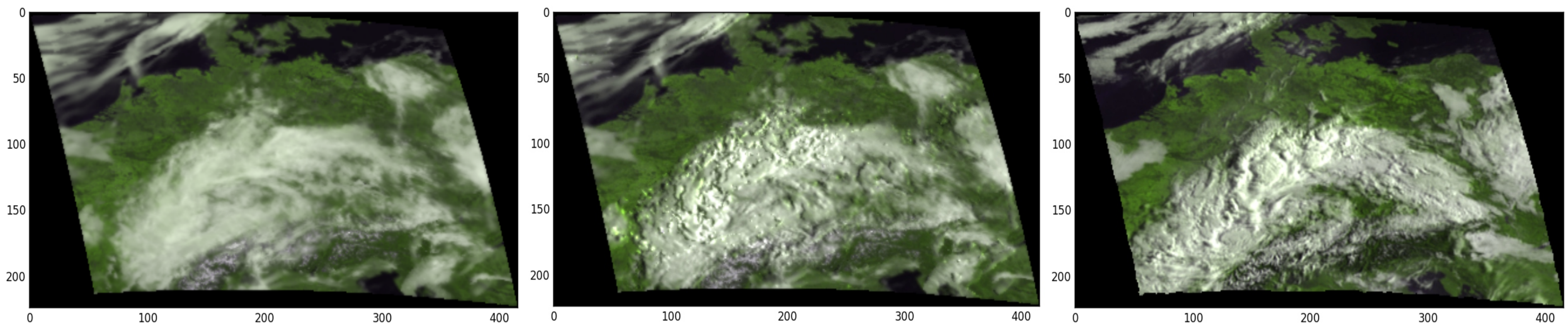
Using visible and near-infrared satellite observations for convective-scale data assimilation

Leonhard Scheck[1,2], Bernhard Mayer[2], Martin Weissmann[1,2]

1) Hans-Ertl-Center for Weather Research, Data Assimilation Branch
2) Ludwig-Maximilians-Universität, Munich



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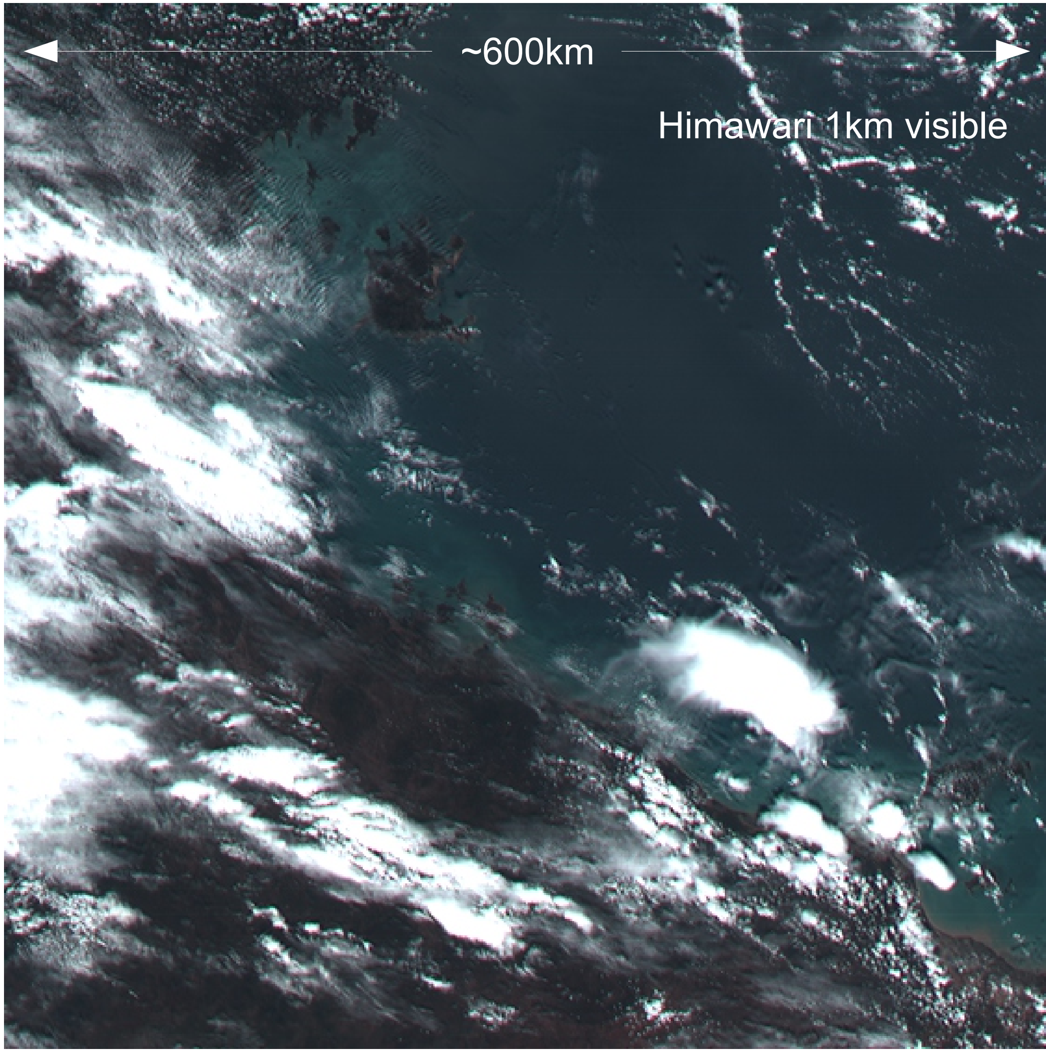
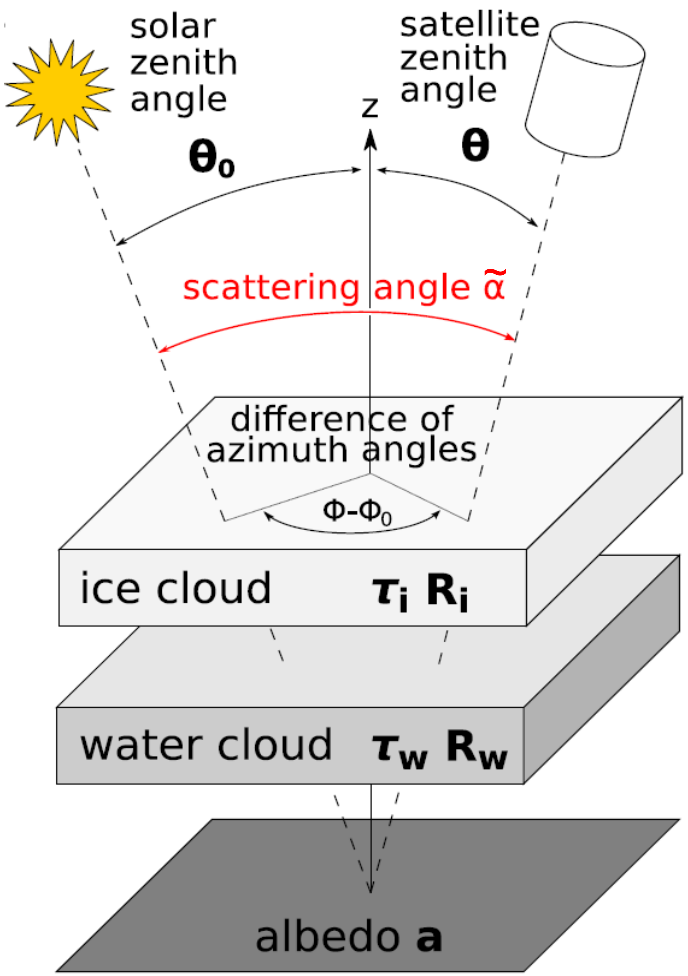
Visible / near-infrared satellite observations for DA

