Observing and Simulating 3D Cloud Shadow Effects in the S5P NO_2 Product

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Introduction

As the spatial resolution of satellite spectrometer instruments is moving towards sub-kilometer scale, 3D cloud effects become more prominent in the retrieval of atmospheric trace gases. Currently in the Sentinel-5P (S5P) / TROPOMI NO_2 product (5.6x3.6 km^2 at nadir) the FRESCO algorithm is used to retrieve a 1D horizontal homogeneous Lambertian cloud layer for cloud correction. However, clouds are 3D objects, they are not spatially homogeneous and can also have effects on neighboring clear-sky pixels by casting shadows on the ground surface or by scattering light into the scene.

In the S5P NO_2 algorithm the retrieved slant column density is translated to vertical column density (VCD) by correcting for the light path using pre-calculated air-mass factors (AMF) from a radiative transfer model, using surface and cloud parameters as input. When a cloud shadow is cast over a clear-sky pixel the downward light intensity is reduced, altering the average observed light path. This lowers the sensitivity of the measurement for the lower atmospheric layers and thus changes the AMF. As this effect is not accounted for in the current 1D AMF calculation, the AMF used in the retrieval is different from the true AMF, causing a bias in the calculated VCD. When located above a polluted region, the cloud shadow affected pixels should show a different VCD than neighboring pixels.

Cloud shadow

Cloud shadows were searched above polluted scenes in winter over China by using VIIRS imagery. In Figure 1 (top row) a clear cloud shadow is visible in the VIIRS image and the retrieved scene albedo. In Figure 1 (middle row) the cloud shadow is visible also in the surface albedo, AMF and NO_2 VCD.

Albedo correction

In Figure 1 (bottom row) the S5P PAL product (v1.5.0) is compared against the S5P OFFL product (v1.3.0) (middle row). As of v1.4.0 the surface albedo can be adjusted downwards to prevent negative cloud fractions, whilst keeping radiative closure. This also occurs in the cloud shadow pixels, lowering the AMF and thereby artificially increasing the NO_2 VCD. After reprocessing the PAL data without the albedo correction, the effect seen in the NO_2 VCD disappeared. The observed effect was thus caused by the algorithm and not by the cloud shadow.

