Impact of three-dimensional cloud-structures on atmospheric trace gas retrievals

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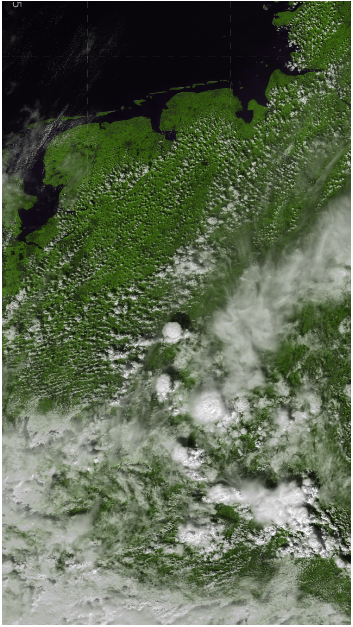
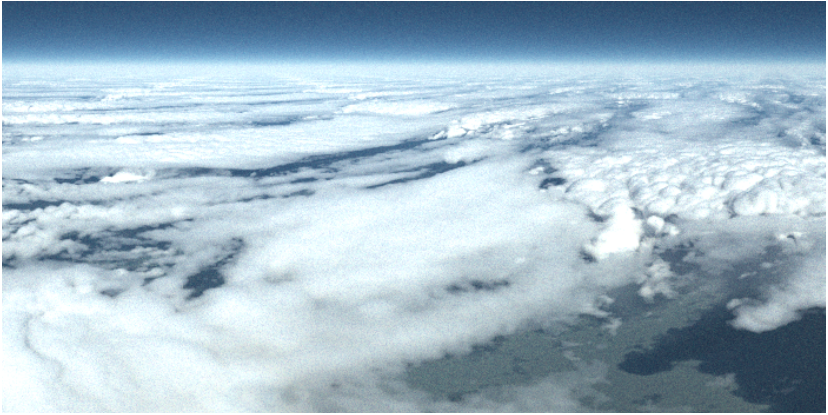
Introduction

- Operational retrievals of tropospheric trace gases from space-borne instruments based on 1D radiative transfer neglect
  1. clouds scattering into clear regions
  2. cloud shadows
- Monte Carlo radiative transfer (MYSTIC-ALIS)
  ⇒ simulation of spectra for realistic 3D model atmospheres
- Application of NO_2 retrieval algorithm on simulated data:
  ⇒ estimation of retrieval error due to 3D cloud scattering



MYSTIC simulation with LES clouds



MYSTIC simulation with clouds from UCLA LES model at 8.4 km altitude (C. Klinger, HD(CP)^2 project).

- Large Eddy Simulation models ⇒ realistic cloud fields
- Monte Carlo radiative transfer (MYSTIC) ⇒ simulation of reflectances, radiances, images ... for LES cloud scenes

3D radiative transfer in high spectral resolution

NO_2 retrieval (DOAS) – fit differential optical thickness

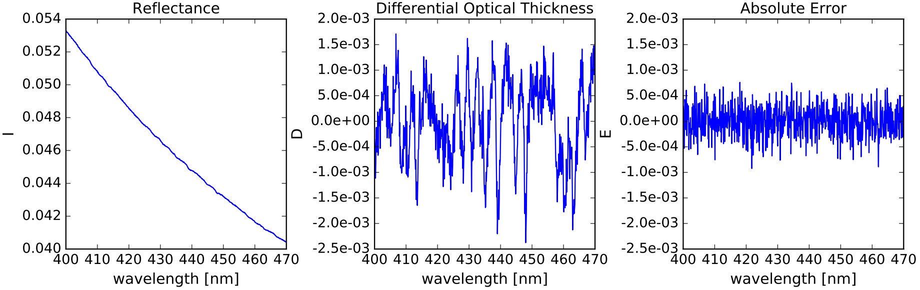
$$D(\lambda) = \ln(I_{TOA}(\lambda)) - P_3(\lambda)$$

I_{TOA}: reflectance, spectral range: $\lambda \approx$ 400-500 nm

Radiative transfer requirements:

$\Rightarrow$ high spectral resolution (resolve characteristic absorption features)

$\Rightarrow$ high accuracy (absorption signal weak compared to Rayleigh continuum)



Standard Monte Carlo method: computational time extremely high

(about 33h for 10^7 photons/wavelength and 0.1 nm spectral resolution!)

