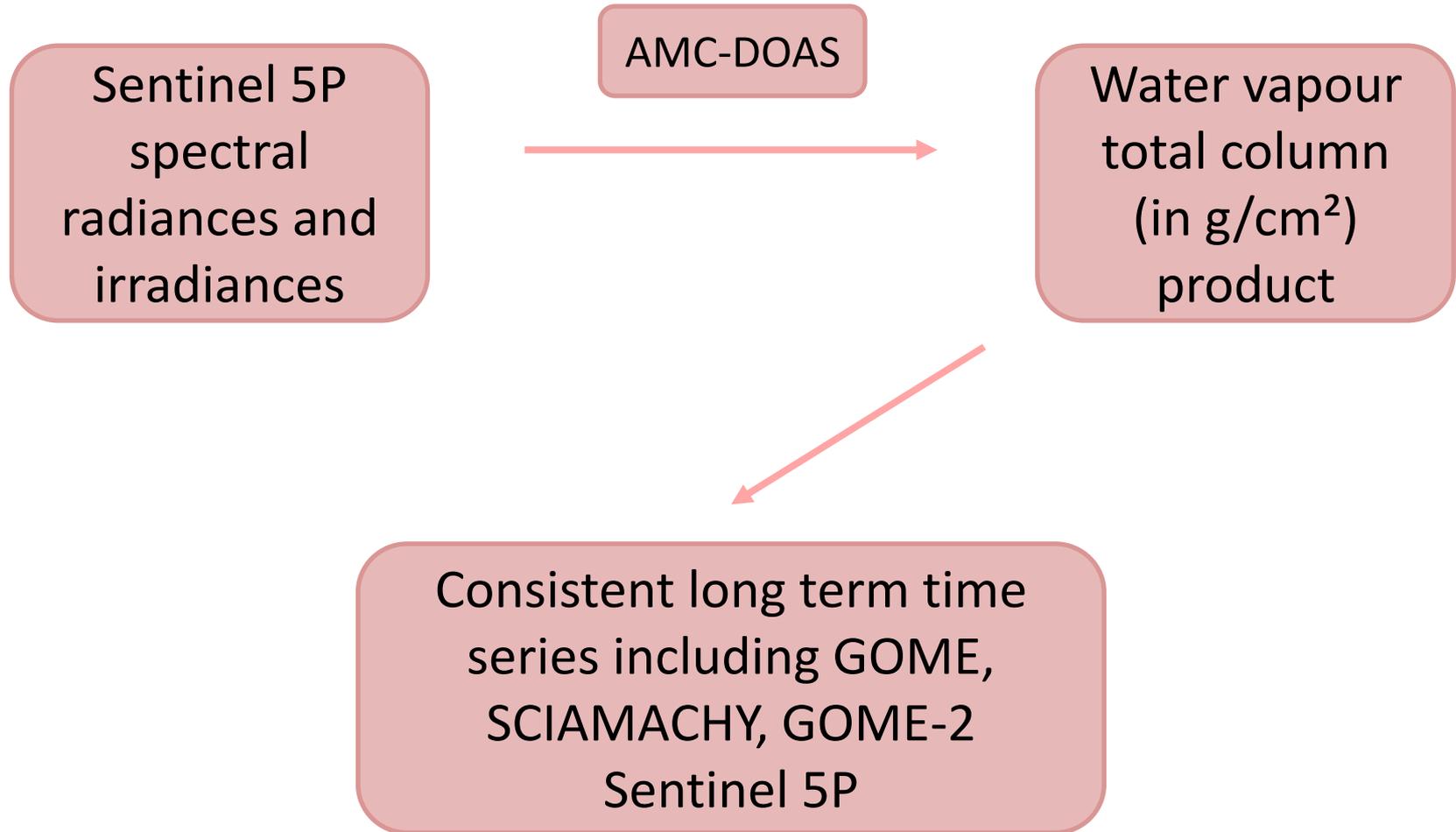


Sentinel-5P specifications

- Part of Copernicus programme
 - Sentinel (1-3) series from April 2014 onwards
 - Sentinel (4-5) planned as payload
- Sentinel 5Precursor
 - Precursor mission to Sentinel 5
 - Launch: 13th October 2017
 - Orbit height: 824 km
 - Nadir viewing with swath width: 2600 km/104°
 - Eq. crossing time: 13:30 (ascending)
 - Orbit repeat cycle 16 days
 - Resolution
 - Spatial: **7km*7km**, daily global coverage
 - Temporal: 14-15 orbits/day



PhD project



Derivation of water vapour

How to derive water vapour from S5P radiances?

- Beer Lambert Law:

$$I = I_0 \cdot e^{-\tau}$$
$$\ln\left(\frac{I}{I_0}\right) = P - \tau_A, \quad \tau_A = \sigma_A \cdot m \cdot C_v$$

Air Mass Factor

Vertical column

- But: standard DOAS approach does not hold
 - Strong spectral variations in H₂O absorption
 - Spectral resolution of sensor → saturation
 - Different approach needed (according to Halthore et al. (1997))



Derivation of water vapour

- Definition changes:

$$\tau_A = \sigma_A \cdot m \cdot C_v \quad \rightarrow \quad \tau_A = a \cdot m^b \cdot C_v^b$$

- Modified DOAS-Equation

$$\ln\left(\frac{I}{I_0}\right) = P - c \cdot C_v^b$$

- Parameters:

- c: air mass factor and absorption cross section
- b: saturation effects

- Assumption: parameters c, b independent of water vapour amount
- Parameters c, b gained via Radiative Transfer Model



Derivation of water vapour

- Additional light path correction
- Information of actual profile needed
 - Additional absorber O_2
 - Used to handle insufficient knowledge of profile:
 - Clouds
 - Albedo
 - Pressure
 - Temperature
 - Aerosols
 - ...



Derivation of b and c, and τ

- Model run scenarios with and without relevant absorbers
- Hence (for O_2):

$$\tau_{O_2} = \ln\left(\frac{I_{without\ O_2}}{I_{with\ O_2}}\right)$$

- And H_2O :

$$\tau_{H_2O} = \ln(c) + b \cdot \ln(C_v)$$

- Variation of modelled C_v : 100% and 20%



Derivation of water vapour

- AMC-DOAS algorithm:

$$\ln \left(\frac{I}{I_0} \right) = P - a(\tau_{O_2} + cC_v^b)$$

- I/I_0 measured sun normalized radiance
- Parameters from Radiative Transfer Model
 - b saturation effects
 - c contains cross section and Air Mass Factor
 - τ_{O_2} O_2 optical depth



Derivation of water vapour

- AMC-DOAS algorithm:

$$\ln \left(\frac{I}{I_0} \right) = P - a(\tau_{O_2} + cC_v^b)$$

- Fit Parameters:

- P polynomial
- a Air Mass Correction Factor
- C_v water vapour vertical column

- Fitting window: 688 nm to 700 nm
- (Currently) application to Level1-data



Characteristics of the AMC-DOAS products

- Limitations:
 - Measurements on dayside
 - Exclusion of too cloudy scenes
- Advantages:
 - Retrievals possible over land and ocean
 - No external calibration source
 - Usage of precalculated RTM database
 - Fast retrieval

