Efficient generation of synthetic near-infrared satellite images for model evaluation and data assimilation

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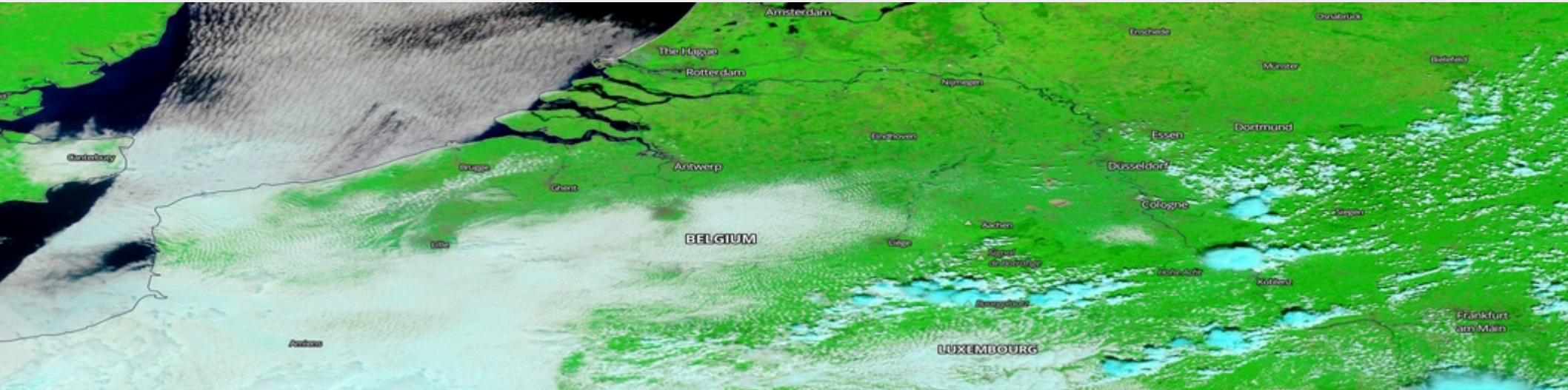
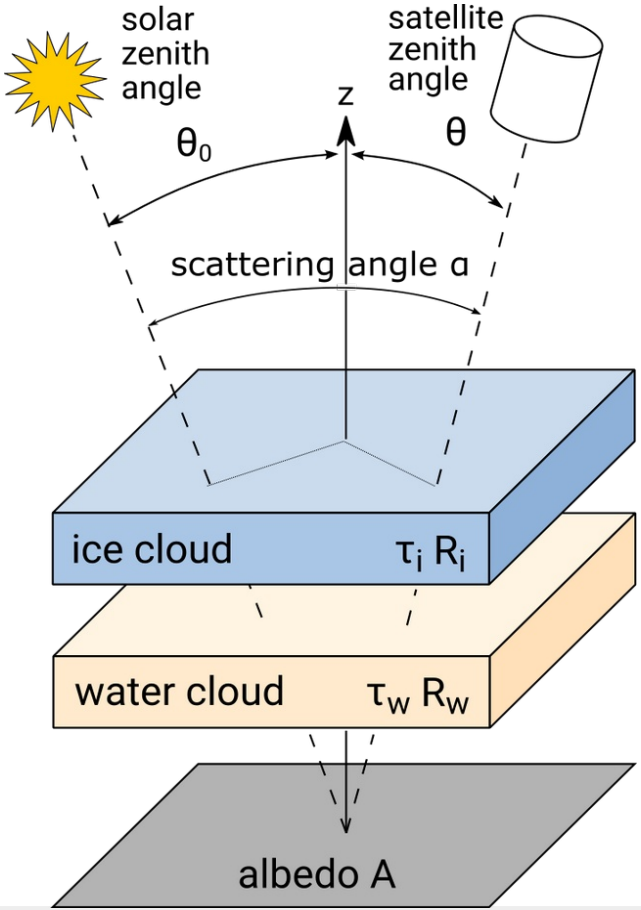


MFASIS (Method for FAst Satellite Image Synthesis) for visible channels



Courtesy of L. Scheck

→ **Forward operator for solar spectrum**

Simplifications of Radiative transfer:

- **Simplified Equation:** 3D → 1D RT (independent columns)
- **Simplified vertical structure**:
  - homogeneous water and ice clouds at fixed heights
  - Simplifications don't change Reflectance significantly

  → **8 parameters per column:** 3 angles + albedo + 4 parameters (optical depth, particle size)

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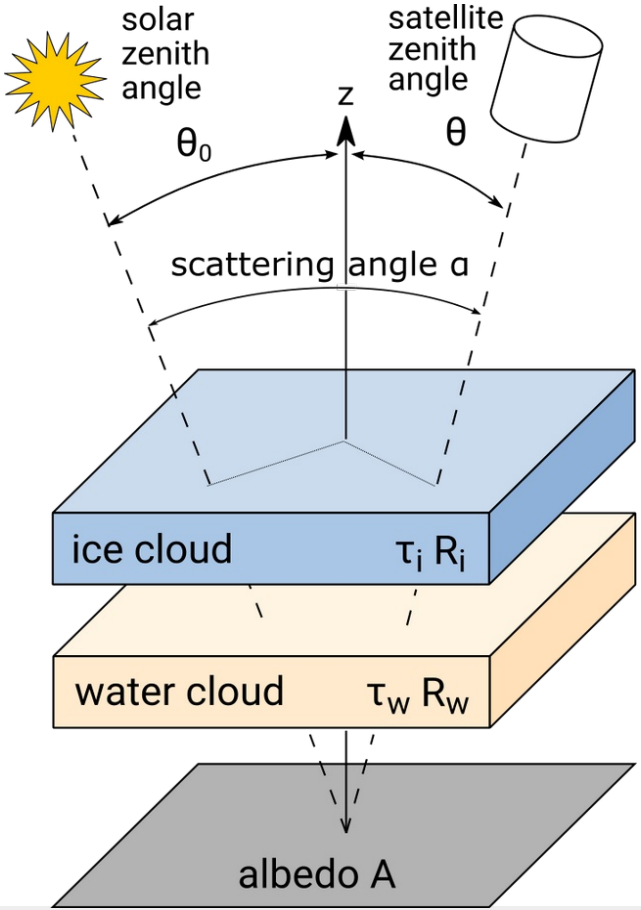

