A fast forward operator for the assimilation of visible satellite observations in KENDA-COSMO

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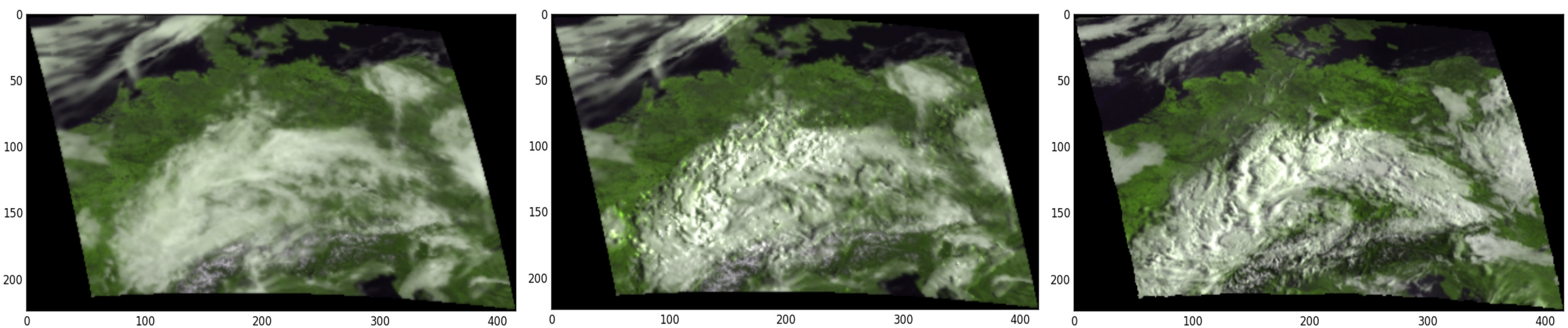
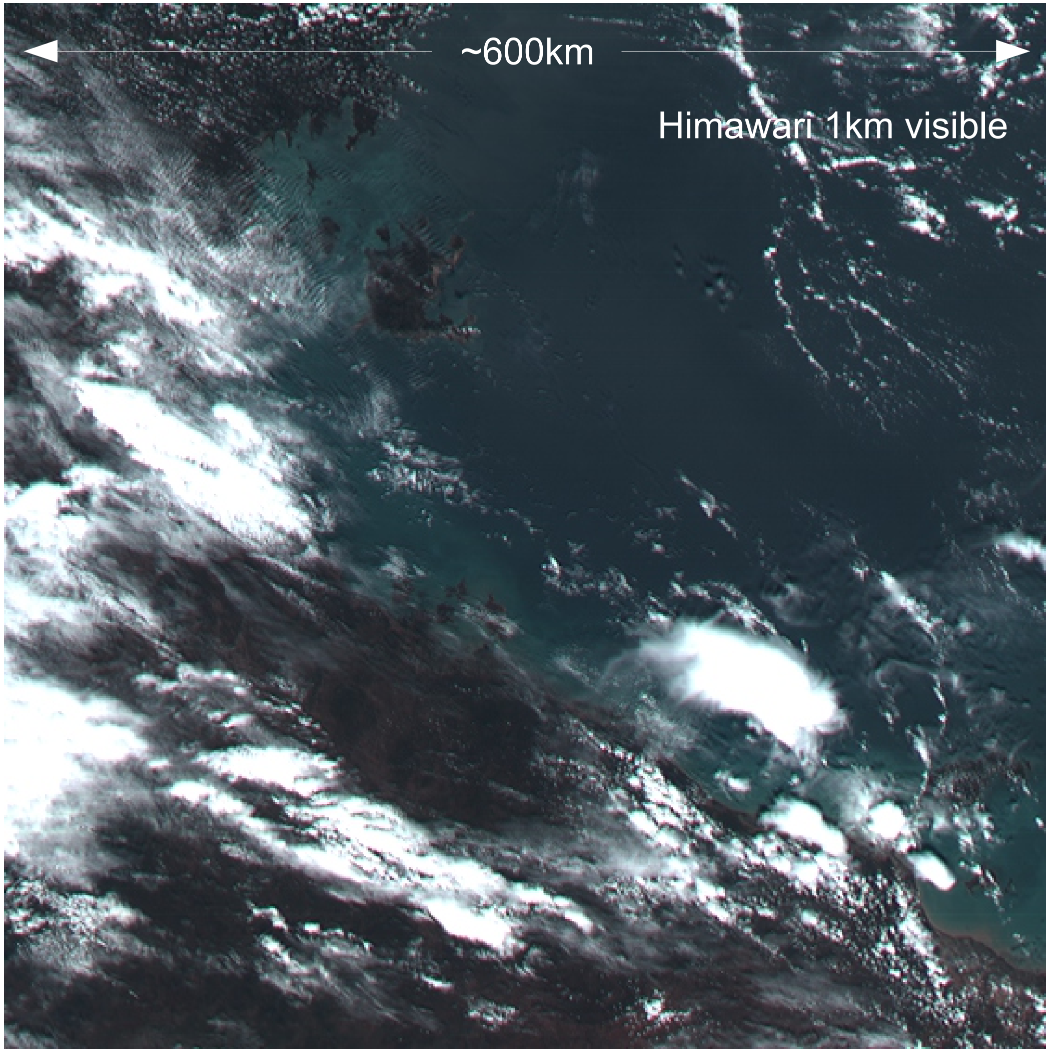


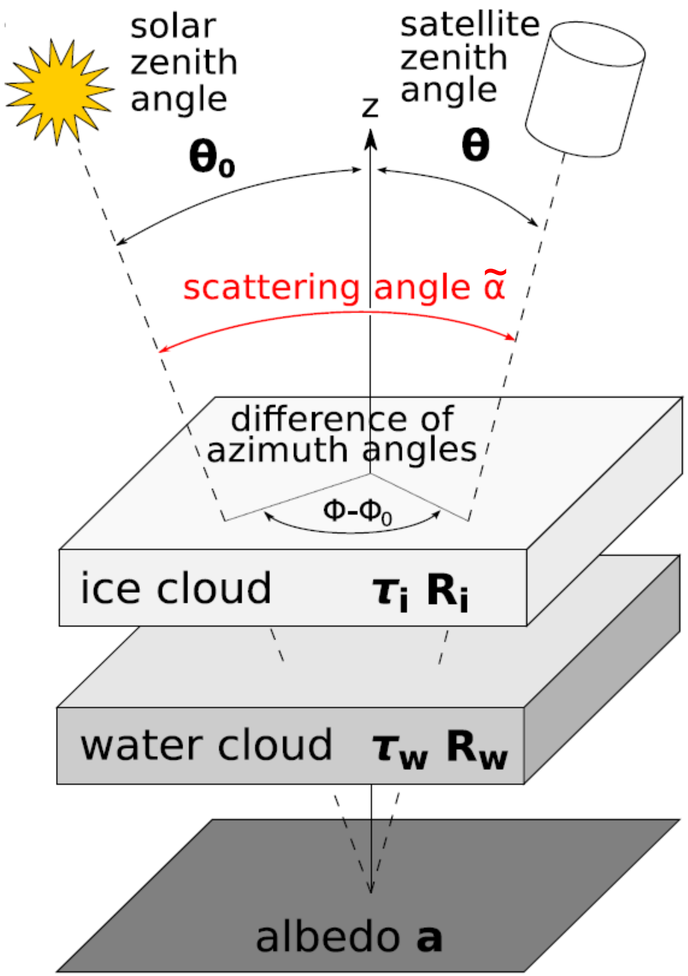
Visible / near-infrared satellite observations for DA

- relevant for **convective scale DA:** high spatial and temporal resolution. Himawari-8/9, GOES-R, MTG: 0.6µm resolution: 500m (IR: 2km) 6-8 of 16 channels λ< 4µm full disc in 5min, target area 30sec
- provide complementary information on **cloud distribution** (convection earlier visible than in radar, low clouds clearly detectable), **cloud properties** (particle size, water phase) and **cloud structure**
- Solar channels are not assimilated in operational DA: **fast forward operators not available** (scattering makes radiative transfer complex) → operator development at LMU



Strategy for fast radiative transfer method MFASIS

Method for Fast Satellite Image Synthesis



Simplifications

- Simplified Equation:
3D RT → 1D RT (plane-parallel, independent columns)
Computational effort for one Meteosat SEVIRI image:
CPU-days (3D Monte Carlo) → CPU-hours (1D DISORT)

