Retrieval of cloud bottom altitude from TROPOMI on Sentinel-5P

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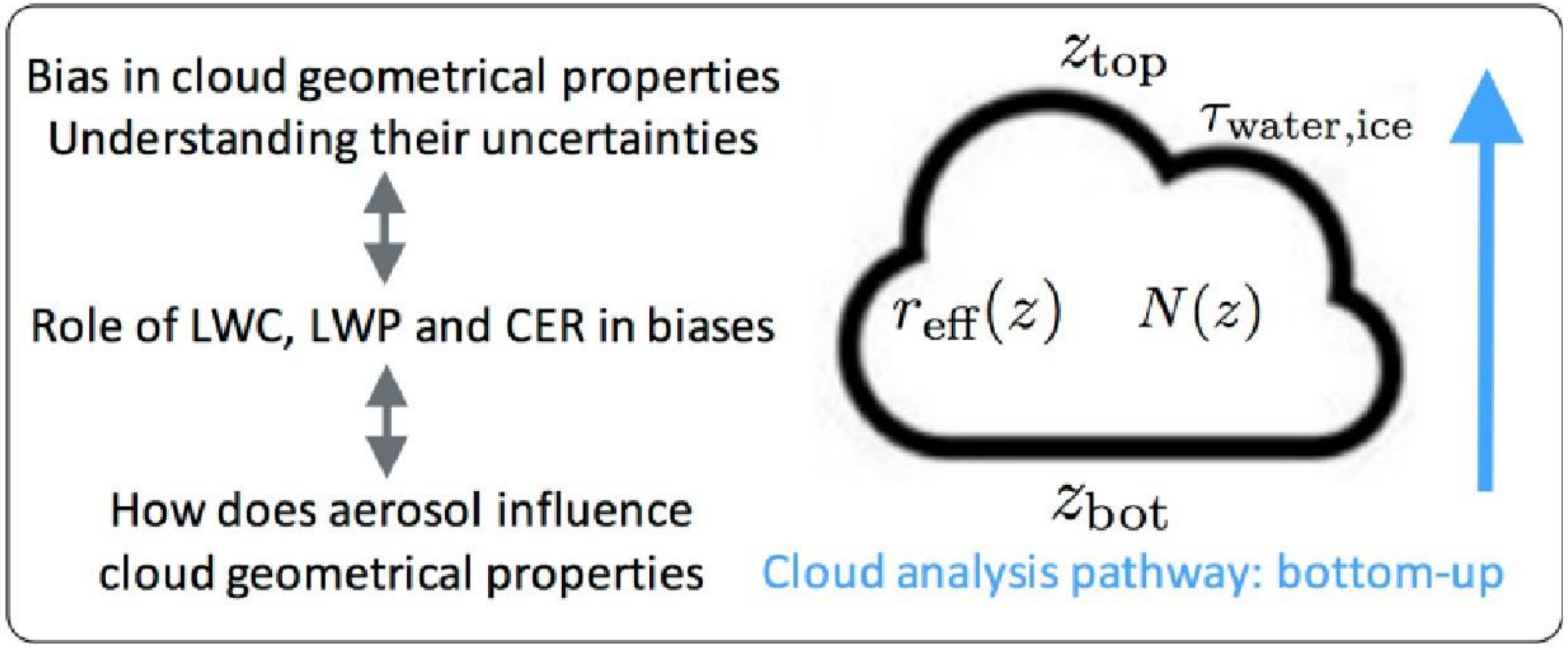
Why is cloud base altitude important?

- For aviation safety
- For controlling the cloud's longwave radiative emission, thus **radiation budget**
- For setting the level at which **aerosol** concentration and updraft speed determine the cloud's **microphysics**
- It forces us to think about a more sophisticated and **realistic cloud model**



“It is not possible”
La Scuderia, Dozza, July 3 2024, 9:15PM

This is because:

1) Variations of cloud and surface parameters in and around the O_2A band are correlated

   How many degrees of freedom per single spectrum? → How many cloud paramenters for a simultanoeus retrieval (CF-CTH or COT-CTH or CTH-CBH)?

   Schuessler, et al IEEE TGRS 2013

2) Even in the case of CTH-CBH retrieval, **light availability in reflection** for CBH is limited

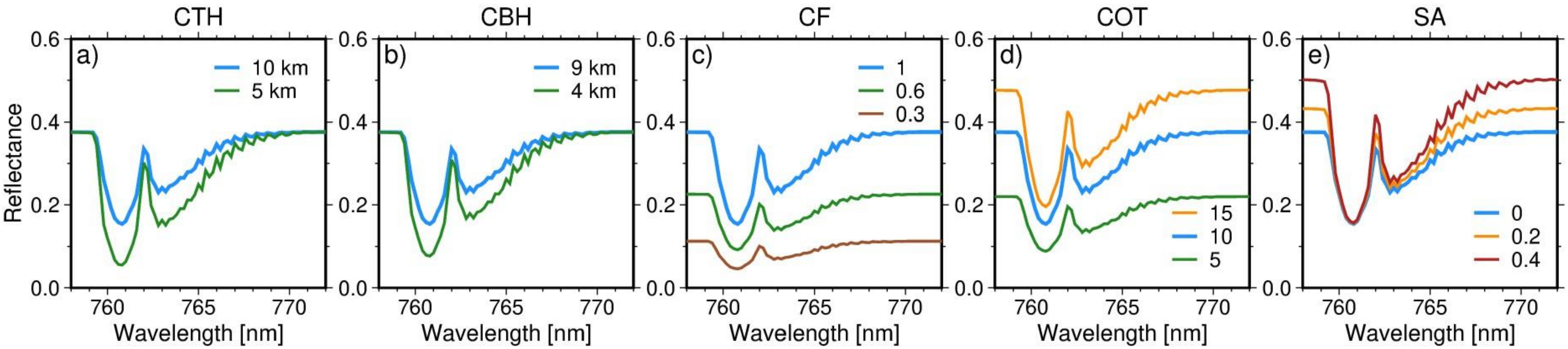
   Platnick, S. (2000). Vertical photon transport in cloud remote sensing problems. Journal of Geophysical Research: Atmospheres, 105(D18), 22919-22935.

3) As a consequence, it is believed that the **O_2A band represents a middle(-ish) cloud height**, which some call “radiative height” or “optical centroid”

   Wang, P. and Stammes, P.: Atmos. Meas. Tech. https://doi.org/10.5194/amt-7-1331-2014, 2014.

   Sneep, M., et al. "Three-way comparison between OMI and PARASOL cloud pressure products." Journal of Geophysical Research: Atmospheres 113.D15 (2008).

The oxygen A-band sensitivity to cloud (and surface) properties

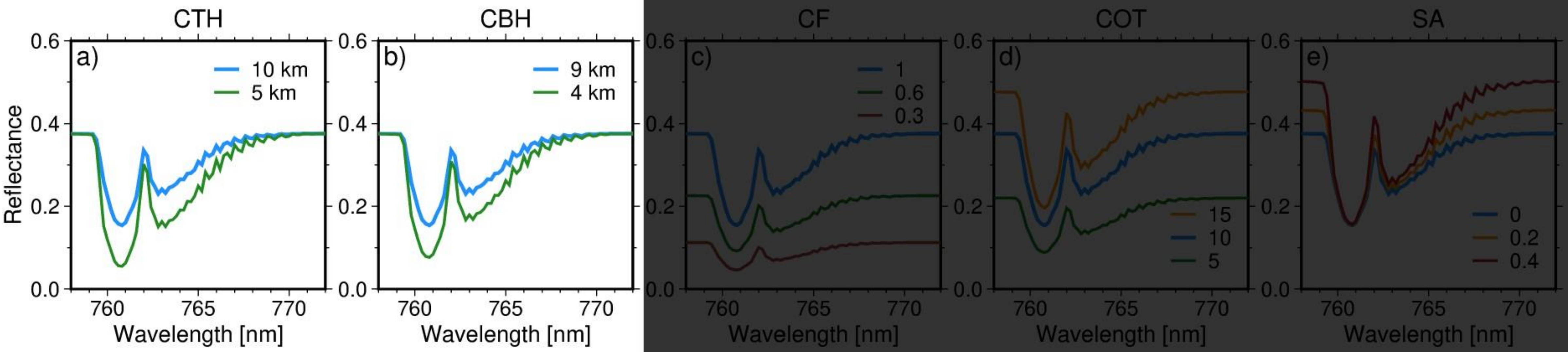


Highly correlated

Extremely correlated

Correlated in continuum

The oxygen A-band sensitivity to cloud (and surface) properties



Highly correlated

Extremely correlated

Correlated in continuum

Alleviate the ill-posedness of the inverse problem

Cloud fraction

broadband or colocated binary

Cloud optical thickness

analytical continuum

Surface albedo

prior or co-retrieved

Independent cloud properties in the O_2A band (OLCI resolution)