- 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 HErZ



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**

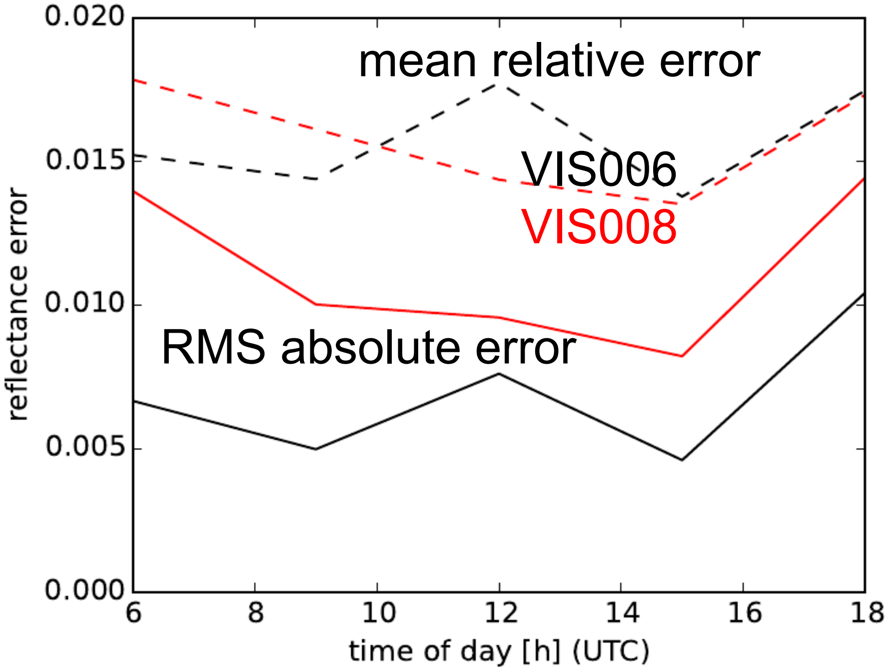
Reduction of computational effort

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

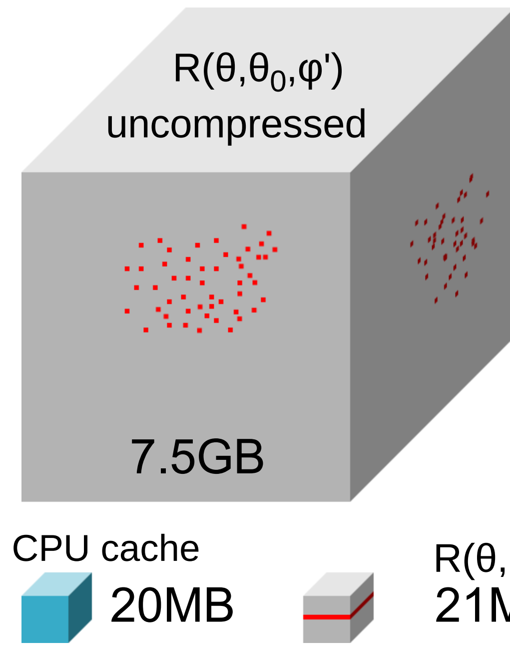
Accuracy and computational effort

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…

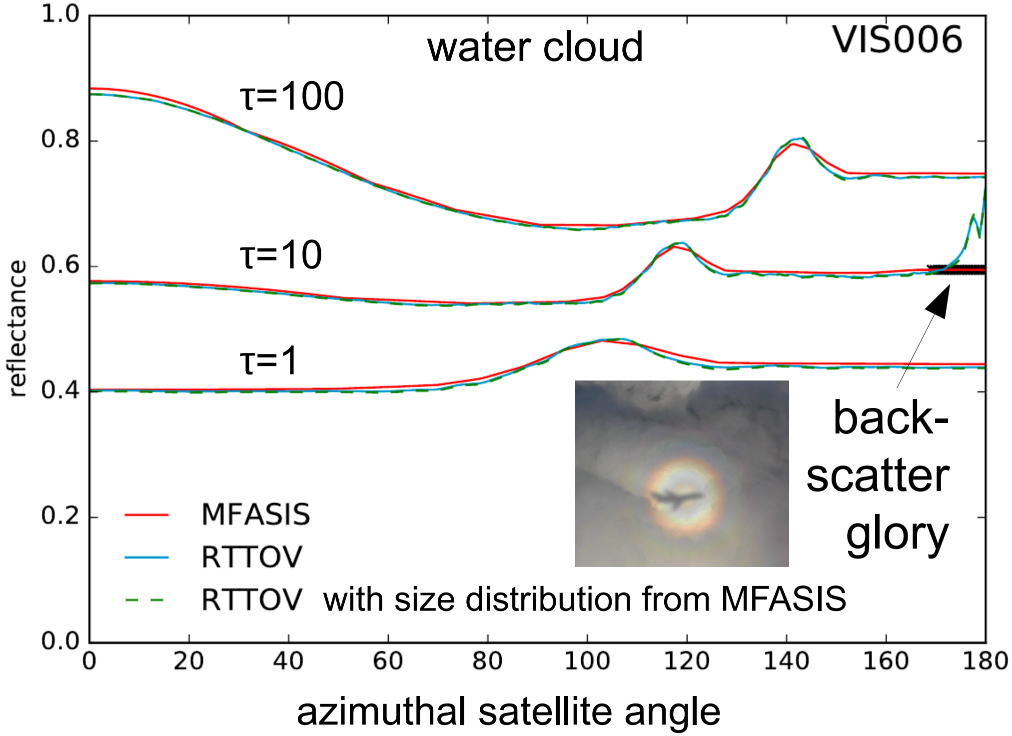
compression → cache used efficiently

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 (affects the 0.8µm channel)

  Requires height-dependent reflectance correction (work in progress)

  - RTTOV-DOM: no multiple cloud - clear-sky scattering processes → negative reflectance bias

Improving accuracy and consistency

Having a fast and sufficiently accurate 1D RT solver is not enough...

Errors sources in the operator
Approximations (e.g. missing 3D),
Inconsistencies (e.g. subgrid clouds)
missing information (→ spread)

Errors in the NWP model state
e.g. cloud displacement (random),
cloud cover bias (systematic)

→ **Errors in synthetic images**

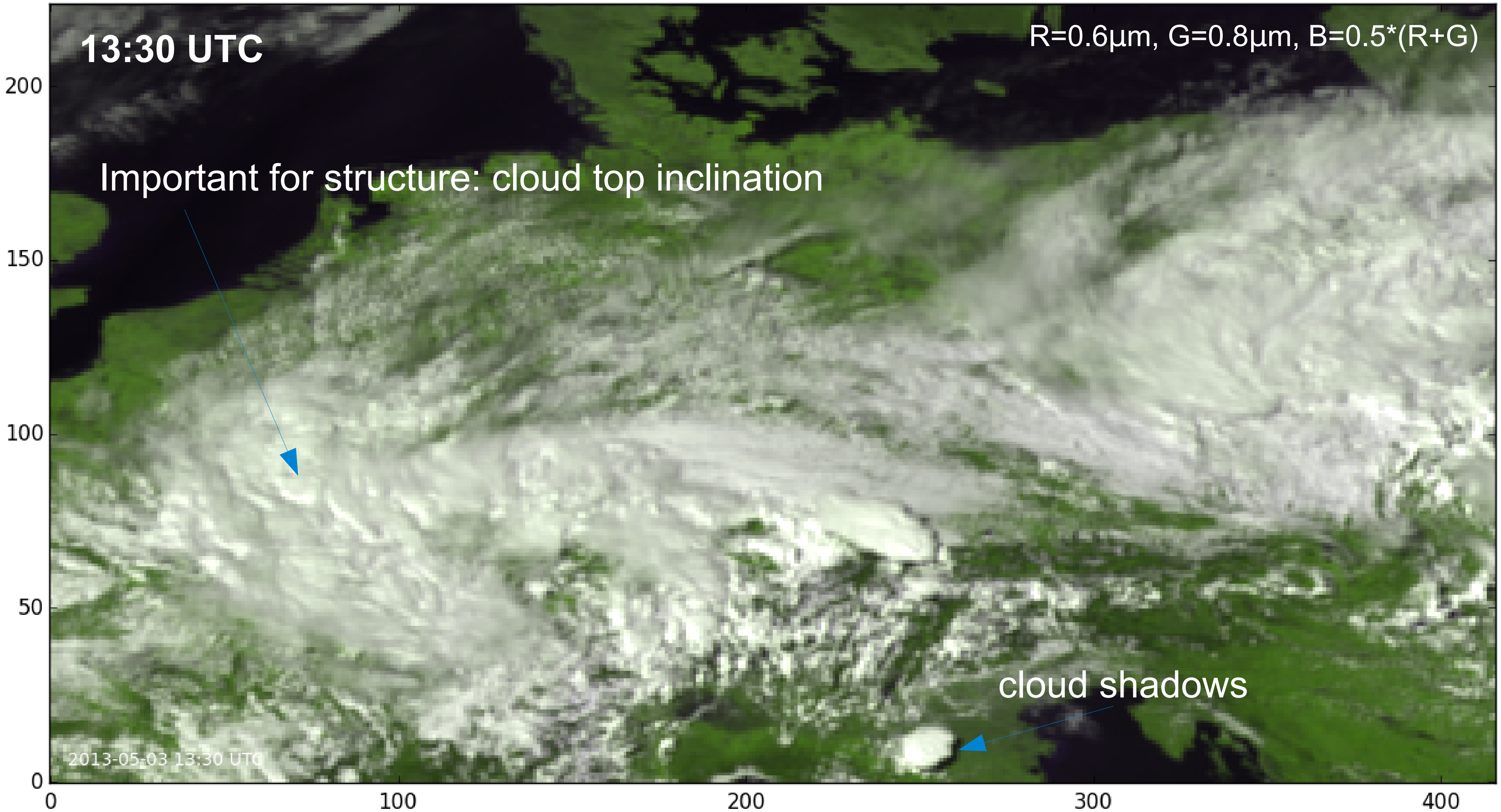
Operator error sources minimized / understood → model bias can be identified and removed → random errors can be reduced in DA

