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

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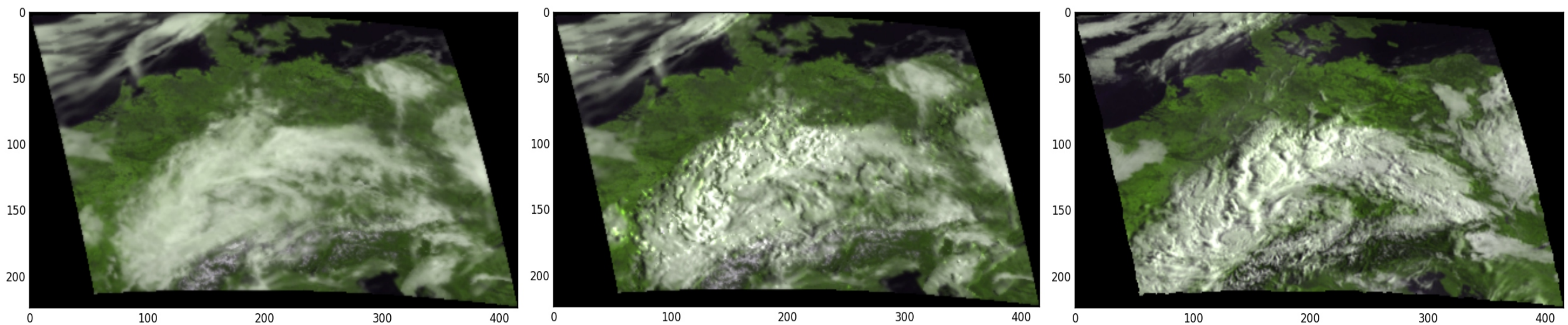
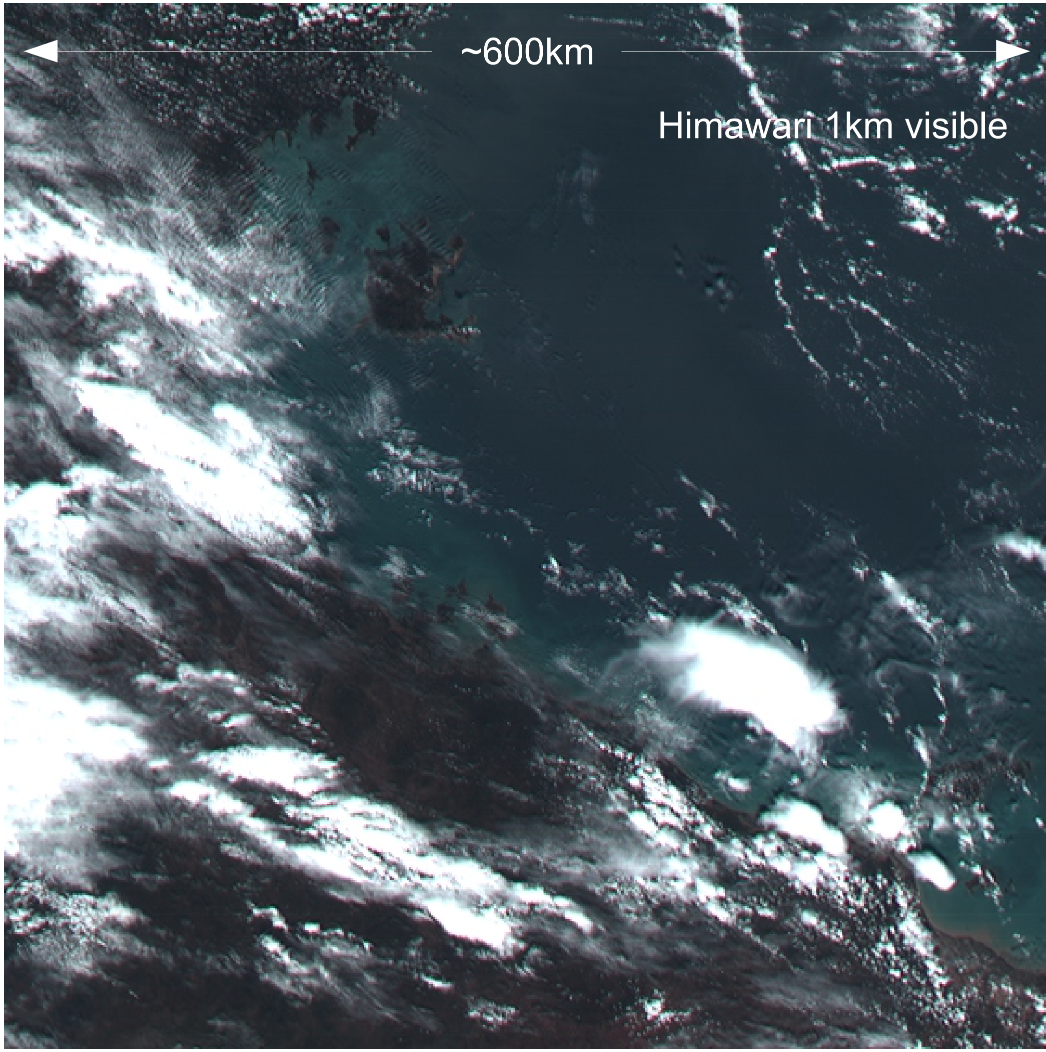


Visible / near-infrared satellite observations

- relevant for **convective scale DA:**
  high spatial and temporal resolution
  Next generation geostat. satellites:
  For 7 of 16 channels λ< 4µm,
  0.6µm resolution: 500m (IR: 2km)
  MTG 10min (full disc) / 2.5min (EU)
  Himawari, GOES-R: 30sec mode
- 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**
- not used in operational DA:
  fast forward operators not available (scattering makes radiative transfer complex)



Operator for visible / near-infrared satellite observations

Requirements: The operator must be

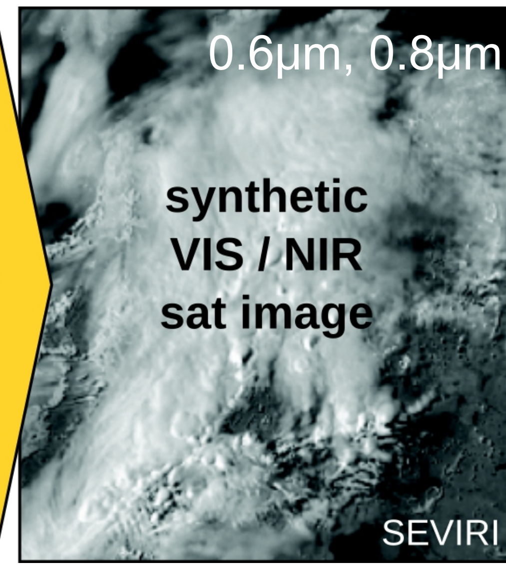
- Fast enough for operational DA (less than a minute for full ensemble)
- Sufficiently accurate (mean reflectance error of a few percent)

NWP model state
(COSMO,ICON)
thermodynamic & cloud-related variables

compute RT input variables
cloud optical depths & cloud cover (incl. subgrid clouds)
eff. particle sizes (parameterized)

extract tilted columns
(accounting for satellite viewing angle)

perform radiative transfer
- account for cloud overlap
- approximate 3D effects
- call MFASIS (fast 1D RT method)



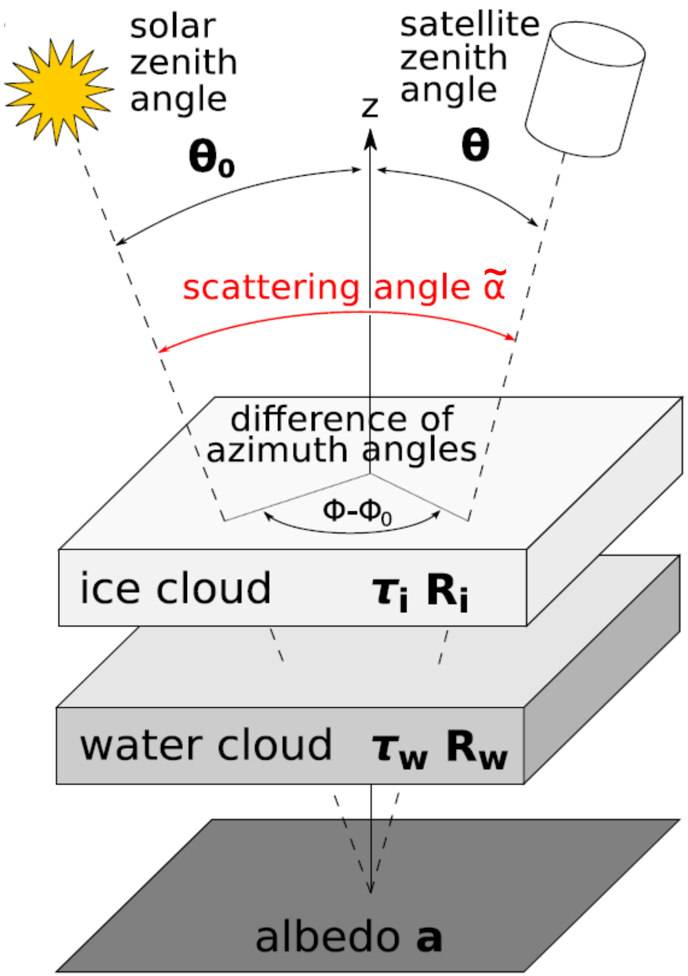
satellite geometry

albedo

Earlier version of the operator: Kostka et al. „Observation Operator for Visible and Near-Infrared Satellite Reflectances“, J. Atmos.Oceanic Technol., 2014