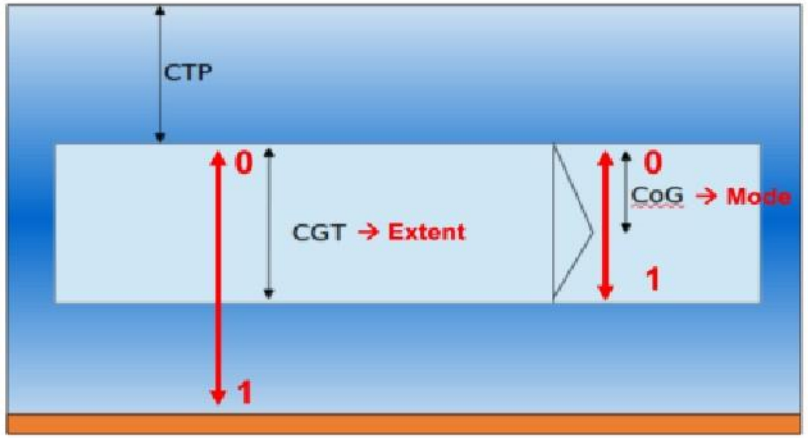
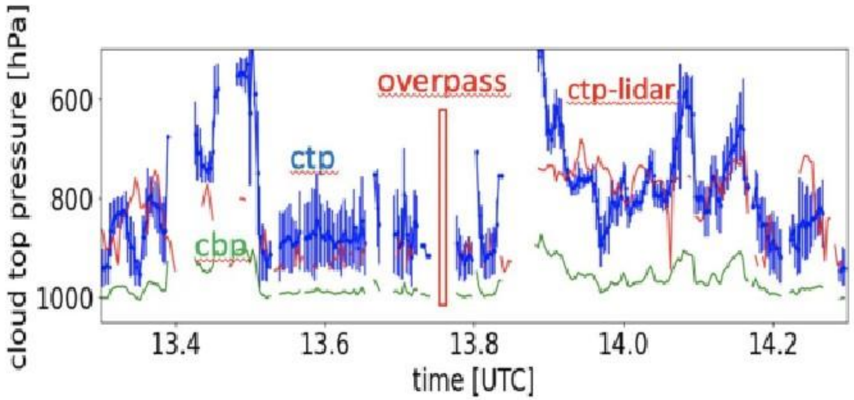


Figure 2: Cloud top pressure CTP, cloud geometrical thickness CGT, and center of gravity CoG.



Jürgen Fischer and Rene Preusker, STUDY ON CLOUD TOP PRESSURE DEVELOPMENT FROM SENTINEL -3 OLCI OCTPO2, Algorithm Product Validation and Evolution Report Issue 2.0, 20.06.2021

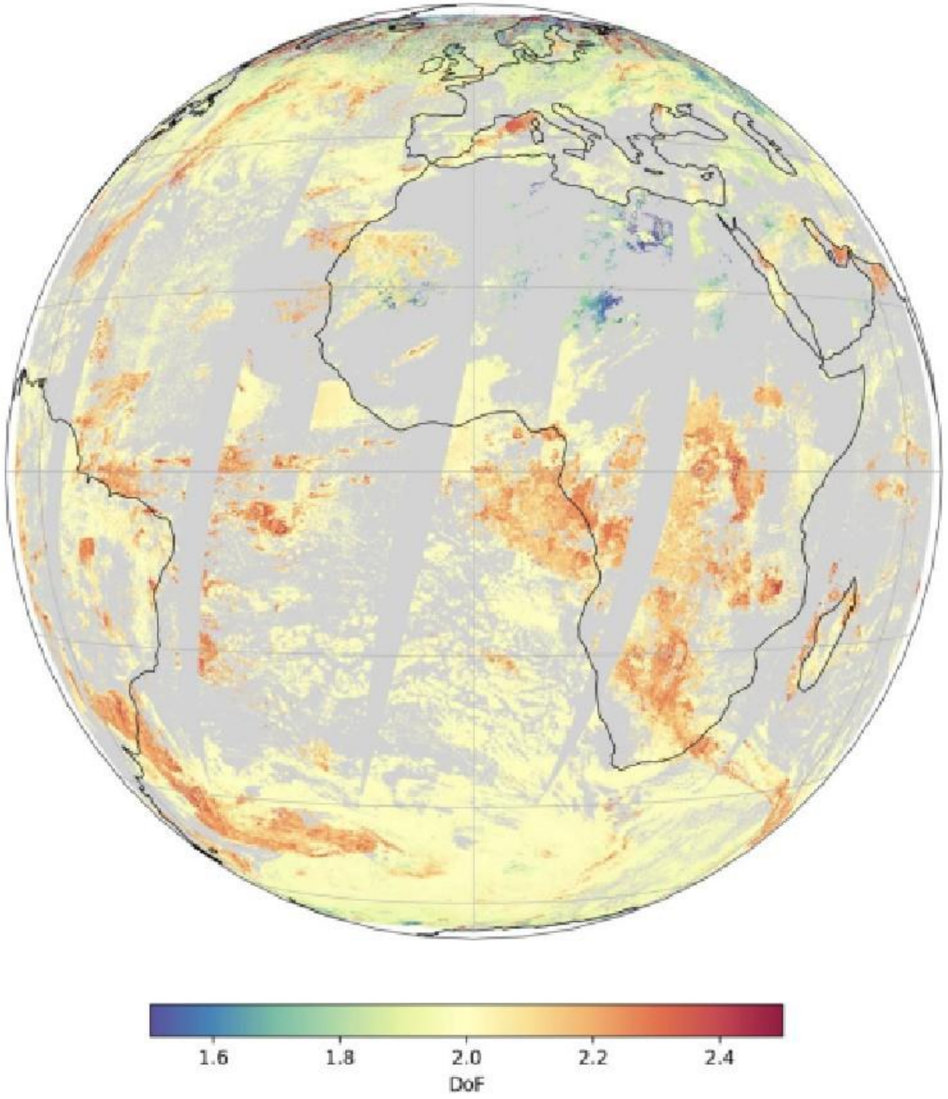
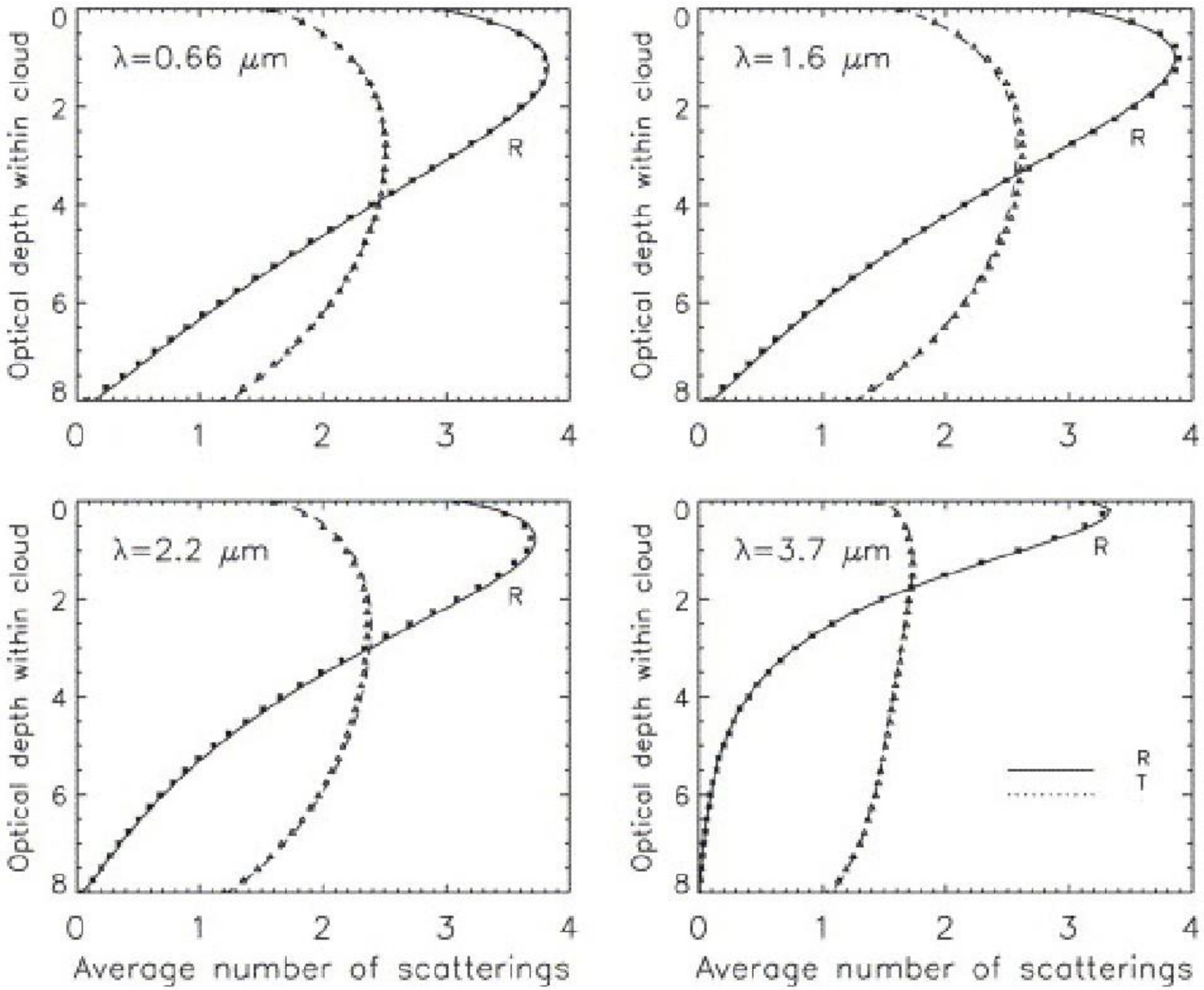


Figure 18: Degree of freedom (DoF) as derived from OLCI on the 18th of Feb. 2020.