Most important features missing in operator version Kostka et al. 2014:

- ➔ **Cloud top inclination (3D RT effect)**
- ➔ **Subgrid cloud overlap (consistency)**

} How to take into account without degrading high performance?

3D effects not accounted for in 1D radiative transfer



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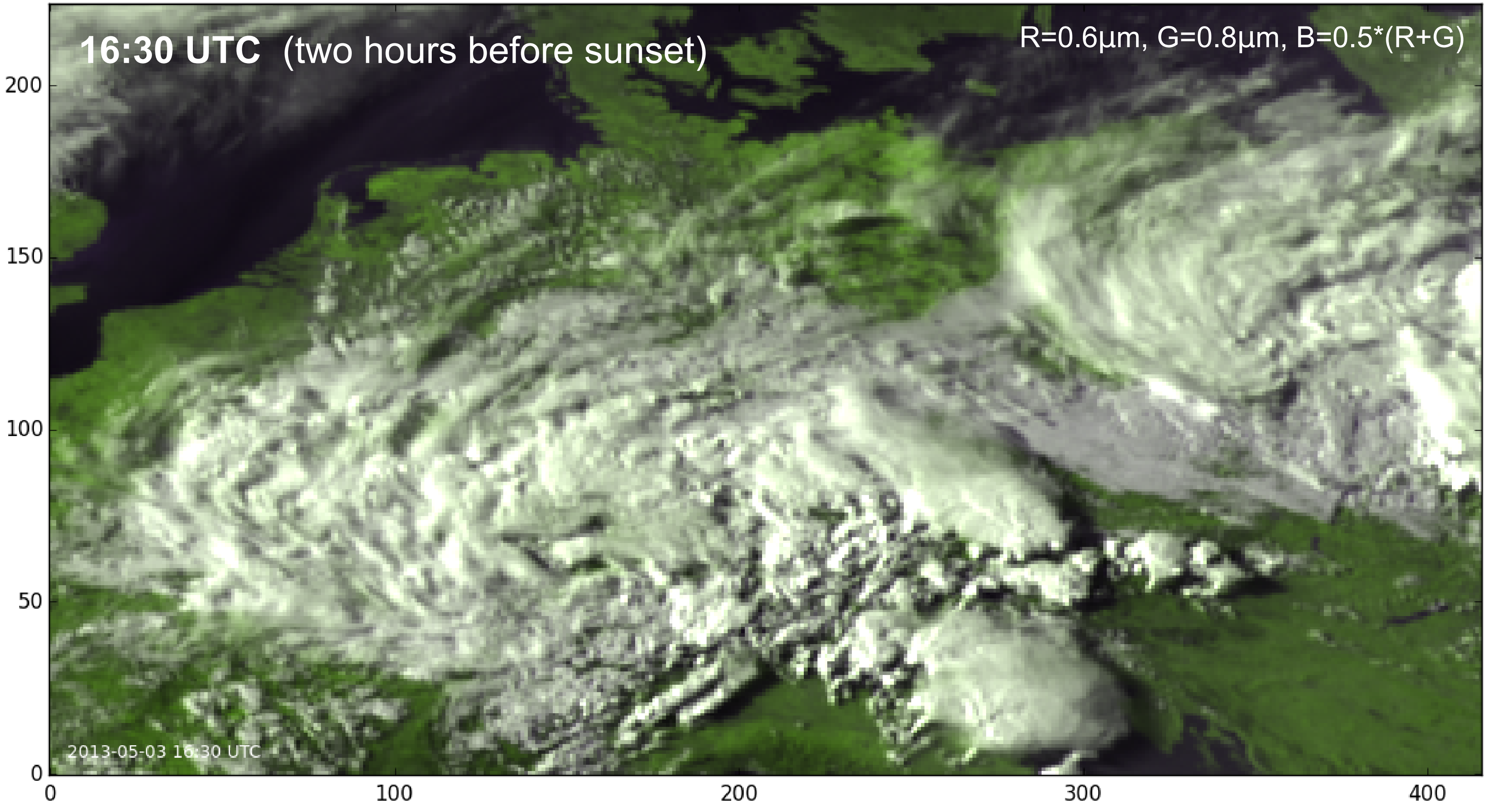
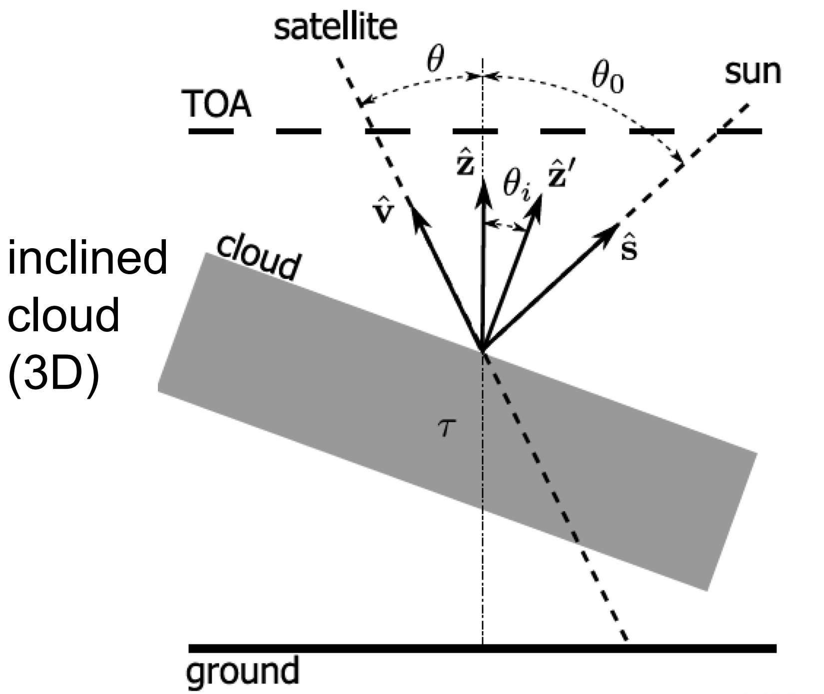
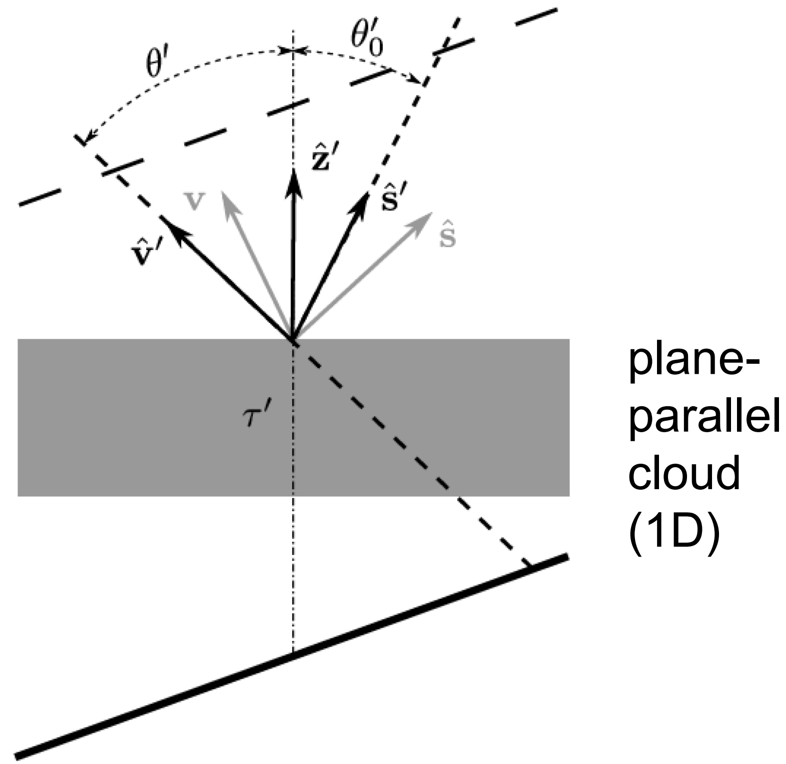