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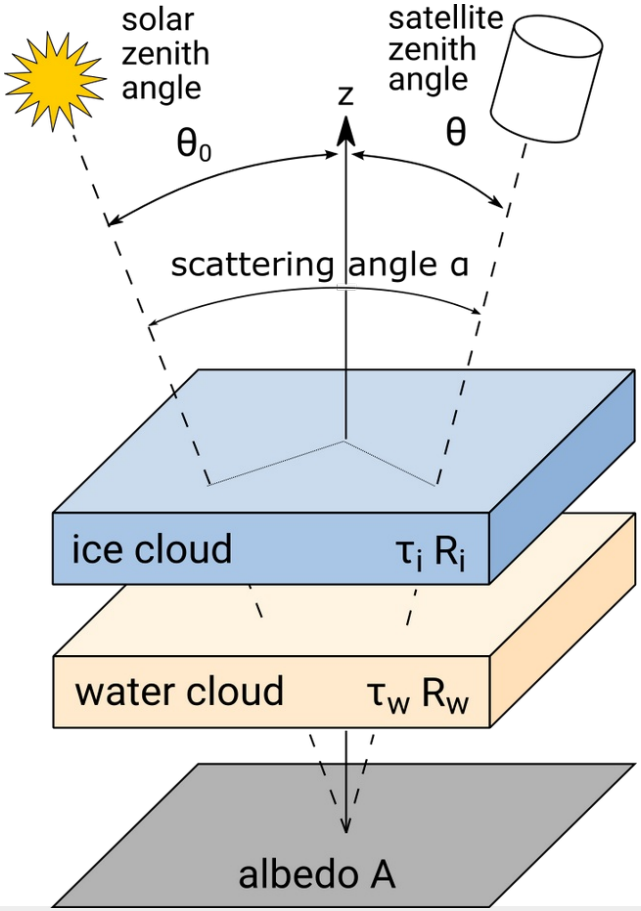
Compressed look-up table approach:

- TOA reflectances approximated by interpolating in **reflectance look-up table (LUT)** computed with a reference method (DISORT) for all parameter combinations
- LUT too big (8GB) for online operator usage → **compress table to 21MB** by only storing lowest Fourier coefficients

MFASIS (Method for FAst Satellite Image Synthesis) for visible channels



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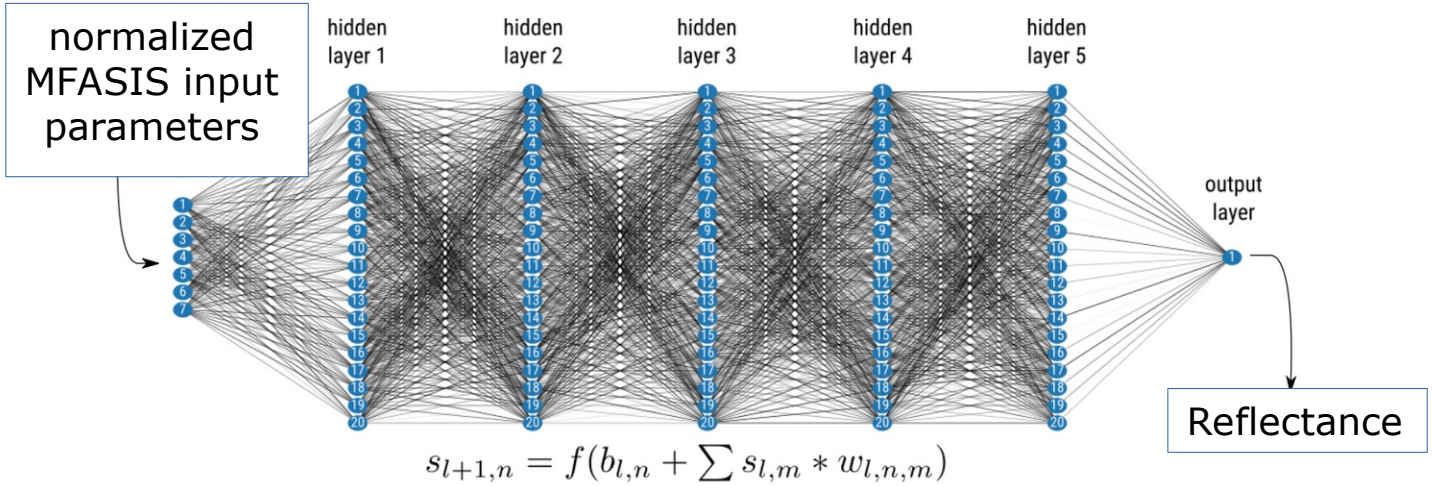
NEW: Neural Network replacing LUT → reduced data by factor 1000

Feed Forward Neural Network replacing the LUT in MFASIS

Advantages of MFASIS based on NN:

- Reduction of training data & memory consumption during computation by a factor of 1000 compared to LUT
- 10-times faster than LUT-version with similar accuracy
- Additional parameters feasible due to reduced data consumption (aerosols, trace gases, clean solution for NIR)
- Tangent-Linear and Andjoint Codes available



$$s_{l+1,n} = f(b_{l,n} + \sum s_{l,m} * w_{l,n,m})$$

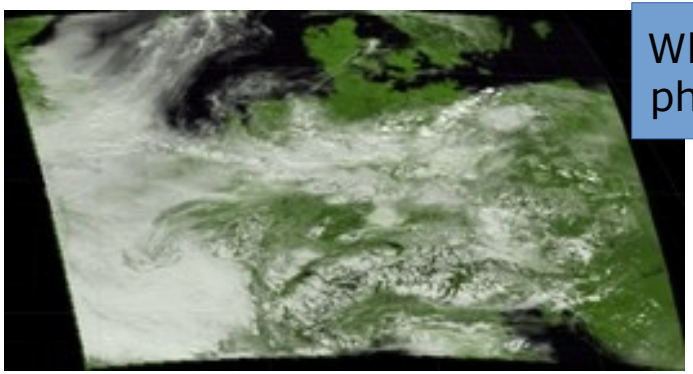
Courtesy of L. Scheck

Outline – extending MFASIS by 1.6µm channel using Neural Network

1) Enables to distinguish between water and ice clouds
   → Should be useful for data assimilation

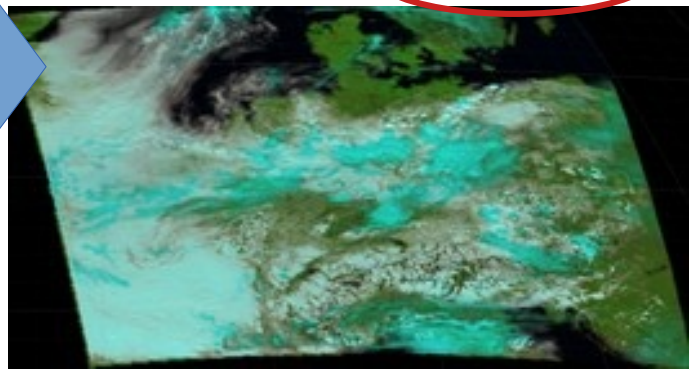
2) Stronger dependence on particle radii in NIR 1.6µm
   → Should be useful for evaluation of microphysics schemes