Light availability in reflection at TOA



Platnick, S. (2000). Vertical photon transport in cloud remote sensing problems. Journal of Geophysical Research: Atmospheres, 105(D18), 22919-22935.

Rozanov, V. V., & Kokhanovsky, A. A. (2005). The average number of photon scattering events in vertically inhomogeneous atmospheres. Journal of Quantitative Spectroscopy and Radiative Transfer, 96(1), 11-33.

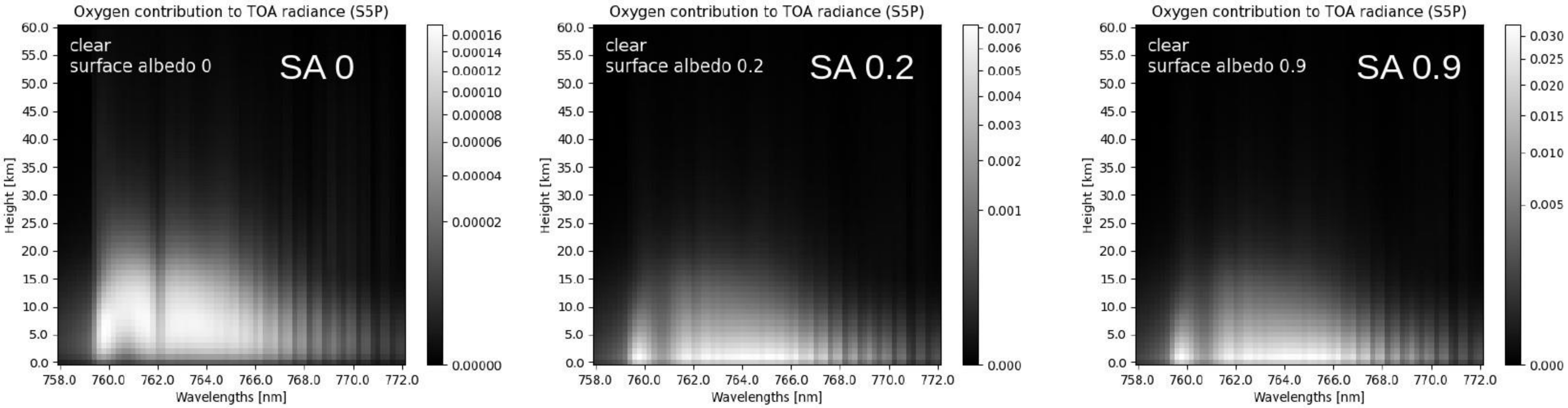
Two effects

1) the longer the wavelength, the closer to the physical top (3.7 um still sensitive to cloud height)

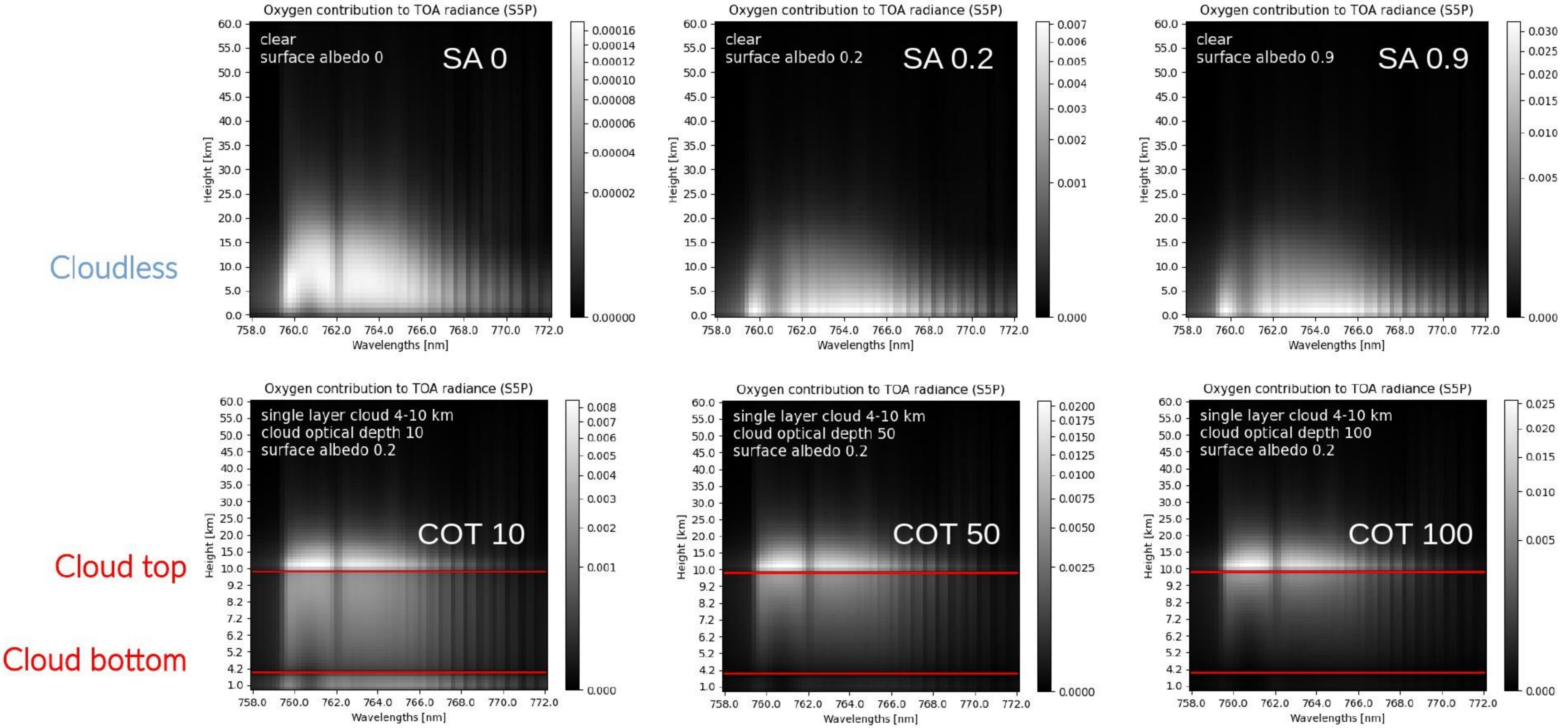
2) the shorter the wavelength, the more light will be scattered downward (forward peak effect)

Derivative of TOA reflectance to oxygen absorption

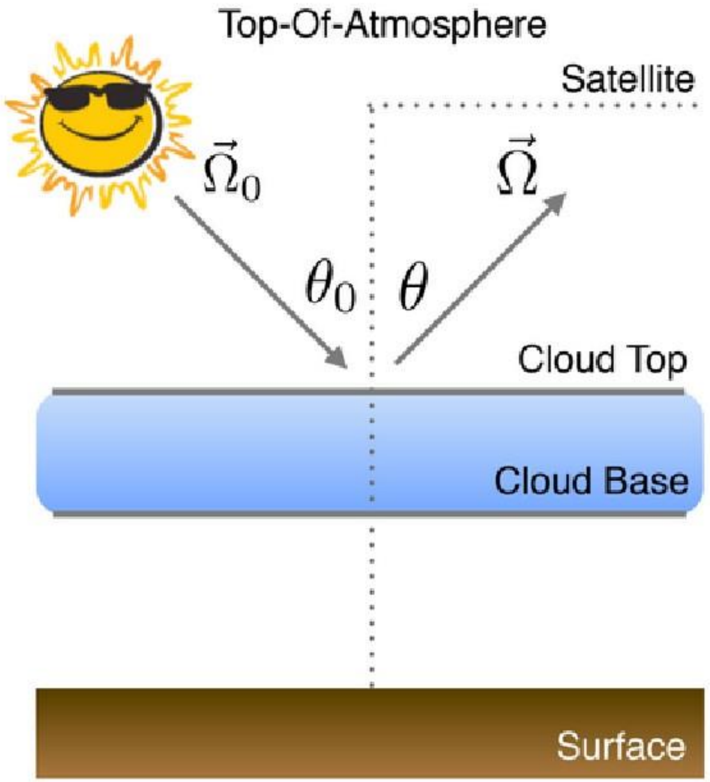
Cloudless



Derivative of TOA reflectance to oxygen absorption



Parameterization of TOA reflectance with a cloud model



$$R_{\mathrm{TOA}}(\lambda) = R_a(\lambda) + T_1(\lambda)\ R_b(\lambda)\ T_2(\lambda)$$

R_a

Above cloud
Aerosol + gas absorption & scattering in single scattering approximation

R_b, T_1, T_2

Inside cloud
Vertical gas profiles (correlated k)
Spherical polydispersed water droplets
LWC constant

Below cloud
Gas absorption & scattering
Diffuse approximation (no direct light)

Yanovitskij, E. G. (2012). Light scattering in inhomogeneous atmospheres. Springer Science

Chamberlain, J. W. (1965). The Atmosphere of Venus Near HER Cloud Tops. Astrophysical Journal, vol. 141, p. 1184, 141, 1184

The cloud reflectance contributes to R_b

R_b *is* calculated from a **semi-infinite layer** (with invariant properties for a **quasi-conservative scattering** regime) finding the atmospheric gaseous (oxygen) **single scattering albedo** → this corresponds to a level inside the cloud where the radiation fields "perishes" (cit. Yanovitskij, p. 250, 2012) → fully absorbing layer → the best we can do.