Cloud top inclination correction

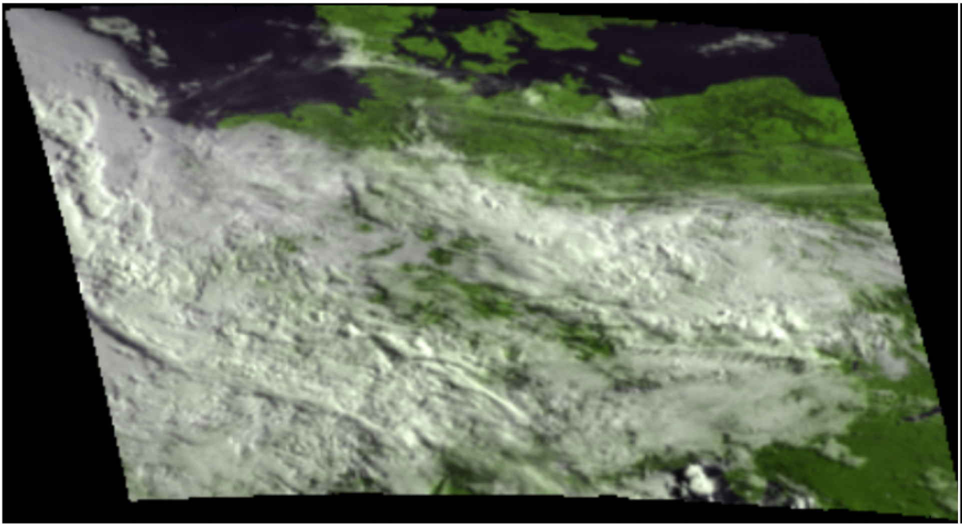




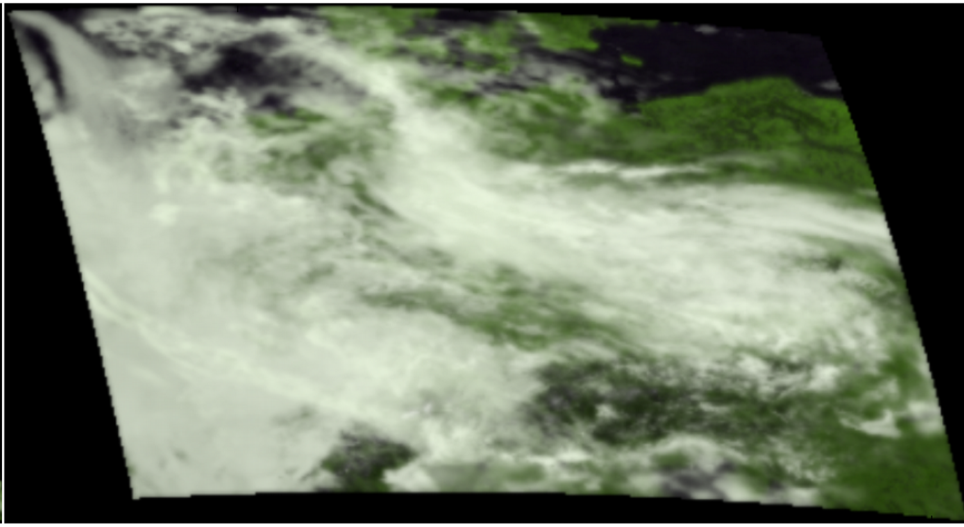
$$R_T(\theta, \theta_0, \alpha, A, \tau, \theta_i) = R(\theta', \theta'_0, \alpha, A', \tau \cos\theta_i) \frac{\cos\theta'_0}{\cos\theta_0}$$

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

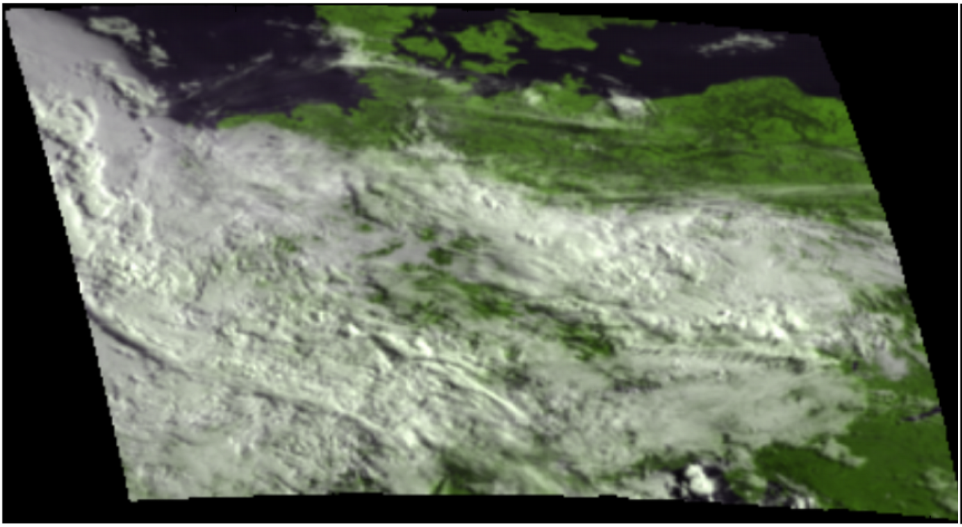


3h COSMO fcst **without 3D correction**

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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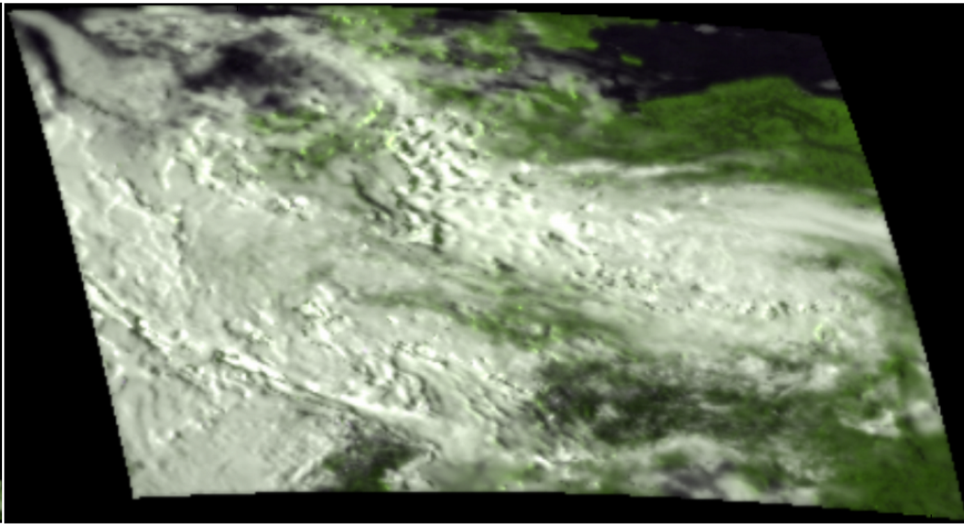