0.6µm & 0.8µm channels

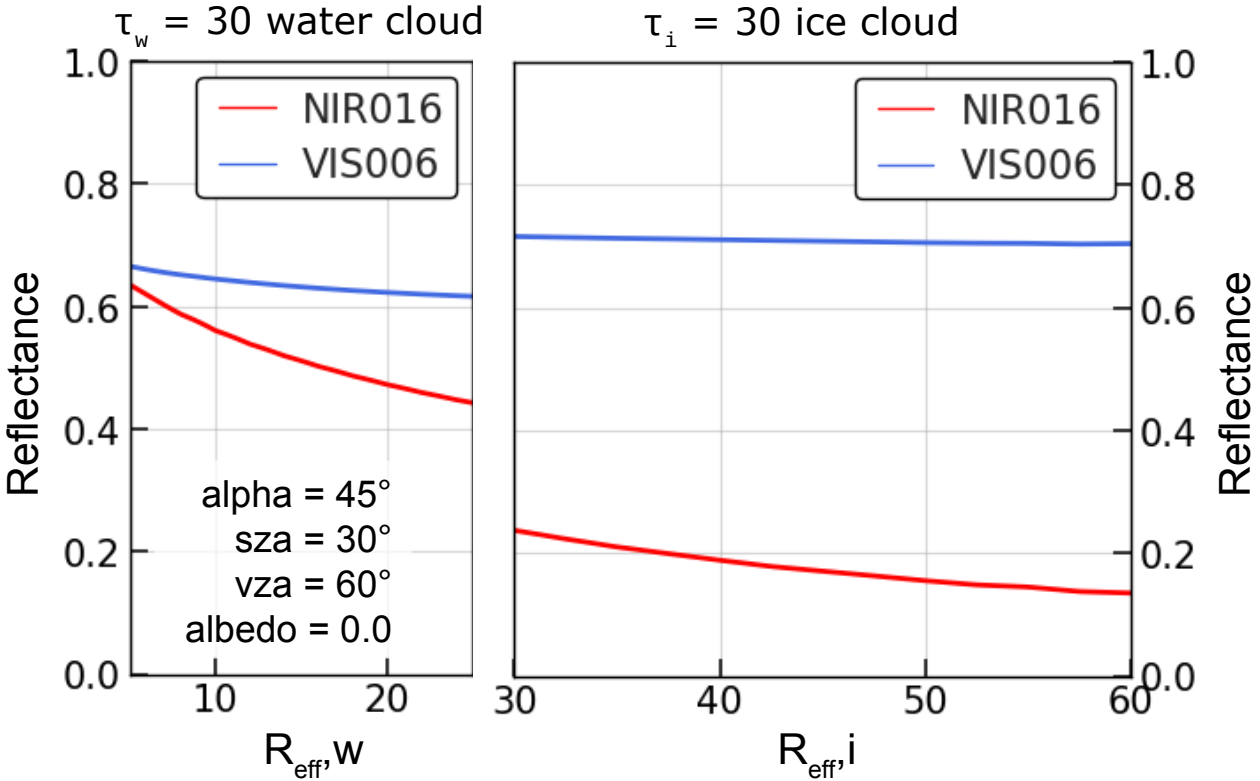


Where is an ice-phase included?

0.6µm & 0.8µm + 1.6µm NIR



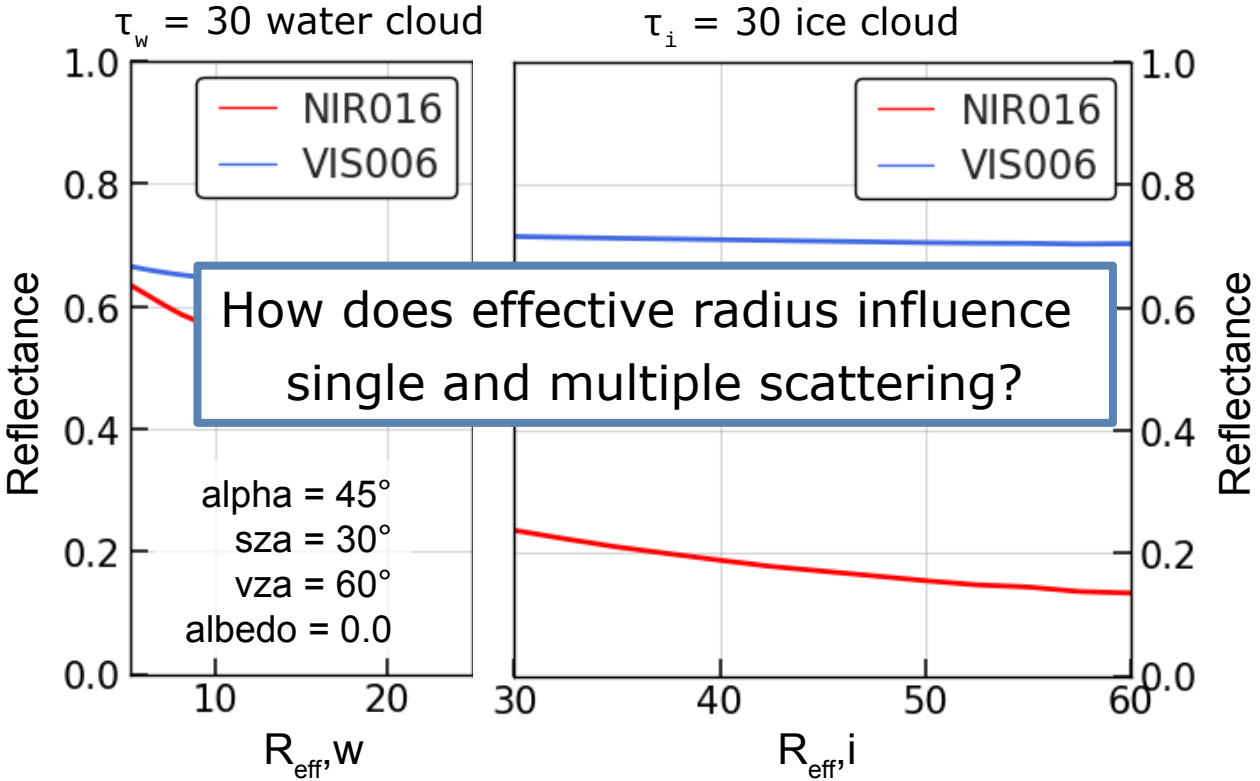
Main differences between 1.6µm-NIR and 0.6µm-VIS channels



1) Comparing reflectance between water (left) & ice (right) cloud:
   VIS: similar magnitude
   → almost no absorption
   NIR: difference in magnitude
   → stronger absorption for ice!