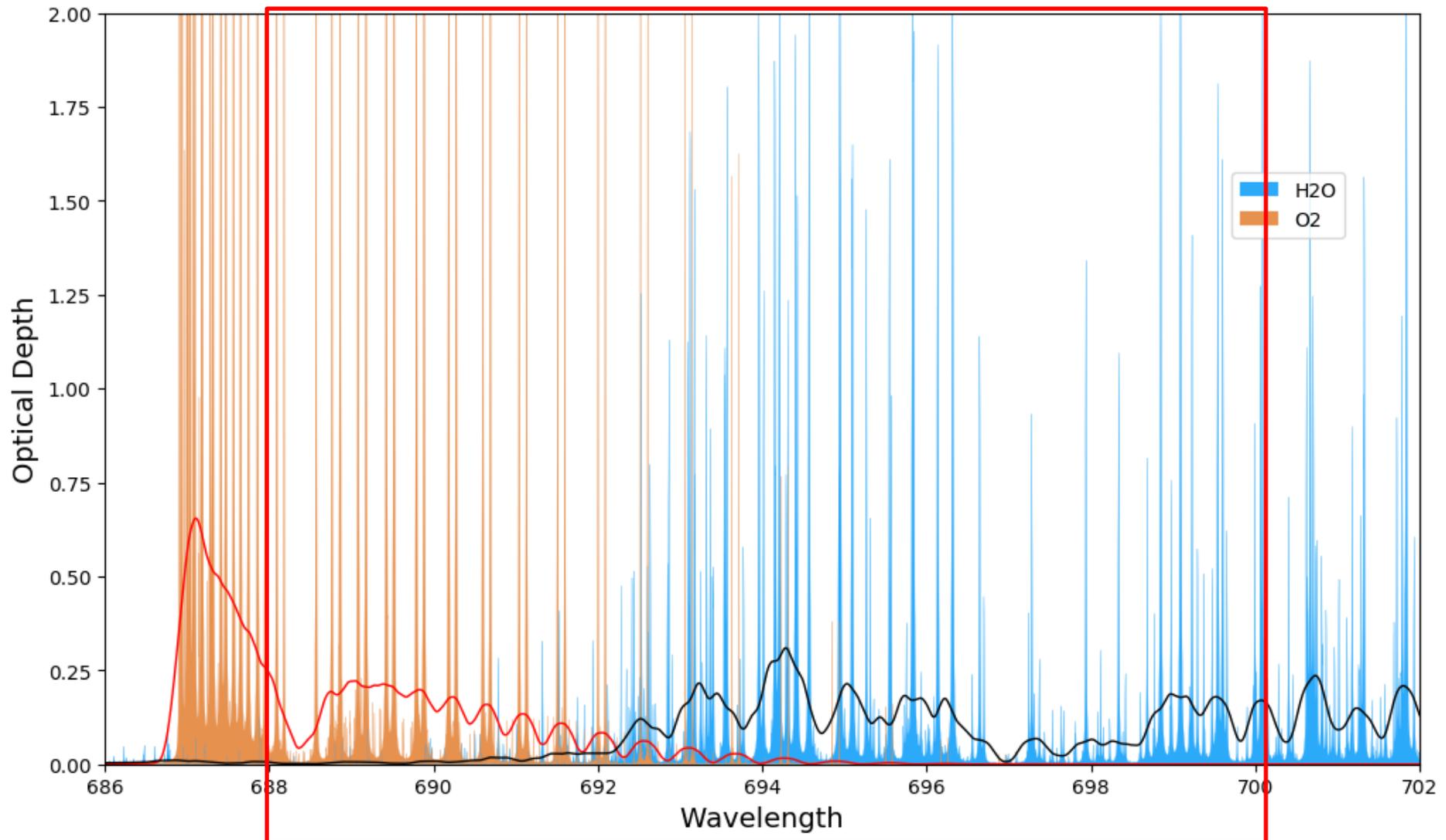


Model setups and assumptions

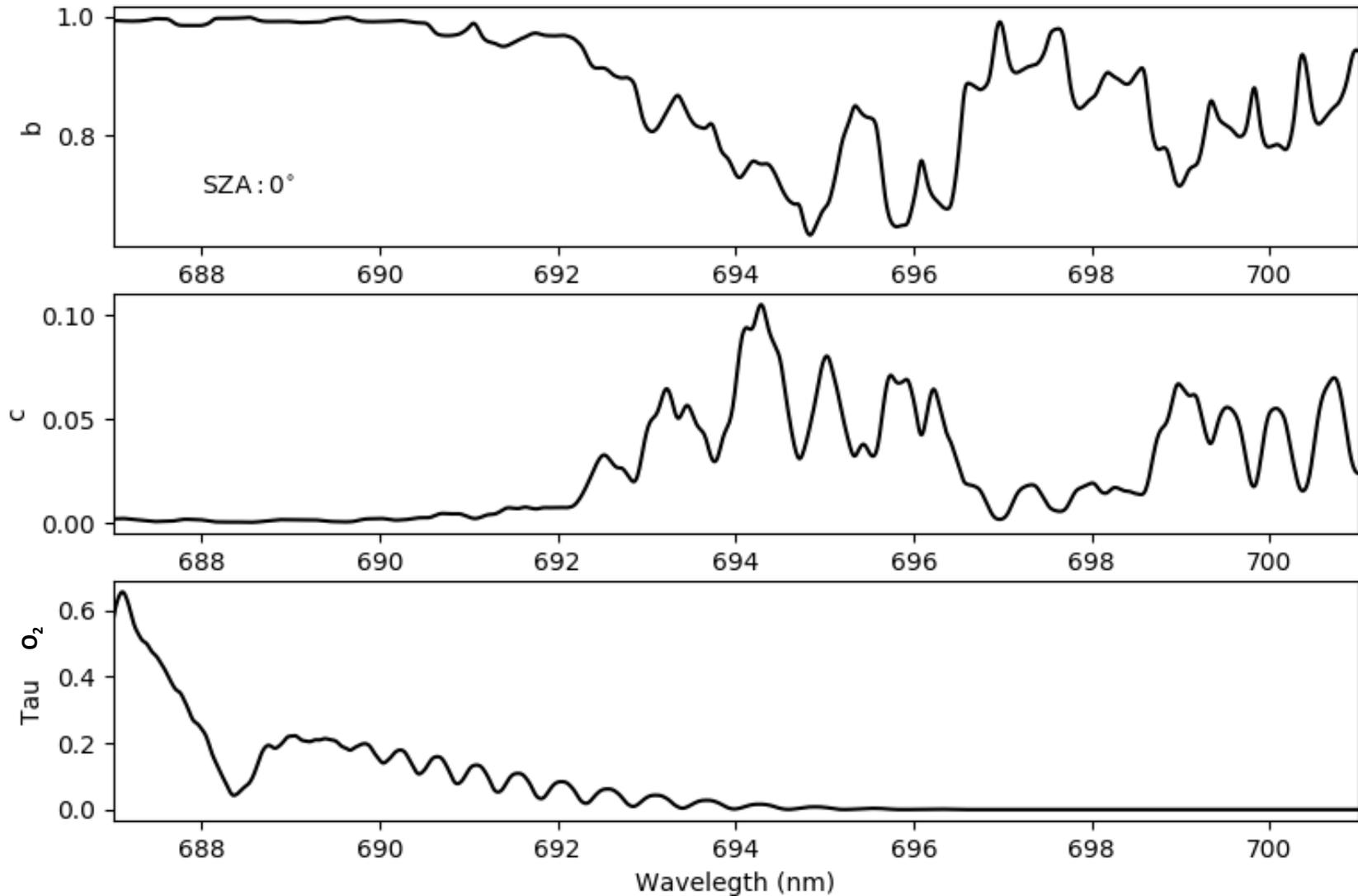
- Radiative Transfer Model (RTM): SCIATRAN 3.8.13
- RTM setups:
 - Tropical atmosphere (4.18 g cm^{-2})
 - No clouds
 - Surface elevation 0 km
 - Constant surface albedo 0.05
 - Solar zenith angles: 0° , 20° , 40° , 50° , 60° , 70° , 80° , 85° , 88°
 - Absorbers: O_3 , H_2O , O_2
- Intensity/Irradiance



Absorption spectra example

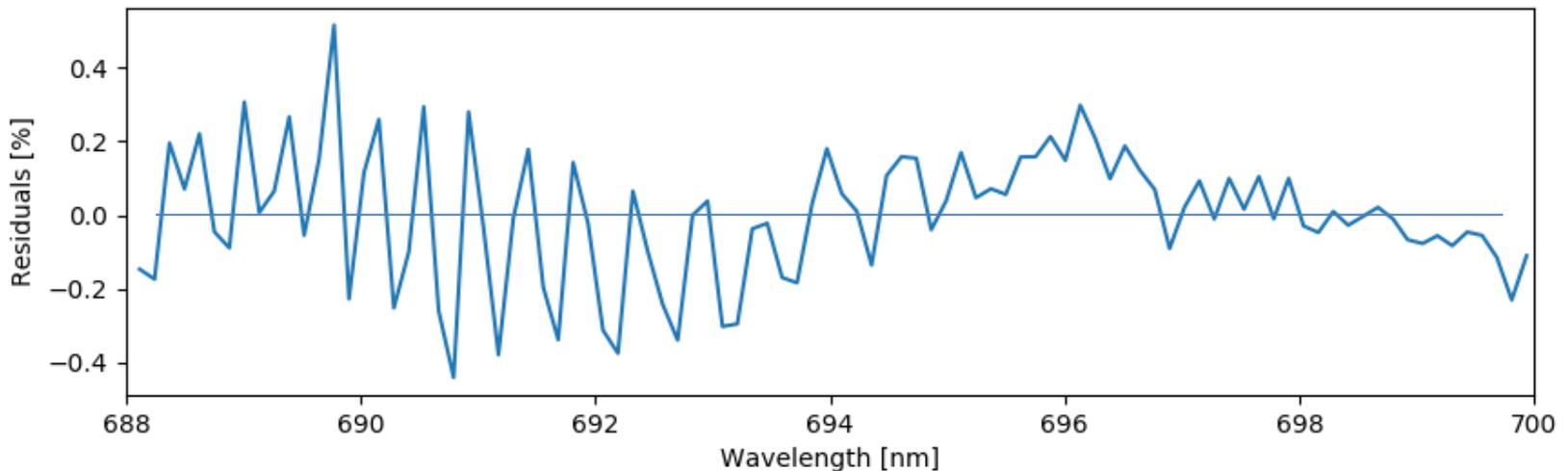
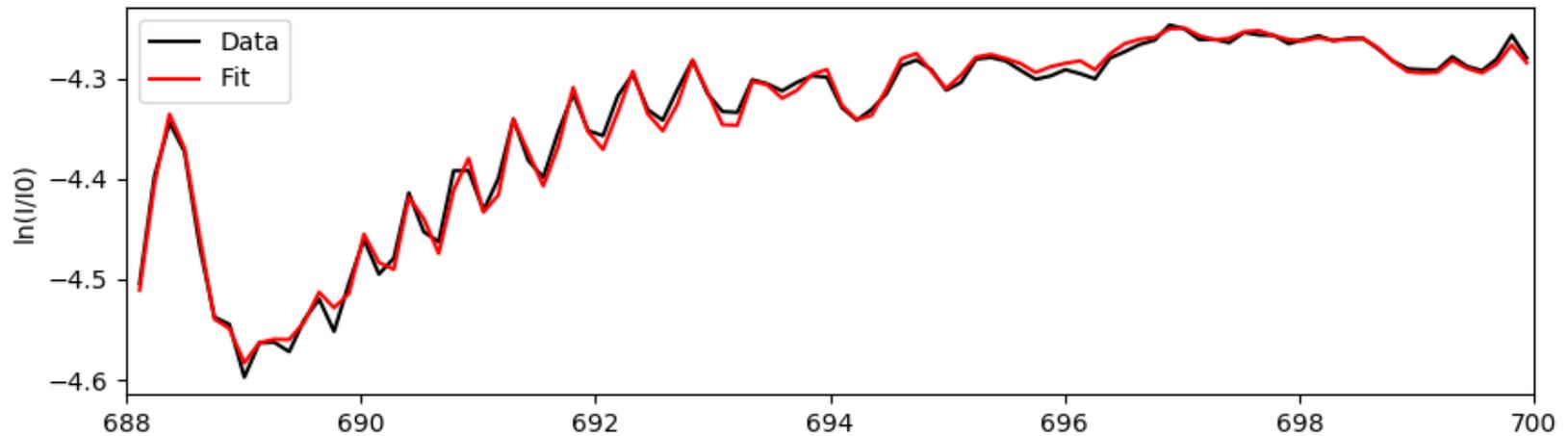


Examples for retrieval input parameters



Fit example to measurements

Fit results on 11.05.2018 10:49



Latitude: -67.42°

SZA: 85.81°

Water vapour amount: 0.302 +/- 0.033 g m⁻²

Longitude: 28.81°

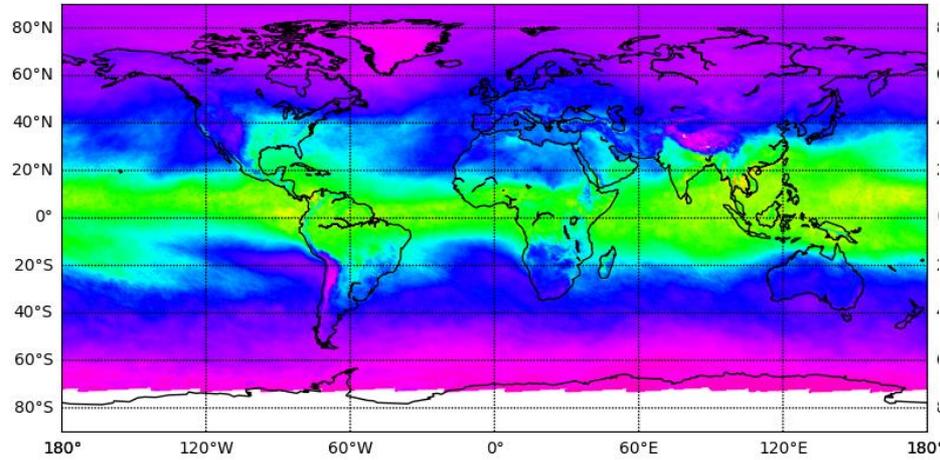
Orbit: 2980

Residual (Sum): 0.557

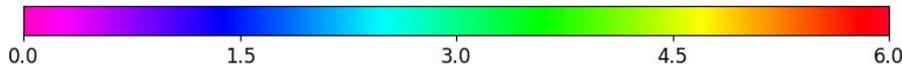


Example for retrieved water vapour

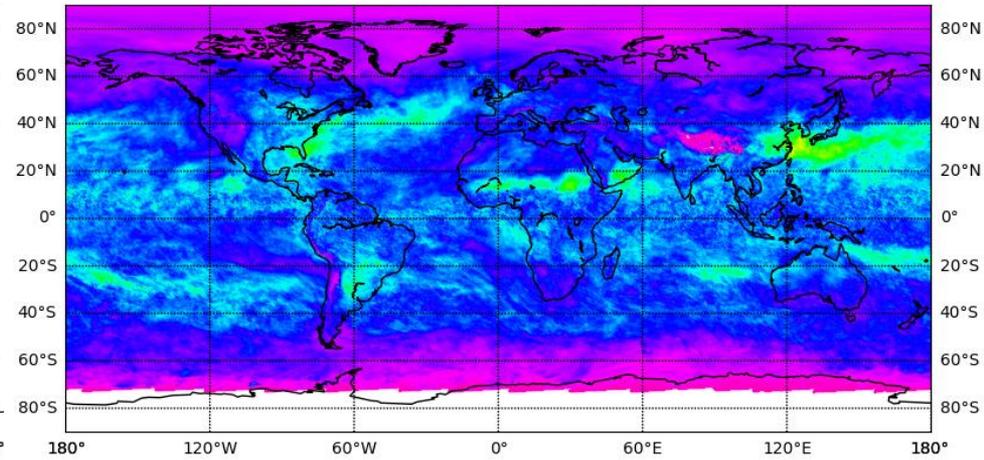
Monthly mean Total Water Vapour Column from S5P for May 2018