- Simplified vertical structure:
Cloud water and ice can be separated to form two two homogeneous clouds at fixed heights without changing reflectance significantly
→ only 4 parameters (optical depth, particle size)
+ 3 angles, albedo → **8 parameters per column**

Reduction of computational effort

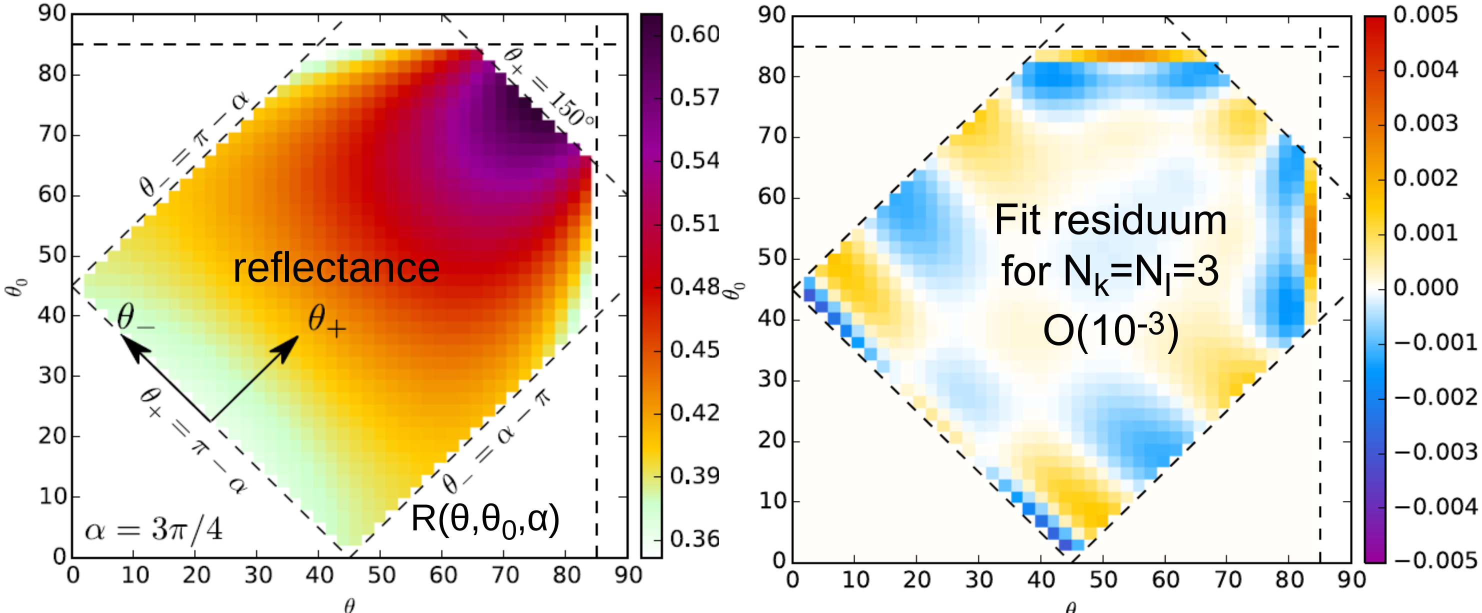
Compute **reflectance look-up table (LUT)** with discrete ordinate method (DISORT) for all parameter combinations
→ effort for looking up reflectances: CPU-minutes

Problem: Table is huge! O(10GB) → not suitable for online operator, slow interpolation → **compress table to 20MB** using truncated Fourier series → CPU-seconds

Look-up table compression in MFASIS

- **Problem:** $R(\theta,\theta_0,\Phi\text{-}\Phi_0)$ contains a lot of rainbow-related small-scale features
- **Solution:** Consider $R(\theta,\theta_0,\alpha)$ instead : smooth function for constant scattering angle α
  → approximate by 2D Fourier series, obtain Fourier coefficients by fit to DISORT results

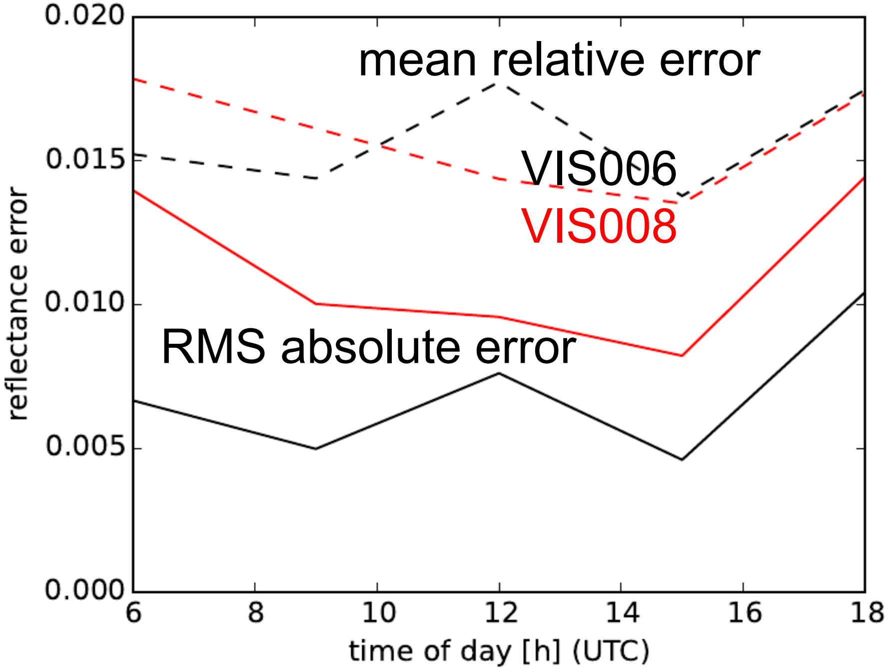
Fit function: $$R(\theta_+,\theta_-) = \sum_{k=0}^{N_k-1} \sum_{l=0}^{N_l-1} \left[C_{k,l}\cos(k\theta_+) + S_{k,l}\sin((k+1)\theta_+)\right]\cos(l\theta_-)$$ where $$\theta_+ = \theta + \theta_0 \qquad \theta_- = \theta - \theta_0$$



We need to store only 18 coefficients C_{kl}, S_{kl} instead of O(1000) reflectance values (for each combination of the remaining 6 parameters) → **compression by a factor of ~O(100)**

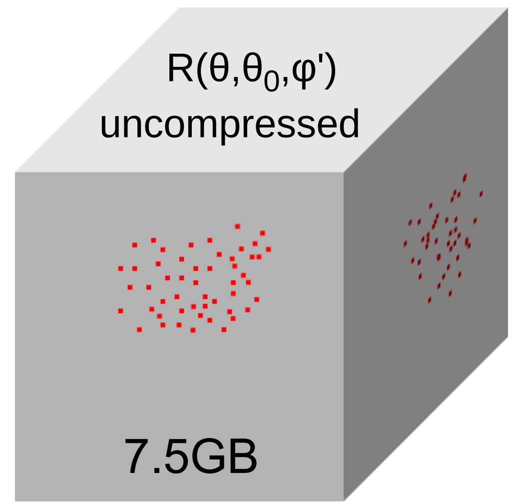
Accuracy and computational effort

Error of MFASIS (8 parameters/pixel) **with respect to DISORT** (full profiles available)
(model data: COSMO-DE fcsts for 10-28 June 2012)



Relative error < SEVIRI calibration error (~4%) for almost all pixels

Computational effort per column:
DISORT (16 streams): 2.3 x 10^{-2} CPUsec
MFASIS (21MB table): 2.5 x 10^{-6} CPUsec
(on Xeon E5-2650, for 51 level COSMO data)



Impact of compression on performance?