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 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

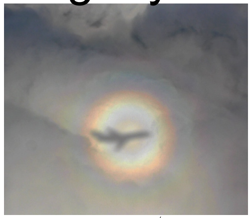
Problem: Table is huge! O(10GB) → not suitable for online operator, slow interpolation → **compress table** using truncated Fourier series → CPU-seconds

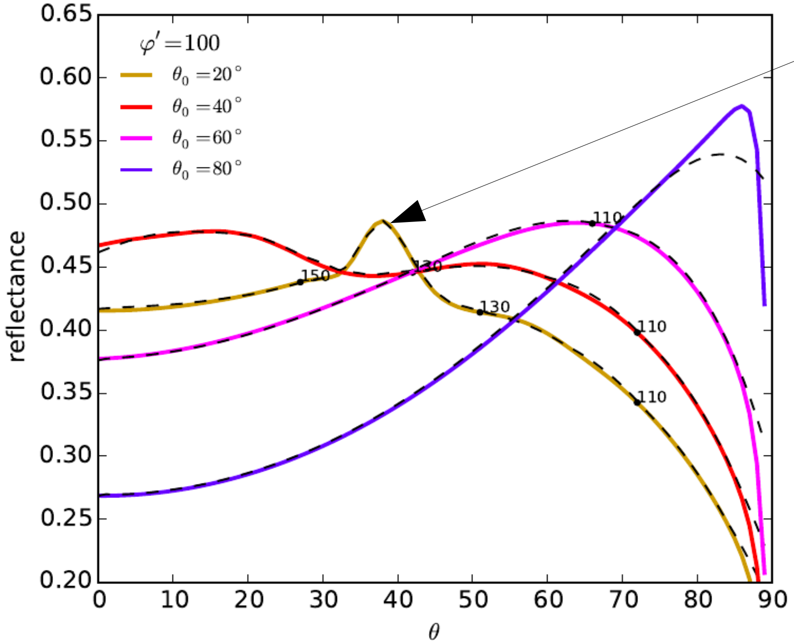
Reflectance curve examples

$R(\theta,\theta_0,\varphi')$: Small scales features due to cloudbow in all angle dimensions (at $\alpha \sim 140°$)

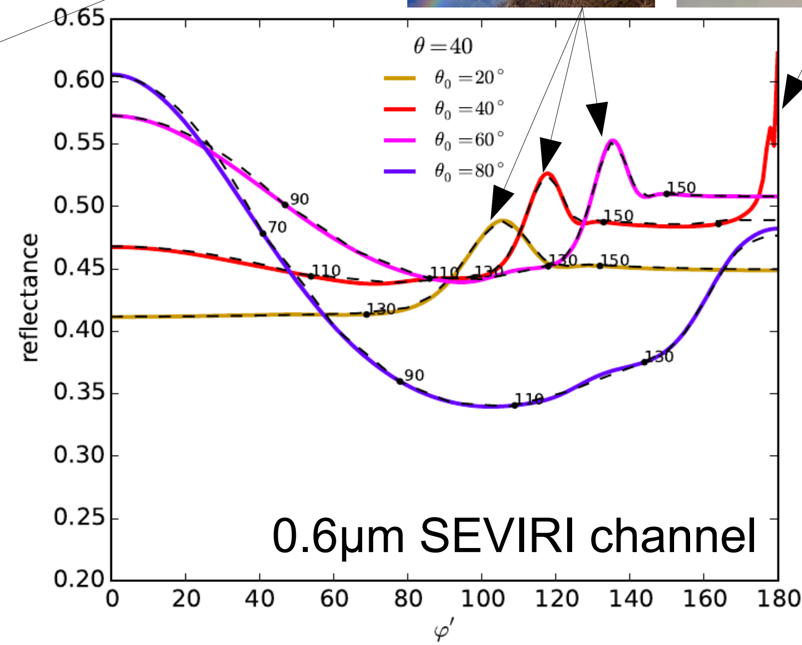
cloudbow

glory





Satellite zenith angle θ



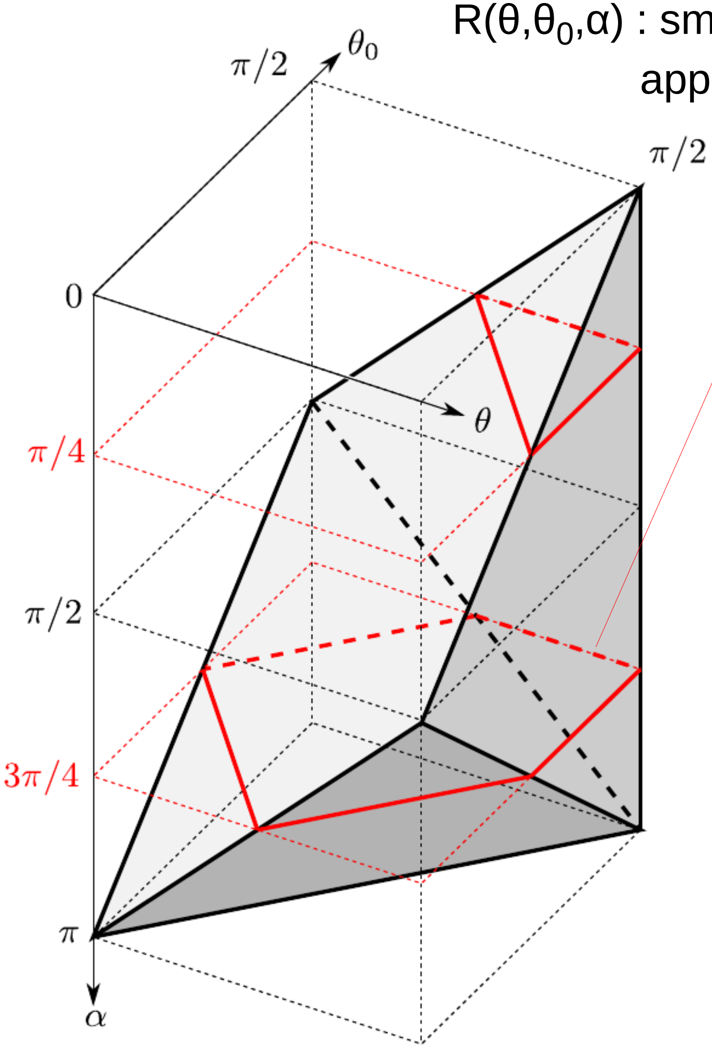
Sat - sun azimuthal angle φ'

Problem: Many Fourier terms would be required to represent these curves
Solution: Use scattering angle α instead of azimuthal angle difference φ'

LUT compression in MFASIS

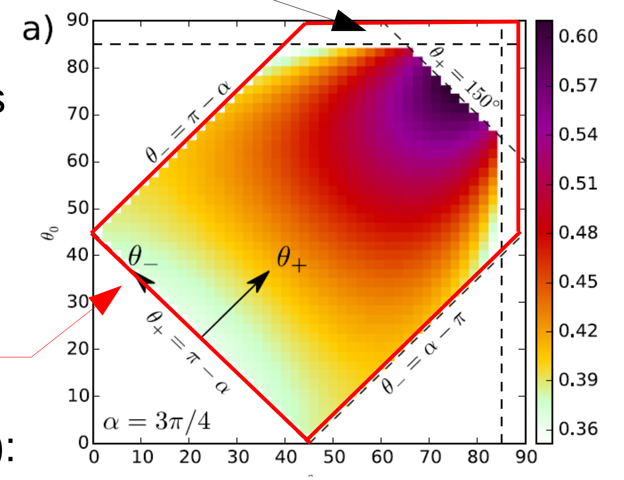
Excluded : large θ,θ_0, very small and large α

$R(\theta,\theta_0,\alpha)$: smooth function for α=const, well approximated by 2D Fourier series



Not all angle combinations are valid:

$$|\theta-\theta_0| \le \pi-\alpha \le \theta+\theta_0$$



Fit function (symmetric in θ_-):

$$R(\theta_+,\theta_-) = \sum_{k=0}^{N_k-1}\sum_{l=0}^{N_l-1}\Big[C_{k,l}\cos(k\theta_+) + S_{k,l}\sin((k+1)\theta_+)\Big]\cos(l\theta_-)$$

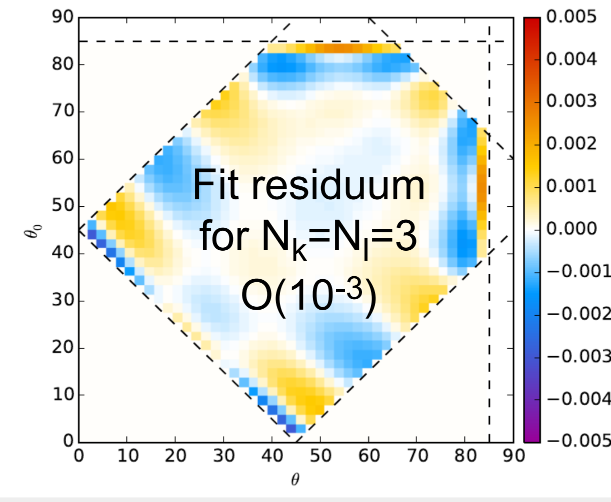
$$\theta_+ = \theta + \theta_0$$
$$\theta_- = \theta - \theta_0$$

Coefficients C_{kl}, S_{kl}: obtained by least squares fit to DISORT results

$N_k,N_l=3 \rightarrow$ 18 coefficients

Compression by factor ~100

Does not limit accuracy!