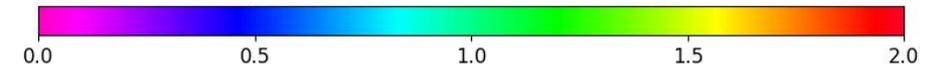
H₂O Total Vertical Column in g cm⁻²



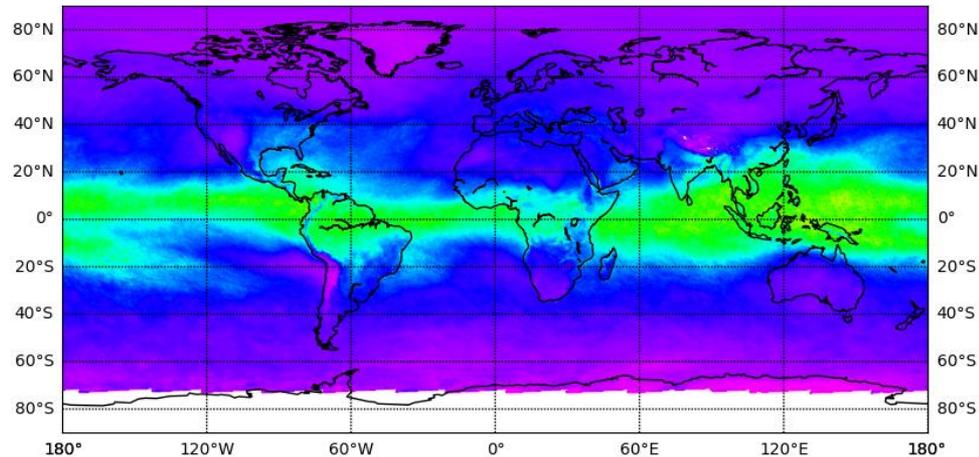
Standard Deviation of Total mean Water Vapour Column from S5P for May 2018



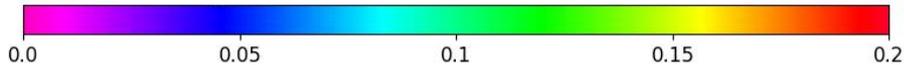
H₂O Standard Deviation of Total Vertical Column in g cm⁻²



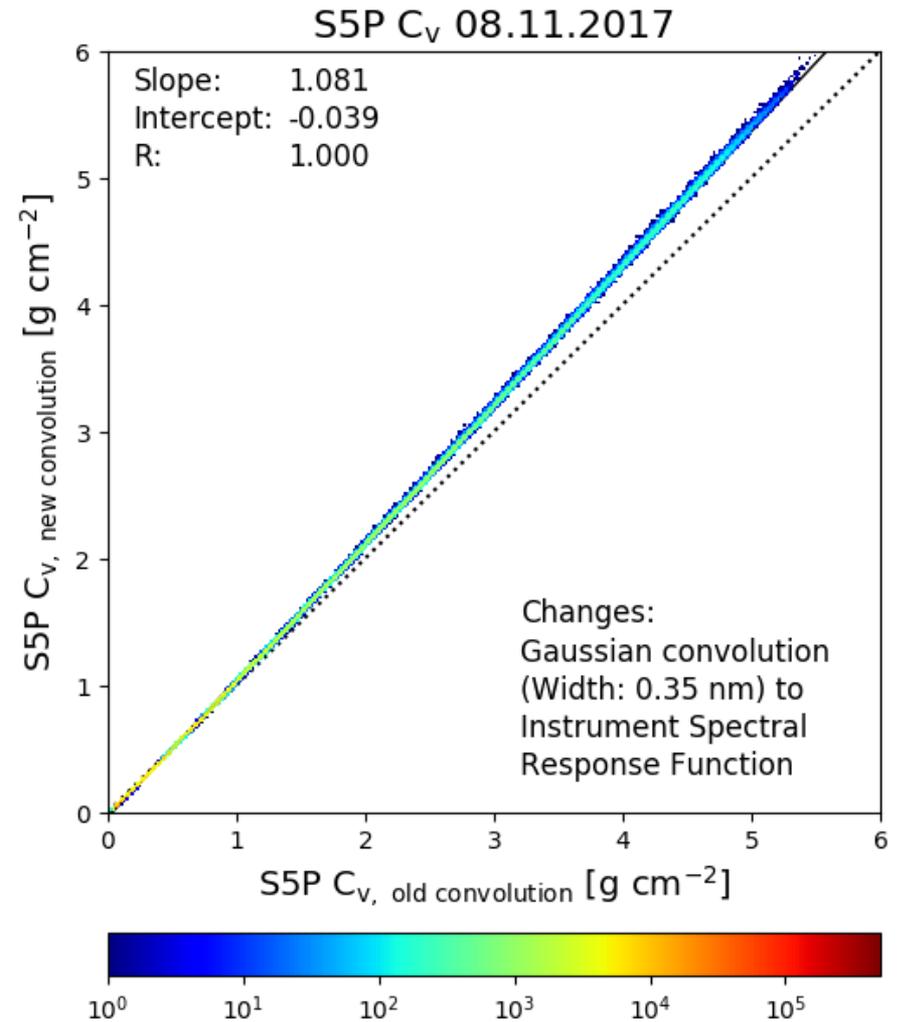
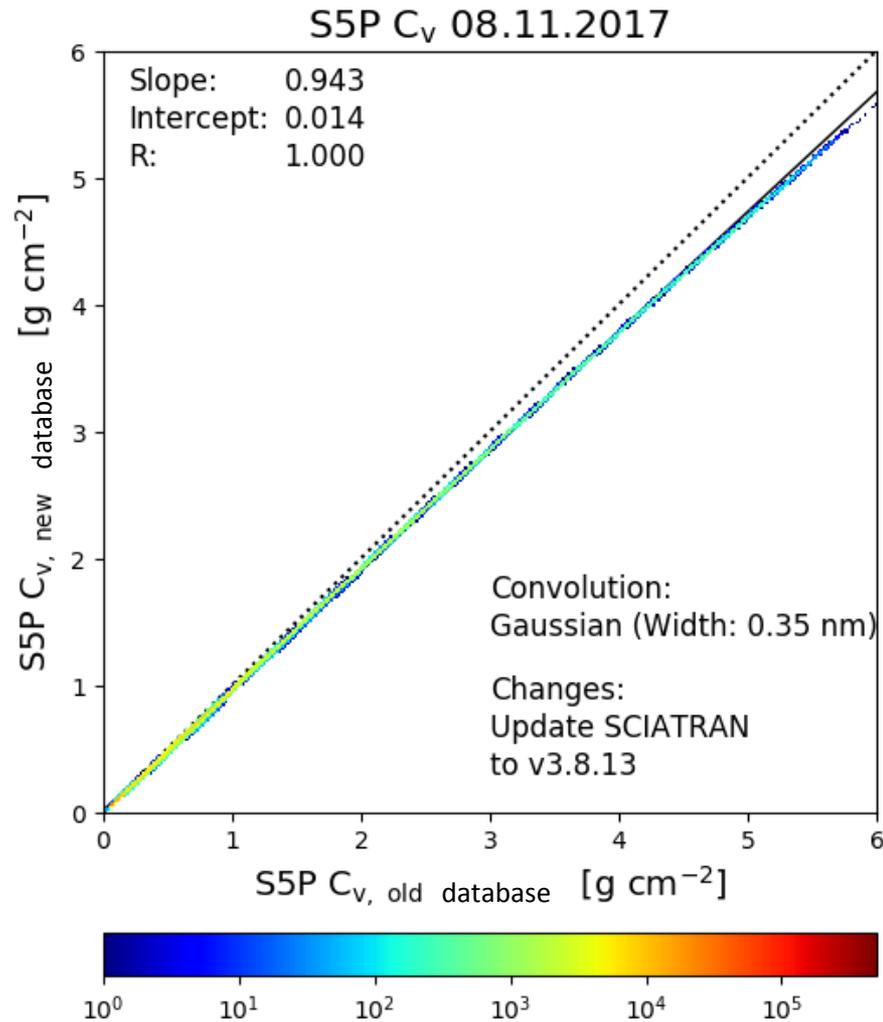
Monthly mean of Product Error of Total Water Vapour Column from S5P for May 2018