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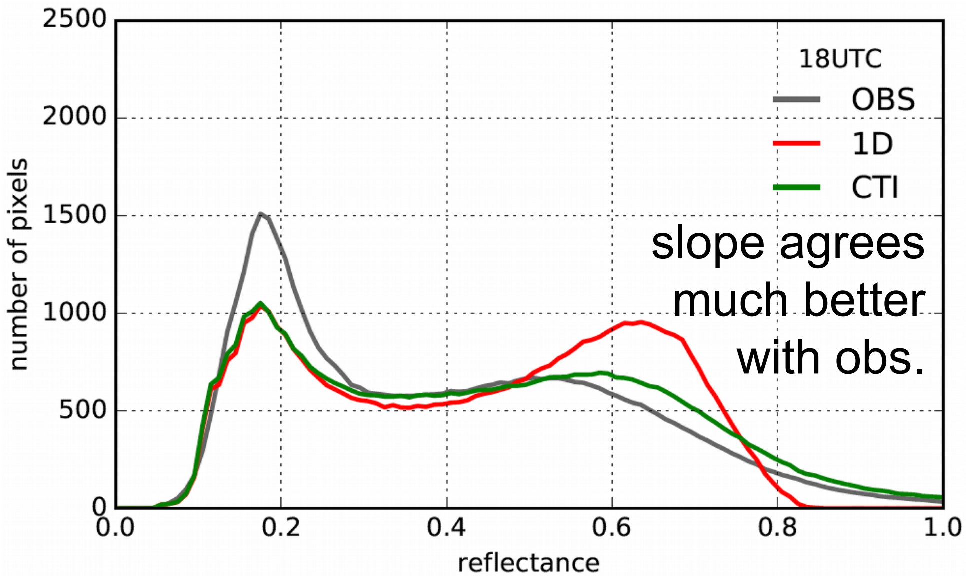
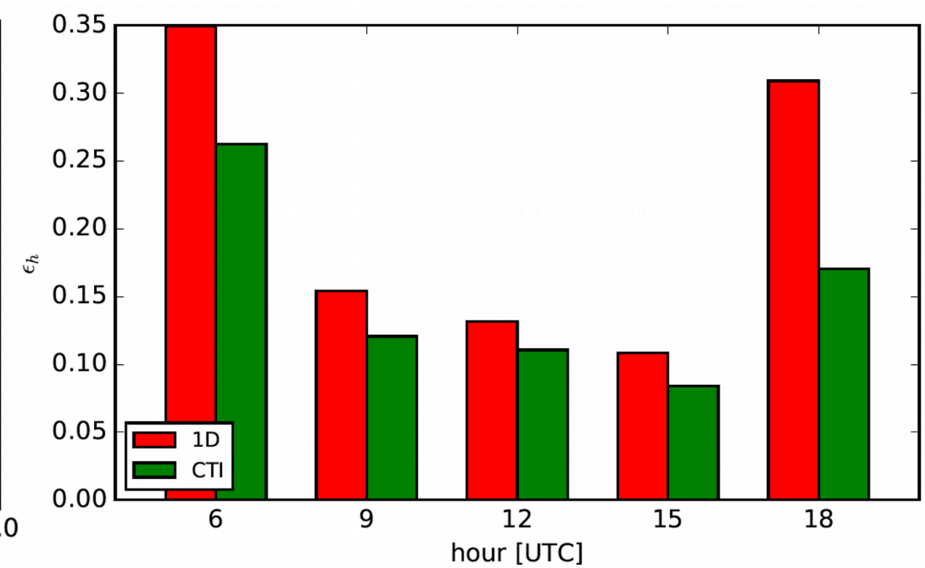
Cloud top inclination correction