Without compr.: LUT >> cache → slow…

compression → cache used efficiently

CPU cache
20MB

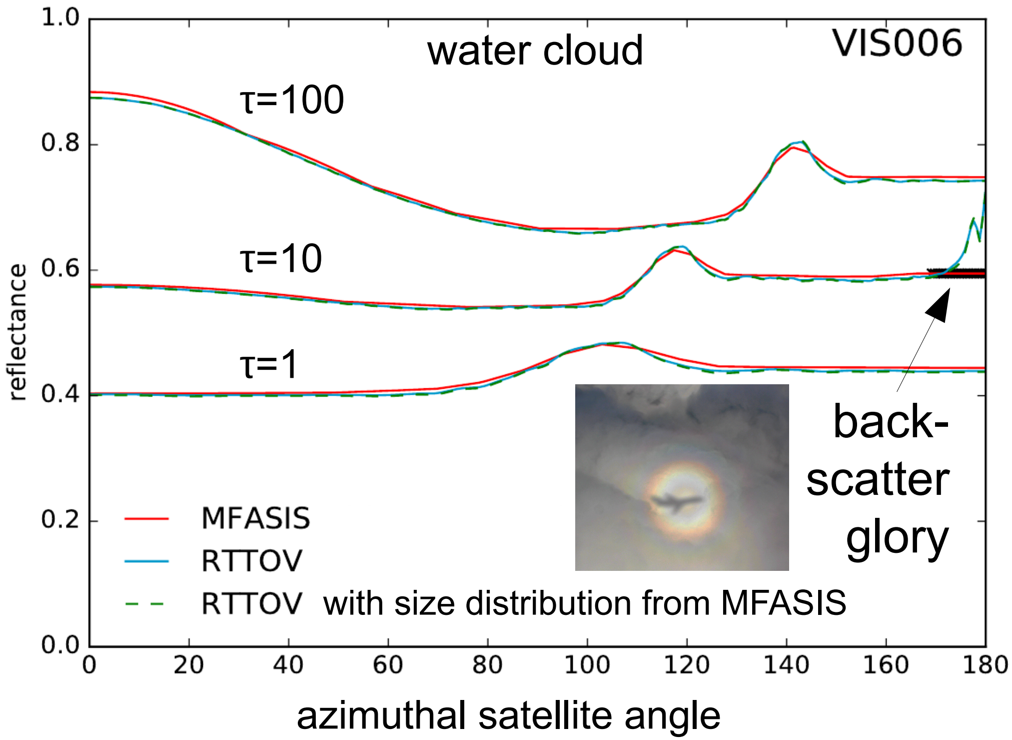
$R(\theta,\theta_0,\alpha)$, compressed
21MB

Scheck et al. 2016: *A fast radiative transfer method for the simulation of visible satellite imagery*, JQSRT, 175, pp. 54-67

Comparison with RTTOV-DOM

(with J. Hocking, R. Saunders)

RTTOV-DOM: Implementation of DISORT in development at MetOffice / NWP-SAF
MFASIS & RTTOV-DOM were compared in the framework of DWDs NWP-SAF contribution

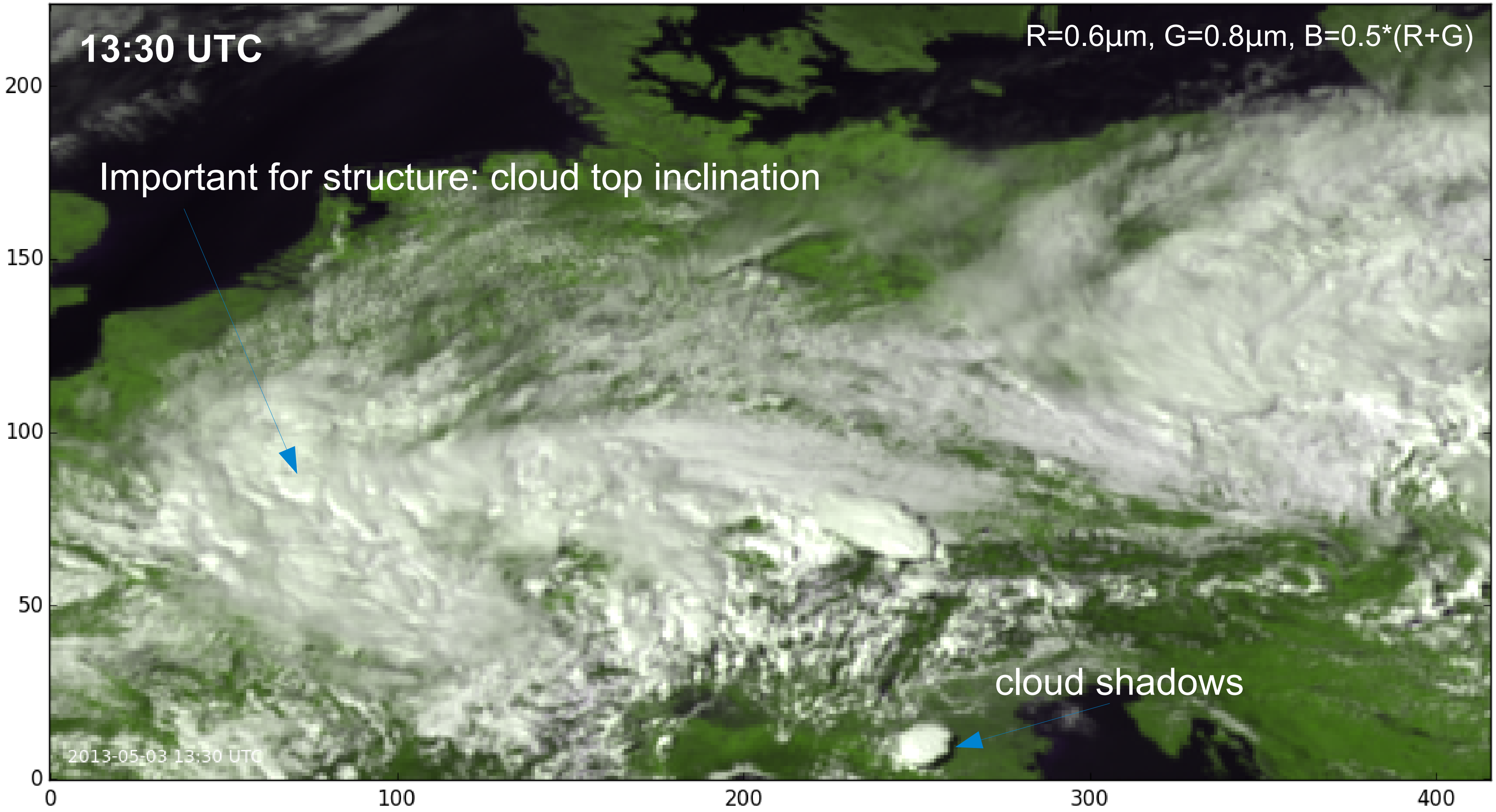


See http://www.nwpsaf.eu/vs_reports/nwpsaf-mo-vs-054.pdf

Results:

- **Reflectances for clouds agree well!**
- Backscatter glory: reduced accuracy depends on unknown width of size dist.
- Clear sky contributions problems:
  - -In MFASIS only a constant profile of water vapour is taken into account, which affects the 0.8µm channel (can be solved, work in progress)
  - - RTTOV-DOM: no multiple cloud - clear-sky scattering processes → negative reflectance bias
- **MFASIS will be included in RTTOV**