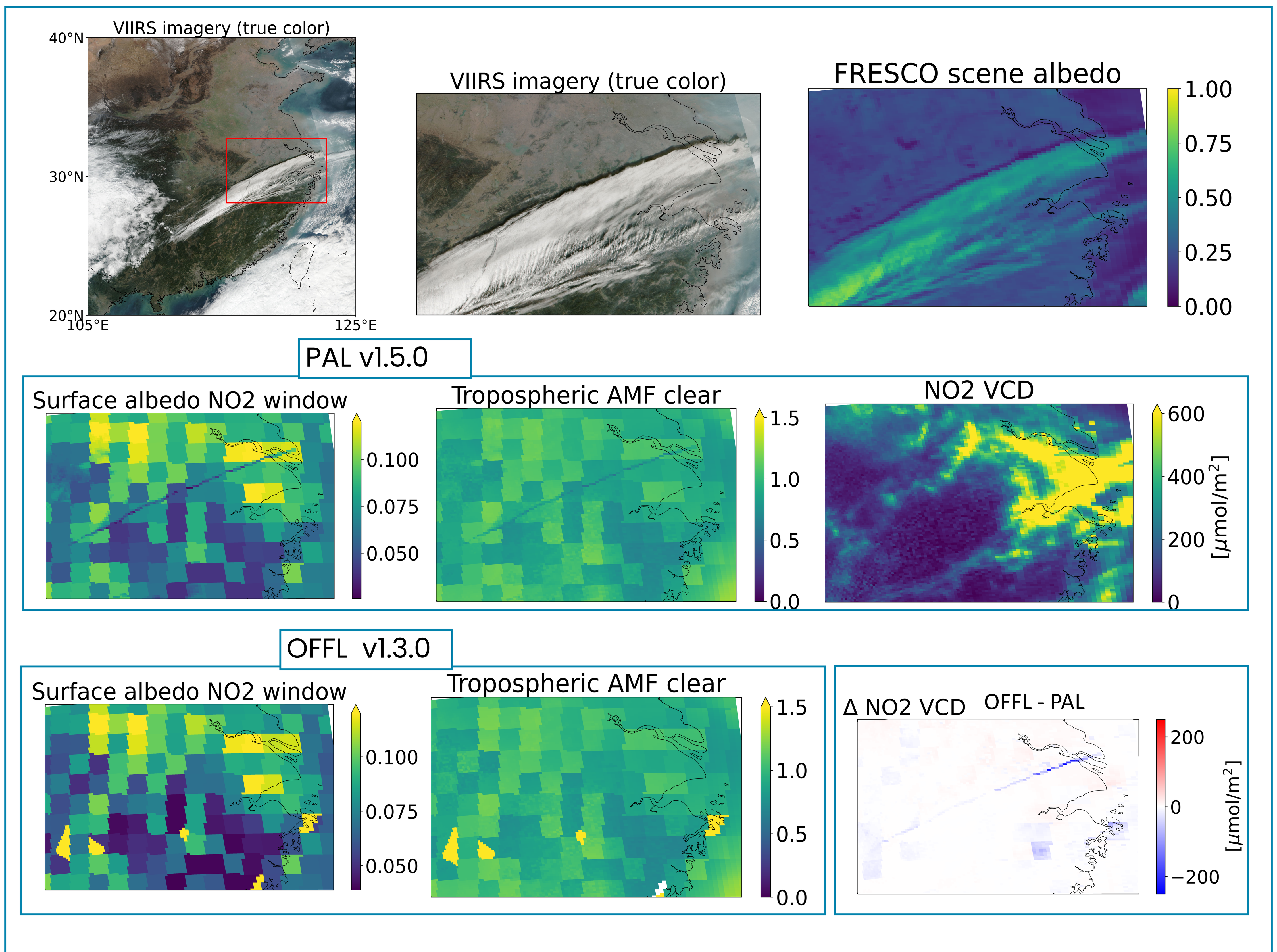


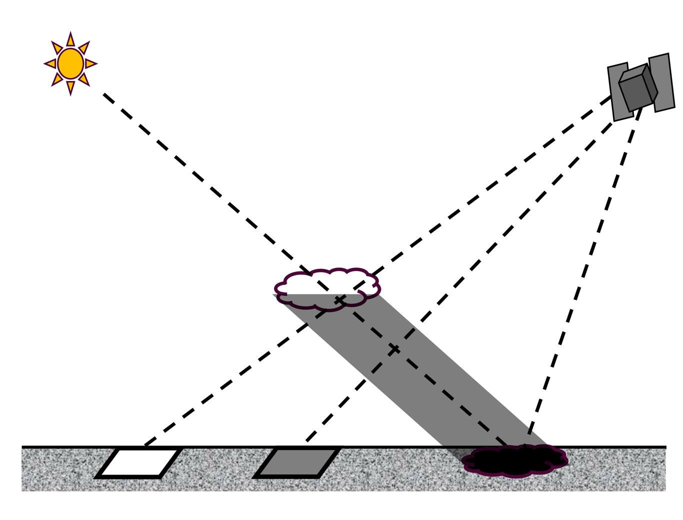
Figure 1: Cloud shadow in Shanghai area on 04-12-2019 in the S5P NO_2 PAL and OFFL products.

3D AMF simulation

The MONKI (Monte Carlo KNMI) 3D radiative transfer model (Trees et al, in prep.) is used to simulate the cloud shadow effect on the AMF calculation. In Figure 2 the simulation is shown for a box cloud at 10 km height with typical cloud properties and observing geometry. The cloud shadow reduces the layer AMF above the shadow pixel. After weighing with a typical NO_2 profile shape the surface layers are most affected, resulting in a reduction of the integrated AMF. For the pixels in between the cloud and ground shadow the (layer) AMF is increased due to the cloud shadow in the atmospheric layers above.

Varying the cloud, surface and geometry parameters showed several interesting features:

1. Larger $|\Delta AMF|$ for higher surface albedo's
2. Larger $|\Delta AMF|$ for optically thicker clouds
3. For low clouds $\Delta AMF < 0$ (surface), for high clouds $\Delta AMF > 0$ (atmosphere)



Layer AMF:

$$AMF_i = \frac{SCD_i}{VCD_i} = \frac{\int_{path} c_i dl}{\int_{z_i}^{z_{i+1}} c_i dz} = \frac{\int_{path} dl}{h_i} = \frac{L_i}{h_i}$$