Parameter values in the LUT

C_{kl}, S_{kl} stored in LUTs with dims. α, τ_w, r_w, τ_i, r_i, A

Parameter values are chosen such that linear interpolation error for reflectance < 0.005

Adaptive α-grid: high resolution (2°) is required only around cloud bow → LUT factor 3 smaller

parameter	values
A	0.0, 0.5, 1.0
τ_w	0, 0.25, 0.5, 1, 2, 4, 8, 16, 25, 50, 100, 300, 1000
τ_i	0, 0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 25, 50, 100, 300
r_w [μm]	2.5, 5, 10, 25
r_i [μm]	20, 40, 60
α [°]	40, 45, 50, 60, 70, 80, 90, 99, 109, 119, 129, 133, 135, 137, 139, 141, 143, 145, 147, 149, 153, 159, 165, 171

Size: 21MB

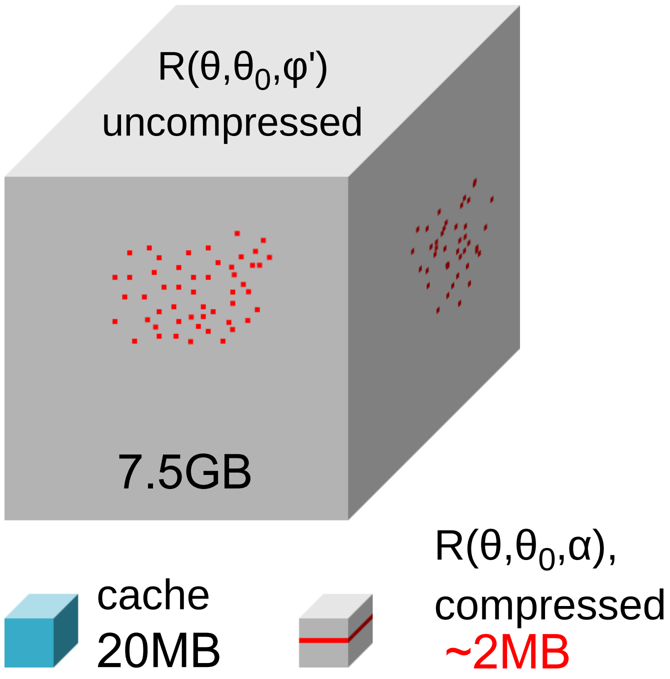
Performance

DISORT (16 streams): 2.3×10^{-2} sec/column
MFASIS (21MB table): 2.5×10^{-6} sec/column
(on Xeon E5-2650 with 20MB level 3 cache, for 51 level COSMO data)

MFASIS: Part of the table required for one SEVIRI image fits into cache → high performance

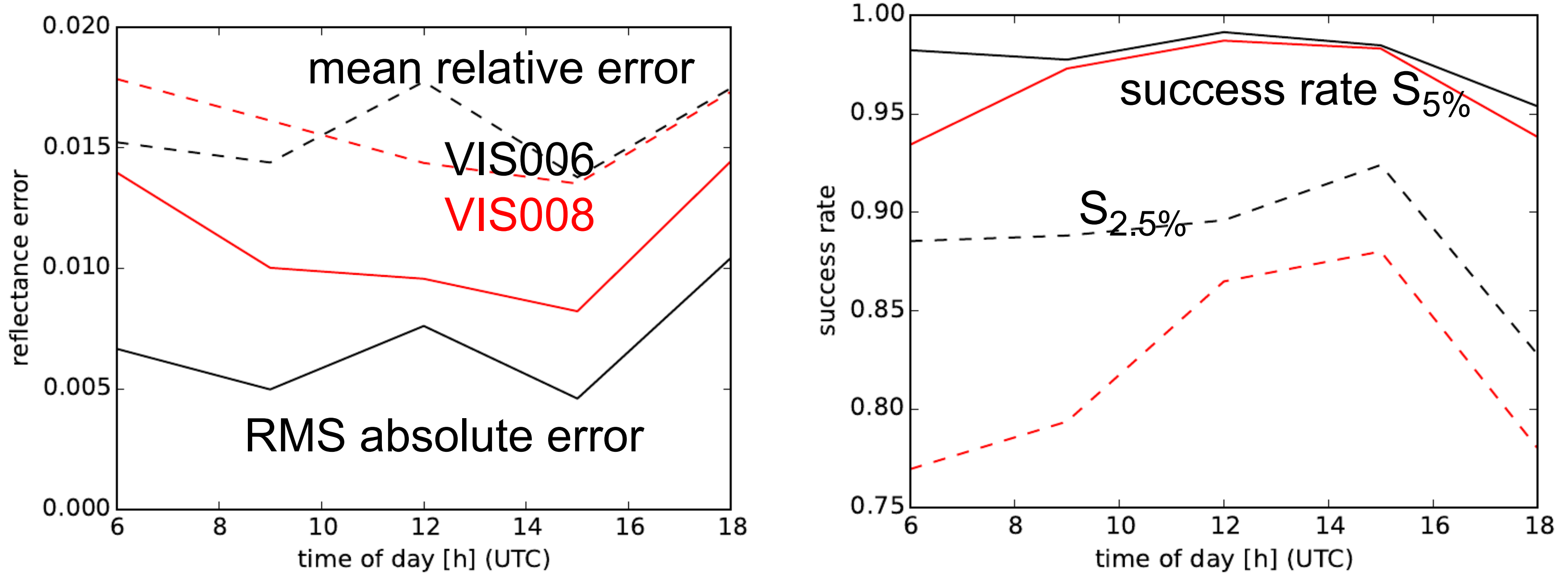
Uncompressed LUT for $R(\theta,\theta_0,\varphi')$: 7.5GB
→ cache misses in almost every pixel → slower!

→ Compression increases performance



Accuracy of synthetic satellite images

Error of MFASIS (8 parameters/pixel) with respect to DISORT (full profiles available)
Period: June 12th – 28th 2012, Model data: Operational COSMO-DE forecasts



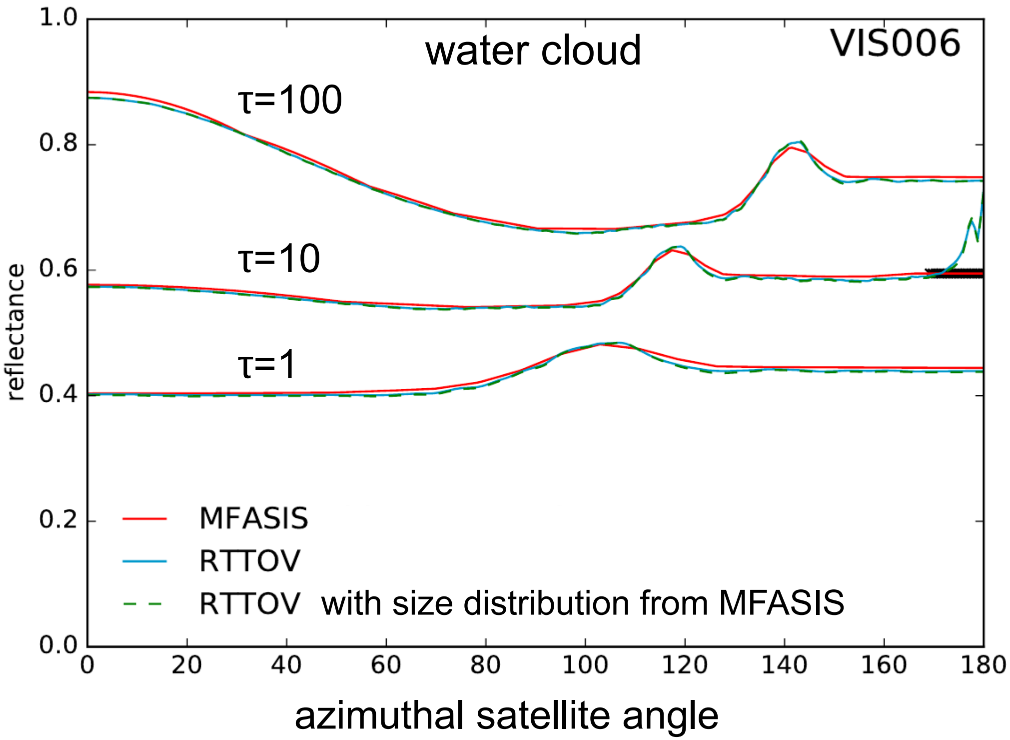
Success rate S_x: Success means relative error < x or absolute error < x/5

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

L. Scheck, P. Frèrebeau, R. Buras-Schnell, B. Mayer: *„A fast radiative transfer method for the simulation of visible satellite imagery“* JQSRT, vol. 175, p. 54-67, 2016

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 during NWP-SAF visiting scientist mission



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

Results:

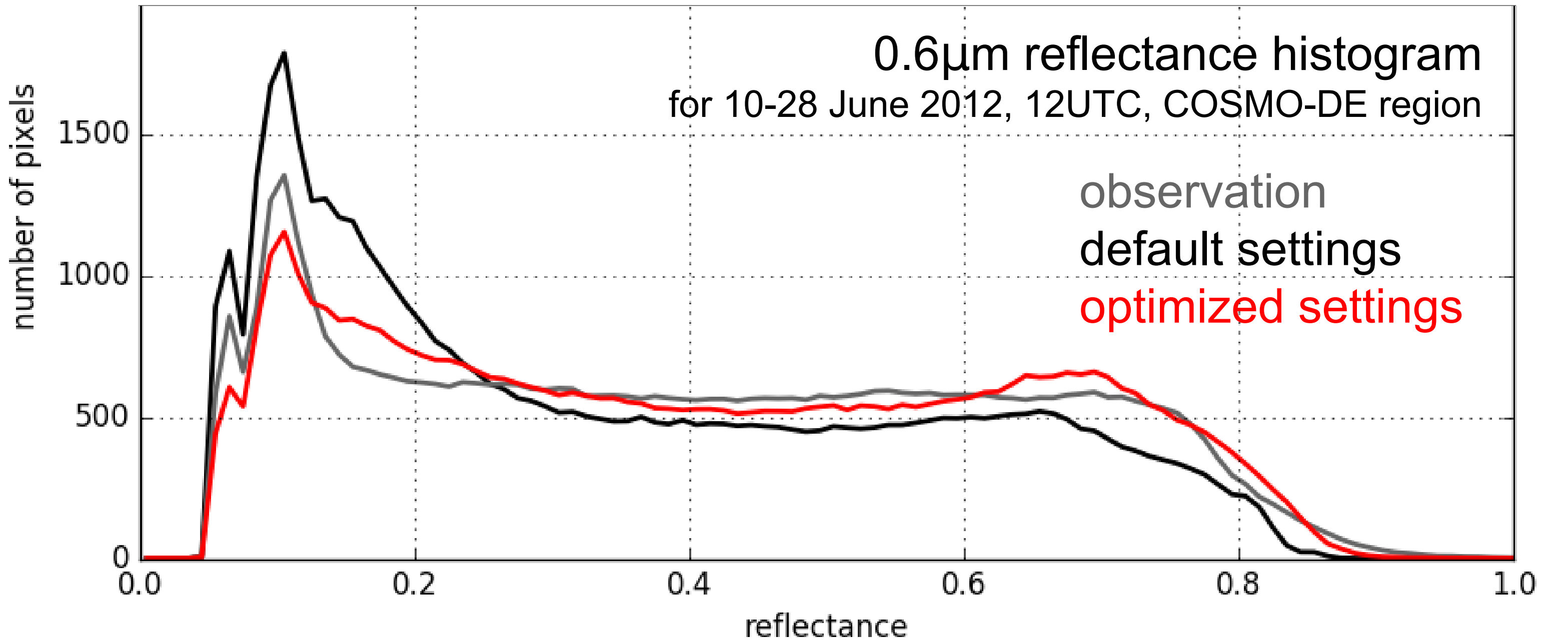
- Reflectances for clouds agree well!
- Clear sky contributions problems:

  -In MFASIS only a constant profile of water vapour is taken into account (affects the 0.8µm channel)

  - RTTOV-DOM: no multiple cloud - clear-sky scattering processes → negative reflectance bias
- Stochastic and deterministic cloud overlap schemes lead to similar results, a more efficient deterministic scheme was implemented that may also be useful for infrared channels

Synthetic vs. real satellite images

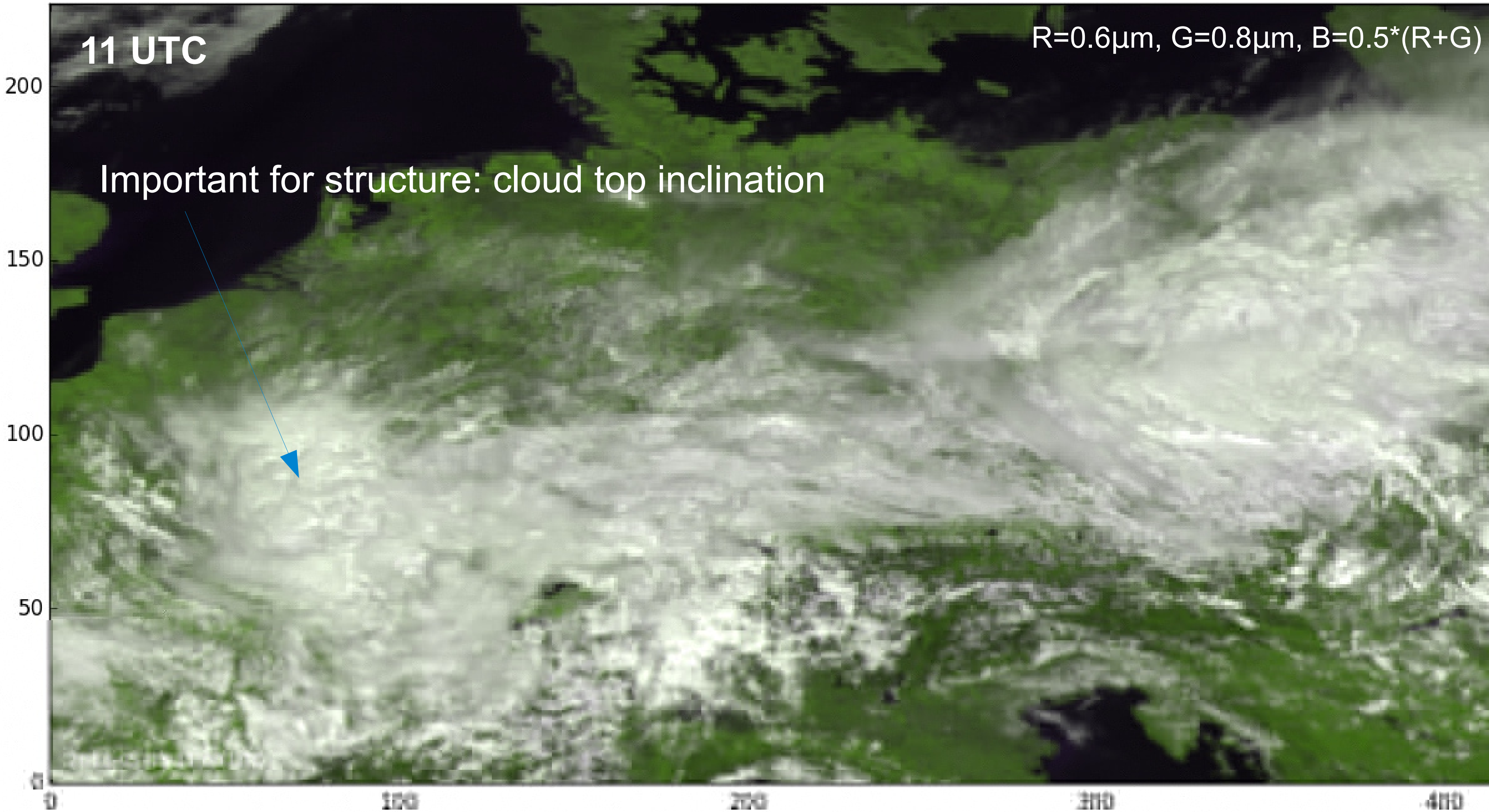
Systematic differences indicate deficiencies in model and/or operator and should be removed by model/operator improvements or tuning to avoid problems in the DA.



Important tuning parameters: particle radii, subgrid cloud cover and water content

Deficiencies that cannot be “tuned away”: imperfect albedo, missing 3D effects...

3D effects not accounted for in 1D radiative transfer



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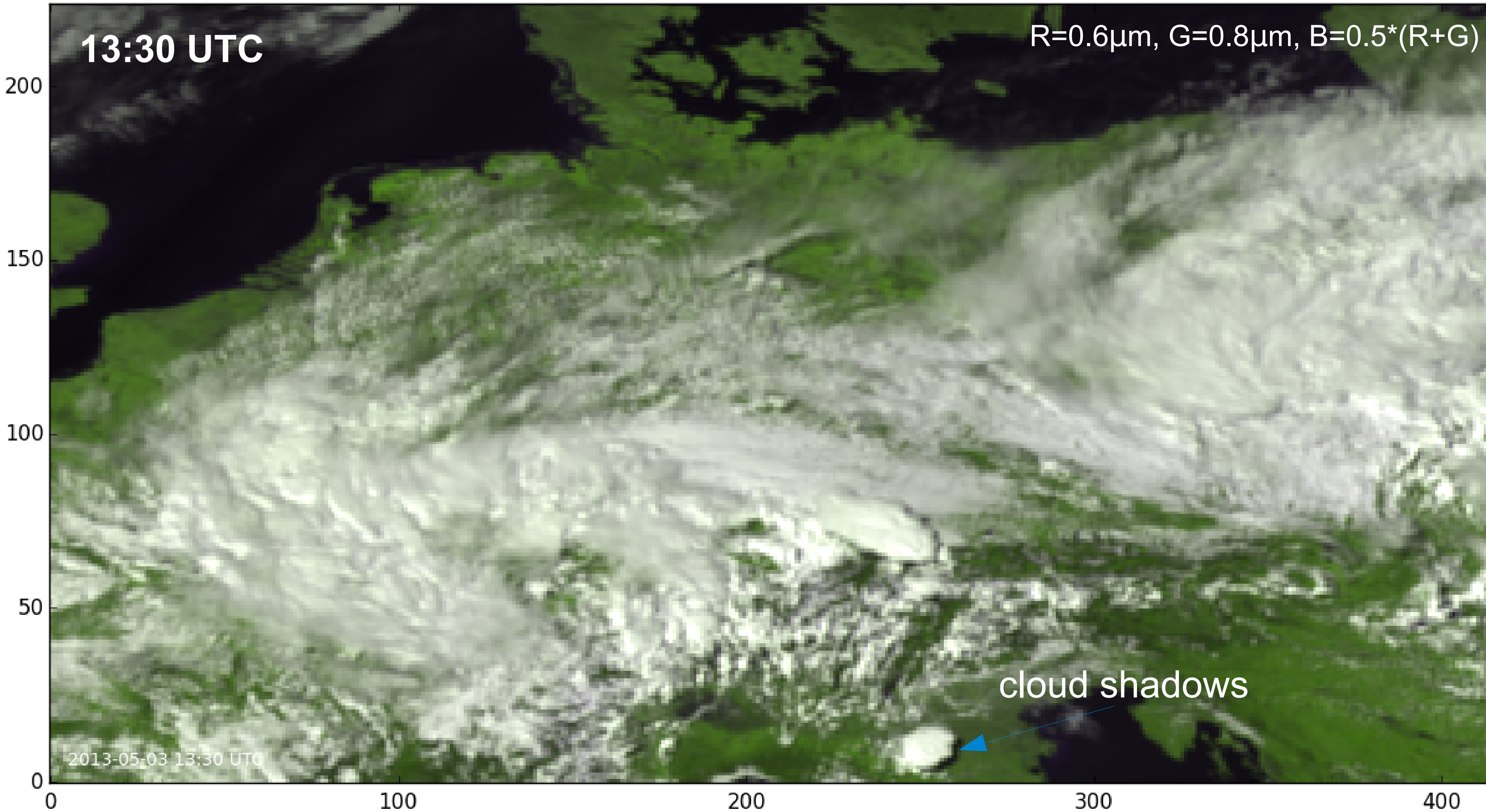