2) Stronger dependence of NIR on effective droplet radius

Main differences between 1.6µm-NIR and 0.6µm-VIS channels



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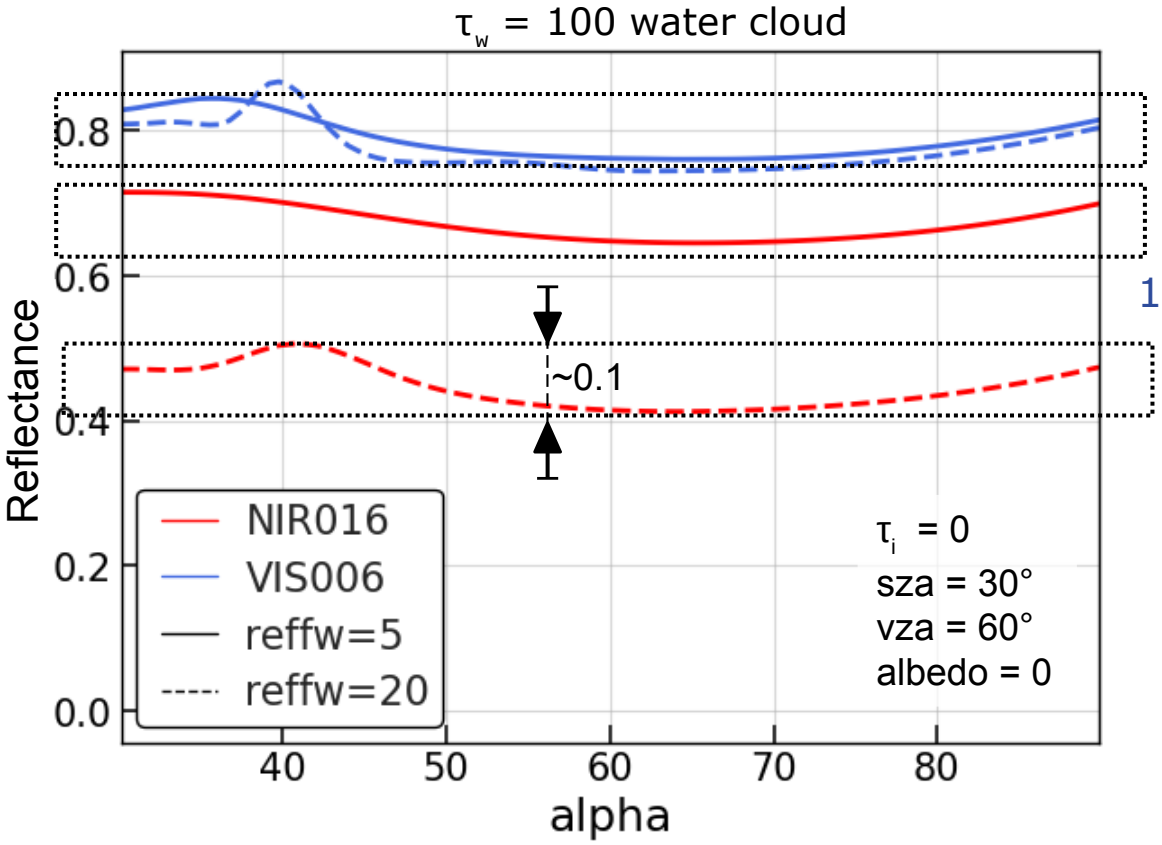
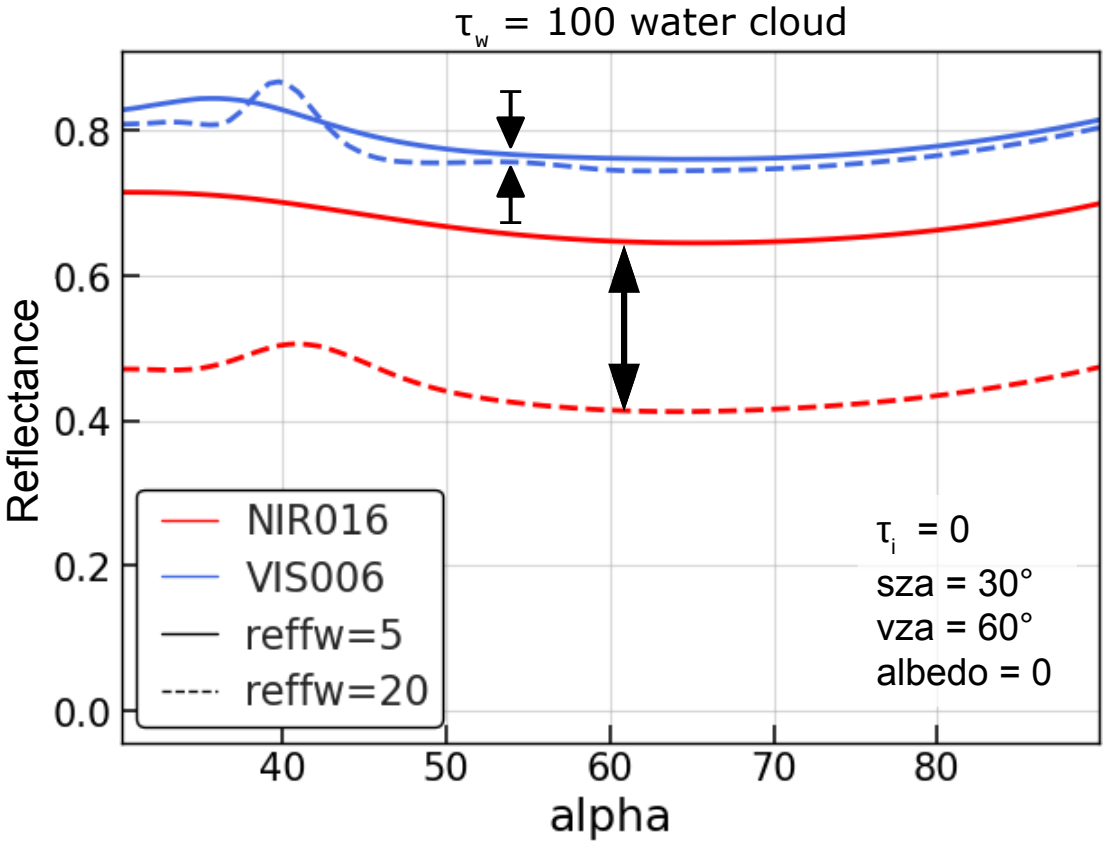
How does effective radius influence single and multiple scattering?



1) Single-scattering contribution from upper cloud layers depends on scattering-angle and radius for both, VIS and NIR

How does effective radius influence single and multiple scattering?