AMF:

$$AMF = \frac{\sum_l AMF_l \, x_l}{\sum_l x_l}$$

x_l = NO_2 partial column

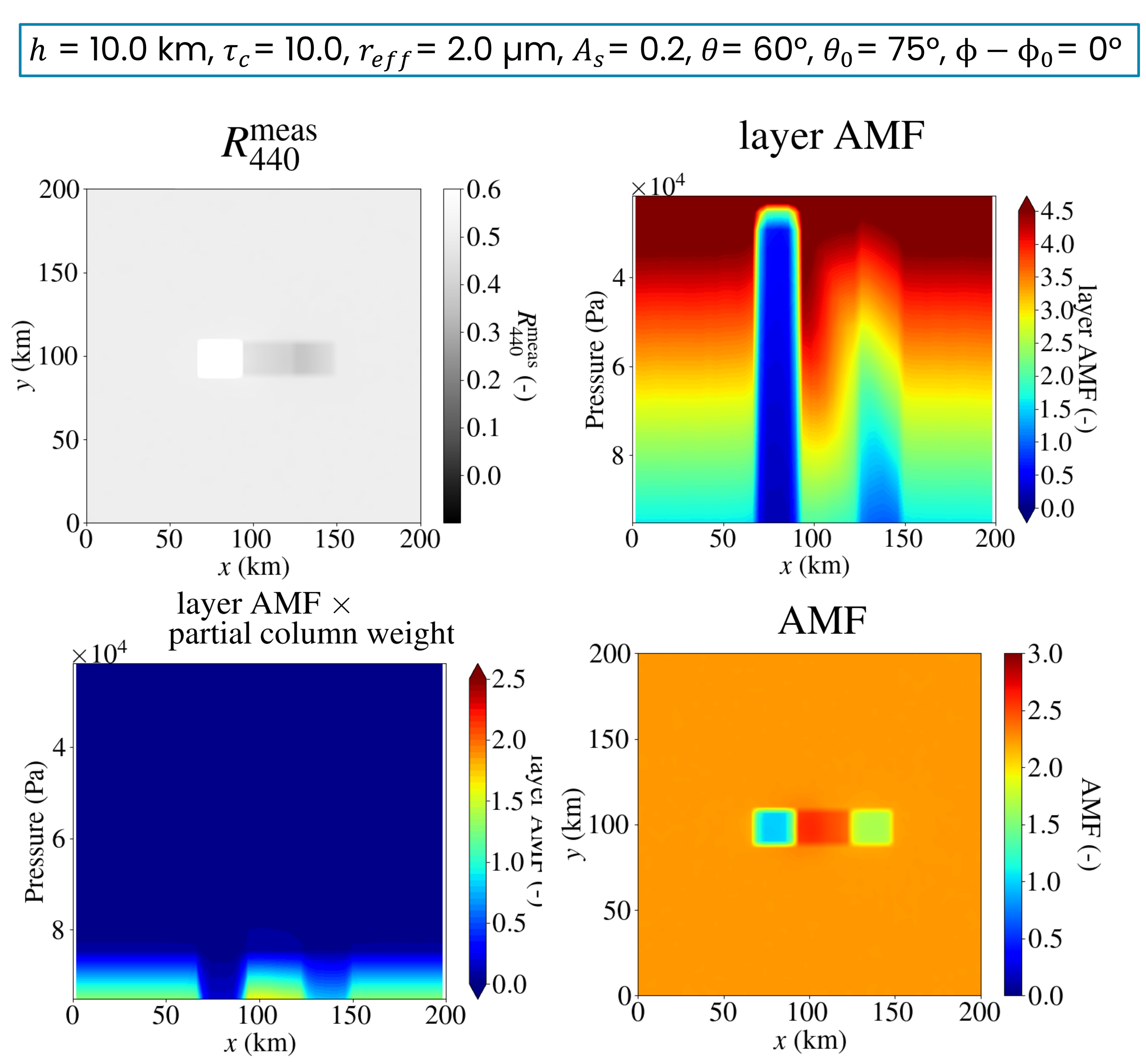


Figure 2: MONKI 3D AMF simulation at 4x4 km of a model cloud. Using Camelot polluted NO_2 profile shape.

Conclusion & Outlook

The expected NO_2 bias in the cloud shadow has not been found yet in S5P data, apart from the algorithm induced enhancement. Model simulations show the theoretical impact on NO_2 retrievals. One potential explanation is that the shadow effect is overshadowed by measurement noise of the NO_2 VCD. Further analysis on this topic is ongoing.

References

- S5P L2 NO2 product: http://www.tropomi.eu/data-products/nitrogen-dioxide
- SUOMI-NPP VIIRS data