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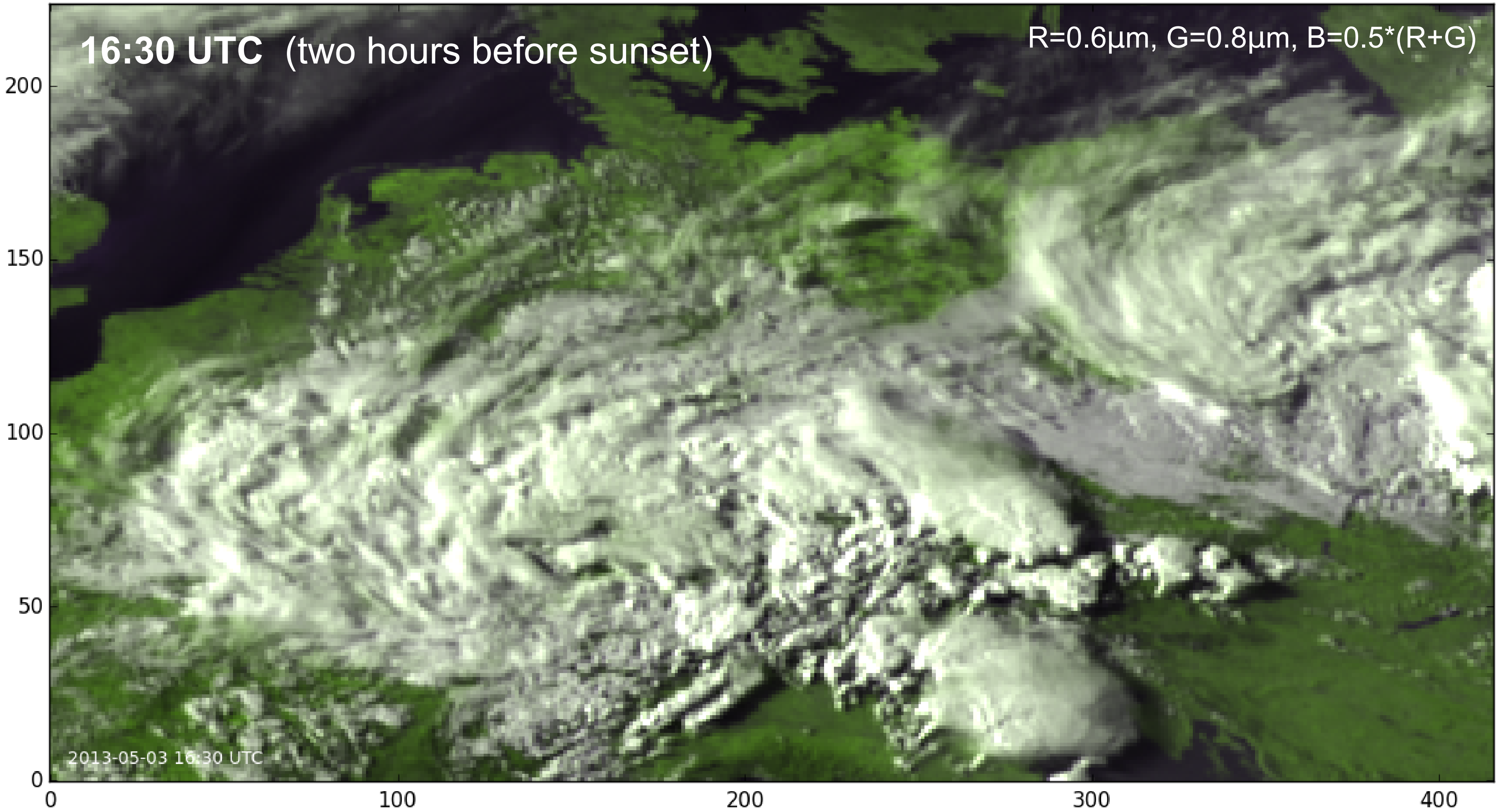


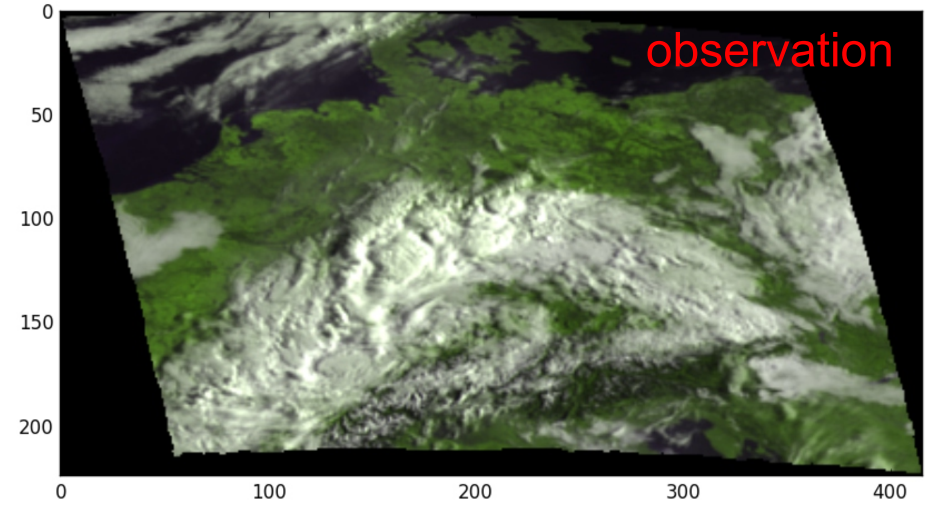
Cheap 3D effects 1: Cloud top inclination

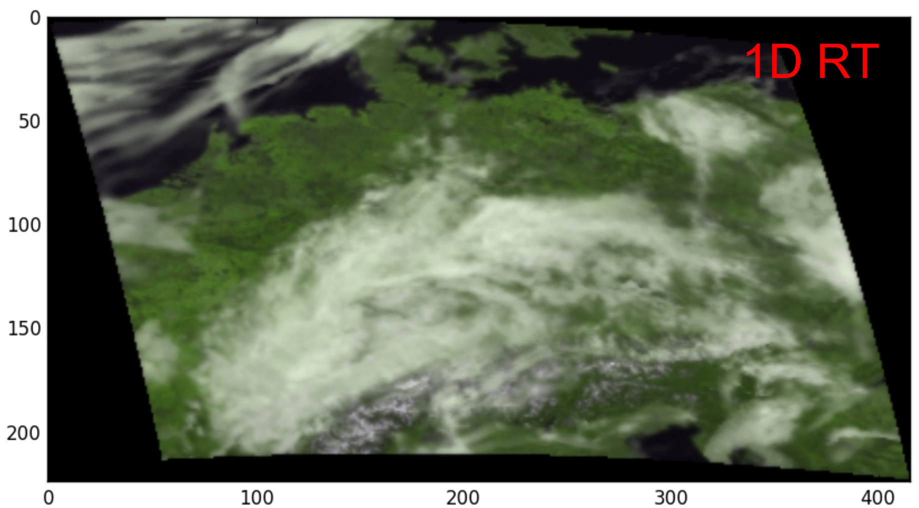
Algorithm

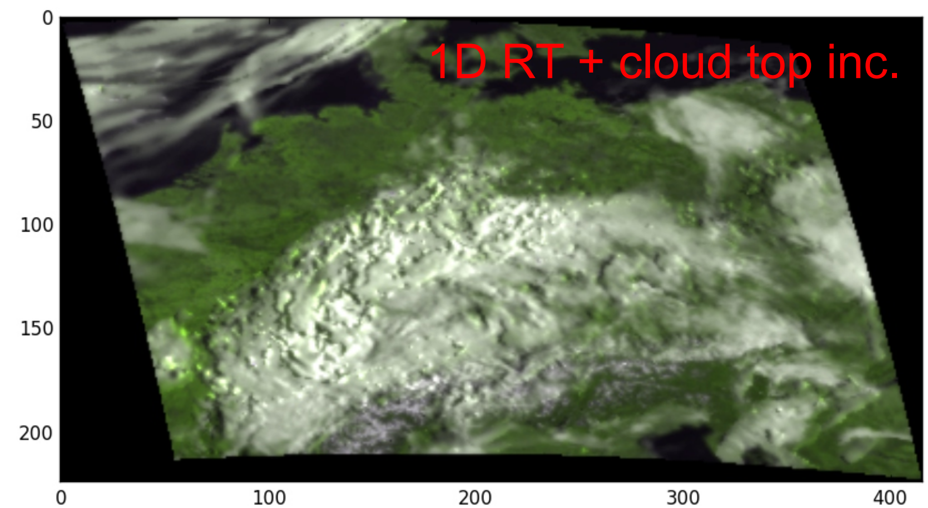
- Fit plane to optical depth 1 surface
- Compute sun/sat. angles relative to plane
- Look up reflectance for these angles
- Correct clear sky contribution

Results

- Much more structure visible – useful e.g. to distinguish convective from stratiform clouds
- Reflectance histogram improved, in particular for large SZA







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Algorithm (computationally cheap!)