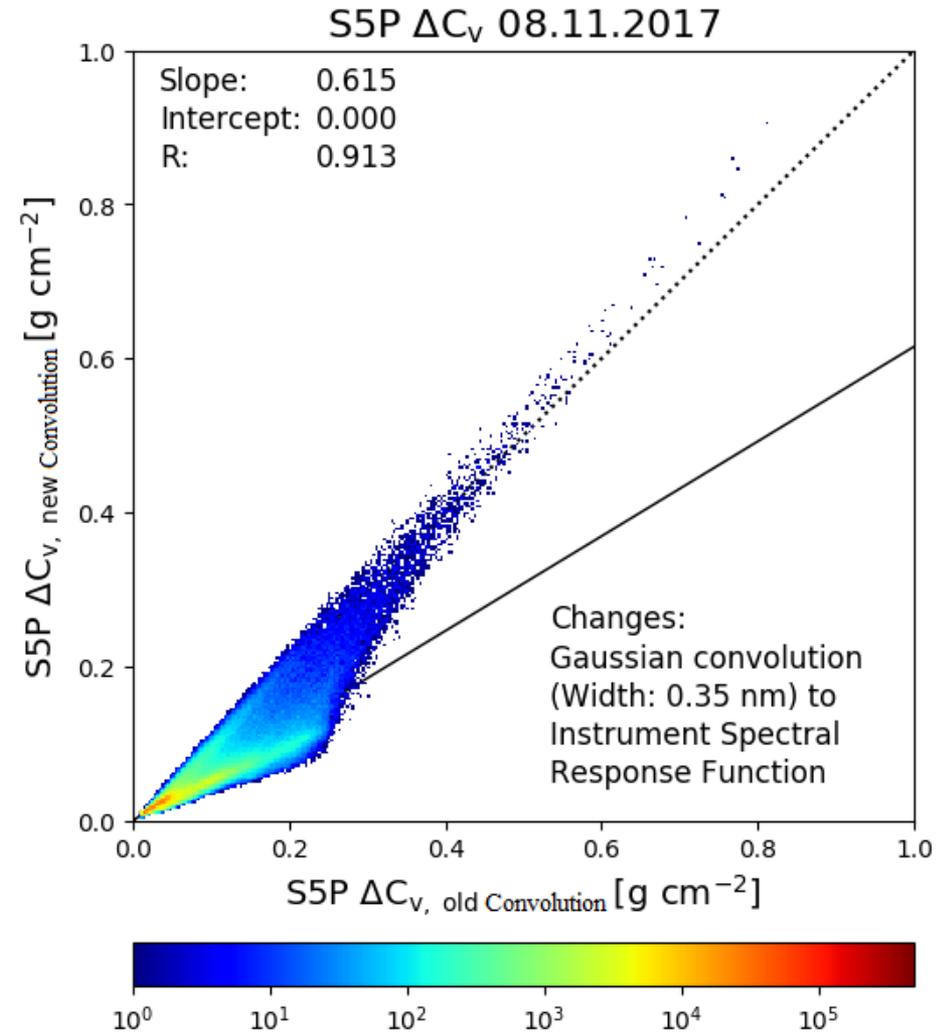
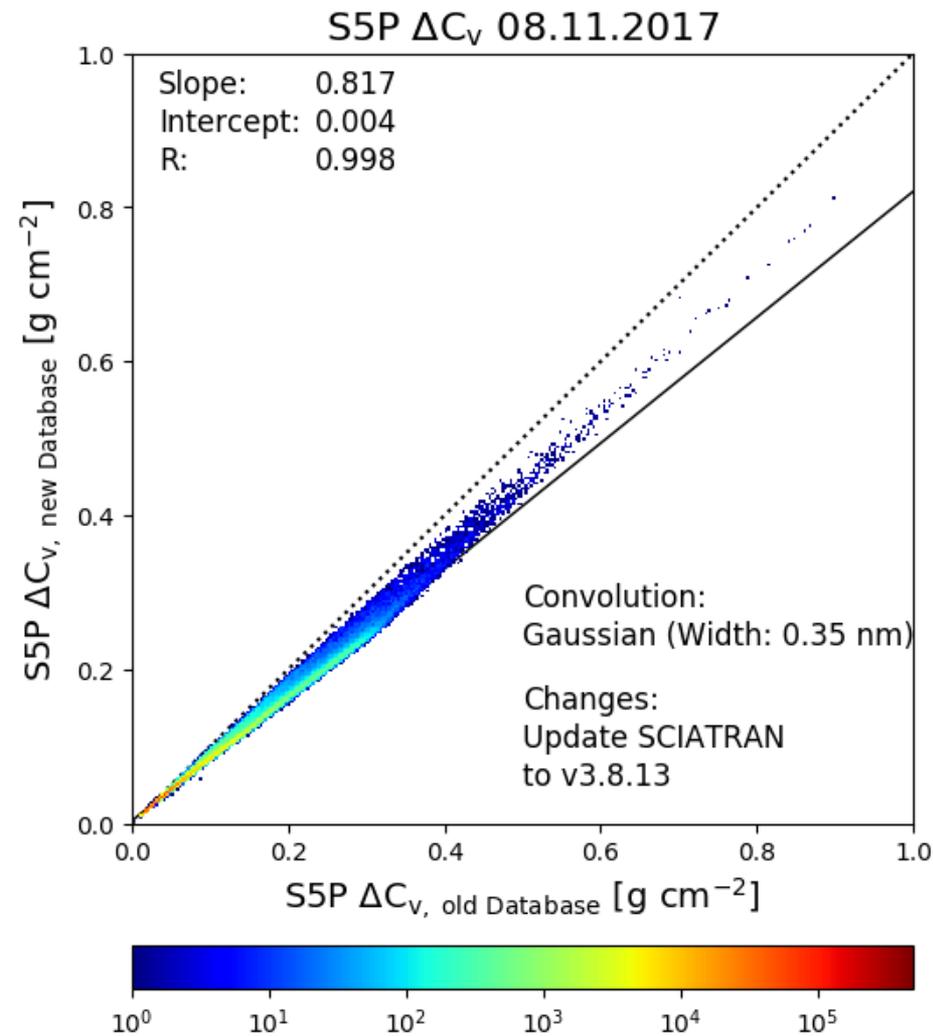
H₂O Product Error of Total Vertical Column in g cm⁻²



Sensitivity of water vapour to change in retrieval

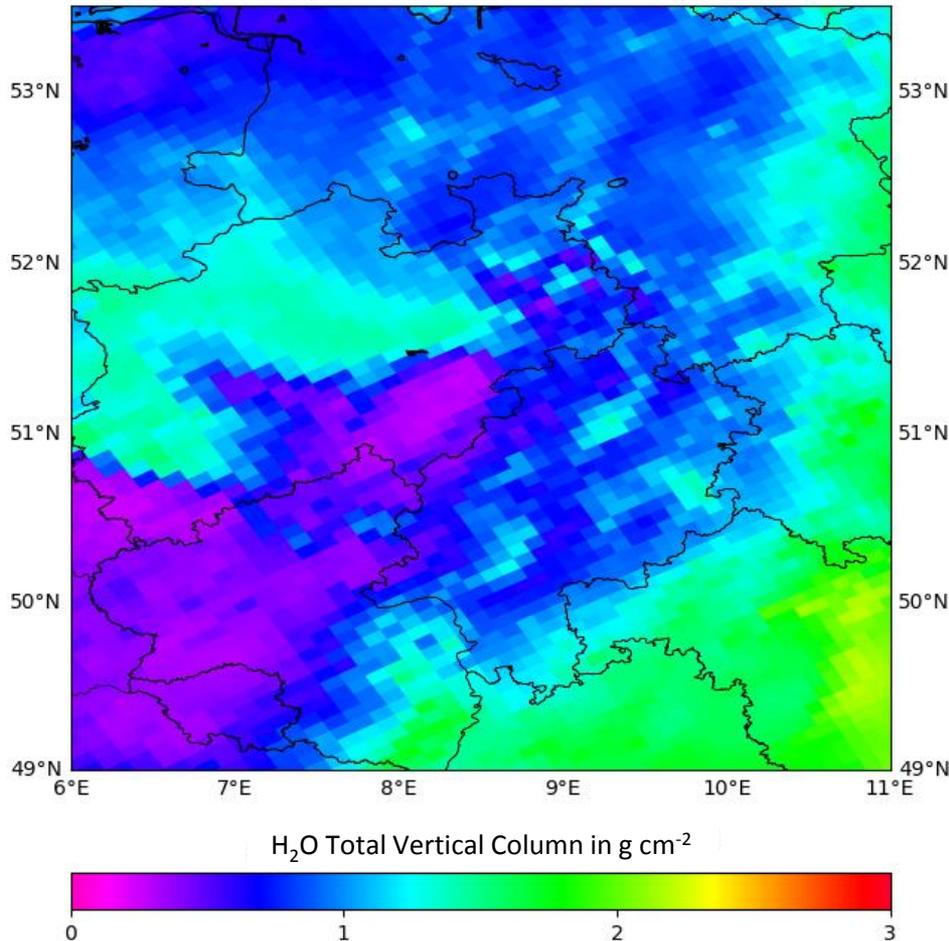


Sensitivity of water vapour to change in retrieval



(Another) Example for retrieved water vapour

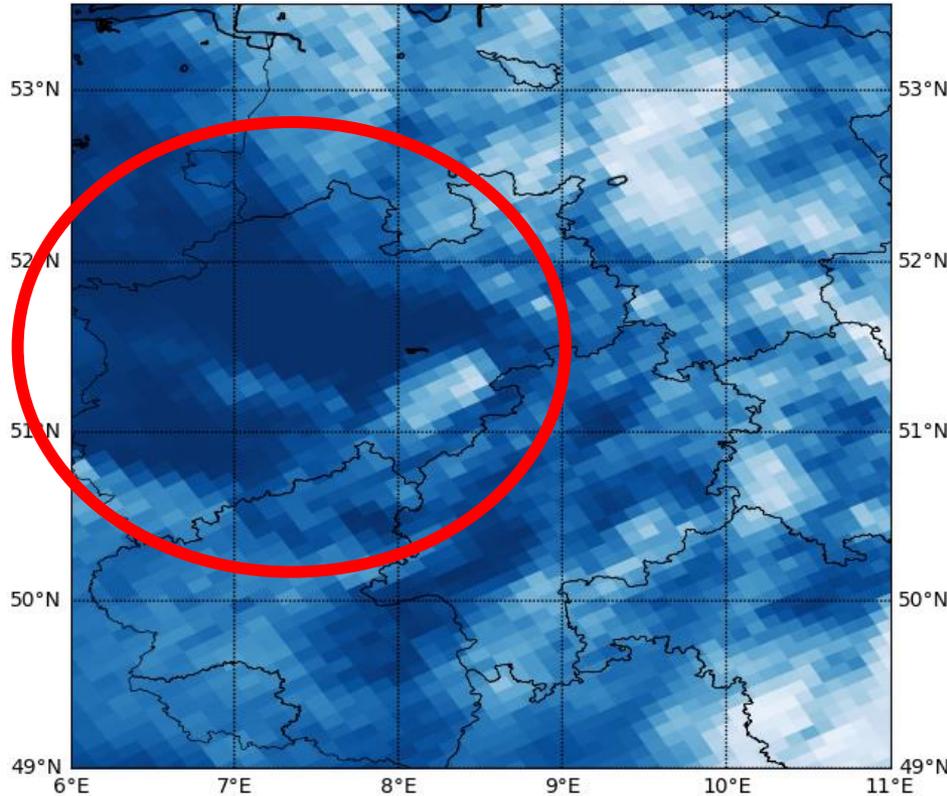
S5P Water Vapour Columns at 11.05.2018 (Orbit 2980)



- Remarkable gradients over Northern Rhine Westfalia
- Reasons:
 - Very dry air ontop moist low level air
 - Clouds (dark blue) and
 - Cloudfree (green) regionsClouds „hides“ moistened low level air layers