1) Single-scattering contribution from upper cloud layers depends on scattering-angle and radius for both, VIS and NIR

2) Multi-scattering contribution from deeper cloud layers (dominating for optically thick clouds):
   VIS: hardly sensitive to particle radius
   NIR: much more sensitive to particle radius

Strategy to include 1.6µm NIR-Channel

Challenges:

1st: Mixed-Phase clouds:

- ➔ Ice particles in mixed-phase clouds often are not at upper cloud-edge
  → water at cloud edge for satellite and Reference (DOM)
- ➔ **BUT**: MFASIS locates ice cloud above water cloud (default)
- ➔ Absorption of ice is stronger for 1.6µm-channel (compared to 0.6µm)
  → mixed-phase clouds too dark in MFASIS?

2nd: Reflectance is sensitive to particle radius in two different regions:

- Scattering-angle-dependent contribution from upper cloud layers
- Non-angle-dependent part from deeper cloud layers (additional for NIR016)

➔ We would need at least 2 different particle radii to cover both sensitivities

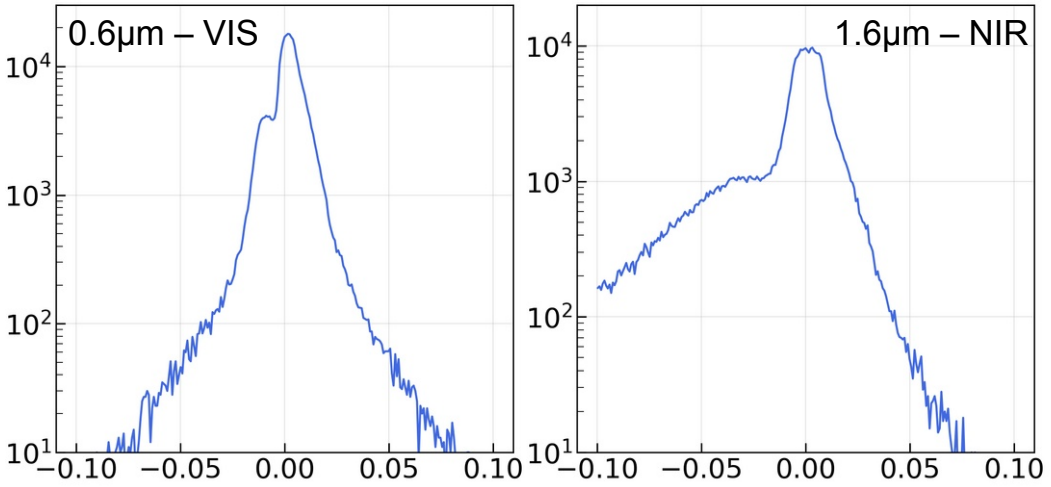
➔ MFASIS has only one particle radius as input parameter (per cloud)

Status-Quo: MFASIS on 64x5000 NWPSAF-Profiles

NWPSAF Data

- 5000 NWPSAF Profiles sampled from 1 year of global IFS short-term forecasts
- Represent realistic global & seasonal variability in cloud parameters
- 64 times different randomly selected viewing geometry
- Reference: Discrete Ordinates Method (DOM)

	Mean absolute error	99%-ile absolute error
MFASIS	0.007	0.046



Mean absolute error	99%-ile absolute error	
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NWPSAF Data

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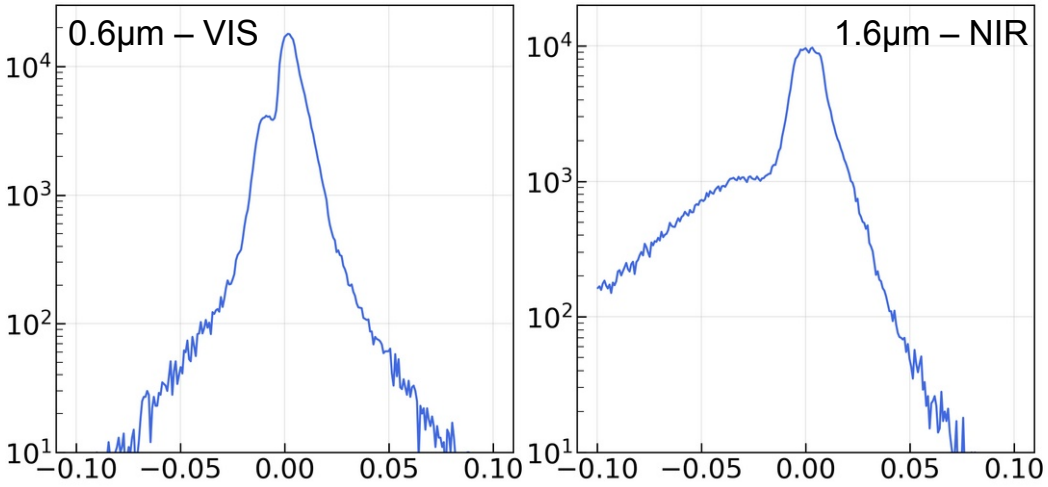
- Represent realistic global & seasonal variability i
- 64 times different randomly selected viewing ge
- Reference: Discrete Ordinates Method (DOM)

Aim: → Reduce 99th percentile of error well below 0.15 (assumed observation error for 0.6µm-channel in data assimilation experiments)

→ Reduce mean absolute error < 0.01 (calibration error of satellite instruments)

	Mean absolute error	99%-ile absolute error
MFASIS	0.007	0.046



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Representation of Mixed-Phase Clouds in 1.6µm NIR-Channel

Challenges:

1st: Mixed-Phase clouds:

- ➔ Ice-part from mixed-phase clouds is located in a separate ice cloud above water cloud by MFASIS
- ➔ Absorption of ice leads to underestimation of reflectance for mixed-phase clouds in MFASIS

Approach: Introduce mixed-phase ice within the water cloud (separate input variable)