0.6mu reflectance histograms for 18UTC



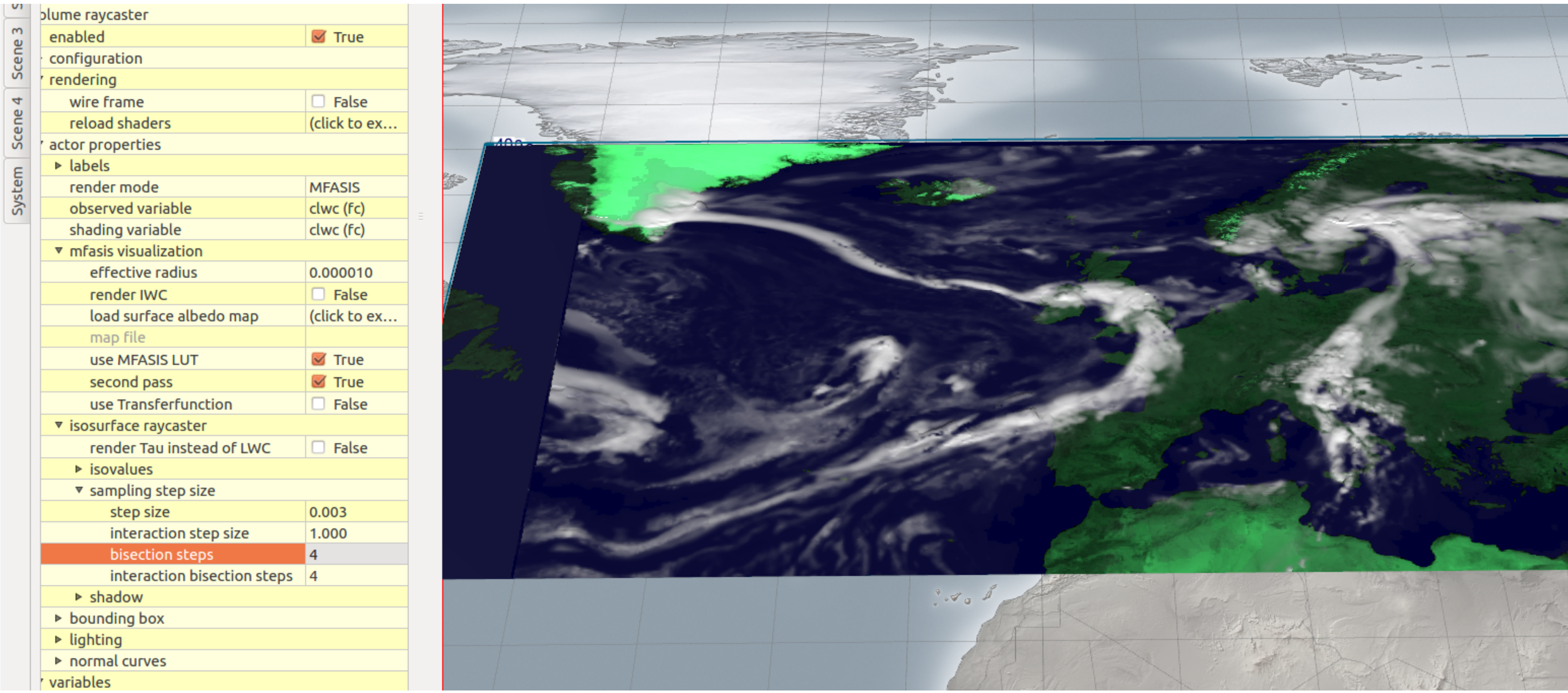
area between obs.& model histogram

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

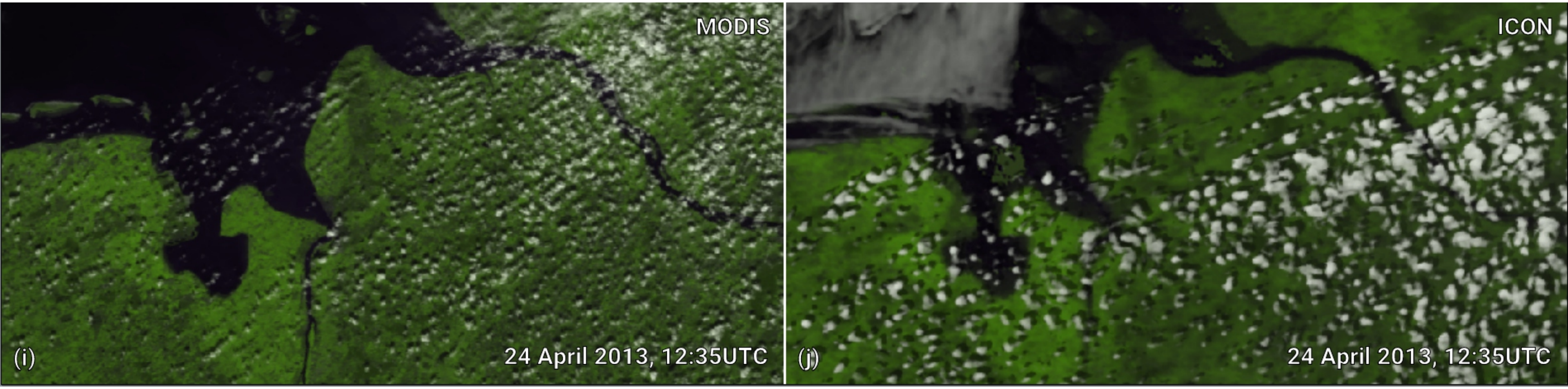
Computational effort: Small (only tau=1 detection + one additional MFASIS call)
It should even be possible to include it in the real-time version (work in progress)

MFASIS + 3D correction in real-time on GPUs

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



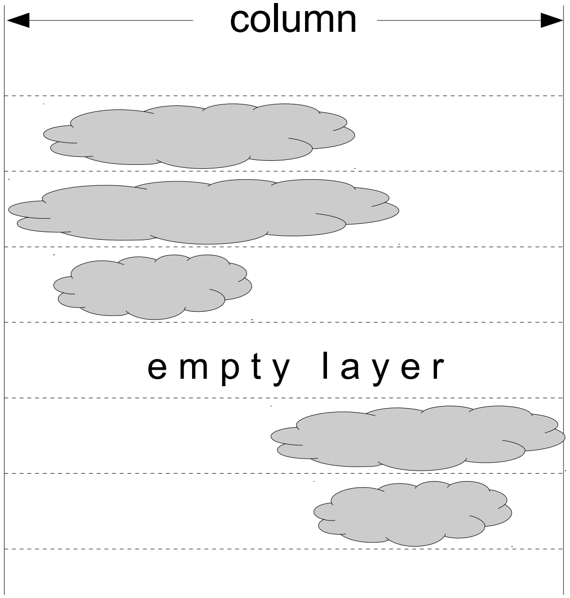
A second 3D correction: Cloud shadows on the ground



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 or online), used for model evaluation (e.g. cloud size statistics)

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.

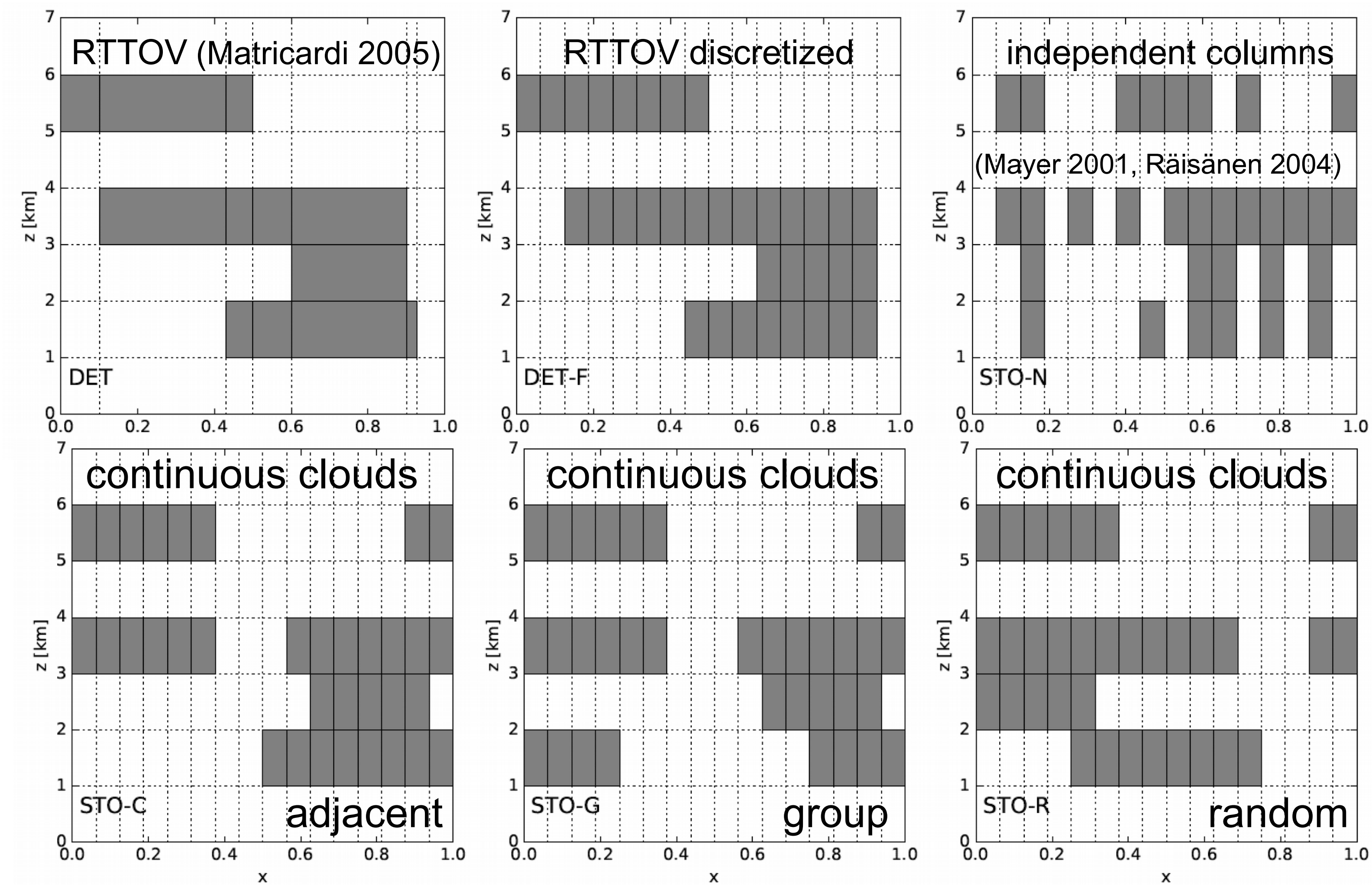
Two or more partially cloudy cells in one column:
How do they overlap? Affects heating, reflectance

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)

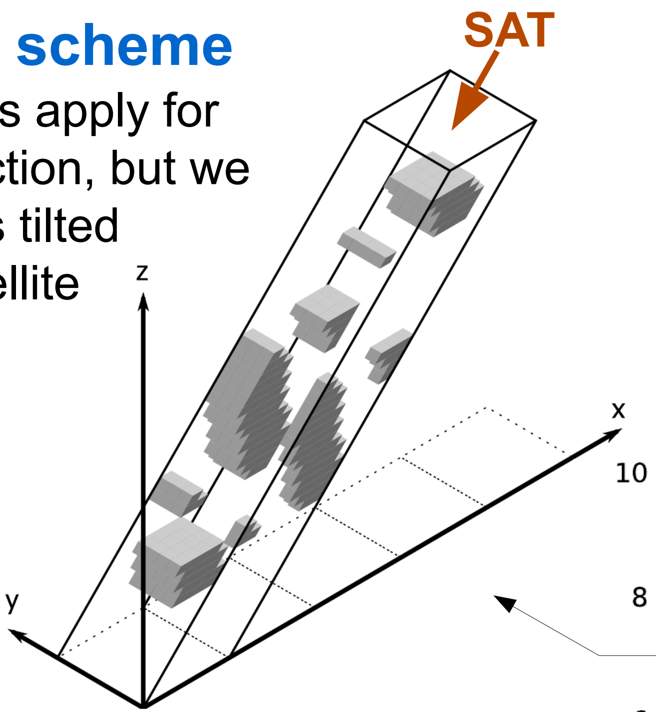
Several schemes were compared to address these questions:
- How well do different deterministic and stochastic implementations agree?
- Is the spread large enough to be relevant for DA?
- Should the slant viewing path of the satellite be taken into account?