(Another) Example for retrieved water vapour

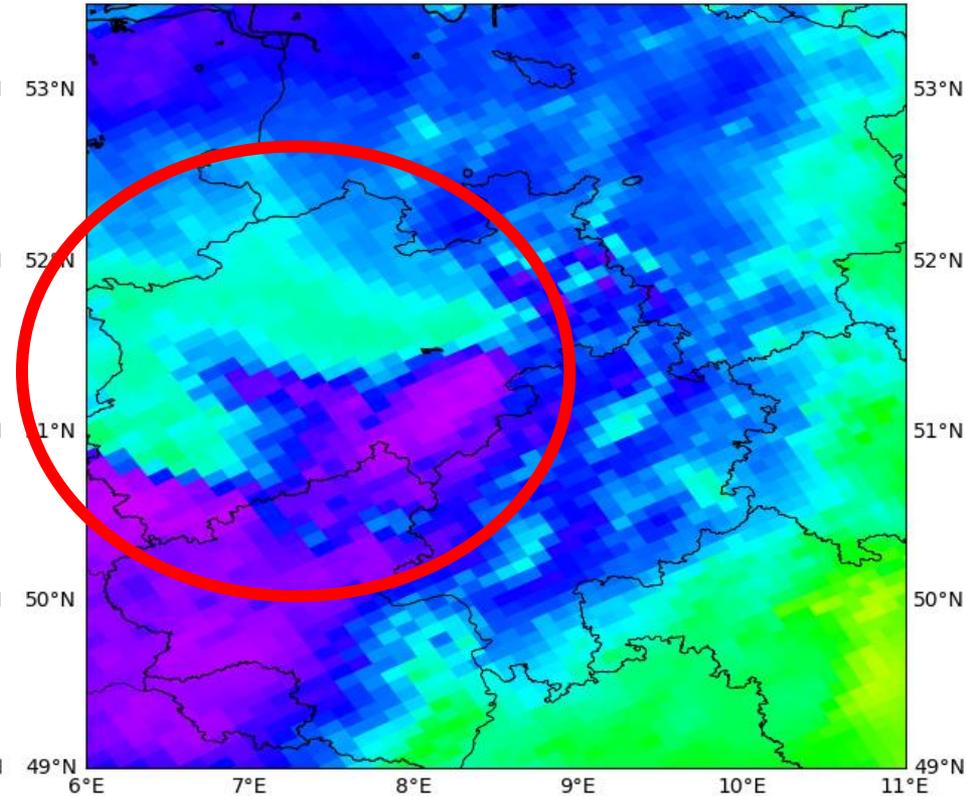
S5P Cloud fraction at 11.05.2018 (Orbit 2980)



Cloud fraction



S5P Water Vapour Columns at 11.05.2018 (Orbit 2980)



H₂O Total Vertical Column in g cm⁻²



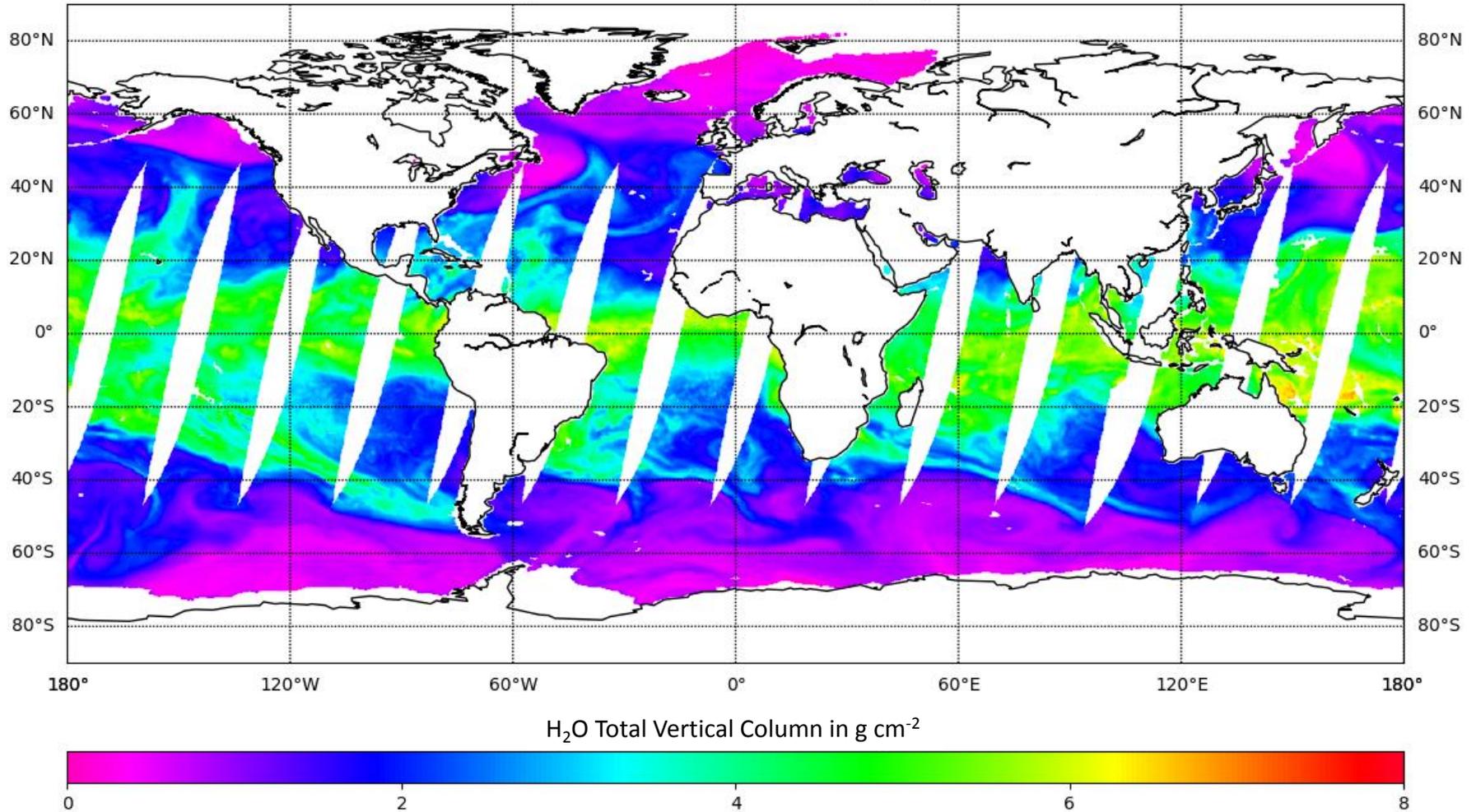
Validation - Combining the various products

Product	SSMIS	GOME – 2 (MetOp B)	ECMWF ERA- interim	SENTINEL 5P
Full name	Special Sensor Microwave - Imager/Sounder	Global Ozone Monitoring Experiment	European Centre for Medium-Range Weather Forecasts	Sentinel 5Precursor
Gridded to Spatial Resolution	0.25 degree	0.5 degree	0.75 degree	0.25 degree 0.5 degree 0.75 degree
Temporal (global)	1d	1d	6h	1d
Crossing time	18:36 ascending	09:30 descending	Closest match	13:30 ascending
Water vapour retrieval	Emission in microwave spectrum ($\lambda \sim 1\text{cm}$)	Absorption in visible spectrum ($\lambda \sim 700\text{ nm}$) AMC-DOAS	Model	Absorption in visible spectrum ($\lambda \sim 700\text{ nm}$) AMC-DOAS