How to model clouds: Lambertian vs scattering

FRESCO
operational cloud product
on CO2M and Sentinel 5

Lambertian cloud model

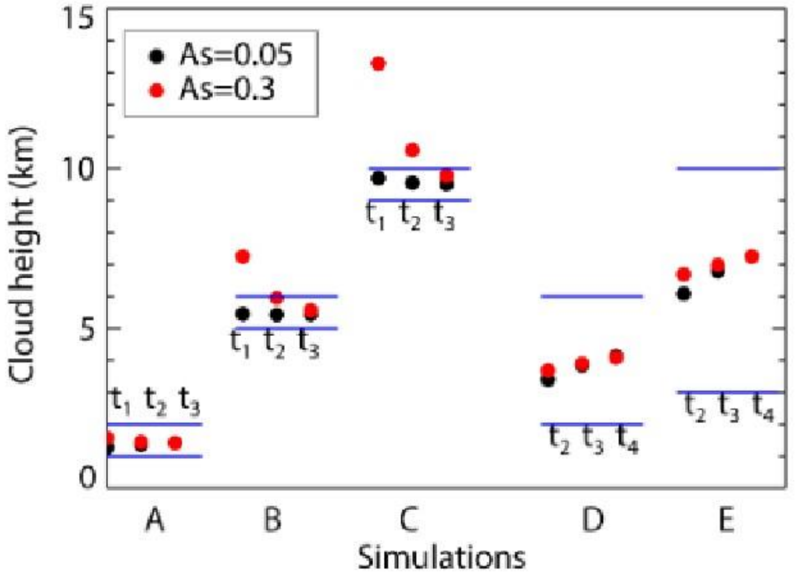
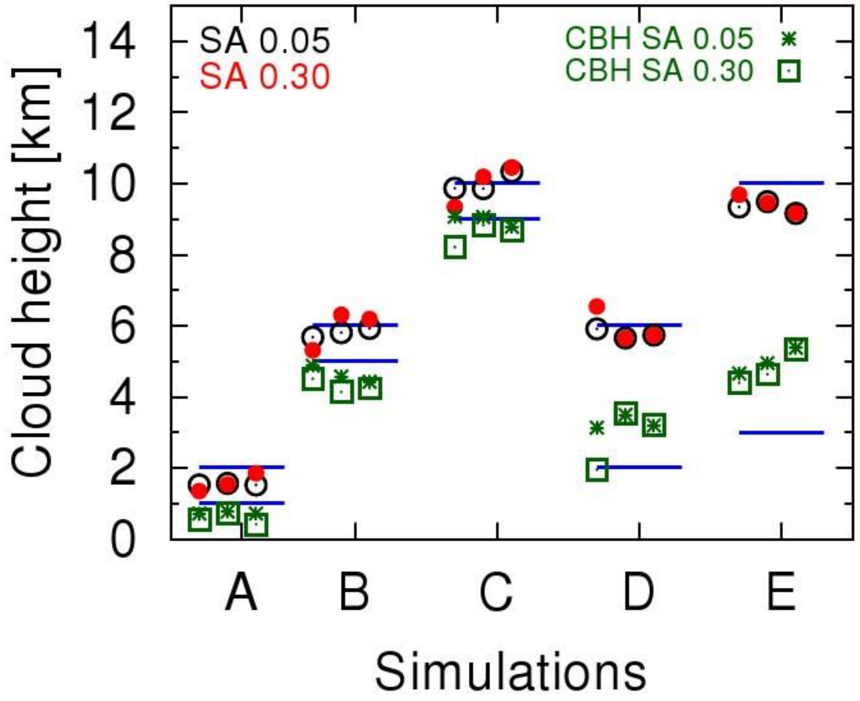


Figure 2. FRESCO-retrieved cloud heights for simulated cloud cases for a solar zenith angle of 60° and nadir view. The cloud optical thickness values are $\tau_1 = 5$, $\tau_2 = 15$, $\tau_3 = 35$, $\tau_4 = 60$. Cloud top and base heights are indicated using blue horizontal lines. The surface albedos (A_s) are 0.3 and 0.05.

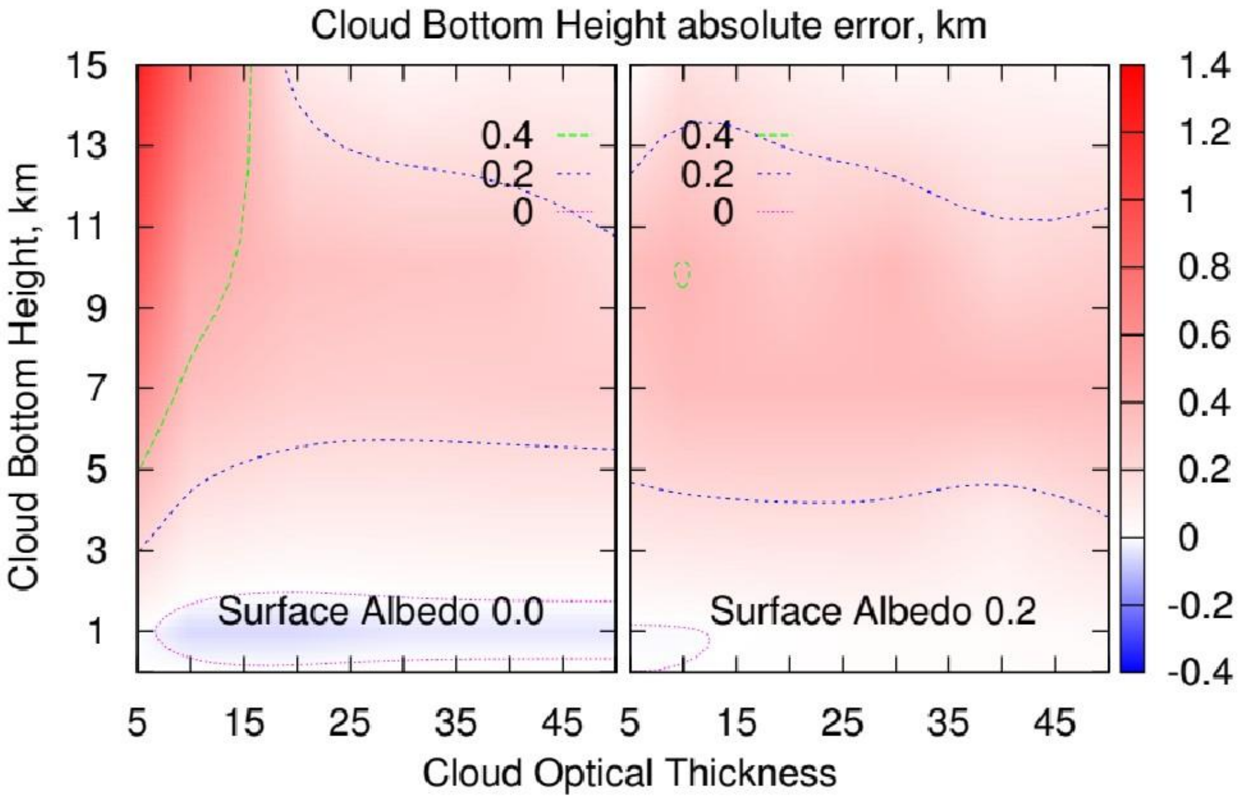
Wang, P. and Stammes, P.: Evaluation of SCIAMACHY Oxygen A band cloud heights using Cloudnet measurements, Atmos. Meas. Tech., 2014.