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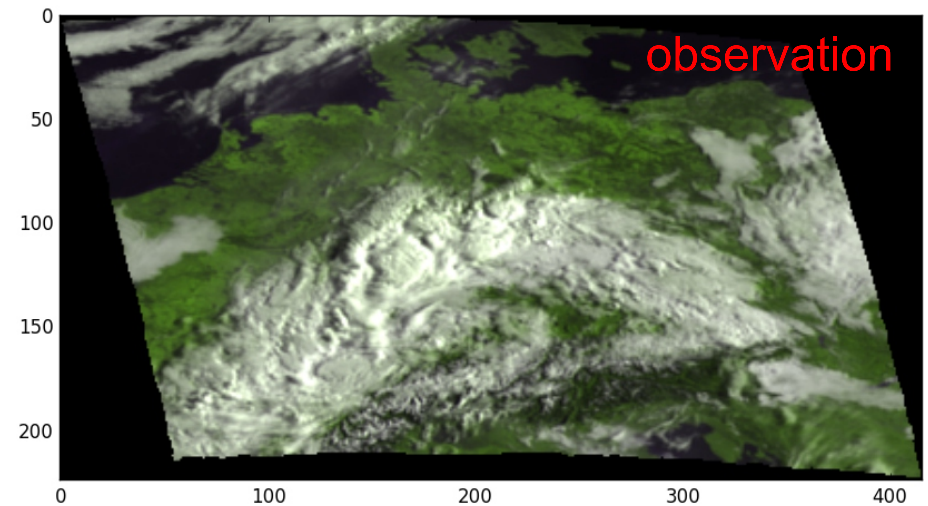
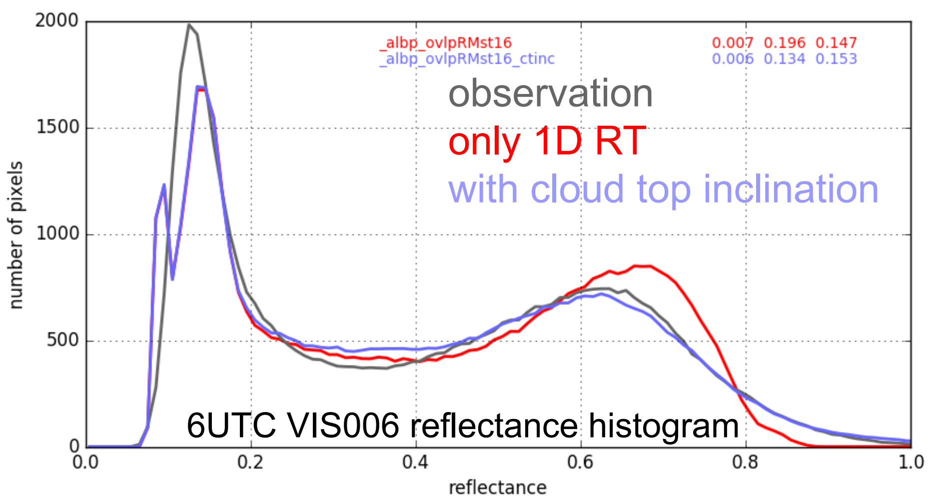
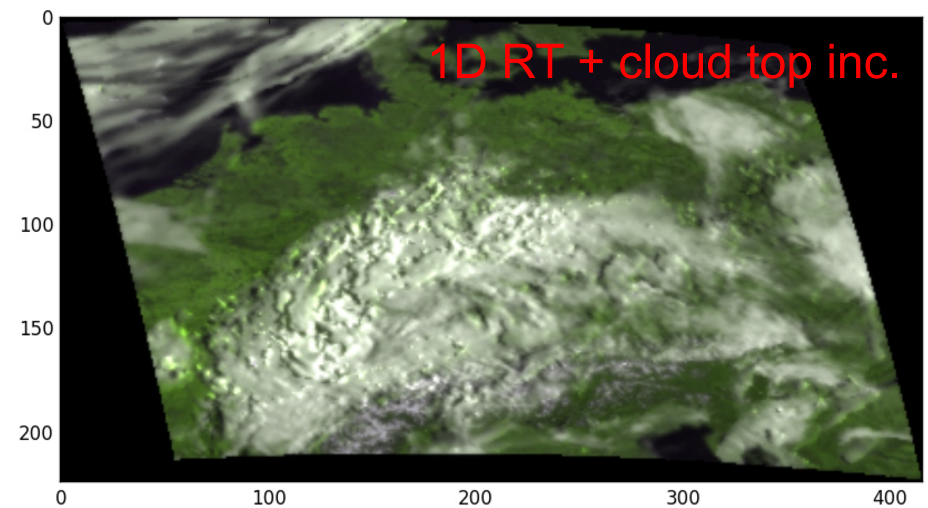
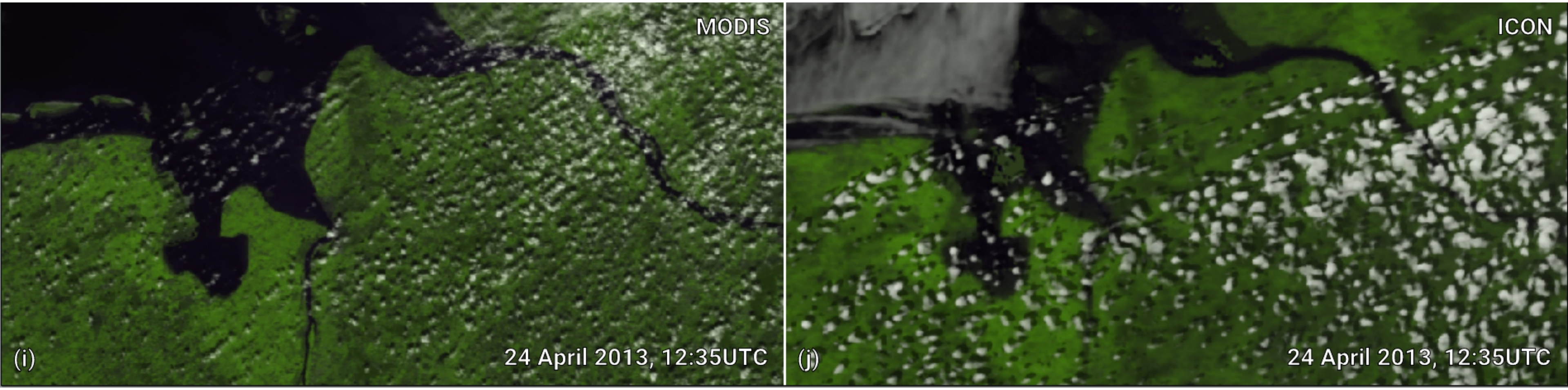






Cheap 3D effects 2: Cloud shadows on the ground



Example: MODIS image + model equivalent for 150m resolution ICON run from HD(CP)^2
(see Heinze et al. (2016) "Large-eddy simulations over Germany using ICON", QJRMS, submitted)

- Important for deep convection and broken cloud fields, in particular for channels with high surface albedo (e.g. 0.8µm)
- Shadow position can be determined by computing optical depth in columns tilted towards sun (same effort as for columns tilted towards satellite)
- Shadow brightness depends on direct (easy) and diffuse (complicated) radiance, parameterization may be possible (work in progress)...

Conclusions & Outlook

- We developed an operator for visible & near-infrared satellite images that is sufficiently fast and accurate for convective scale DA
- High performance due to MFASIS, a RT method based on a compressed LUT
- Comparison to RTTOV-DOM: Cloud results are in good agreement, some problems related to clear sky should be corrected, stochastic and deterministic cloud overlap schemes lead to similar results
- The most important 3D effects can be taken into account in a computationally efficient way (work in progress) → reduction of systematic error, synthetic images contain more structure and thus potentially useful information
- Next step: New assimilation experiments with KENDA (DWD)...