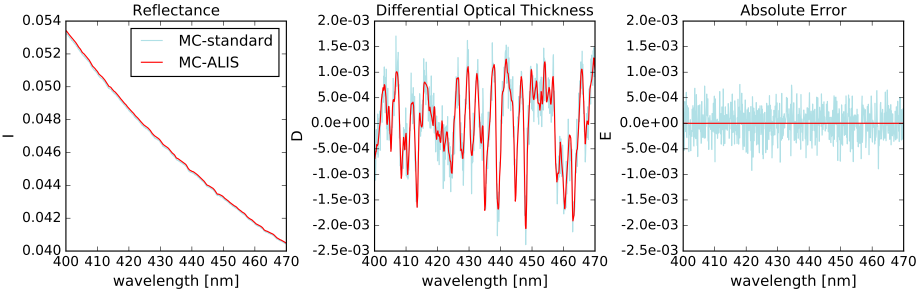
Absorption Lines Importance Sampling

Trace photons at only one wavelength and calculate full line-by-line spectra

Spectral absorption and scattering included by photon weights

Statistical error causes bias (decreasing with $\sqrt{N}$) over full spectral range, not for each wavelength

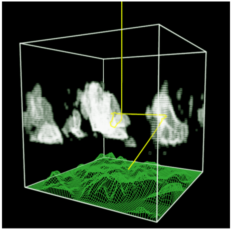
Computational time: 1.5 minutes (comparable to DISORT)



C. Emde, R. Buras, and B. Mayer. *ALIS: An efficient method to compute high spectral resolution polarized solar radiances using the Monte Carlo approach.* JQSRT, 2011

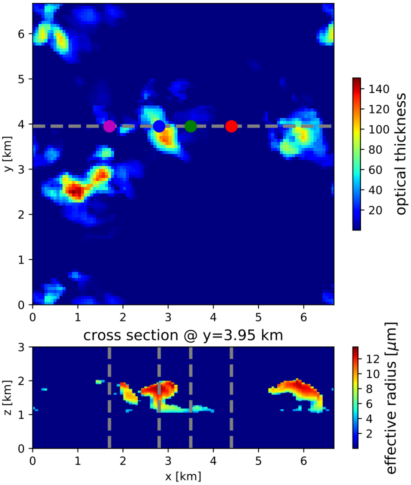
Radiative transfer model MYSTIC

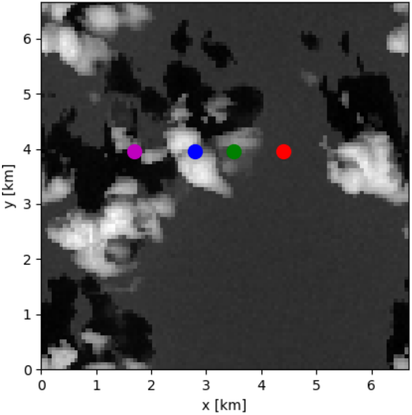
Monte carlo code for the phYSically correct Tracing of photons In Cloudy atmospheres (Mayer 2009)



- *Special features:*
  - Polarized radiative transfer (*Emde et al., 2010*)
  - VROOM: variance reduction methods (*Buras and Mayer, 2011*)
    $\Rightarrow$ radiance calculations for strongly peaked scattering phase functions
  - ALIS method (*Emde et al., 2011*)
    $\Rightarrow$ very efficient high spectral resolution calculations
  - complex topography (*Mayer et al., 2010*)
  - spherical geometry (*Emde and Mayer, 2007*)
  - box-airmass factors in 3D domain
- Integrated in libRadtran package `www.libradtran.org` (*Mayer and Kylling, 2005, Emde et al. 2016*)