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



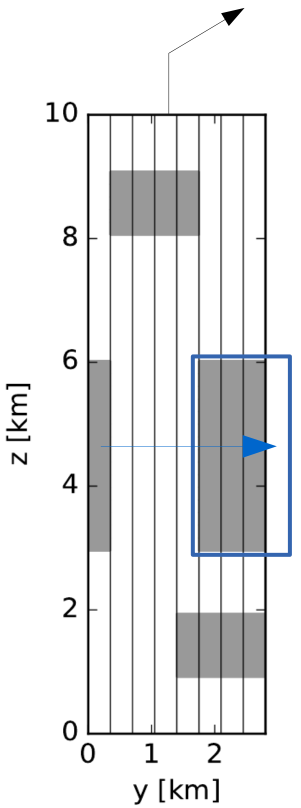
A new 3D scheme

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



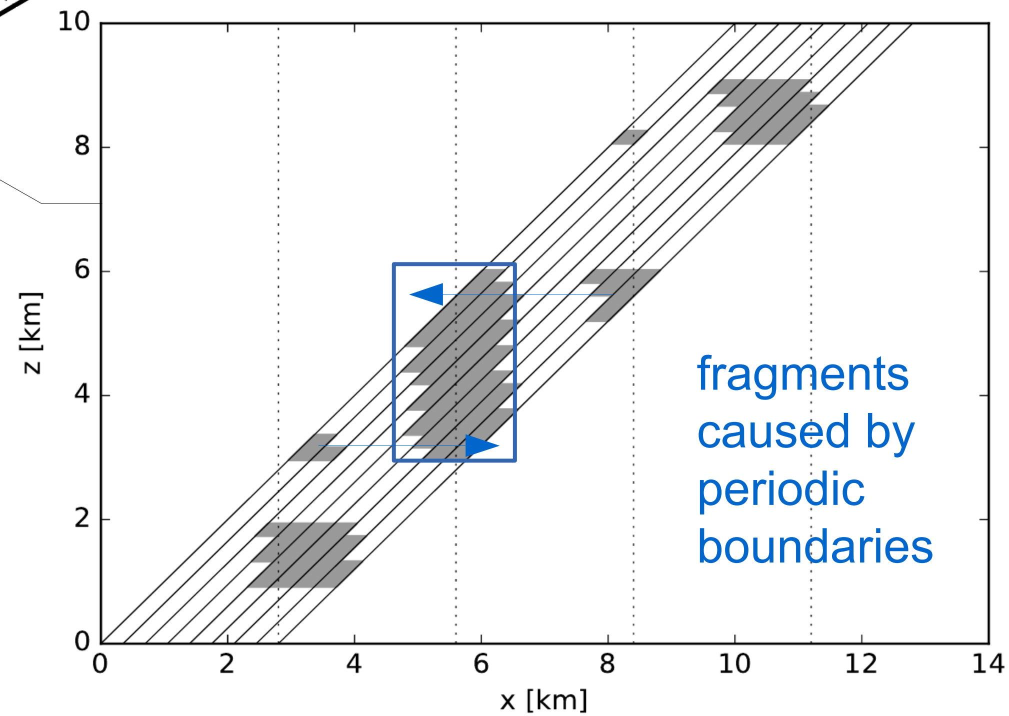
Approach: Use bundle of N x N sub-columns (3D), compensate for slant viewing path by shifting clouds into x-direction in each layer

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

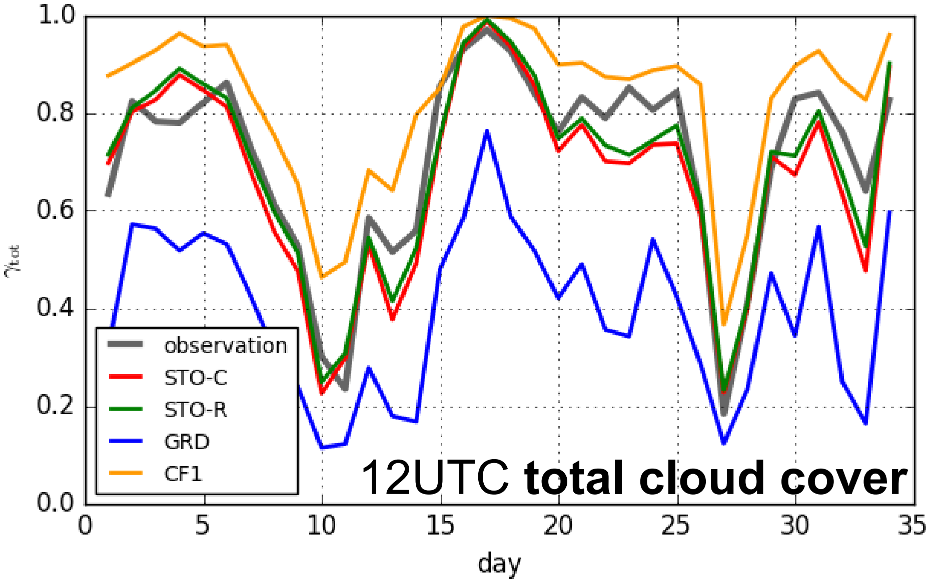


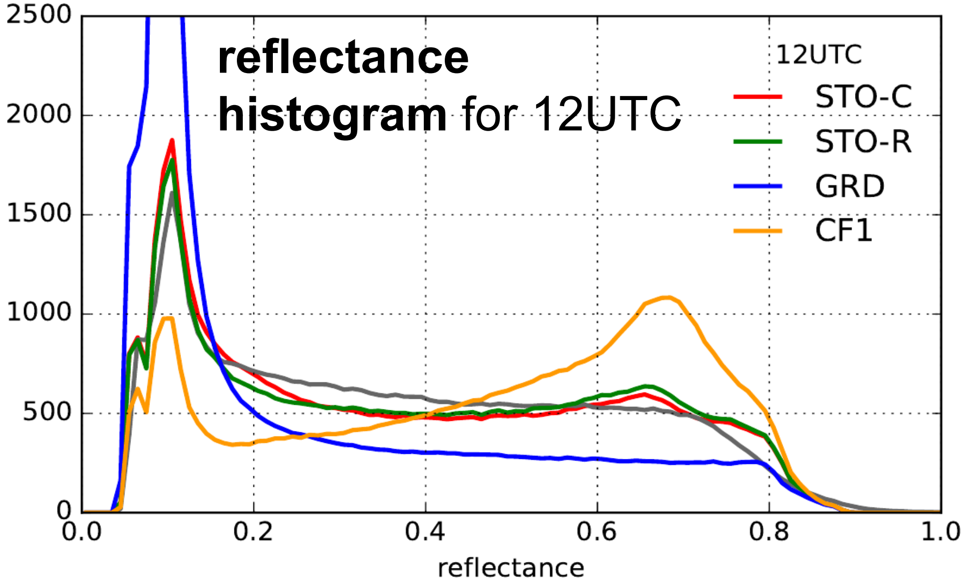
→ **Increased total cloud cover**
(also cloud sides contribute)

Not more expensive than 2D schemes.



Results for operational COSMO forecasts in June 2016





It is essential to take cloud overlap into account, setting all clouds fractions to 1 or using only grid scale clouds causes large errors.

Differences related to different assumptions or implementations are much smaller.