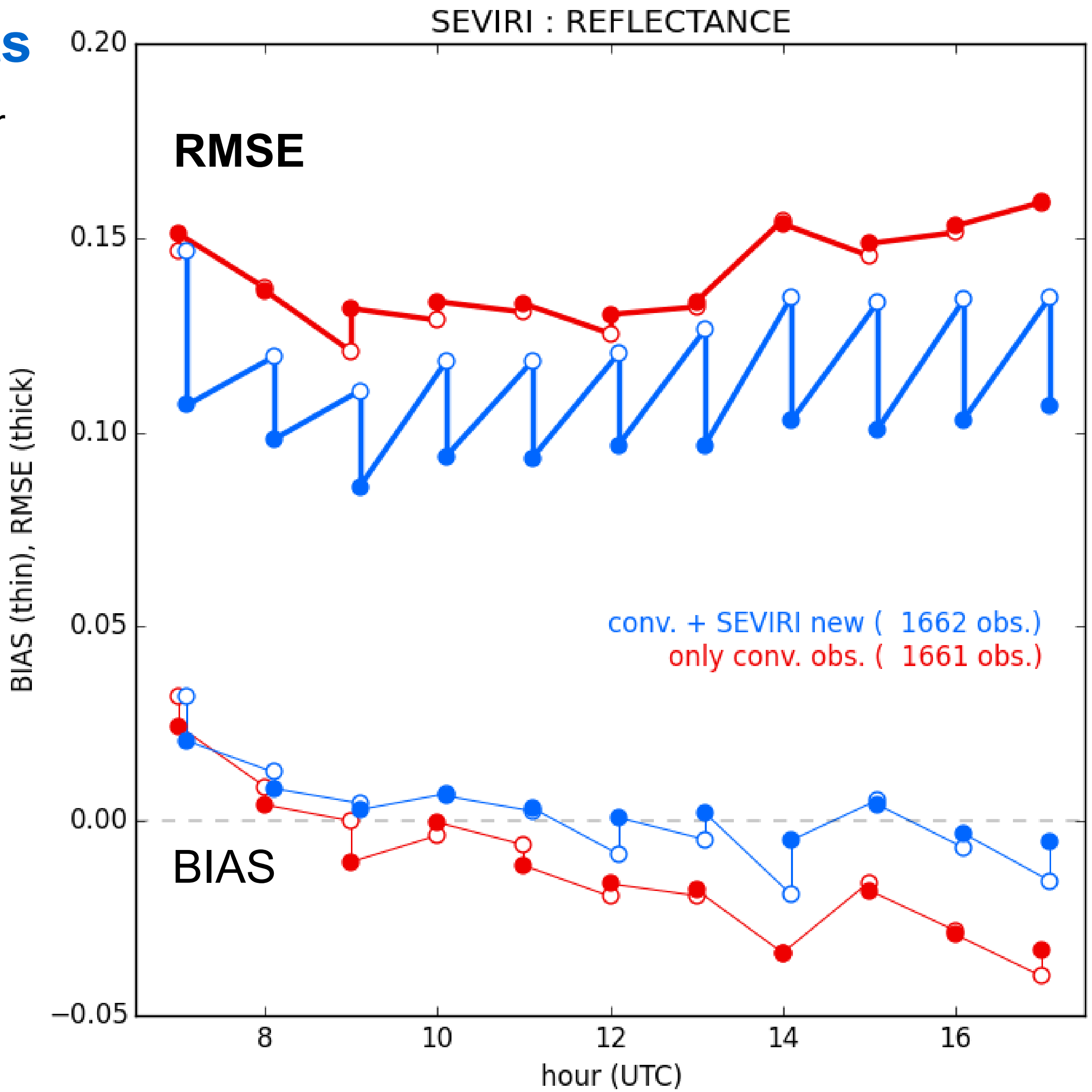
First assimilation results

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

Setup:
40 member LETKF
1h assimilation interval
600nm 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



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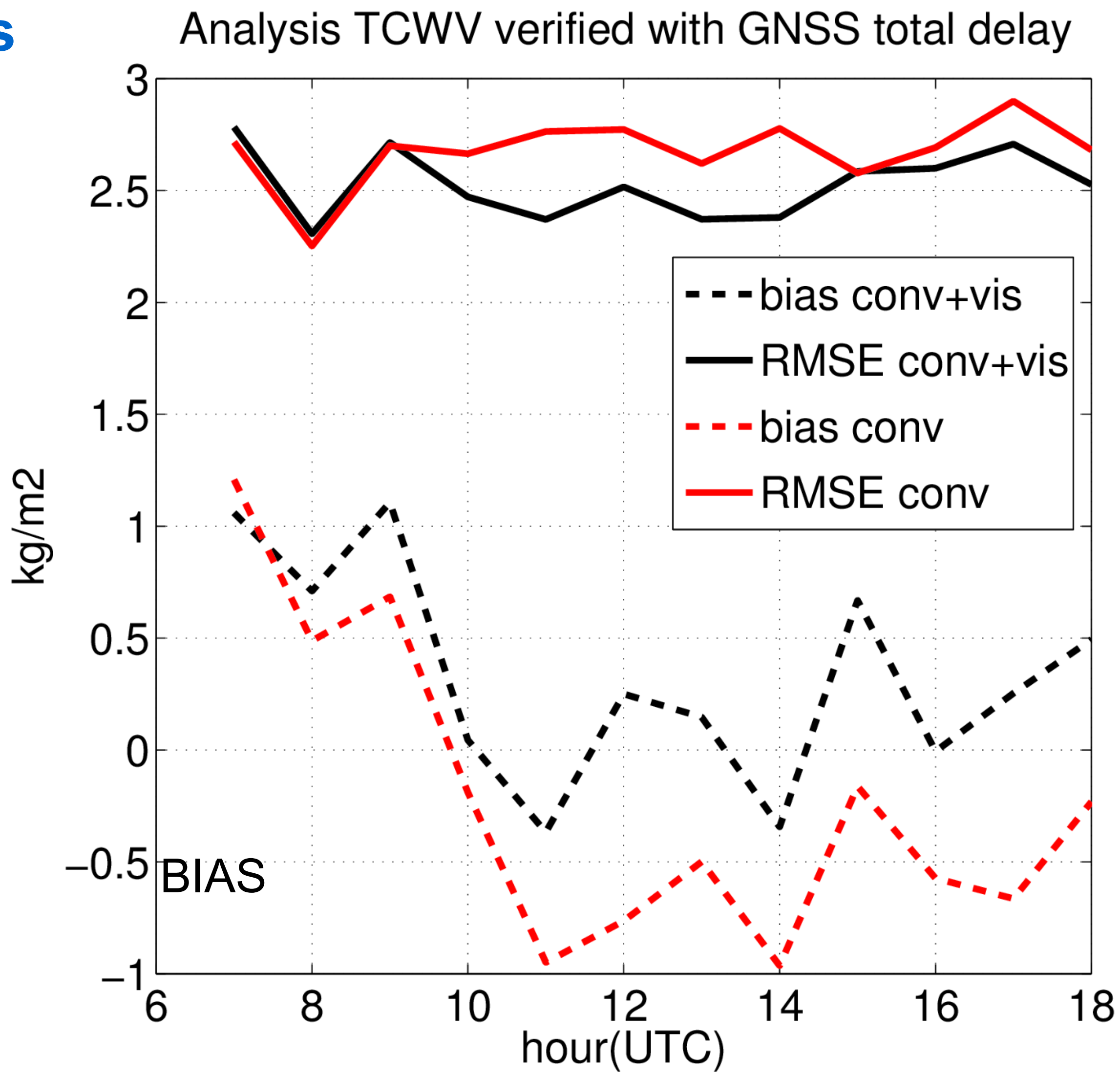
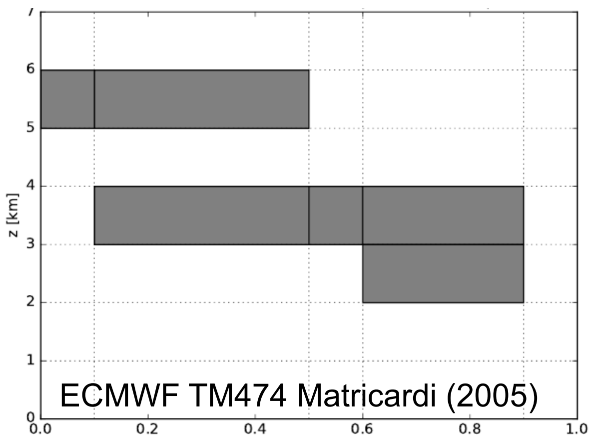


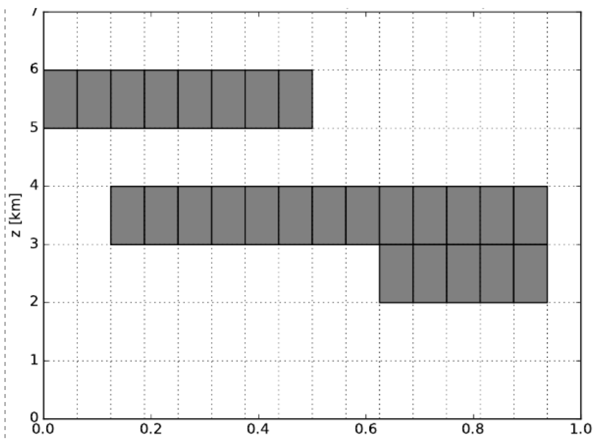
Cloud overlap schemes

Partially cloudy cells (subgrid clouds) → cloud overlap assumption required
Most common: random-maximum overlap. We compared different implementations:

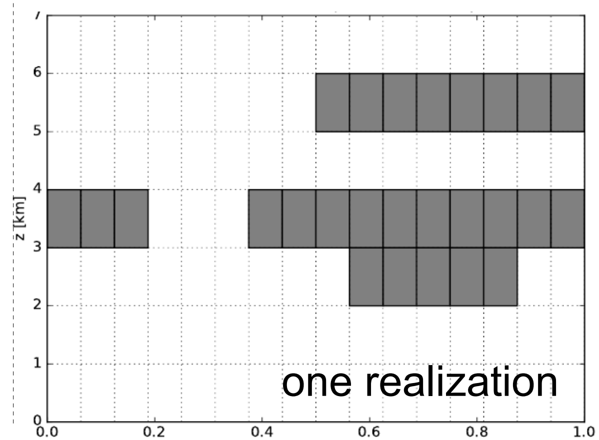
„Streams“ method (RTTOV)
deterministic



Discretized Streams method
deterministic



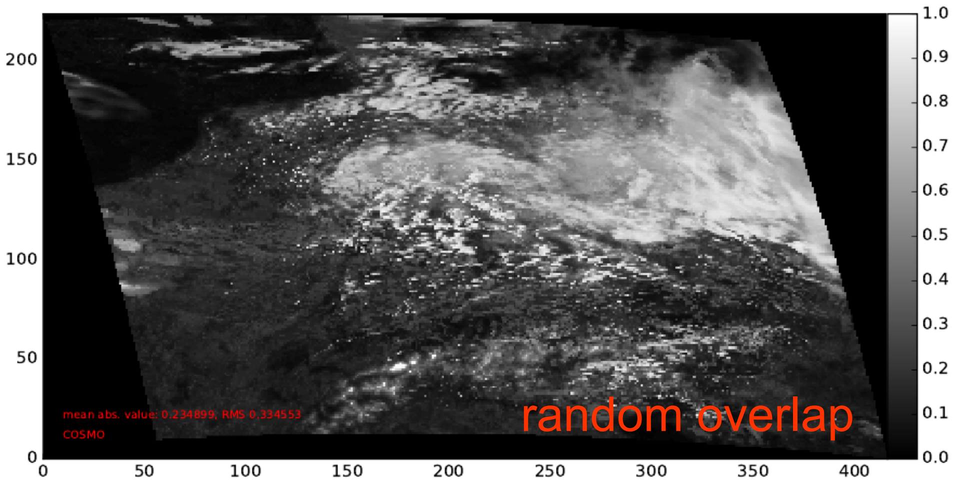
MFASIS
stochastic

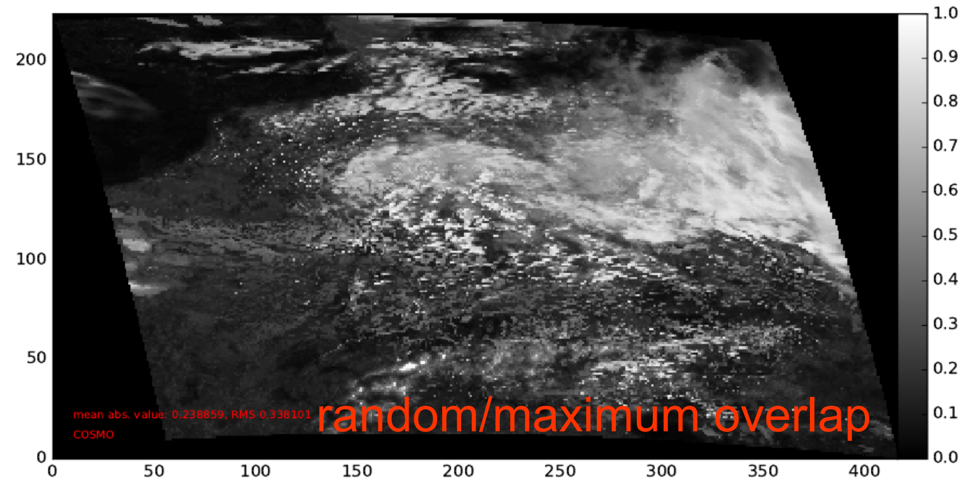


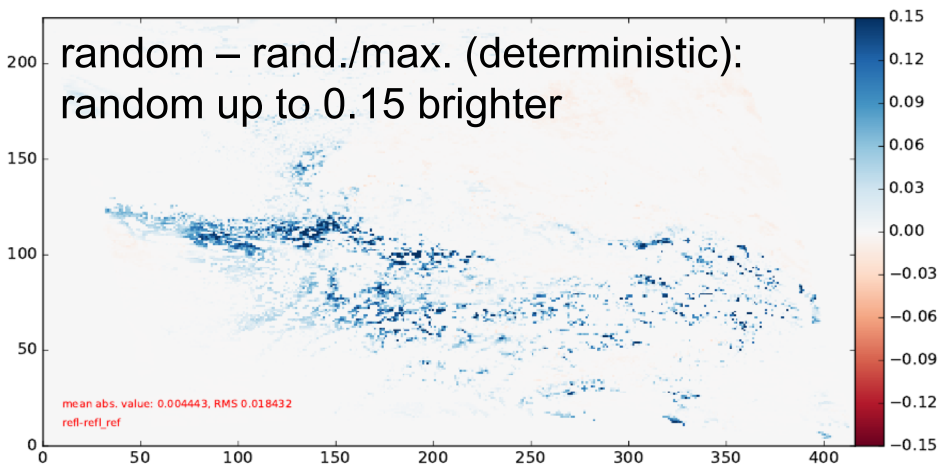
Requires up to $2N_z$ streams!

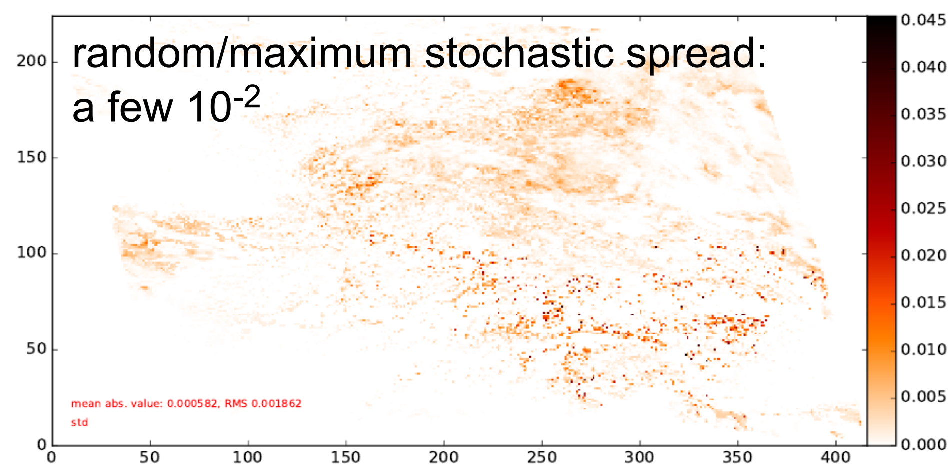
stream number can be limited (<10 may be sufficient)

- Mean of many stochastic realizations ≈ deterministic value (bias $O(10^{-3})$)
- Spread is typically a few 10^{-2}, affects most pixels. Some outliers differ by up to 0.2.
- Fixed stream number schemes are computationally cheaper (maybe also for IR)


random overlap
mean abs. value: 0.234899, RMS 0.334553
COSMO


random/maximum overlap
mean abs. value: 0.238859, RMS 0.338101
COSMO


random – rand./max. (deterministic):
random up to 0.15 brighter
mean abs. value: 0.004443, RMS 0.018432
refl-refl_ref

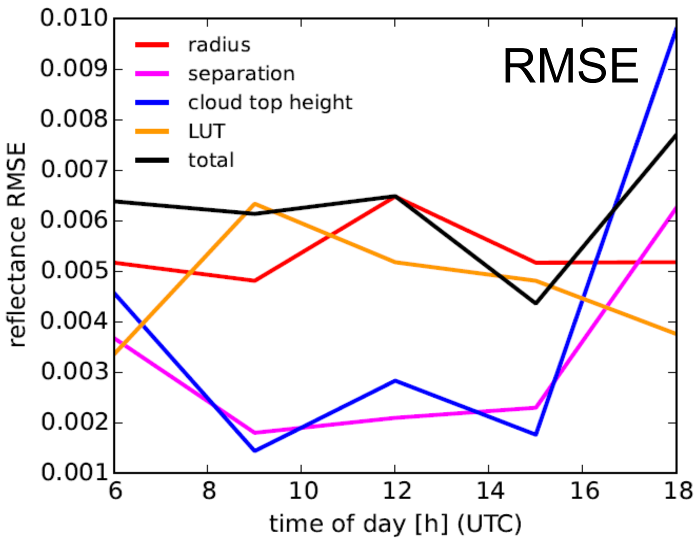

random/maximum stochastic spread:
a few 10^{-2}
mean abs. value: 0.000582, RMS 0.001862
std

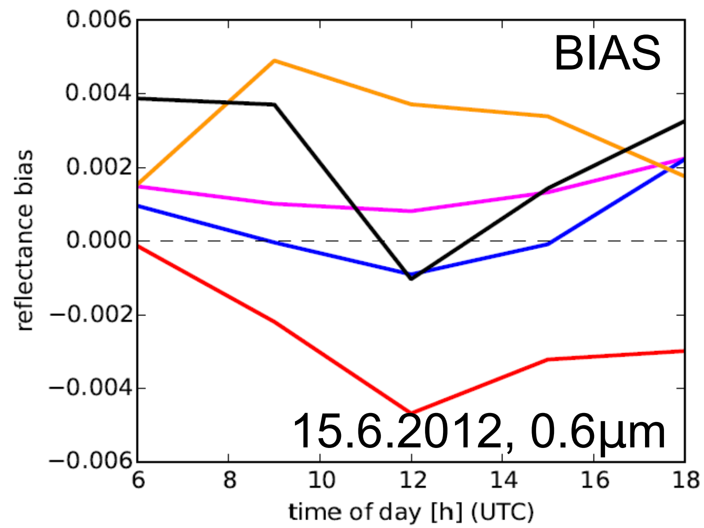
Error decomposition

What is the contribution of the various simplifications to the total error?

one effective radius instead of full profile — separation of cloud water and ice — fixed cloud top heights — fit residuum — interpolation error

$$R_{DISORT} - R_{MFASIS} = \Delta R_{tot} = \Delta R_{rad} + \Delta R_{sep} + \Delta R_{cth} + \underbrace{\Delta R_{fit} + \Delta R_{int}}_{\Delta R_{lut}}$$





ΔR_{rad} and ΔR_{int} are the most important and compensate each other partially.

Higher accuracy (e.g. for 1.6µm) requires better way to compute effective radius.