3D effects not accounted for in 1D radiative transfer



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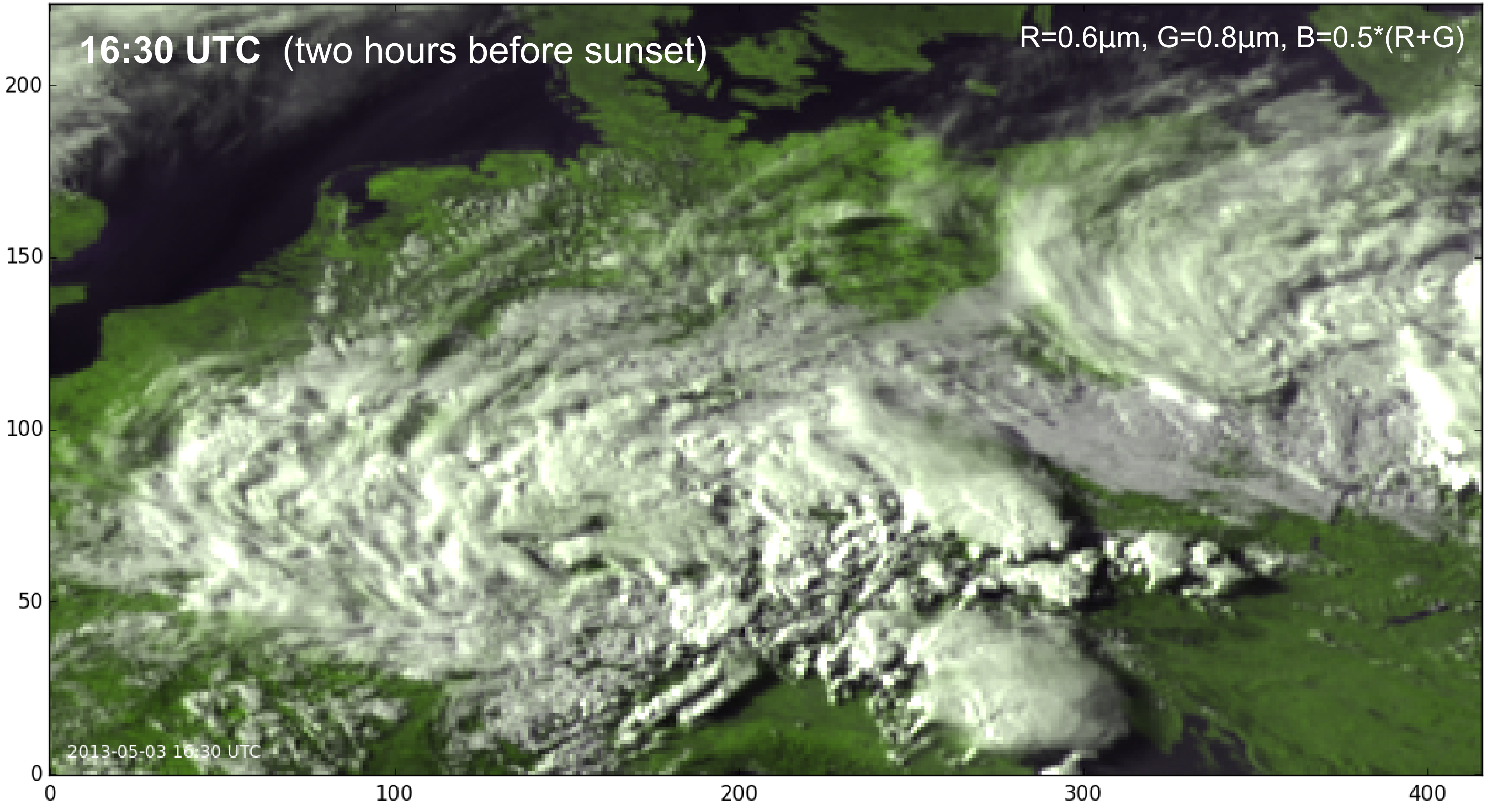
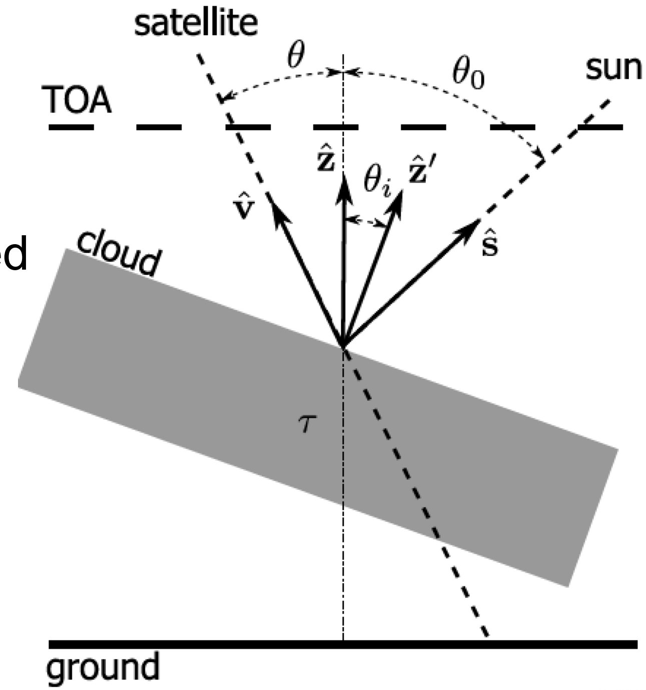
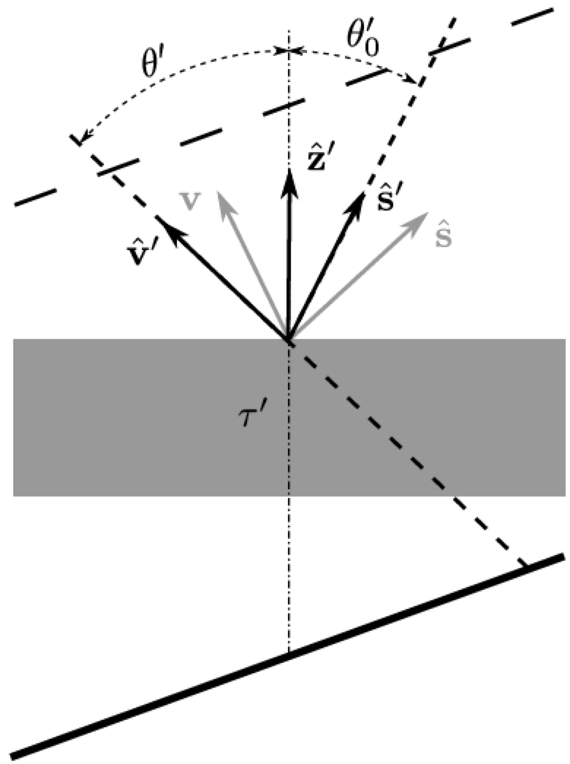


Cloud top inclination correction

inclined cloud (3D)



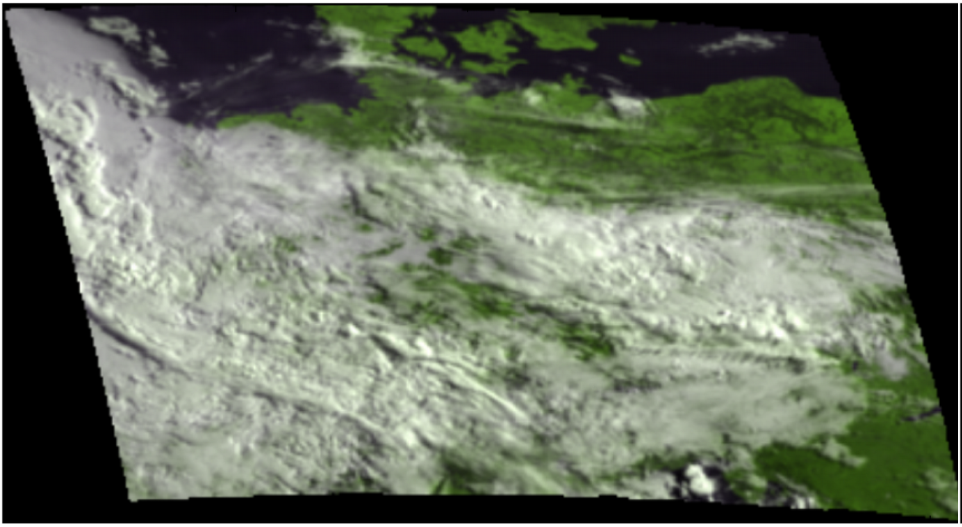


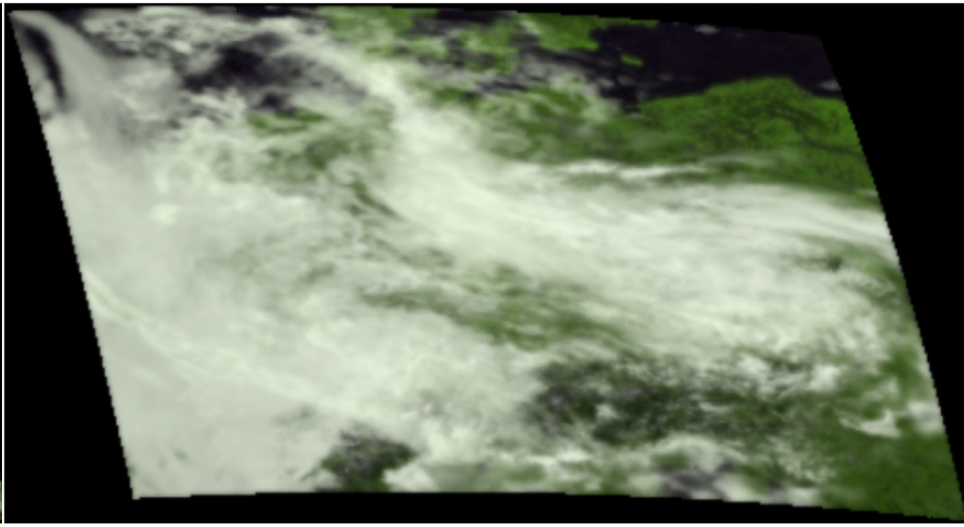
plane-parallel cloud (1D)

$$R_T(\theta,\theta_0,\alpha,A,\tau,\theta_i) = R(\theta',\theta_0',\alpha,A',\tau\cos\theta_i)\,\frac{\cos\theta_0'}{\cos\theta_0}$$

Rotated frame of reference with ground-parallel cloud → nearly a 1D problem (inclined ground is taken into account by using a modified surface albedo)
→ Solve modified 1D problem, transform back to non-rotated frame.