Good agreement with observations (no tuning!)

SEVIRI observation

grid scale clouds only

Subgrid cloud fraction 1

random overlap

random-maximum overlap

(2D stochastic continuous clouds)

Overlap schemes: local impact

Random vs. rand.-max. overlap

Local impact can be significant, ensemble mean random - randmax can be > 0.1, i.e. several 10%, but only ~10% of the pixels are sensitive to the type of the overlap assumptions

Random-maximum Implementations

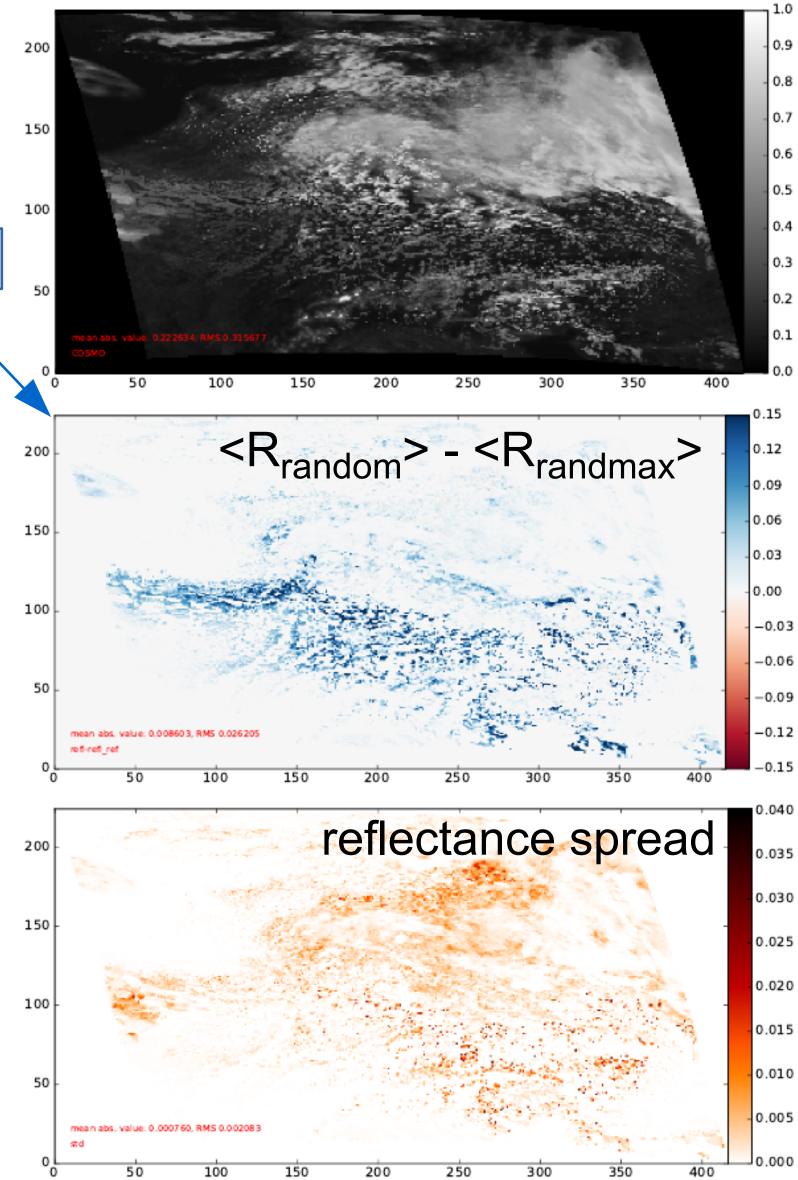
Mean reflectances of 2D stochastic schemes are very similar, also to deterministic schemes. ~10 subcolumns are sufficient.

Consistency

Taking slant viewing angle into account (3D) has same impact as switching rand./max. → random (at latitude ~45°, stronger effect for higher lats.)

Spread

Small, spread > 0.01 only in ~15% of pixels
→ should not have significant impact on DA



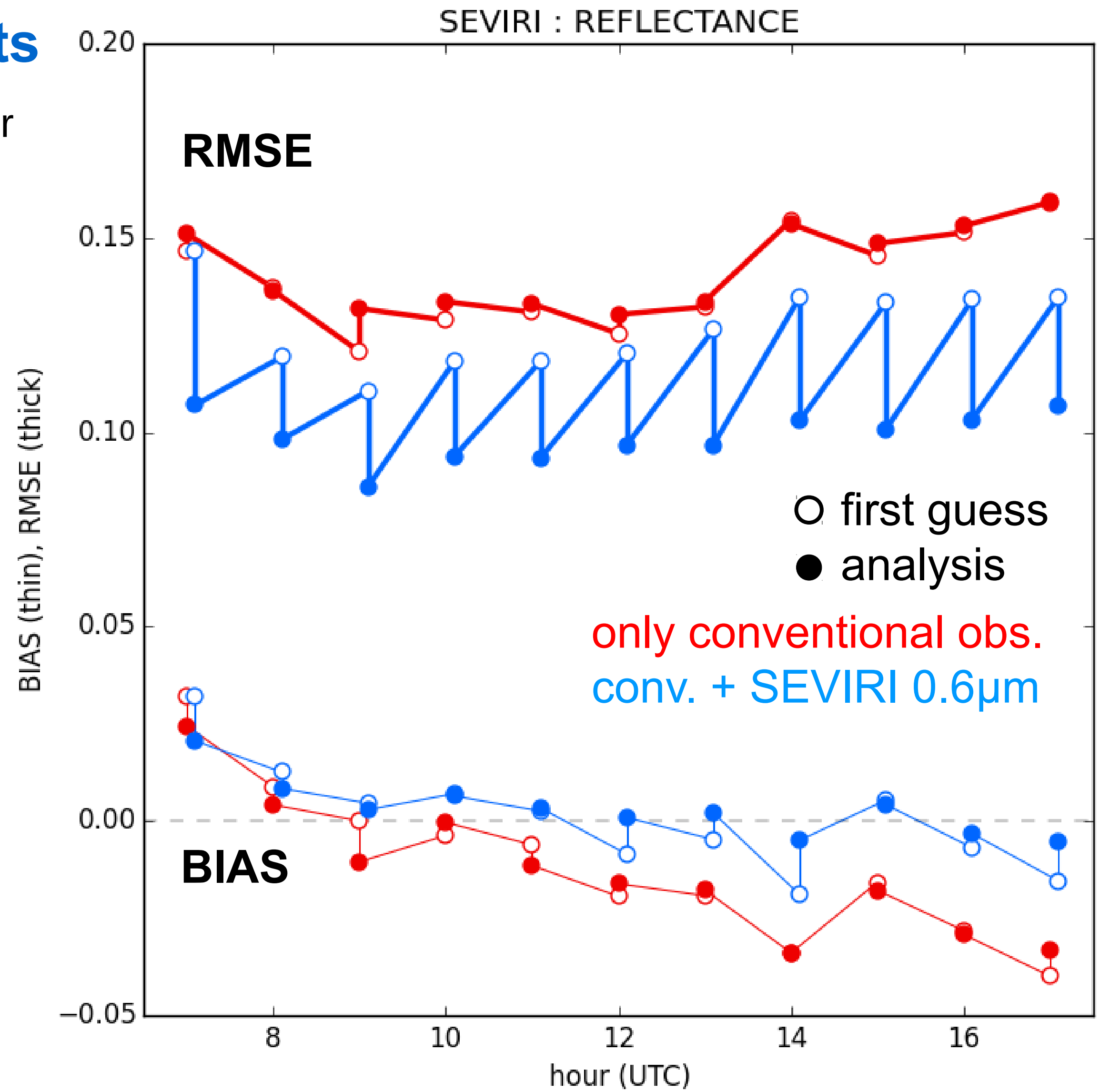
First assimilation results

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



Summary

- 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
  → increased information content,
  reduced systematic error
- Overlap of subgrid clouds is important. Most consistent scheme takes slant satellite viewing path into account.
- First assimilation experiments with DWD KENDA (LETKF) are promising, more experiments with new operator version will be performed soon...