Scattering cloud model

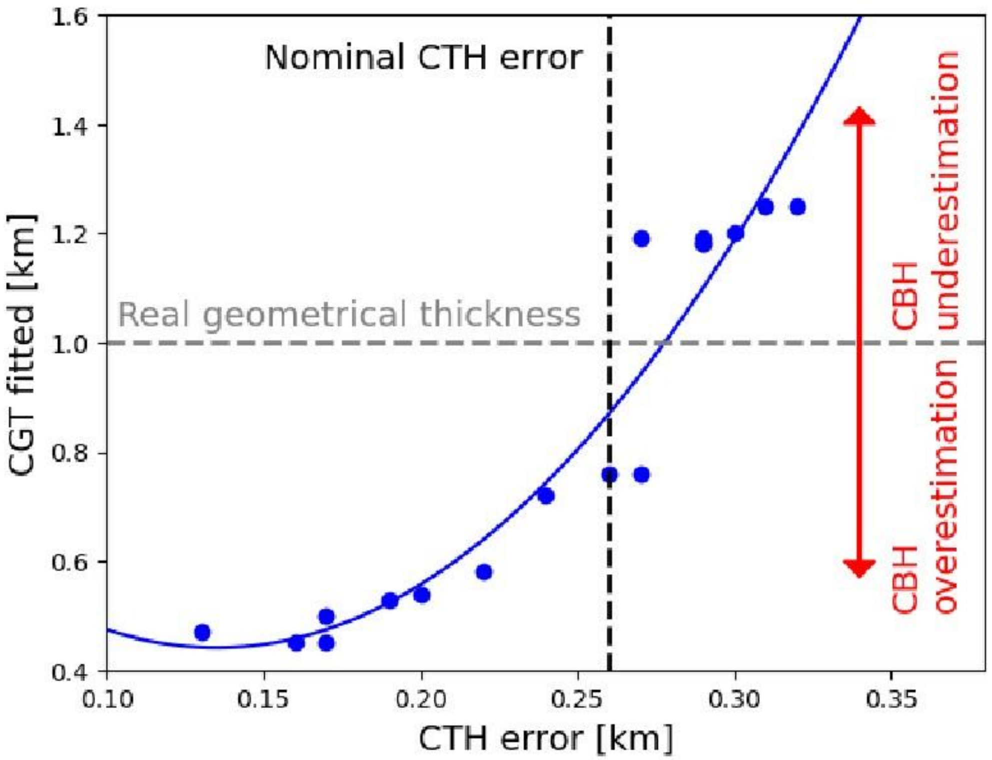


Synthetic error assessment

- CBH errors not depedent on COT or SA



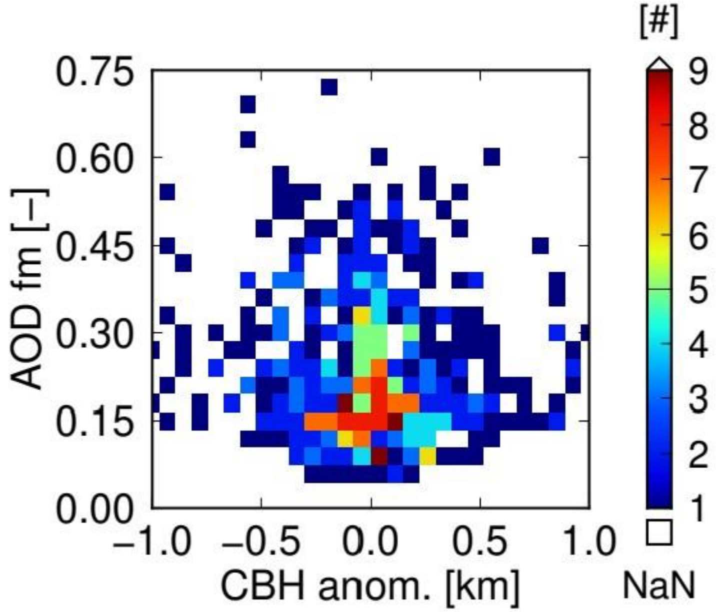
- CTH and CBH errors are correlated
- CBH errors ~ β * CTH errors β ~ 1.5-2.5