Sensitivity to particle radius in 1.6µm-NIR

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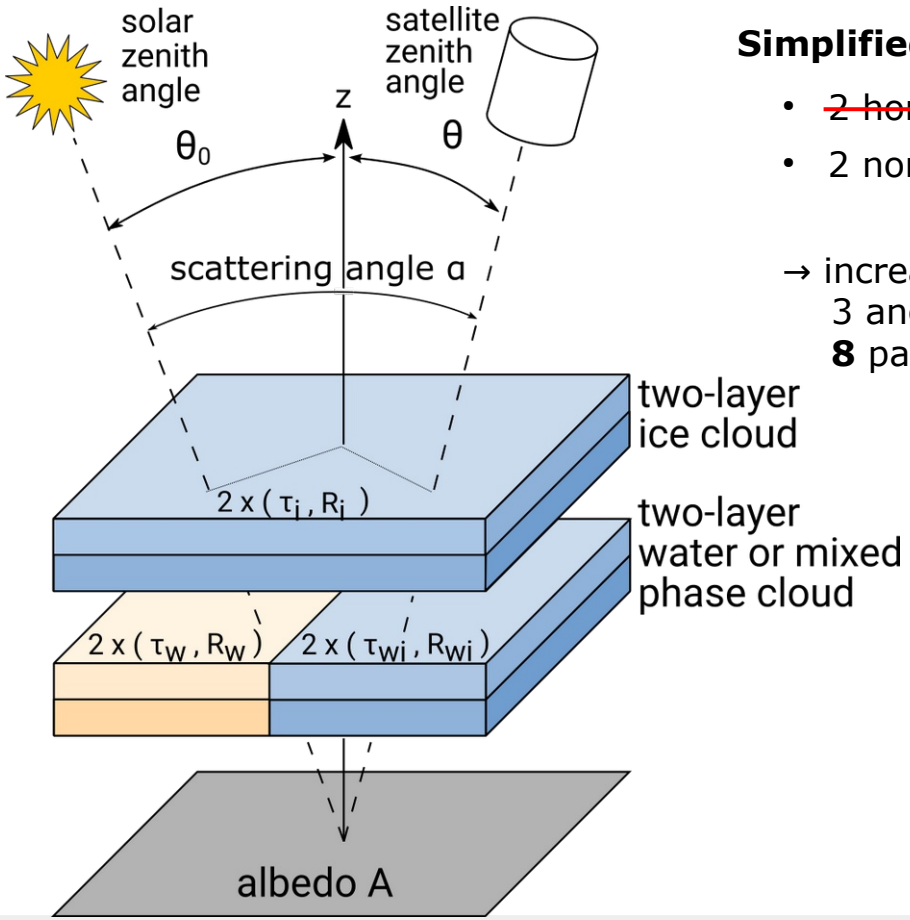
2nd: Reflectance is sensitive to particle radius in two different regions:

- ➔ We would need at least 2 different particle radii to cover both, single- and multi-scattering sensitivities
- ➔ MFASIS has only one particle radius as input parameter (per cloud)

Approach: split clouds and provide effective radii for upper and lower parts

Improving the vertical cloud structure



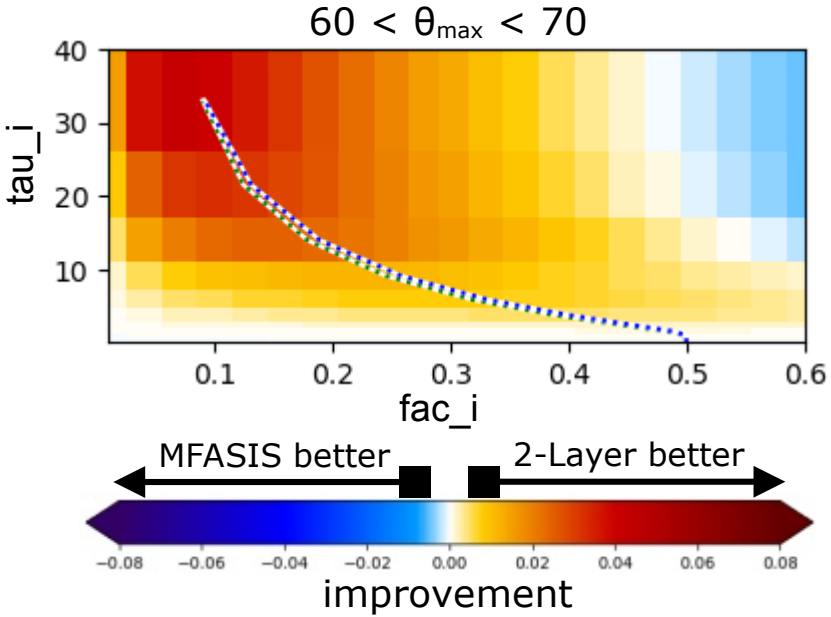
Simplified vertical structure:

- ~~2 homogeneous water and ice clouds at fixed heights~~
- 2 non-homogeneous 2-layer water and ice clouds **+** 2-layer mixed-phase-ice cloud

→ increase number of parameters: 8 → 14
3 angles + albedo + surface-pressure + cloud-top pressure
8 parameters: **water cloud** → **1** optical depth, **2** particle sizes
ice cloud → **1** optical depth, **2** particle sizes
mixed-phase cloud → **1** optical depth, **1** particle sizes

Operationally feasible with Neural Networks

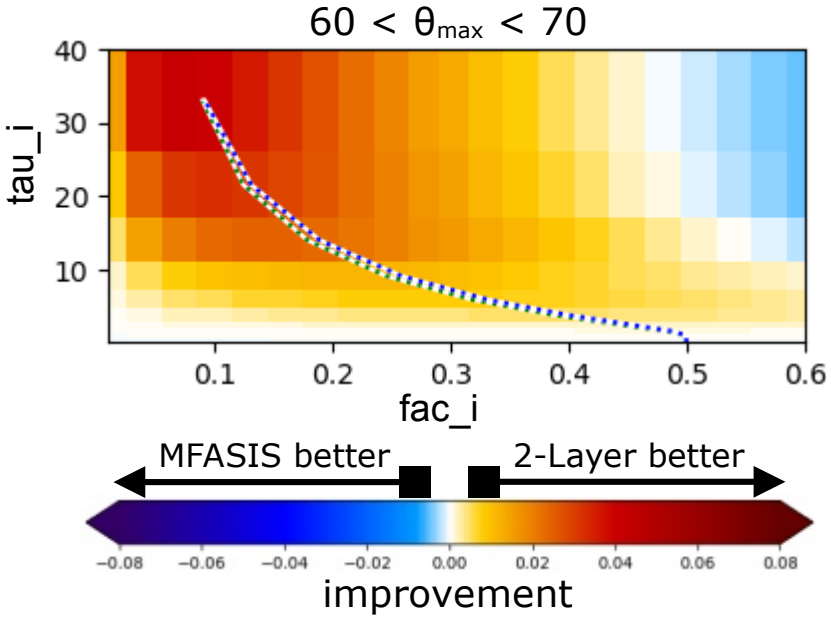
2-Layer – Where to split the clouds into upper and lower part?