SSMIS descending mode

Water Vapour Column SSMIS - DMSP F17(desc) 20180401



Morning overpass



Descending

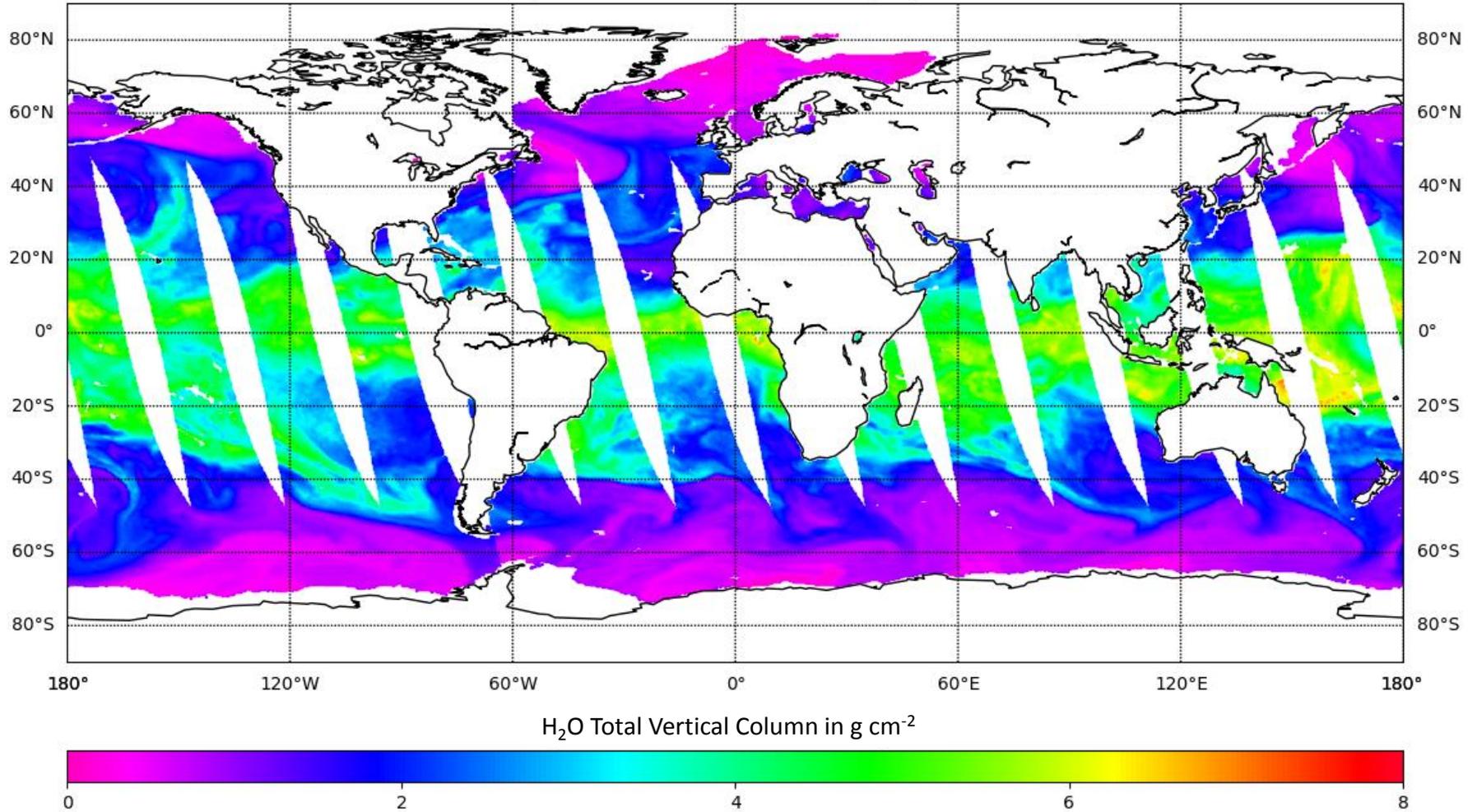


Crossing time at equator: 06:36 local time



SSMIS ascending mode

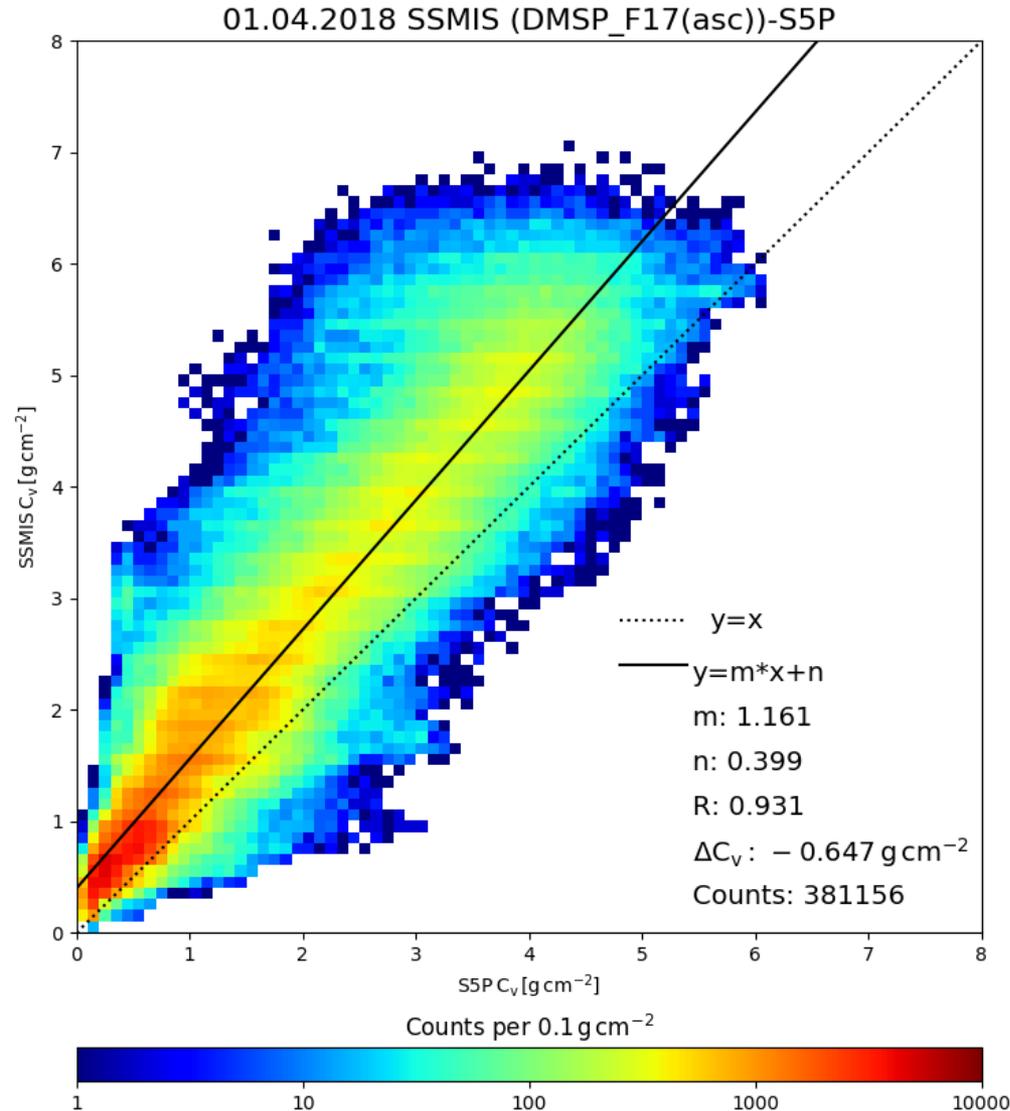
Water Vapour Column SSMIS - DMSP F17(asc) 20180401



Evening overpass • Ascending • Crossing time at equator: 18:36 local time



Validation with SSMIS

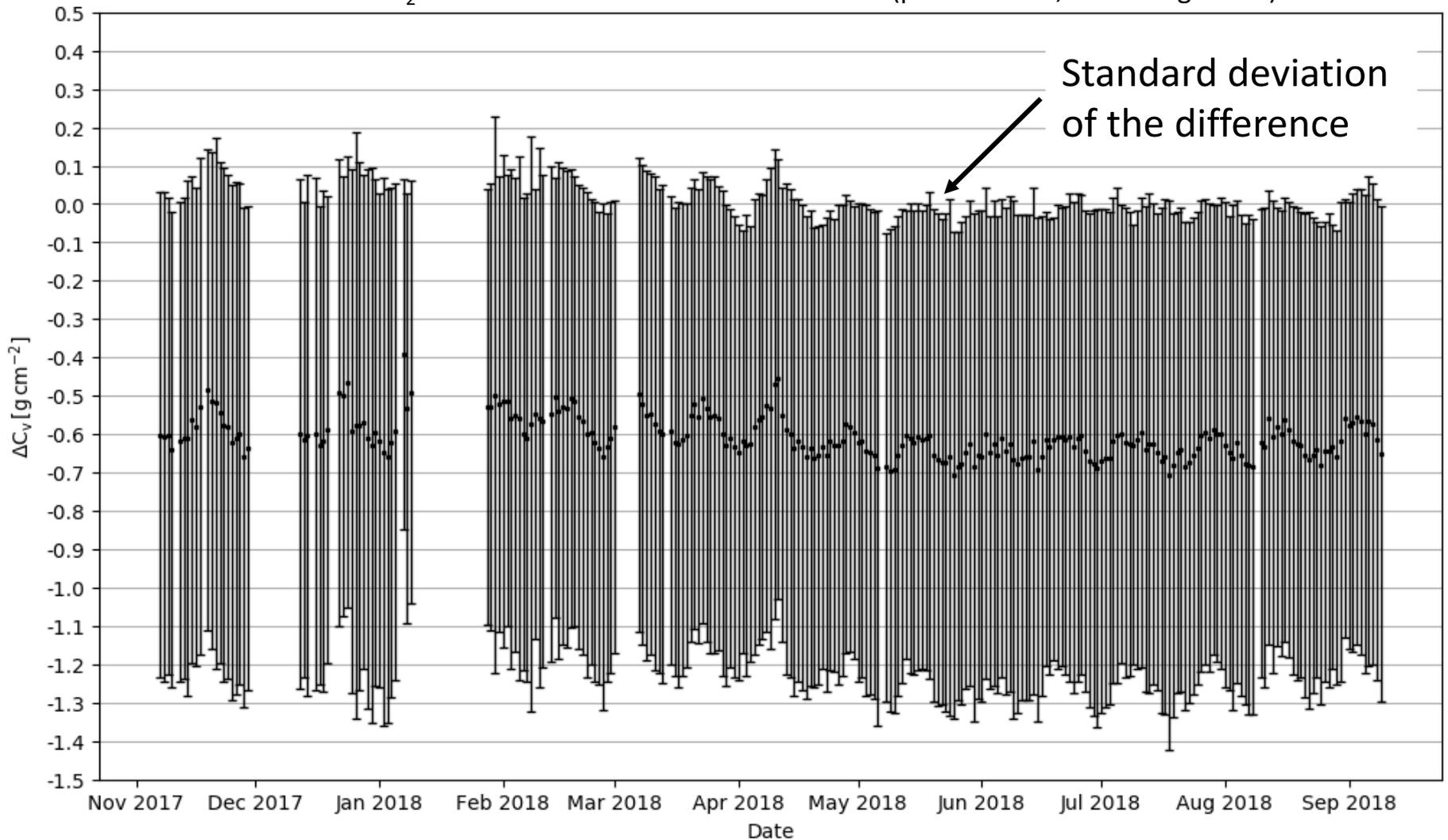


- Histogram of C_v :
0.1 g cm^{-2} bins with
logarithmic colour scale
- Regression line (black):
 - Good agreement ($R = 0.93$)
 - SSMIS $\text{H}_2\text{O} >$ S5P H_2O
 - Offset larger for higher H_2O
- $\Delta C_v = \text{mean}(C_{v,S5P} - C_{v,SSMIS})$



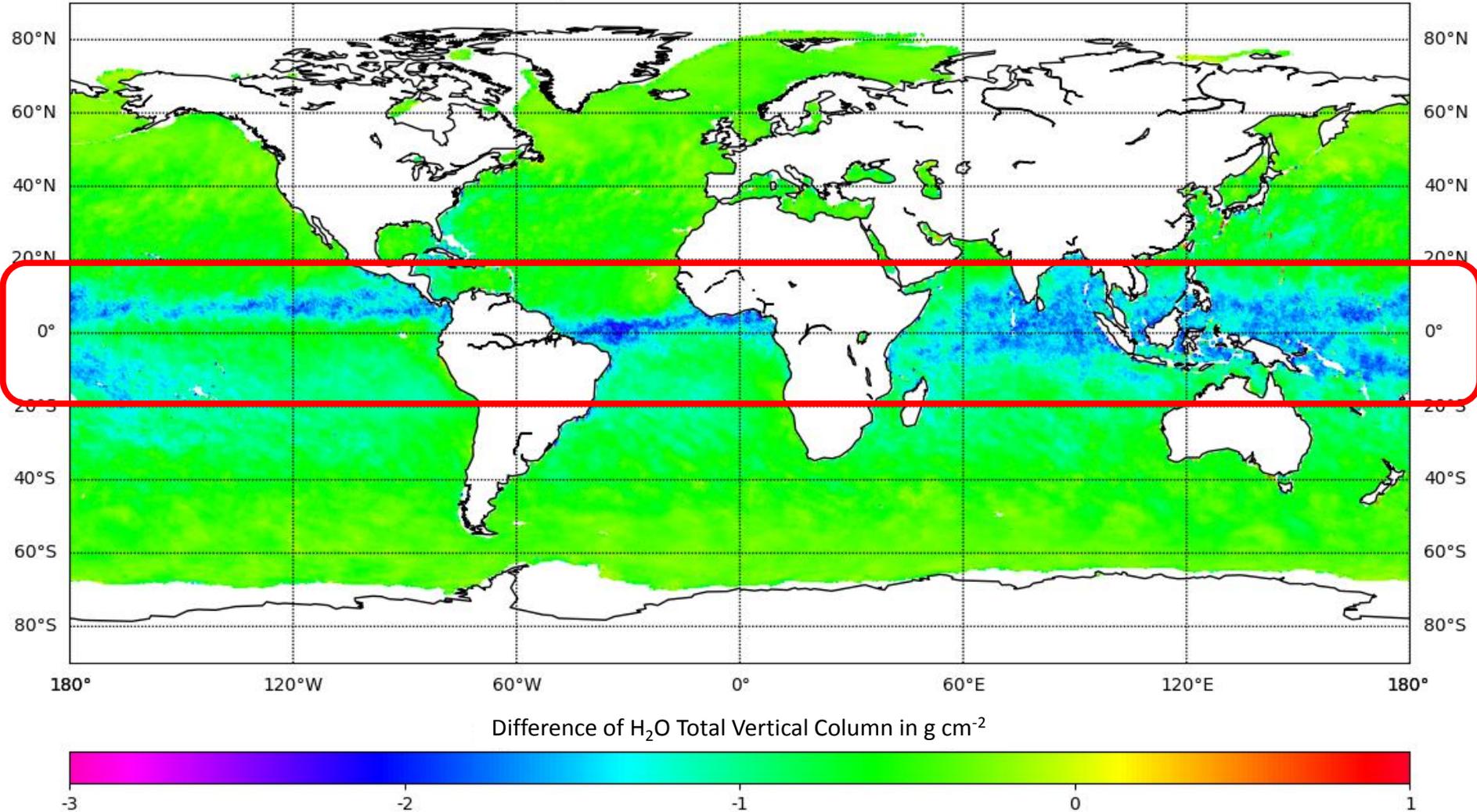
Validation with SSMIS

Time series of the H₂O – difference between S5P and SSMIS (platform F17, ascending mode)