Cloud top inclination





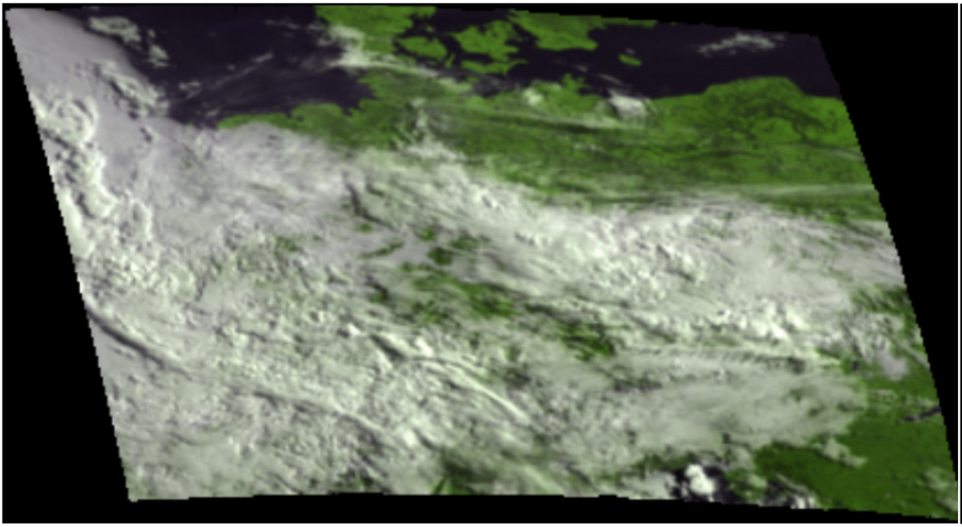
SEVIRI 0.6mu+0.8mu, 3 June 2016, 6UTC

3h COSMO fcst **without 3D correction**

Cloud top definition : optical depth 1 surface
(detect tau=1 in all columns, fit plane to column and 8 neighbour columns)

Cloud top inclination correction → Increased information content
Much more cloud structure is visible, in particular for larger SZAs
For instance, one can distinguish convective from stratiform clouds

Cloud top inclination



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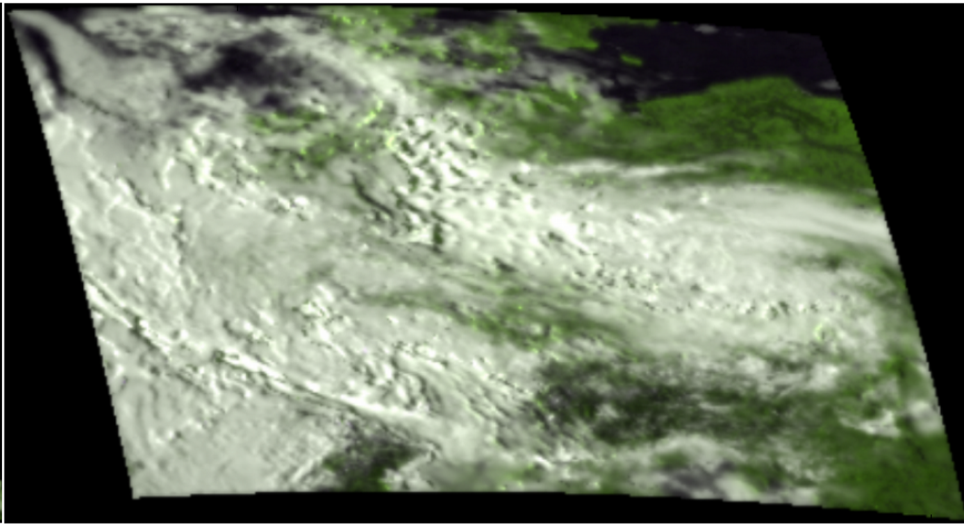

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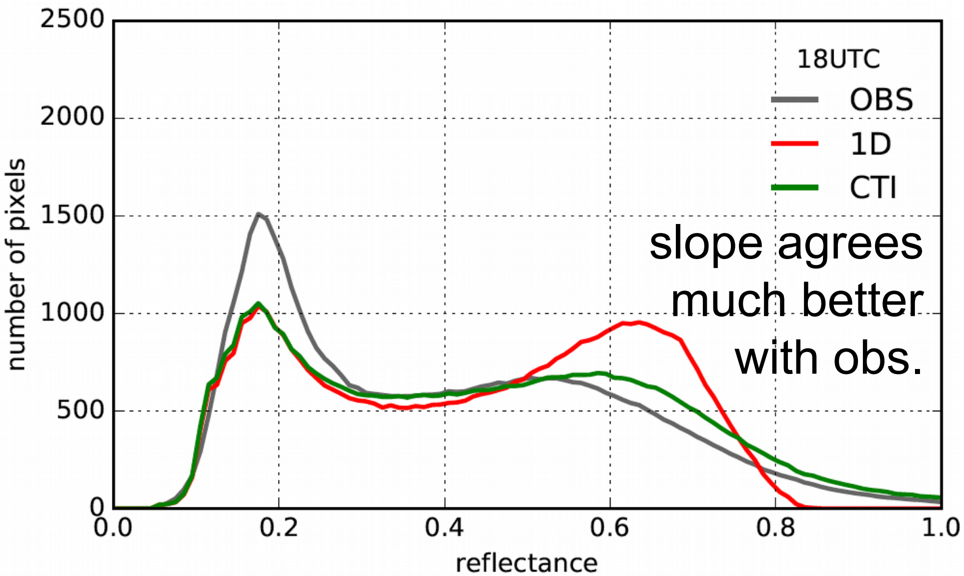
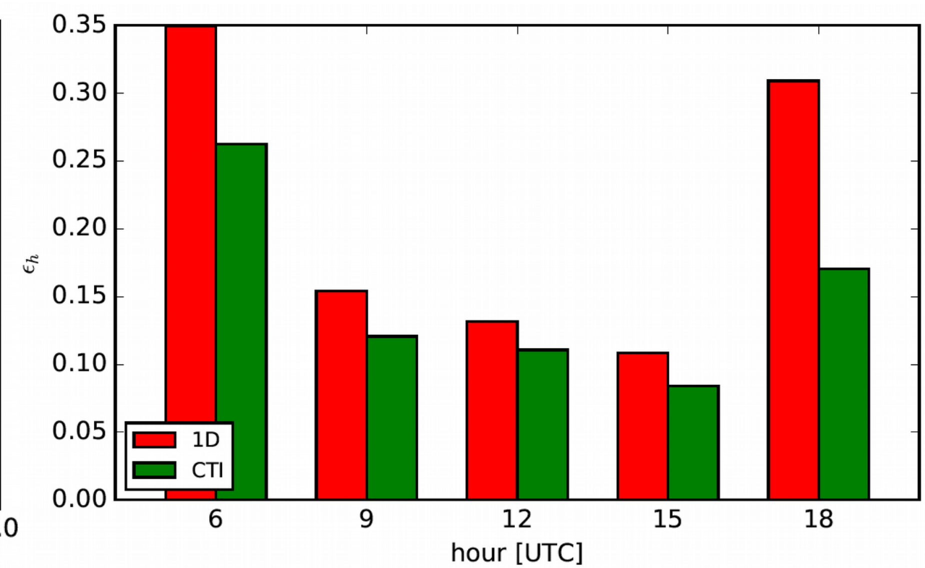