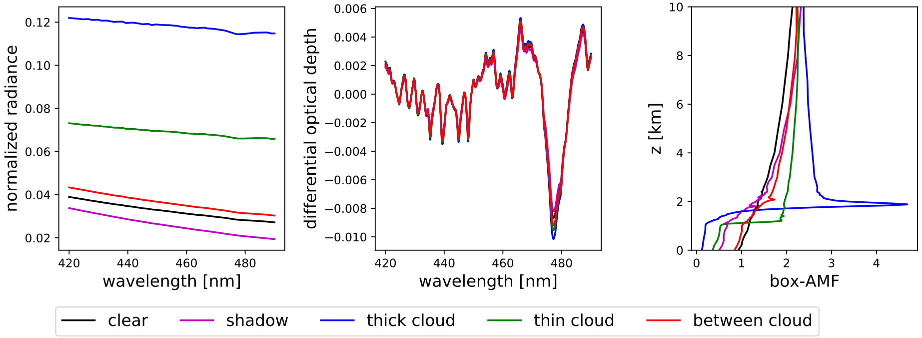
Example simulations for LES cloud field



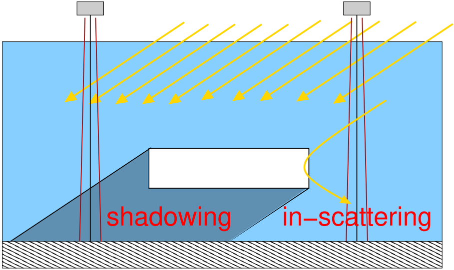


Solar zenith angle: 30°
Surface albedo: 0.1
Reflectance at 450 nm

Example simulations for LES cloud field



Impact of cloud scattering in vicinity of clouds



Base case cloud settings

- cloud base at 2 km altitude
- cloud top at 3 km altitude
- cloud optical thickness: 10
- cloud droplet effective radius 10 μm
- optical properties from Mie calculations

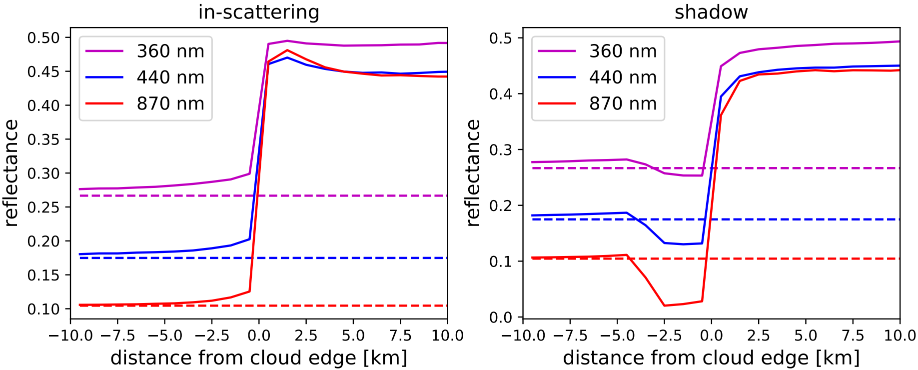
Geometry settings

- nadir observation geometry
- 1x1km^2 square field-of-view
- solar zenith angle: 50°