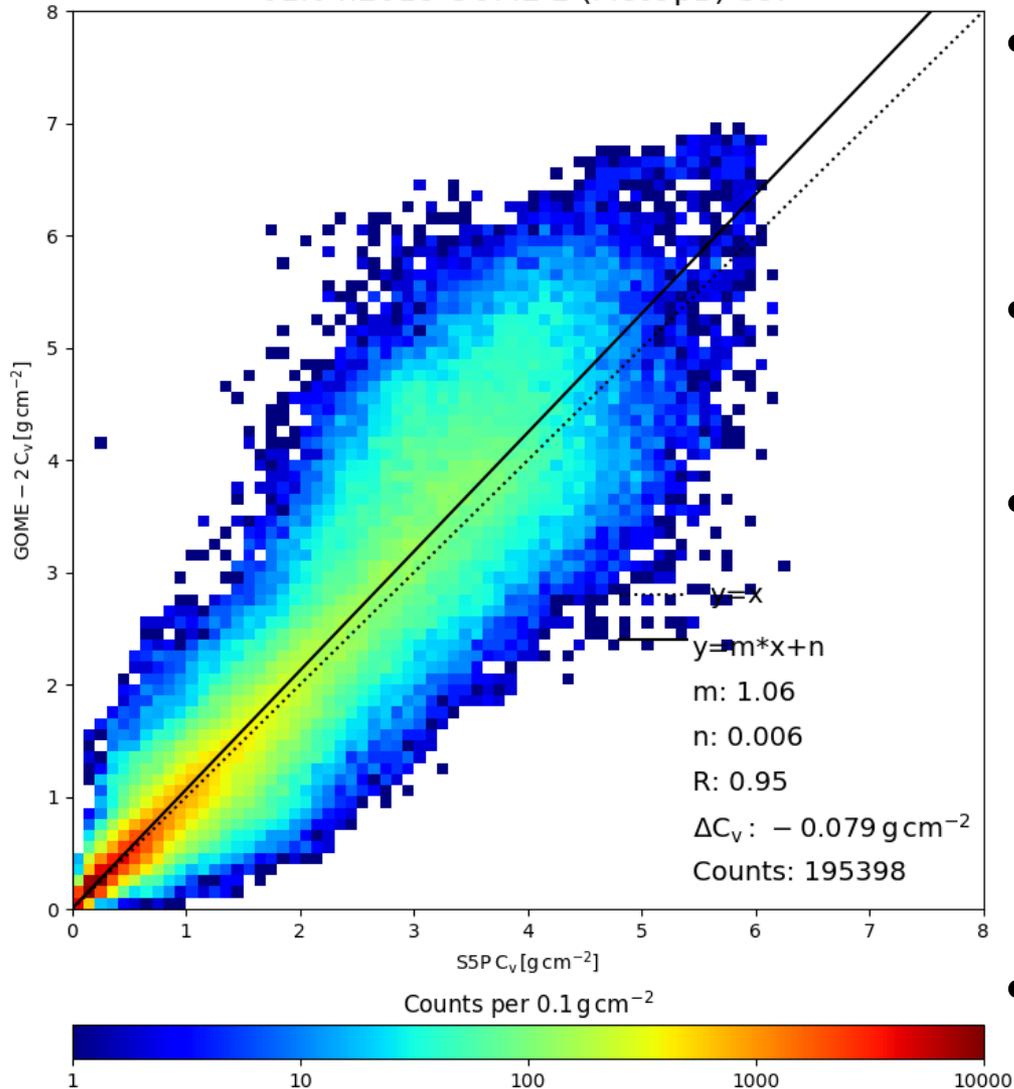
Monthly Mean Difference (S5P - SMISS)

Monthly mean of Total Water Vapour difference between S5P and SSMIS (platform F17)



Validation with GOME-2 (MetOpB)

01.04.2018 GOME-2 (MetOpB)-S5P

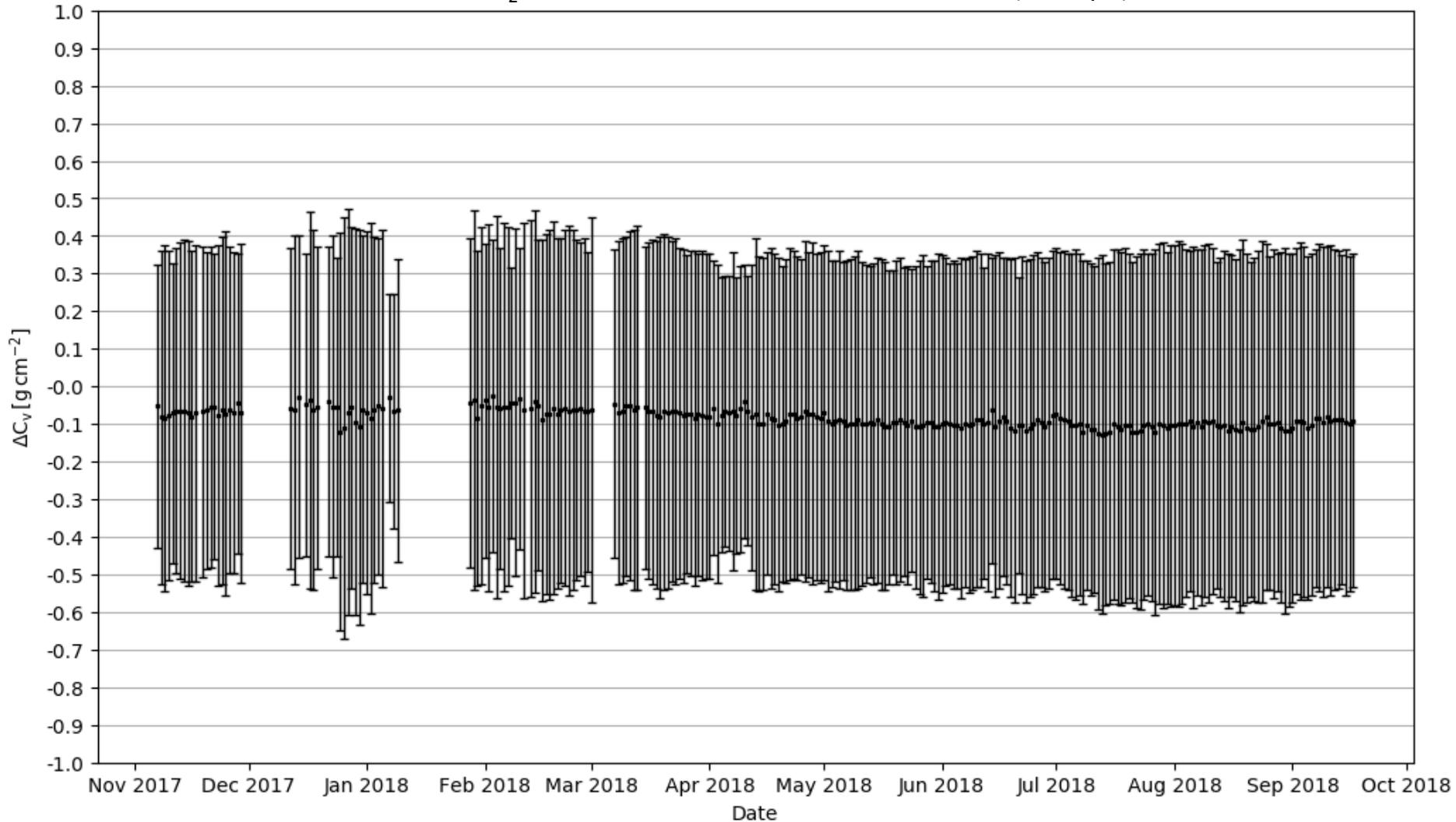


- Histogram of H_2O : 0.1 g cm^{-2} bins with logarithmic colour scale
- Similar product: AMC-DOAS
- Regression line (black):
 - Good agreement ($R = 0.95$)
 - GOME-2 H_2O slightly larger than S5P H_2O
 - Smaller offsets compared to SSMIS H_2O
- $\Delta C_V = C_{V,S5P} - C_{V,GOME-2}$



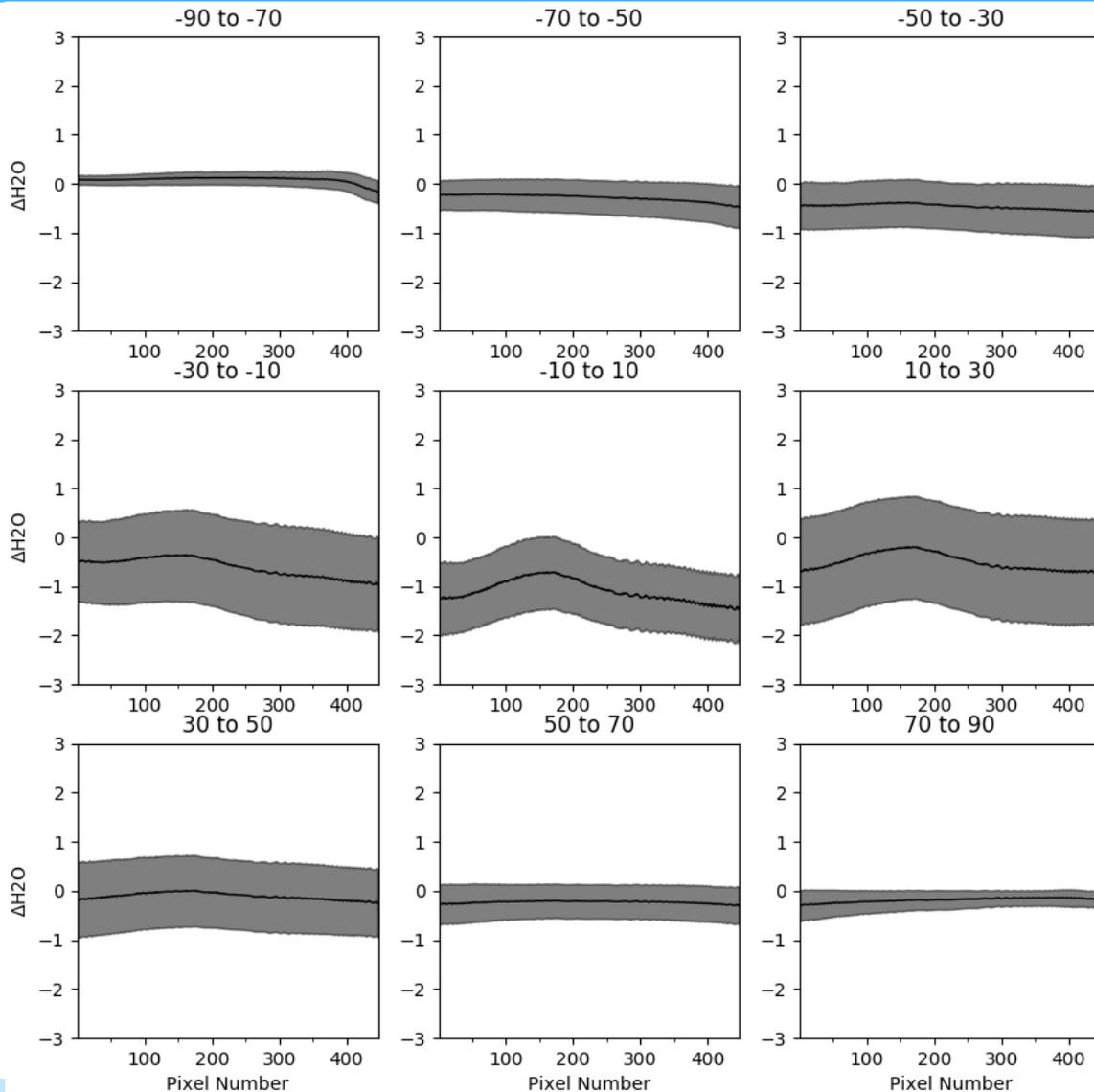
Validation with GOME-2 (MetOpB)