0.6mu reflectance histograms for 18UTC

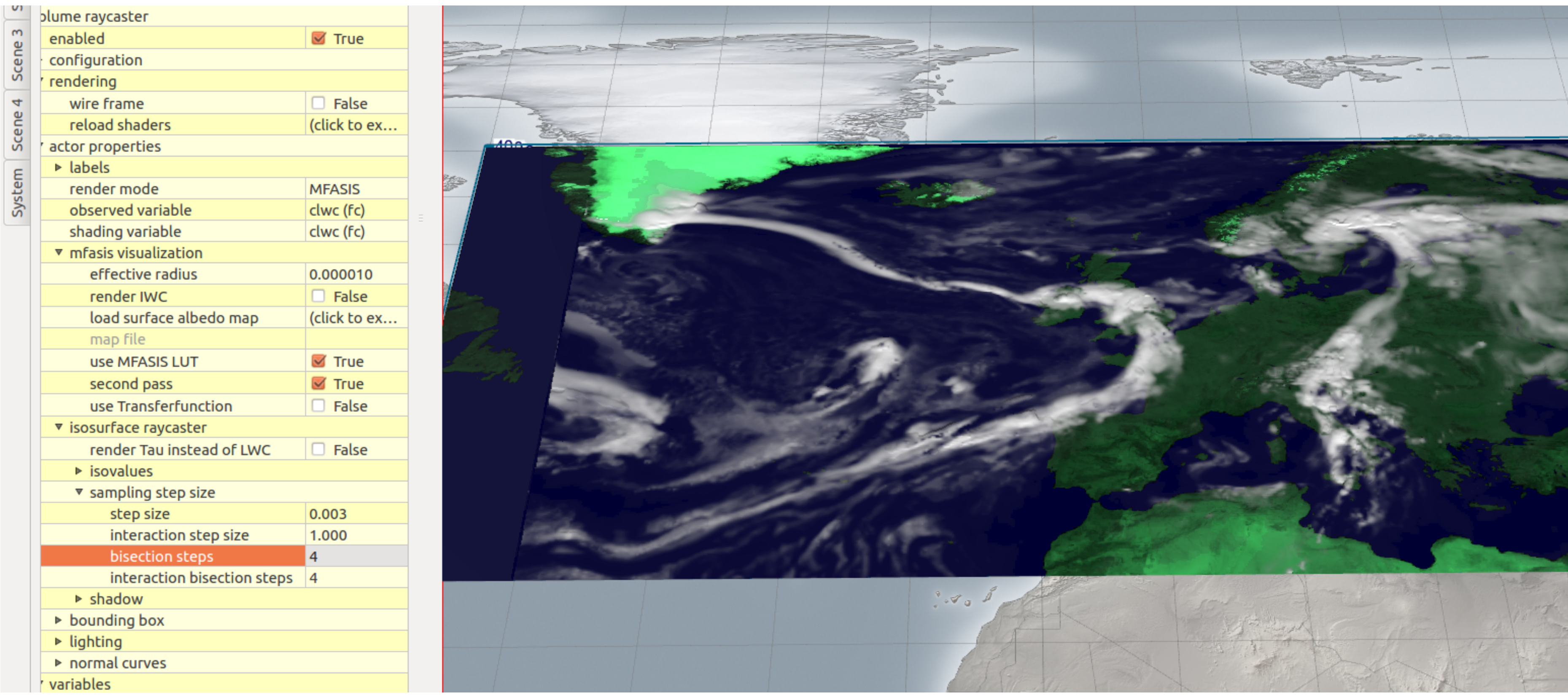
area between obs.& model histogram

Cloud top inclination correction → Systematic errors are reduced
in particular for larger SZA, but some impact is always visible

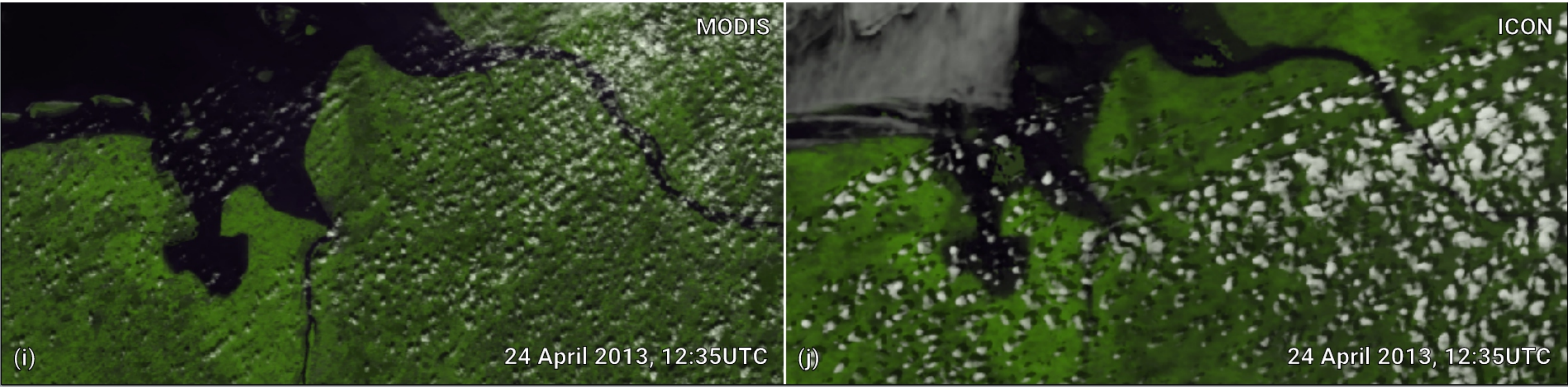
Computational effort: Small (only tau=1 detection + one additional MFASIS call)
It should even be possible to include it in the real-time version (work in progress)

MFASIS + 3D correction in real-time on GPUs

Master thesis by Theresa Diefenbach (“Waves to Weather”, Tobias Selz)
MFASIS in Met3D (Marc Rautenhaus, TUM), runs interactively with ~10 frames/sec



A second 3D correction: Cloud shadows on the ground

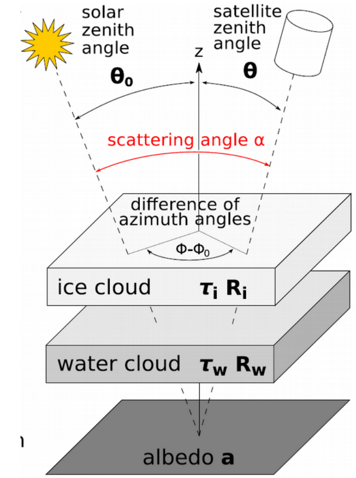


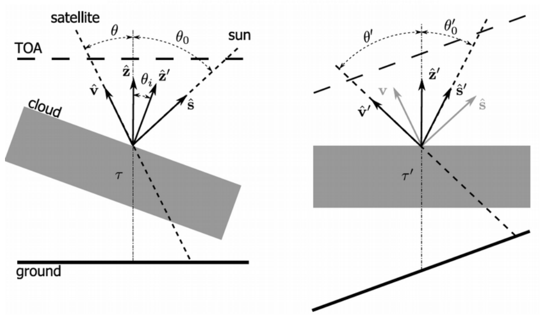
Example: MODIS image + model equivalent for 150m resolution ICON run from HD(CP)^2
(see Heinze et al. (2017) “Large-eddy simulations over Germany using ICON”, QJRMS)

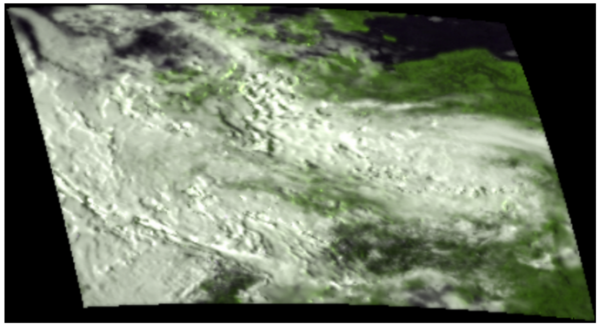
- Important for deep convection and broken cloud fields, in particular for 0.8µm
- Columns tited towards sun → shadow position. Brightness of shadows will often be dominated by diffuse radiation (problematic...)
- Preliminary implementation in operator version for the ICON model (parallel offline, MESSy online), used for model evaluation (e.g. cloud size statistics) in HD(CP)^2

Summary & Outlook

- Visible & near-infrared channels could provide useful information for convective scale DA
- We have developed MFASIS, a 1D RT method that is sufficently fast for operational DA
- The most important 3D RT effect is related to the inclination of cloud tops and can be taken into account approximately in a efficient way
- Cloud shadows have been included in a preliminary ICON version of the operator
- First assimilation experiments with DWD KENDA (LETKF) are promising, more experiments with new operator version will be performed soon…
- NWP-SAF: MFASIS will be integrated into RTTOV (work in progress at DWD, MetOffice, LMU)