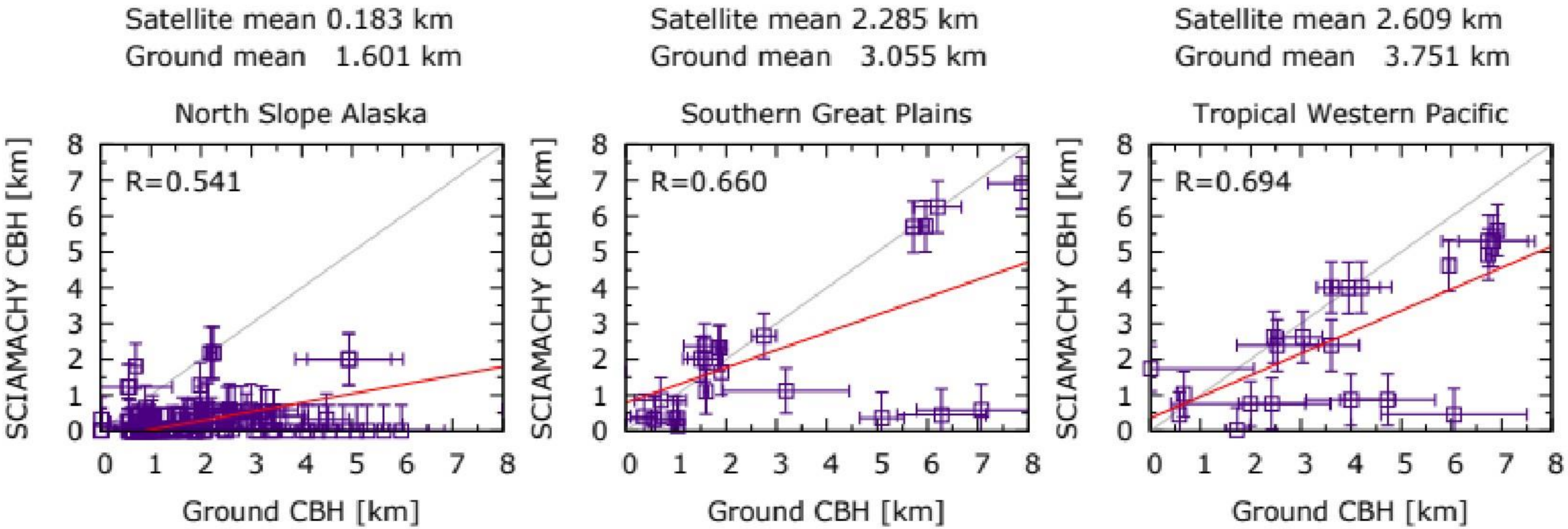


Lelli et al, ACP, 2014

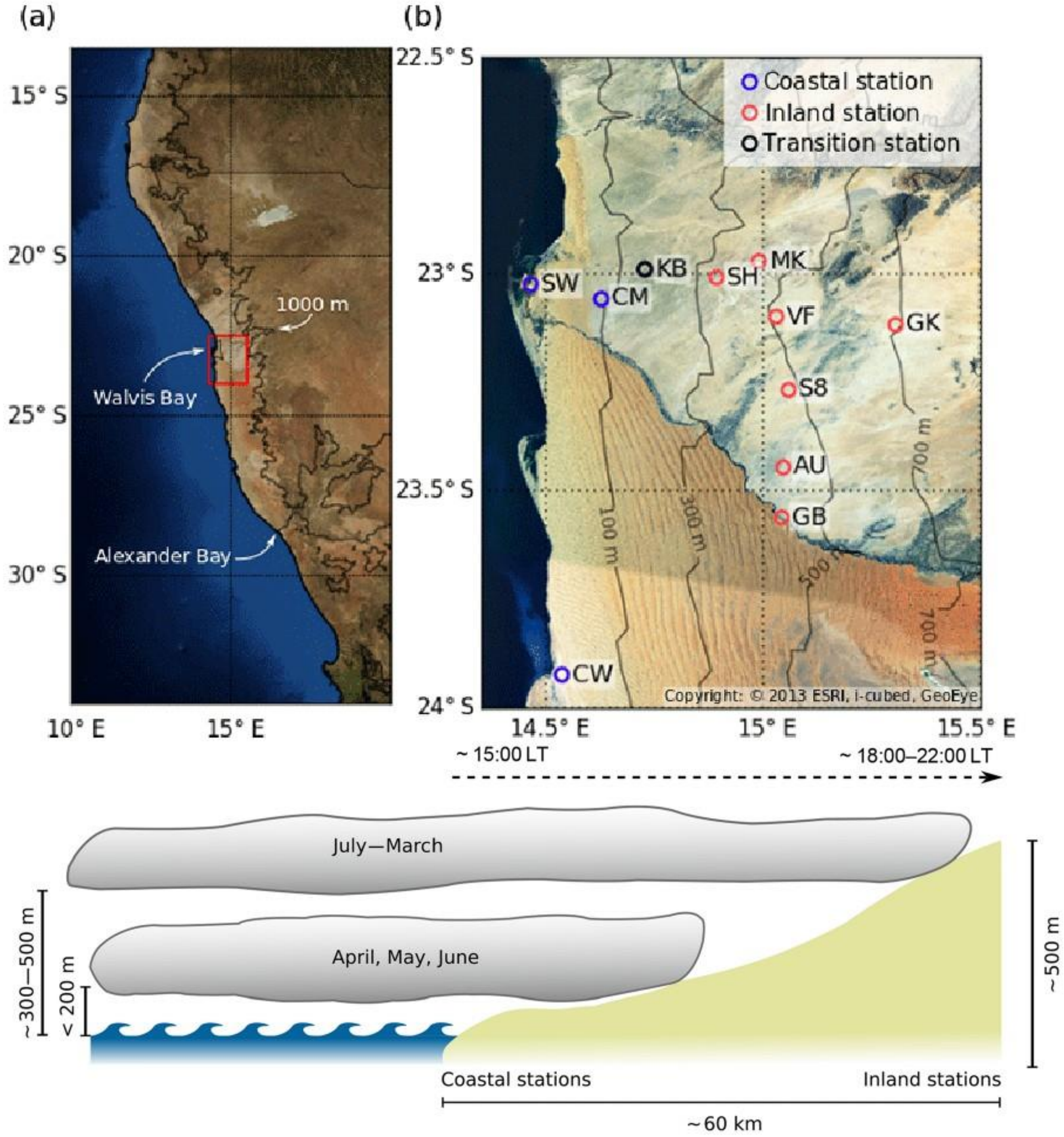
Real data: SCIAMACHY cloud base height

Lelli and Vountas, 2018



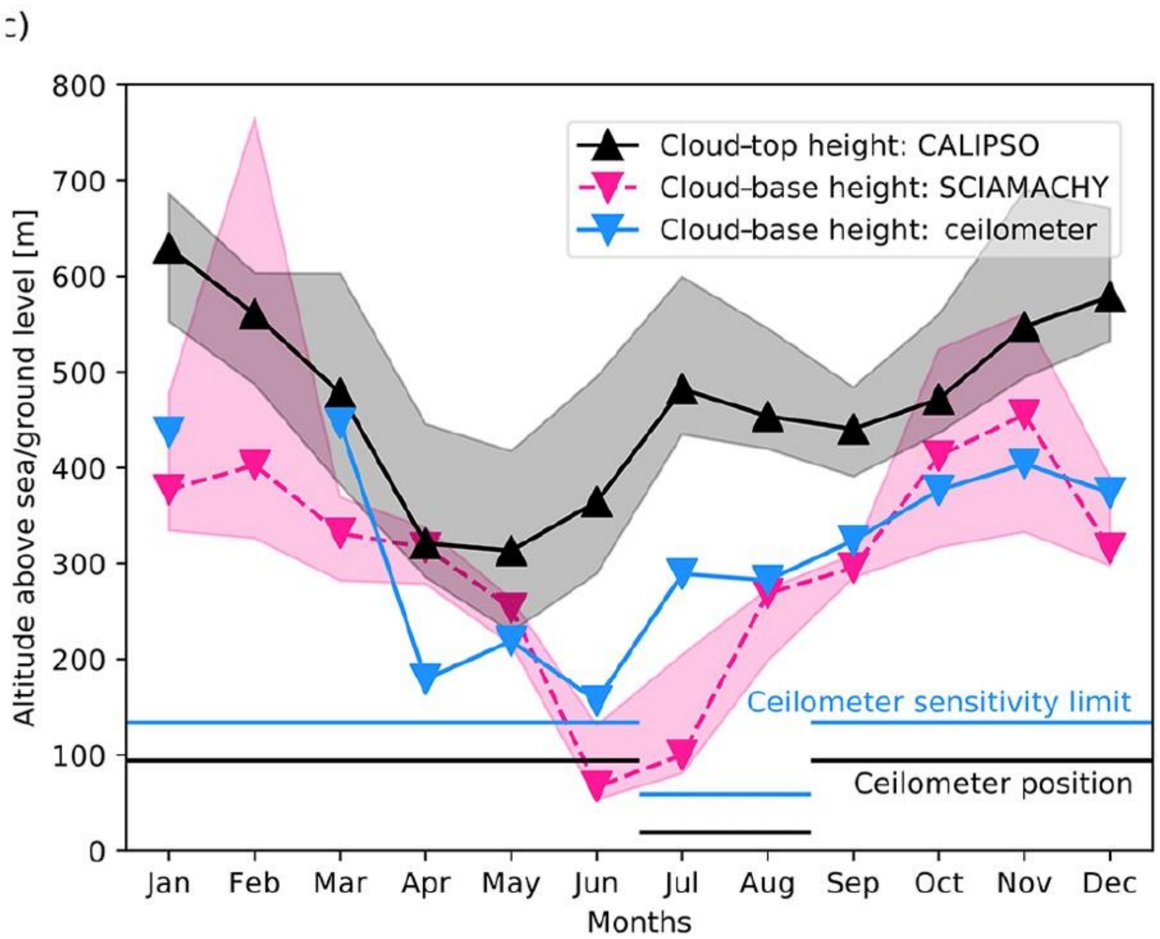


Real data: SCIAMACHY cloud base height in the Namib



DLR

Andersen, H., Cermak, J., Solodovnik, I., Lelli, L., and Vogt, R.: Spatiotemporal dynamics of fog and low clouds in the Namib unveiled with ground- and space-based observations, Atmos. Chem. Phys., 2019.



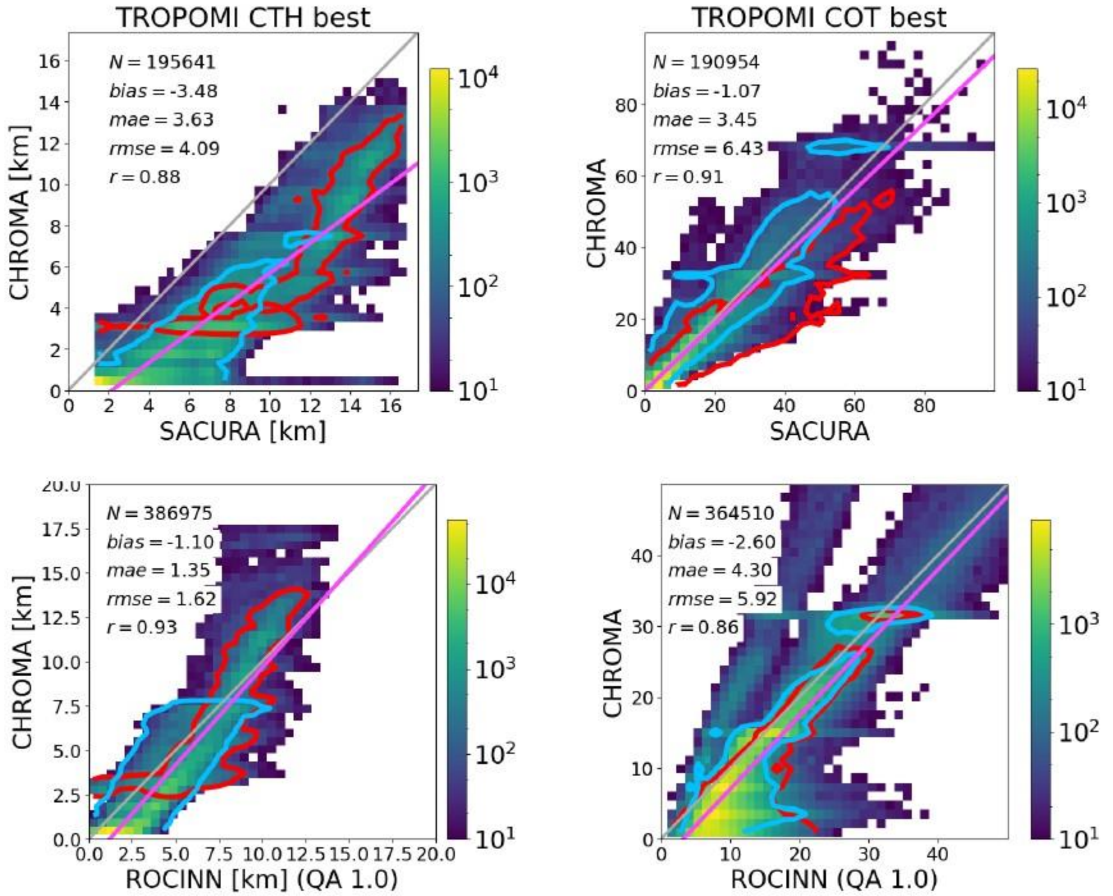
Real data: 3 algorithms applied at TROPOMI on Sentinel-5P

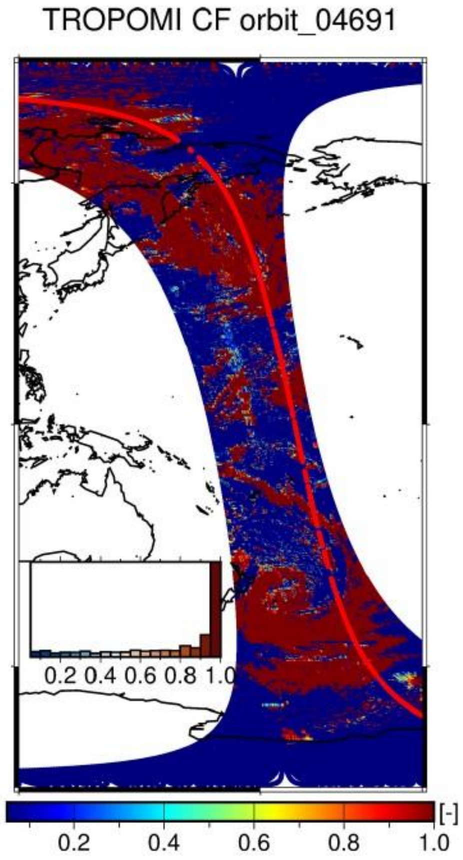
SACURA (Lelli at al. AMT, 2012) – CTH and CBH