Time series of the H₂O – difference between S5P and GOME-2 (MetOpB)



Validation with ECMWF ERA interim

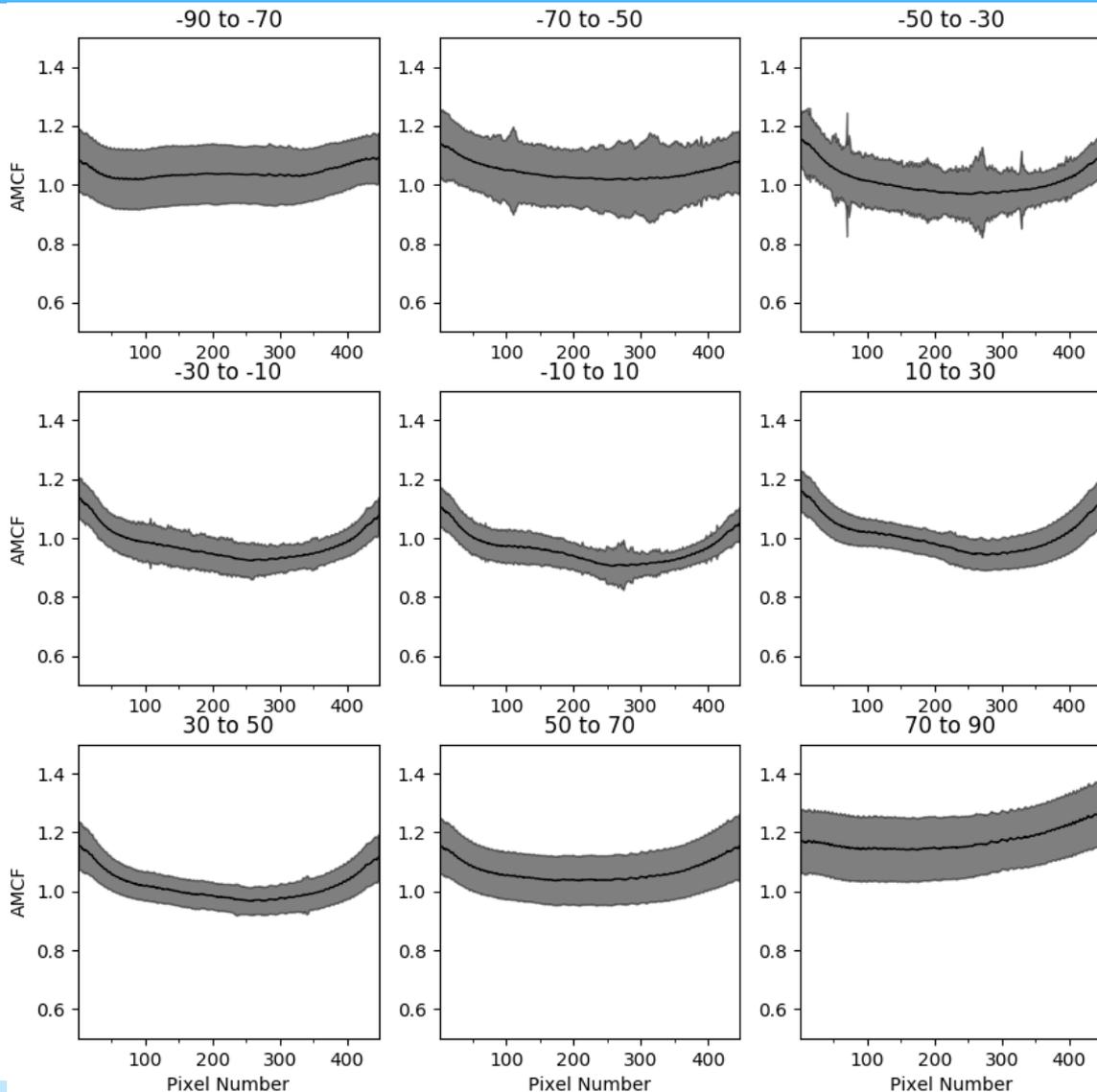
Swath effects in S5P total water vapour



- Mean difference of total water vapour column between S5P and ECMWF as function of satellite pixel (or viewing angle) in g/cm^2 with shading indicating standard deviation
- for every valid pixel selection of nearest model grid pixel
- Selecting time period from November to end of July
- Calculation performed for different latitude bands



Swath dependency of AMCF



- Air Mass Correction Factor (AMCF) as function of satellite pixel (or viewing angle) with shading indicating standard deviation
- Improper AMCF masked out
- Selecting time period from November to end of July
- Calculation performed for different latitude areas



Summary

- AMC-DOAS
 - Applied to Sentinel 5P
- Validation
 - Good overall comparison results
 - High discrepancies of total water vapour columns near equator
- Viewing angle dependencies (VZA):
 - Air mass correction factor U-shaped
 - At tropics, total water vapour columns peaks near VZA of 0°



Future plans

- Algorithm improvements
 - Changing reference profile
 - Accounting for pressure, temperature
 - Surface elevation and albedo
- Accounting for
 - Viewing zenith angle dependencies
 - Cloud filtering (adapt AMCF limits?)



Future plans

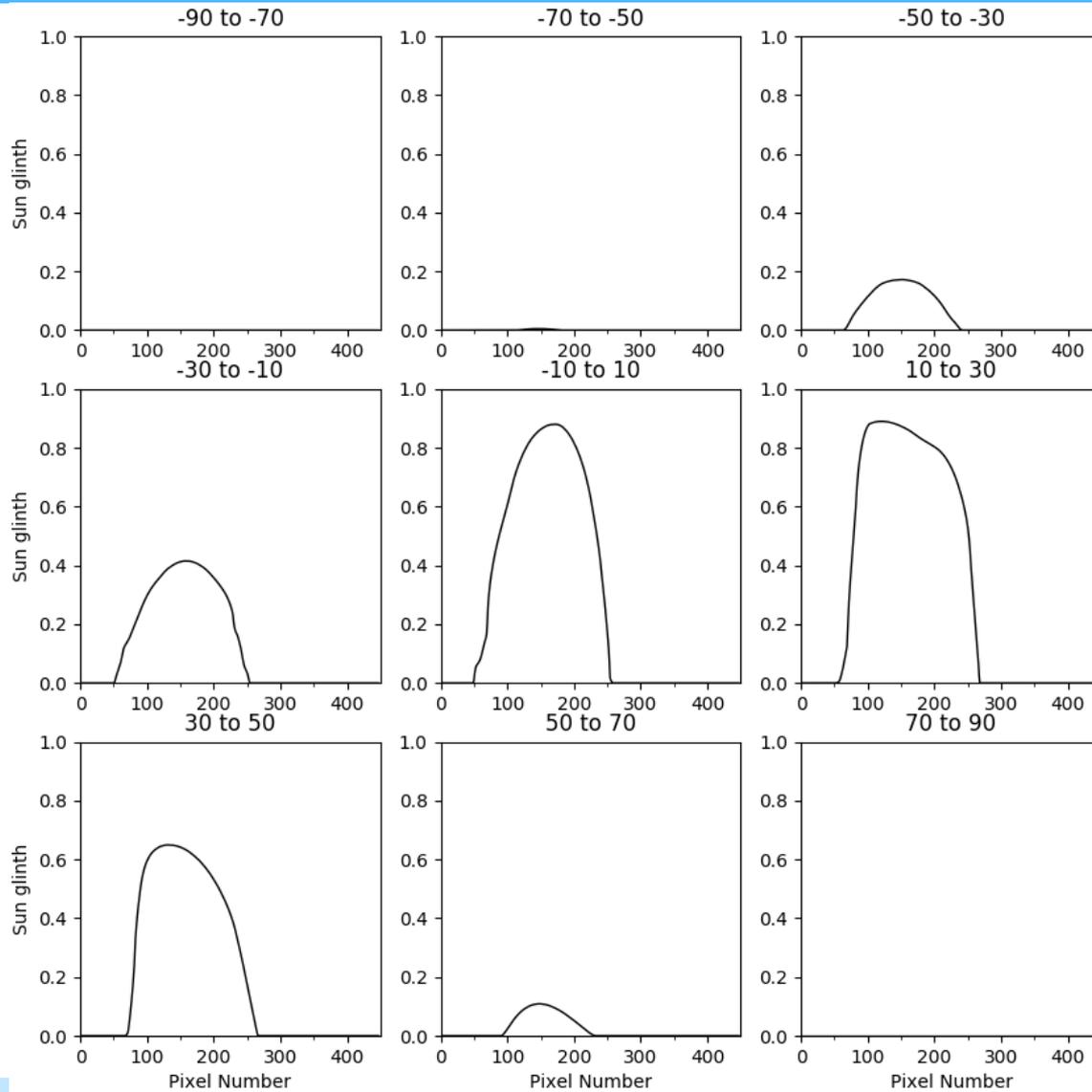
- Case studies
 - regional features and gradients
 - Arctic → arctic amplification
 - Human activities (cut of rain forests)
 - deserts
- Creating long term data sets
 - Apply to GOME, SCIAMACHY, GOME-2
 - Trend analysis
 - Changes in water vapour total columns
 - Arctic ↔ tropics



Thank you very much
for your attention.



Appendix



Timeseries of Cv-Difference (S5p - smif17_desc)