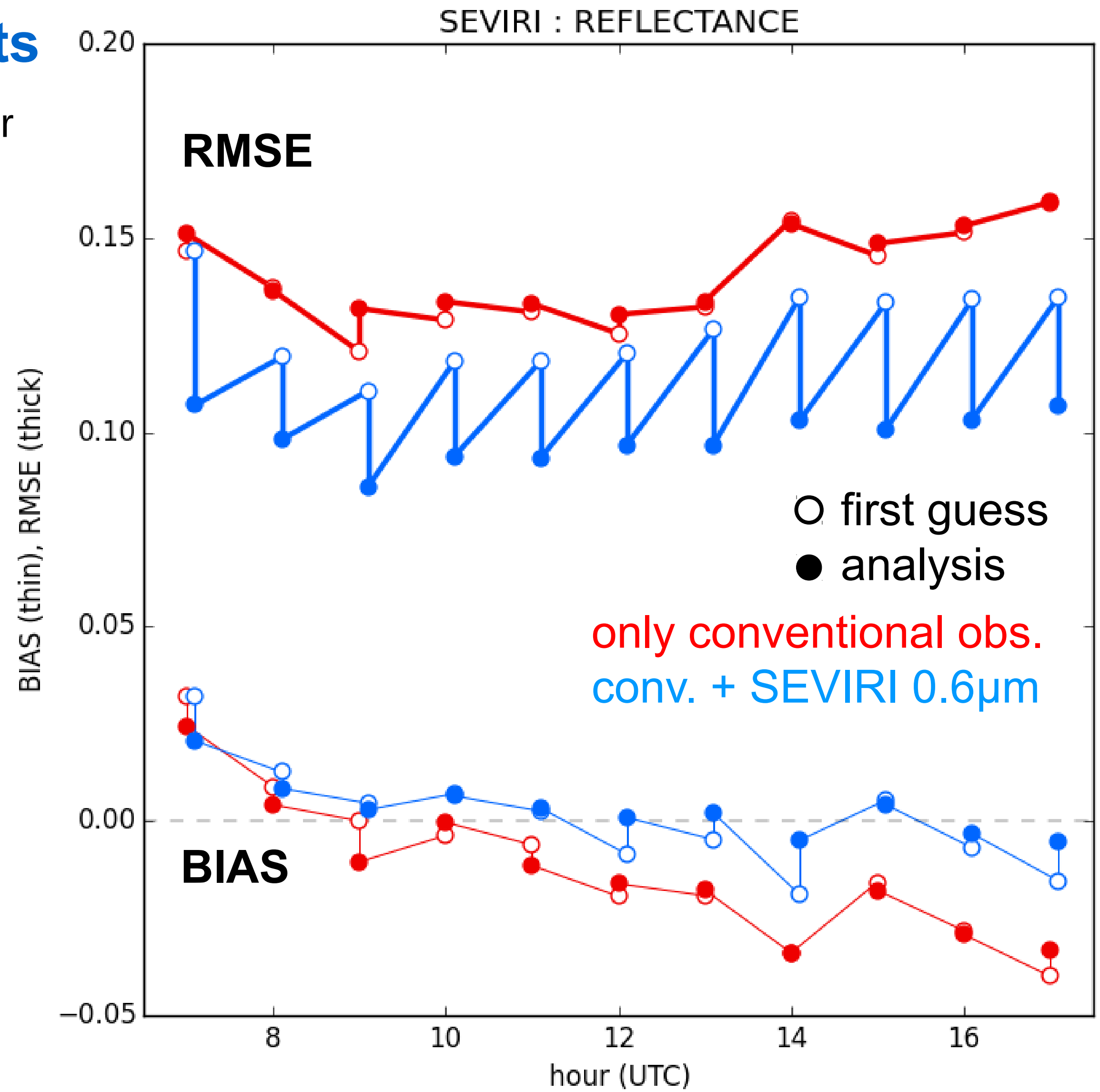
First assimilation results

Assimilation of conventional and/or SEVIRI obs. in COSMO/KENDA

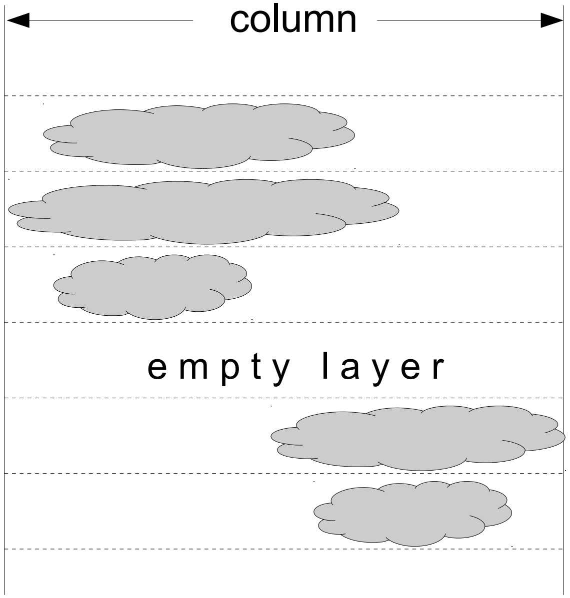
Setup:
40 member LETKF
1h assimilation interval
0.6µm observations
Observation error 0.2
Superobbing (radius 3 pixels)
Horiz. localization 100km
No vertical localization

Assimilation of SEVIRI observations:
lower reflectance RMSE and bias

Independent GPS humidity observations: reduced error



Subgrid cloud overlap



Common for NWP models: **Subgrid clouds** covering only a fraction of the grid cell are assumed to exist where relative humidity exceeds critical value.

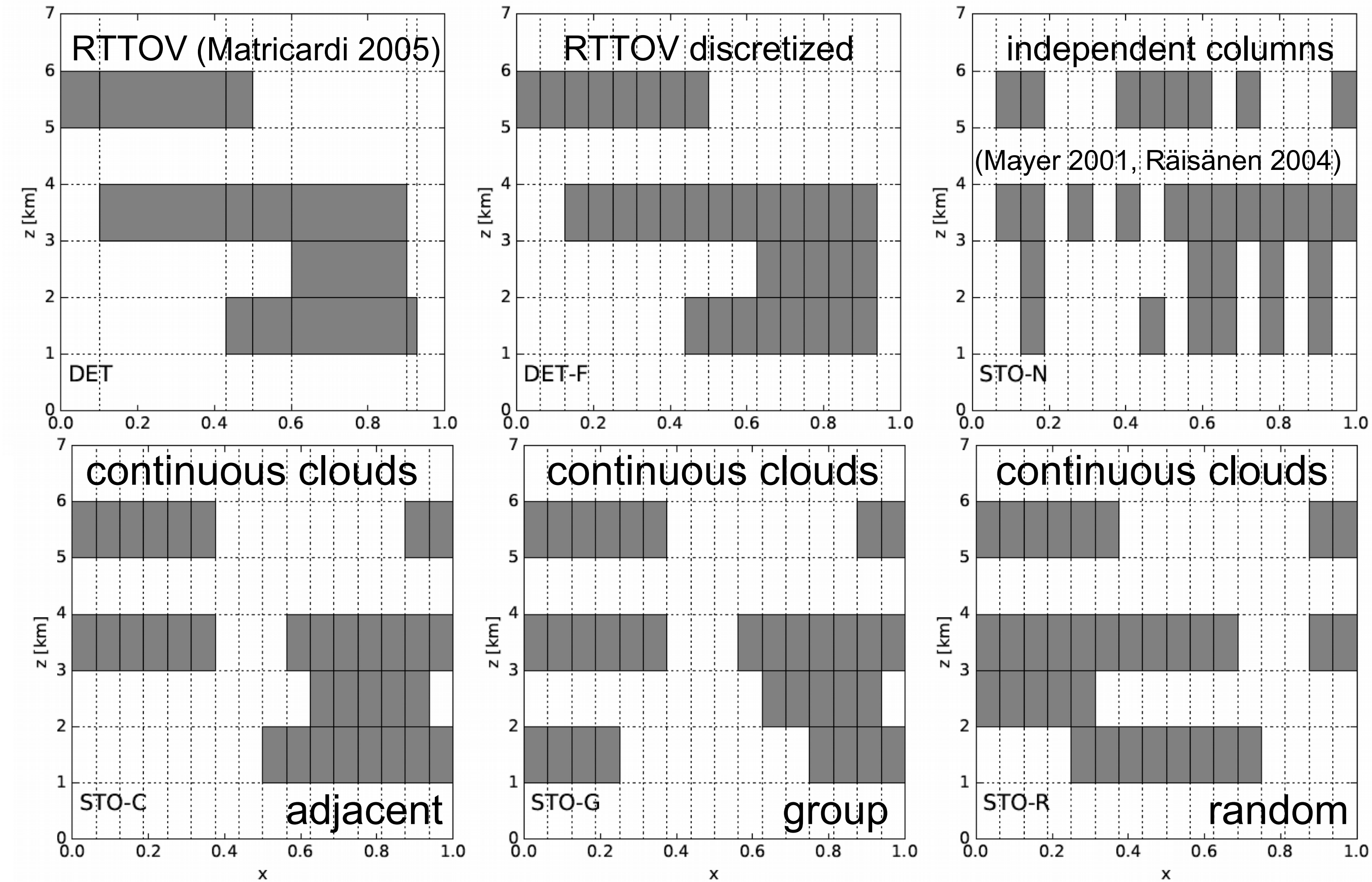
Two or more partially cloudy cells in one column: **How do they overlap?** Affects heating, reflectance

COSMO: **Random-maximum overlap rules:** Clouds in adjacent layers overlap maximally, clouds separated by empty layers overlap randomly.