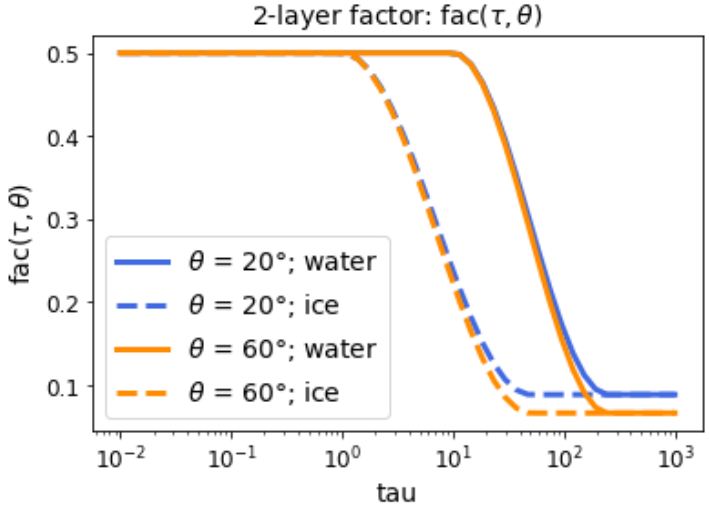


$$fac = \frac{\tau_{top}}{\tau_{top} + \tau_{bot}}$$

- Optimize 2-Layer factor to minimize reflectance error
- Optimization for water-/ ice-clouds separately
- Parametrization $\texttt{fac}(\tau, \theta_{max})$ depends on optical depth τ and maximal zenith angle $\theta_{max} = \texttt{max(sza, vza)}$
- Compute effective Radii for upper / lower cloud layer

Parametrization – Two-Layer factor $fac(\tau, \theta_{max})$

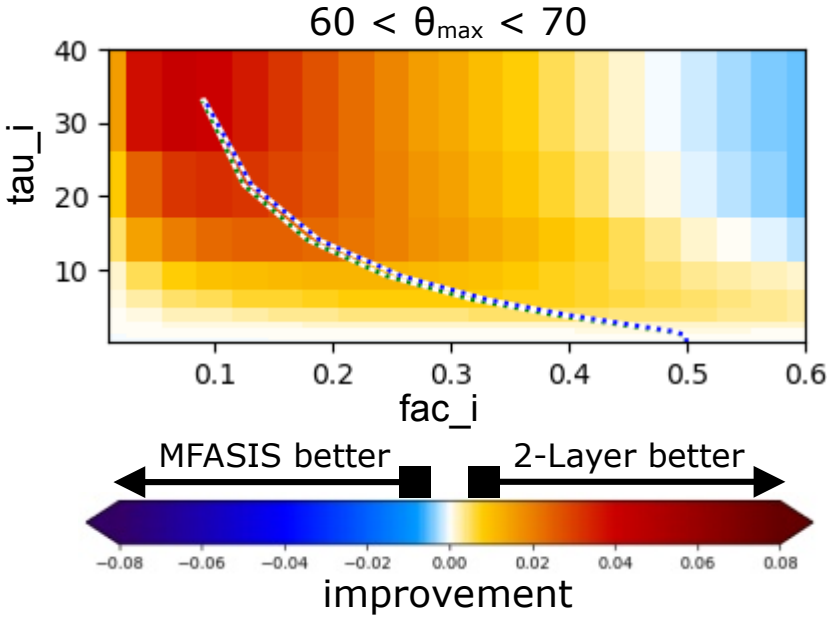




$$fac = \frac{\tau_{top}}{\tau_{top} + \tau_{bot}}$$

- Small optical depth: $fac(\tau, \theta_{max}) = 0.5$
  - → Equal probability of photons being scattered in upper or lower half of the cloud
- Large optical depth: $fac(\tau, \theta_{max}) < 0.1$
  - → Most of the photons reaching the satellite have been scattered in uppermost cloud layers
  - → Region of most relevant information on effective radius

Example: Two-Layer parametrization – only Ice-clouds



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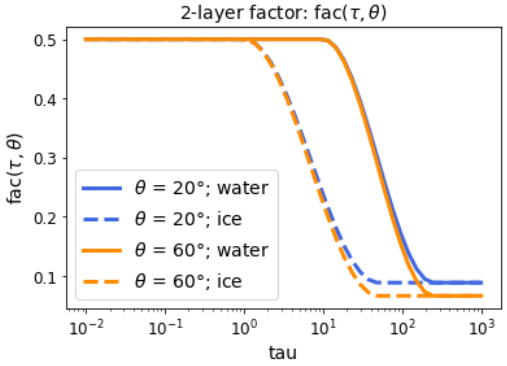
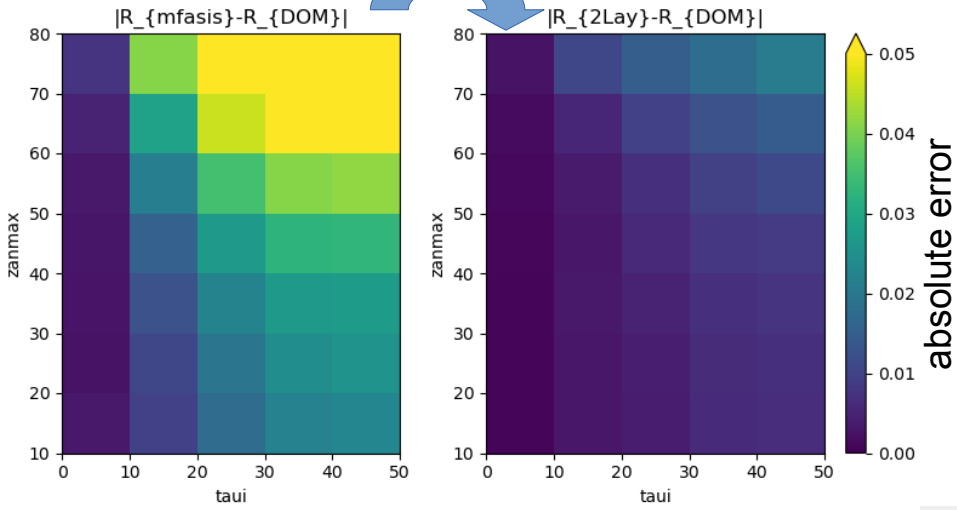