CHROMA (Sayer et al. AMT, 2023) – CTH only (operational for OCI on NASA PACE)

ROCINN (Loyola et al. AMT, 2018) – CTH only (operational for TROPOMI on S5P)

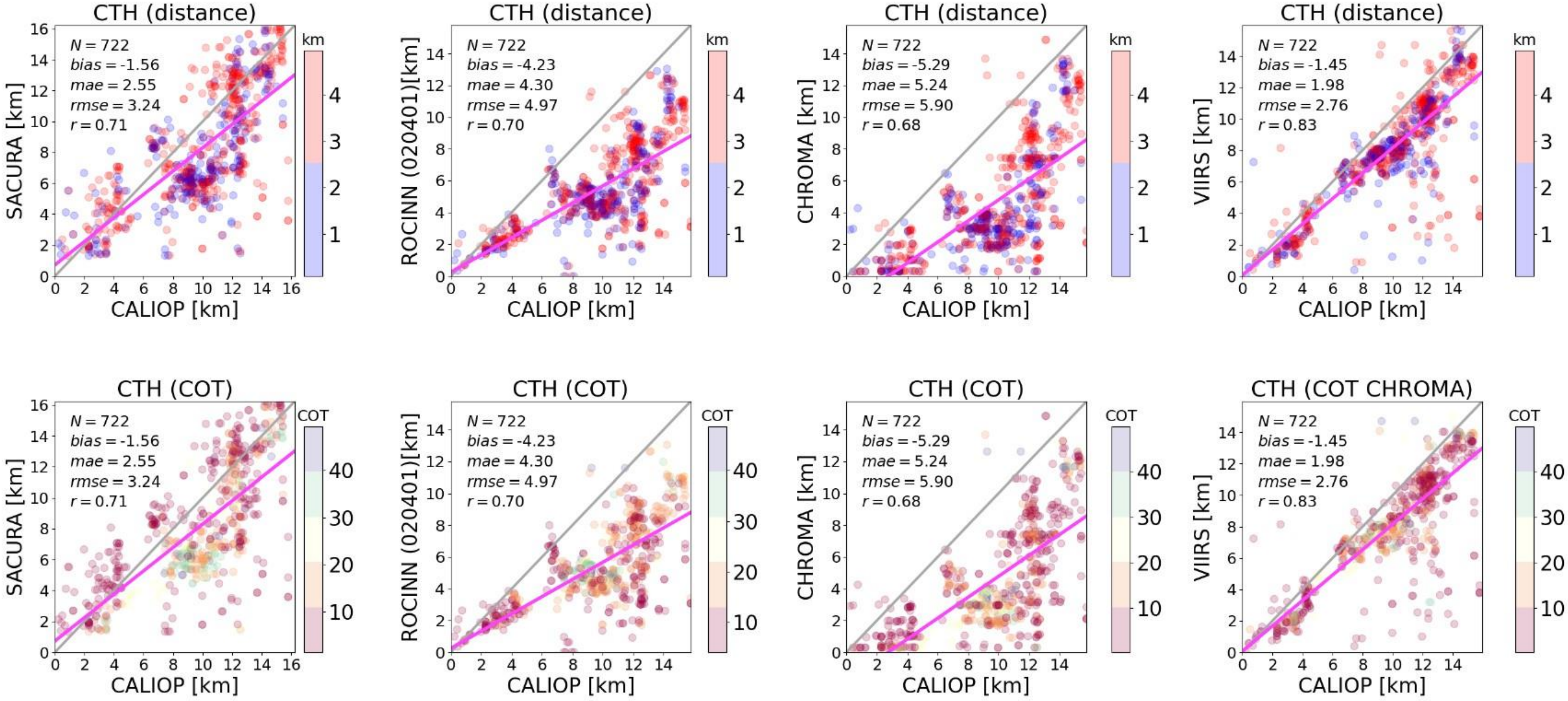
90% Liquid
90% Ice





Real data: first results with TROPOMI on Sentinel-5P

O_2A CTH with CBH	O_2A CTH without CBH		CTH
SACURA	ROCINN	CHROMA	VIIRS



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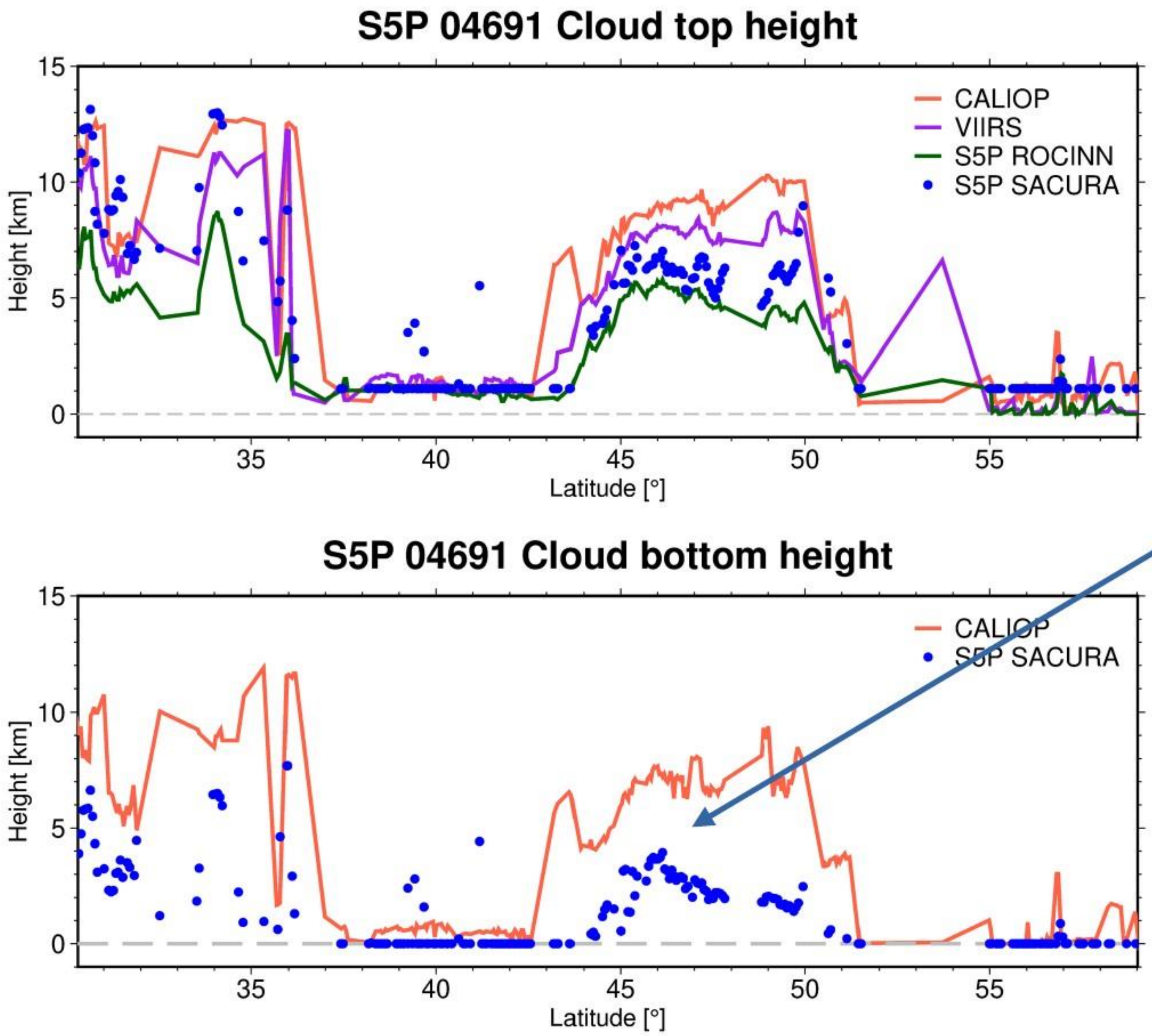
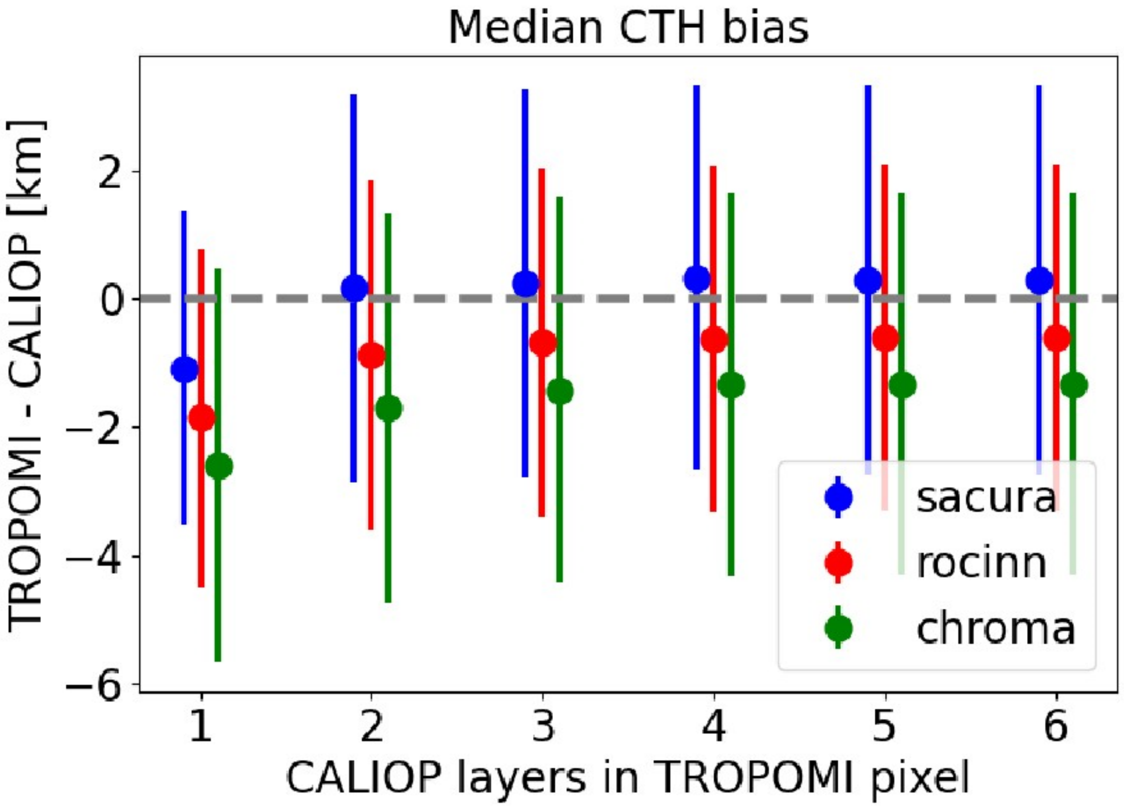
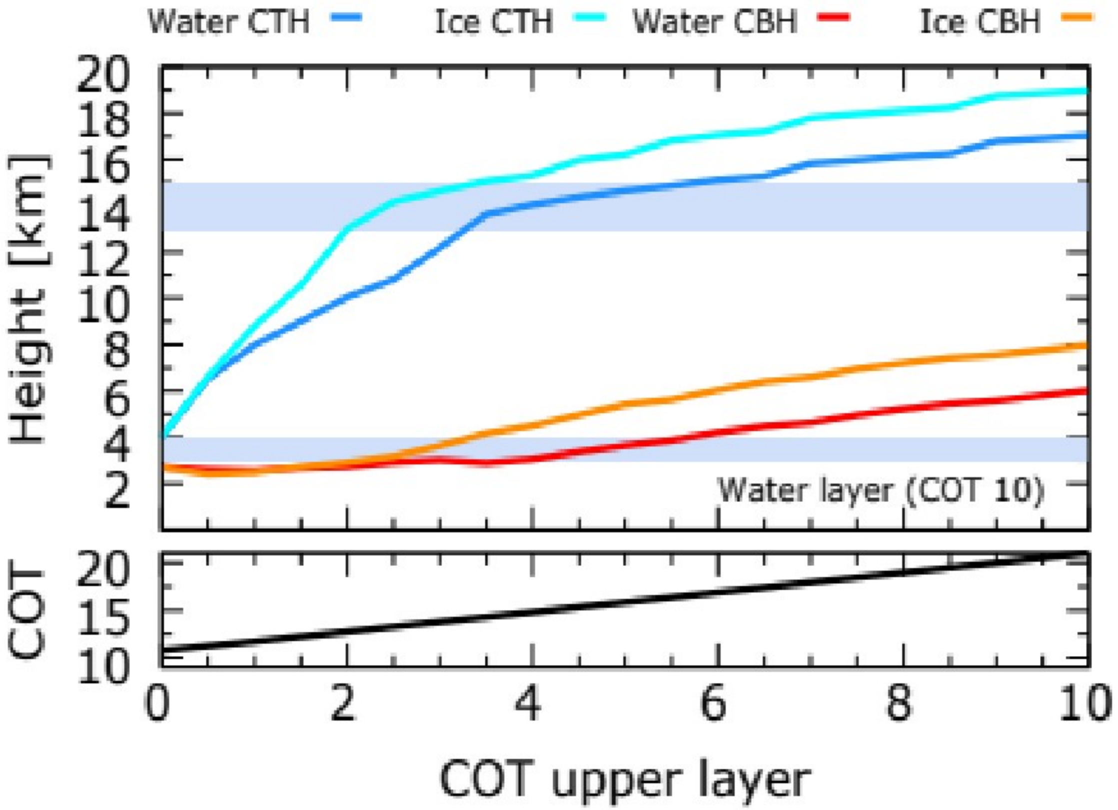