Deterministic schemes: Estimate mean reflectance of all allowed configurations
Stochastic schemes: Compute reflectance for one random realization (spread quantifies uncertainty in cloud distribution)

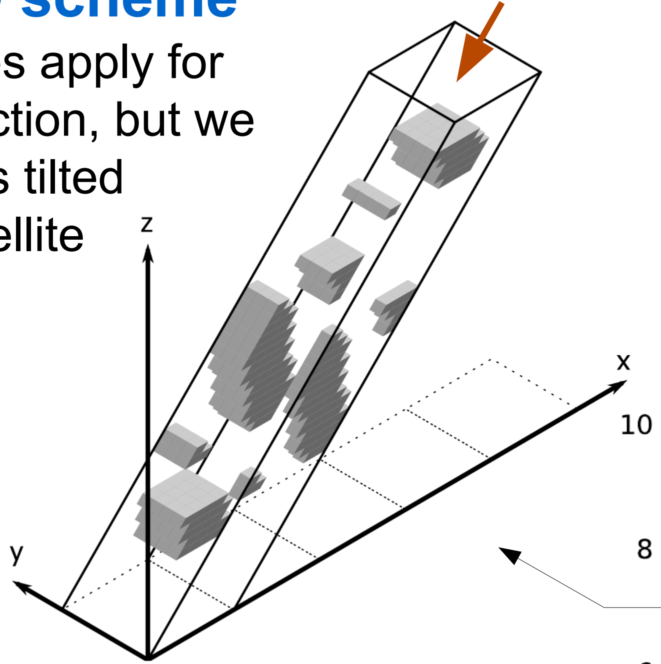
Several schemes were compared to address these questions:
- How well do different deterministic and stochastic implementations agree?
- Is the spread large enough to be relevant for DA?
- Should the slant viewing path of the satellite be taken into account?

Common strategy: Subdivide column, fill subgrid cells according to overlap rules (different cloud size dist. possible), perform RT for each subcolumn, average results



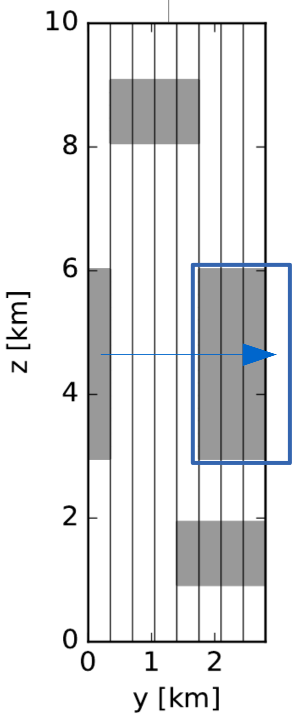
A new 3D scheme

Overlap rules apply for vertical direction, but we use columns tilted towards satellite



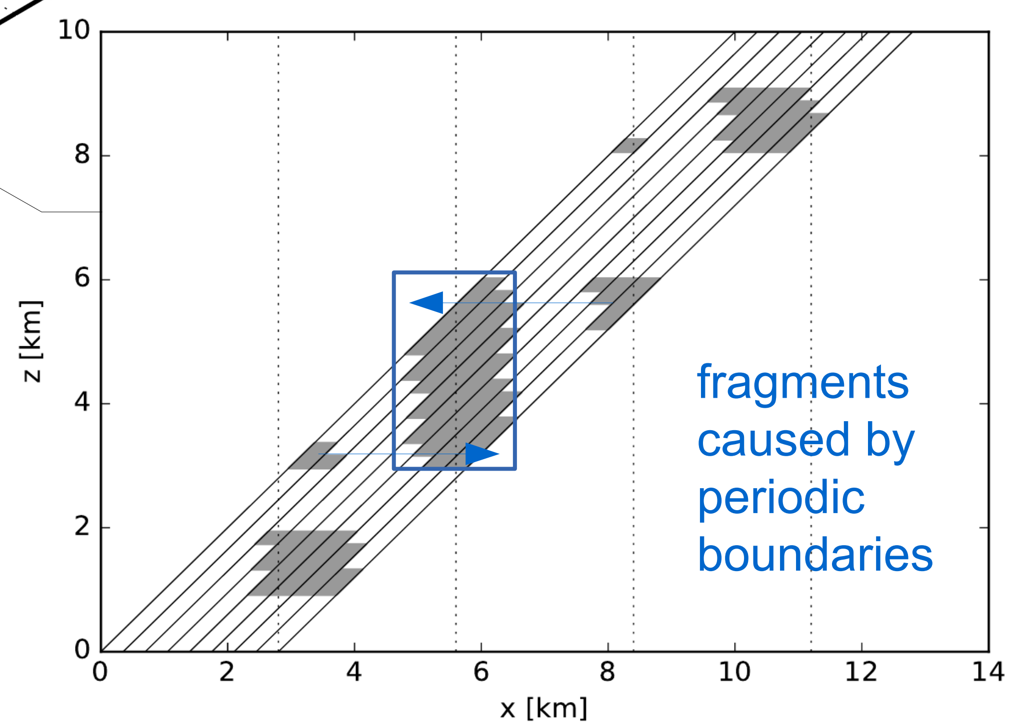
Approach: Use bundle of N x N sub-columns (3D), compensate for slant viewing path by shifting clouds into x-direction in each layer

Example: 3 clouds with constant cloud fraction 0.25 spanning several layers
→ vertical clouds, consistent with model

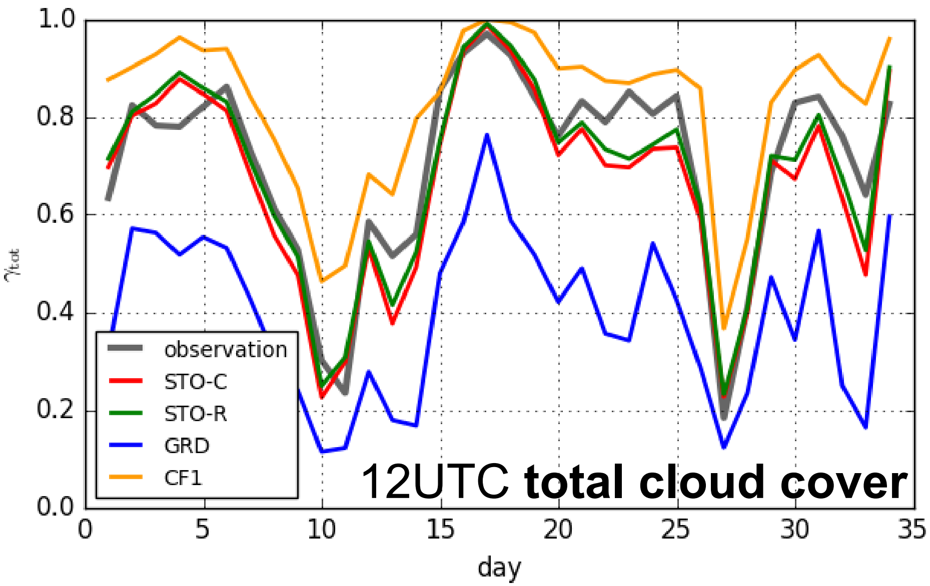


→ **Increased total cloud cover**
(also cloud sides contribute)

Not more expensive than 2D schemes.



Results for operational COSMO forecasts in June 2016



SEVIRI observation

grid scale clouds only

Subgrid cloud fraction 1

random overlap (2D)

random-maximum overlap (2D)

→ **It is essential to take cloud overlap into account!**

Random vs. rand.-max. overlap: Local differences can be significant, ensemble mean random - randmax can be > 0.1, i.e. several 10%

Rand.-max. 2D implementations: very similar results, ~10 subcolumns are sufficient

3D implementation (most consistent): ~same impact as rand./max. → random (at latitude ~45°, stronger effect for higher lats.)

Spread is small, > 0.01 only in ~15% of pixels → probably not relevant for DA