Other settings

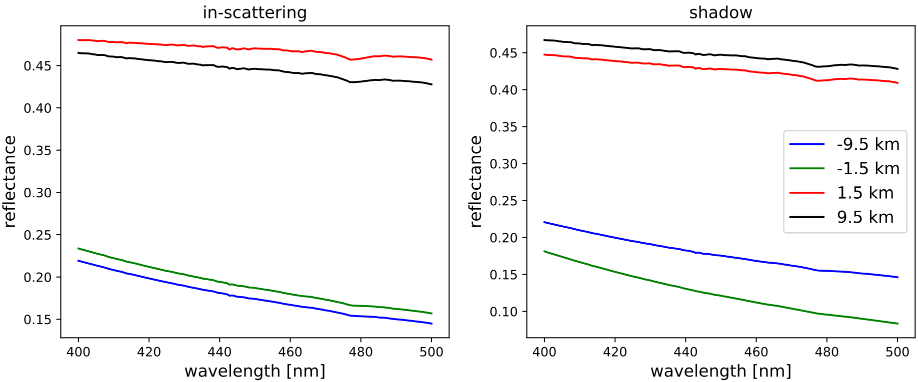
- surface albedo: 0.1
- no aerosol

Reflectance as a function of distance from cloud edge



- *left:* cloud scattering into clear region
- *right:* shadowing

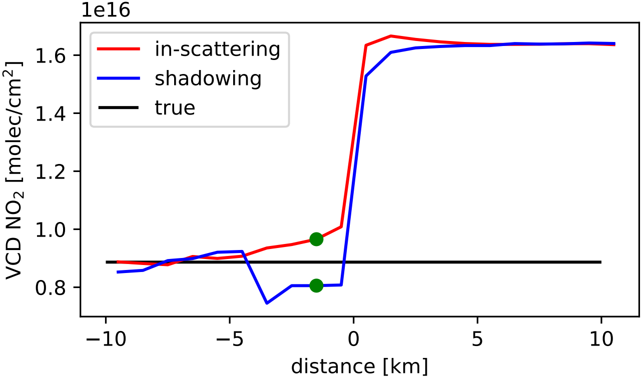
Simulated spectra – VIS



- red and black: spectra for pixels above cloud
- green and blue: spectra for clear pixels
- green line corresponds to pixel from 1-2 km away from cloud edge
  $\Rightarrow$ this pixel is used for sensitivity study

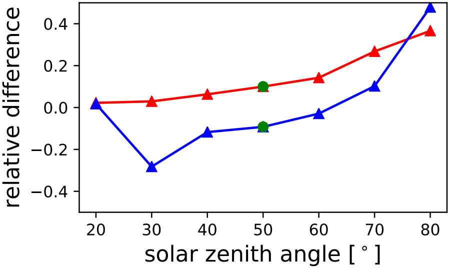
Retrieval error - NO_2 vertical column density

DOAS retrieval algorithm developed at BIRA applied on synthetic spectra ⇒ vertical column density of NO_2



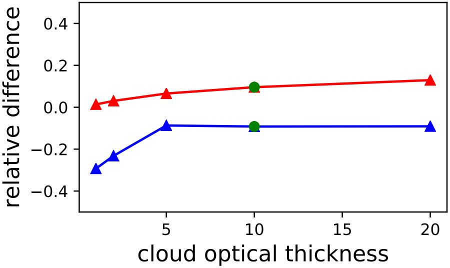
- in clear region (<5 km from cloud edge)
  - VCD underestimation in cloud shadow
  - VCD overestimation due to in-scattering
- error of the order of ≈10%

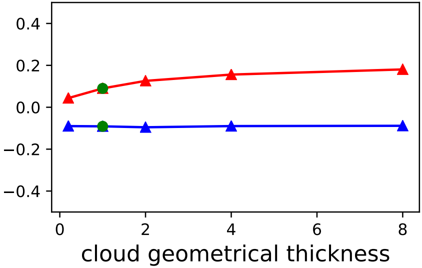
Sensitivity study – NO_2 VCD retrieval error



Preliminary results

Further parameters:
surface albedo
aerosol optical thickness





Summary and Outlook

- Summary:
  - Operational trace gas retrievals (e.g. Sentinel-5P) neglect 3D radiative transfer effects
  - Pixels classified as “clear” can be influenced by clouds (shadows, in-scattering)
  - MYSTIC-ALIS method $\Rightarrow$ simulation of reflectances in high spectral resolution for realistic 3D atmospheres including clouds
  - Sensitivity study: Retrieval error (NO_2 VCD) dependence on distance from cloud edge, solar zenith angle, cloud optical thickness, cloud geometrical thickness
- Next steps:
  - Investigate sub-pixel inhomogeneity for typical Sentinel-5P footprint (3.5×7 km)
  - Perform simulations using realistic LES cloud fields
- ESA Study: “Impact of 3D Cloud Structures on the Atmospheric Trace Gas Products from UV-VIS Sounders”

libRadtran

http://www.libradtran.org
1991 – 2019
Mayer und Kylling, ACP, 2005
Emde et. al, GMD, 2016

spectral range	UV, visible, infrared (250nm-100μm)
model geometry	plane-parallel, spherical, three-dimensional
observer position	surface, air-borne, satellite
absorption	quasi-spectral, correlated-k, line-by-line
RT solvers	DISORT, Monte Carlo, twostream, ...
output quantities	(polarized) radiance, irradiance, heating rate, actinic flux

- Optical properties parameterizations for clouds and aerosols
- Mie tool
- Single scattering lidar and radar simulators

- Validated in various model intercomparison studies
- More than 600 peer-reviewed publications that used libRadtran
- Development partly funded by ESA (ESASLight I+II)