GEOPROF dataset not available for this orbit because CloudSAT went on a solo career in 2018 and left the A-train

Real data: first results with TROPOMI on Sentinel-5P





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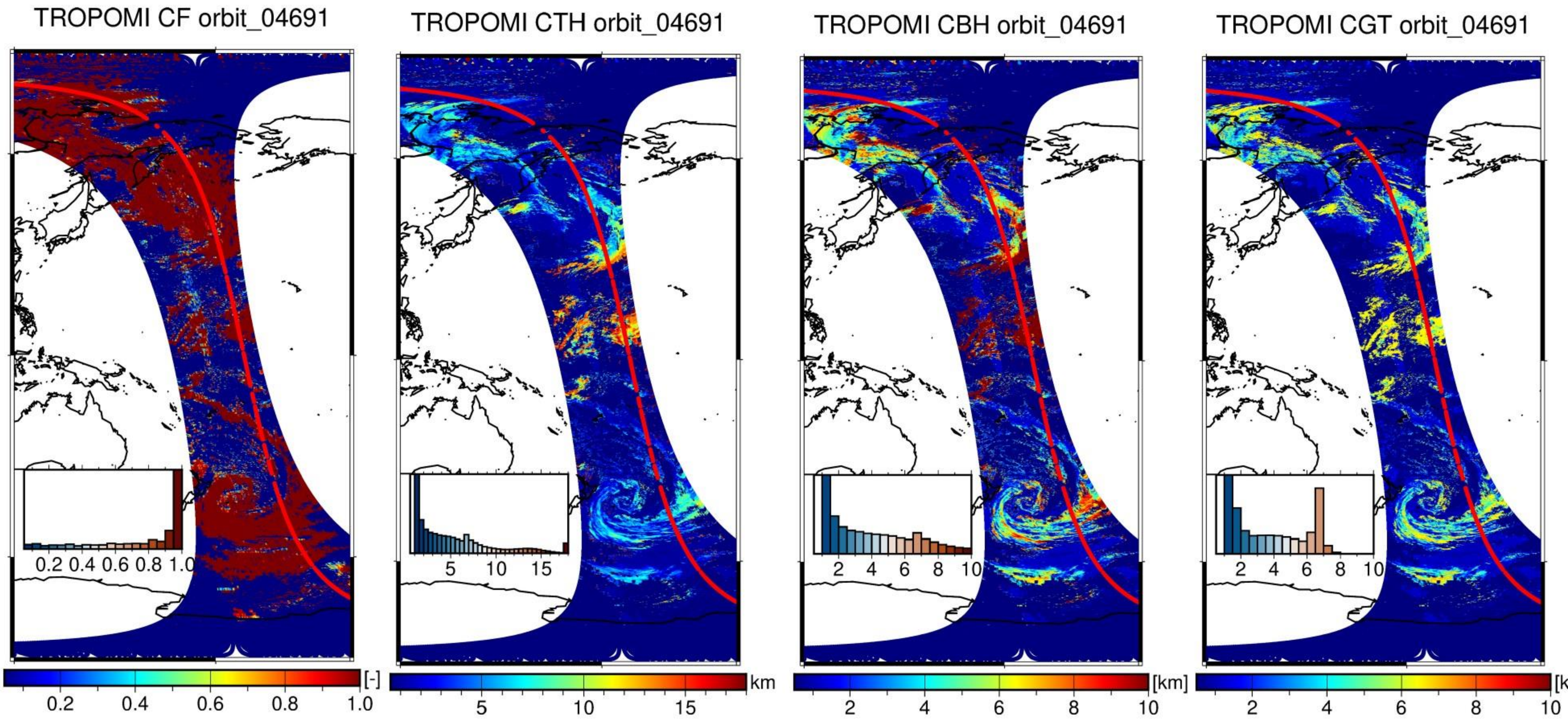

What have we seen in this talk?

1. The oxygen A-band can be used to infer CBH and geometrical thickness
2. CBH retrieval is beneficial to the CTH accuracy
3. Prerequisite: scattering cloud model. Lambertian cloud model is not useful

Ongoing work

- Validation, validation. More validation. Validation!

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Ongoing work

- Validation, validation. More validation. Validation!

Reach out if you are interested in:

1. CBH and geometrical thickness from spectrometers
2. Generate ECV for CDR from the oxygen A-band
3. Advance trace gas retrievals by use of scattering clouds to correct lightpath (no ghost columns)
4. Exploring 2nd moment of light path distribution in the wing > 763 nm to retrieve thermodynamic phase
5. Exploring synergy with other spectral windows to diagnose inhomogeneous clouds