Apply 2-Layer parametrization

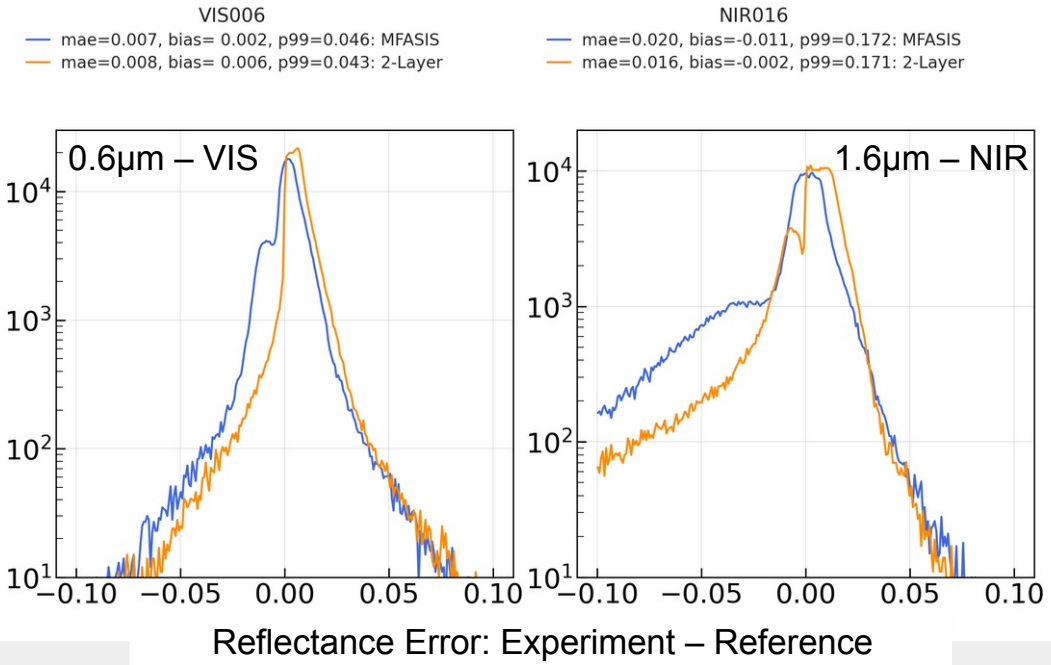


Introducing 2-Layer Clouds improves Water- & Ice-clouds

Application of 2-Layer method on complete NWP-SAF data

- Reduction in mean absolute error by almost 25% (NIR)
- 99th percentile of absolute error remains unchanged (VIS & NIR)
- Errors dominated by misrepresentation of Mixed-Phase clouds

	Mean absolute error	99%-ile absolute error
MFASIS	0.007	0.046
2-Layer	0.008	0.043



Mean absolute error	99%-ile absolute error	
0.020	0.172	**MFASIS**
0.016	0.171	**2-Layer**

Introducing 2-Layer Clouds improves Water- & Ice-clouds

Application o

- Reductio
- 99th perc
- Errors do

What to do with Mixed-Phase clouds?

- Ice of **1st** water-cloud-layer → remains in place as mixed-phase ice
- Ice of **2nd** water-cloud-layer → transferred to water with large particle radius
  → need one input parameter less

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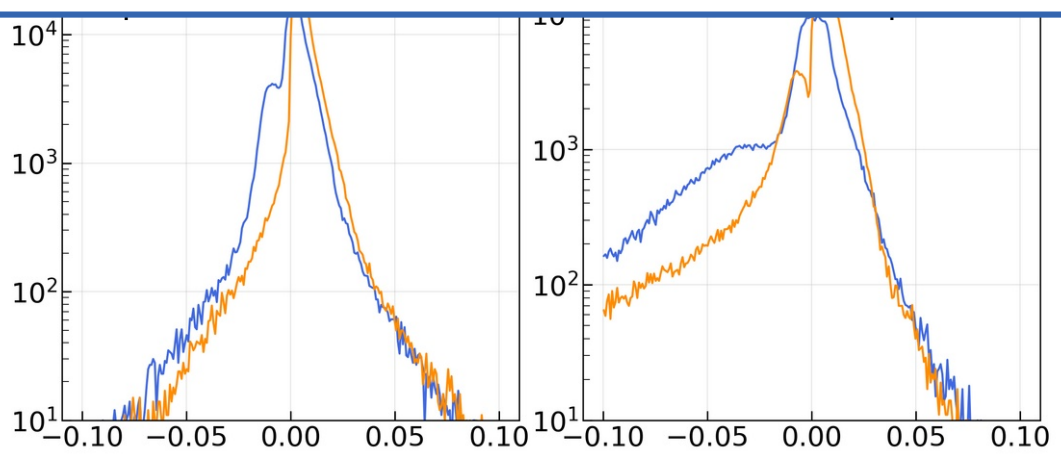

Reflectance Error: Experiment – Reference

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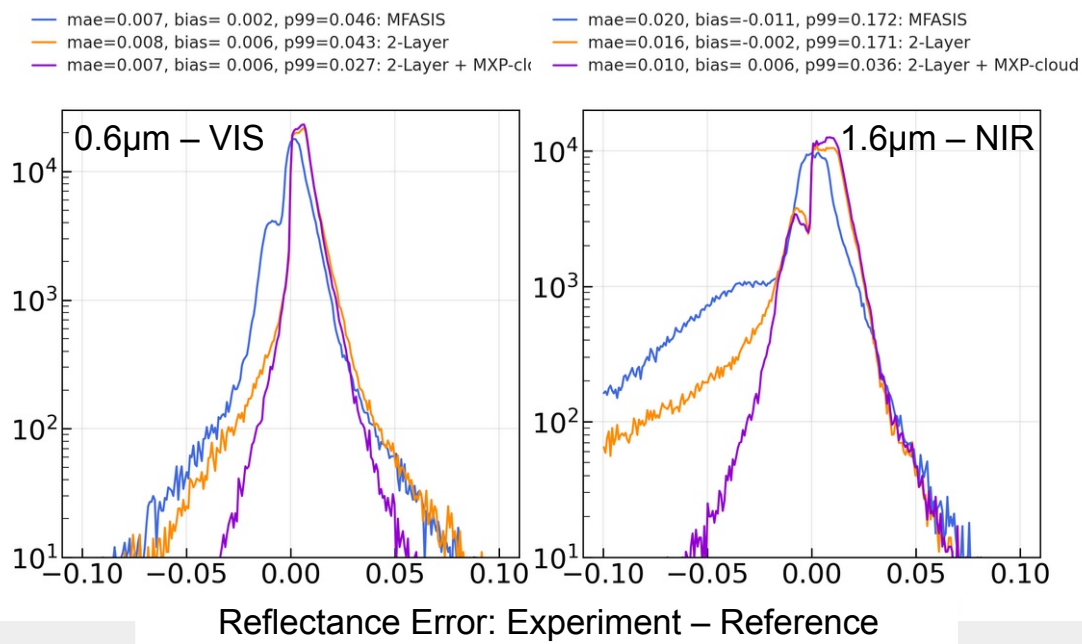
Adding a Mixed-Phase Cloud in upper Layer reduces largest errors

Combined representation improvements reduce largest errors for VIS 0.6µm and NIR 1.6µm

- ➔ Reduction in 99th percentile of absolute error by almost 40% (VIS) and 80% (NIR)
- ➔ Reduction in mean absolute error by 50% (NIR)

	Mean absolute error	99%-ile absolute error
MFASIS	0.007	0.046
2-Layer	0.008	0.043
2-Layer + MX-Cloud	0.007	0.027



Mean absolute error	99%-ile absolute error	
0.020	0.172	**MFASIS**
0.016	0.171	**2-Layer**
0.010	0.036	**2-Layer + MX-Cloud**

Adding a Mixed-Phase Cloud in upper Layer reduces largest errors

Can we train a Neural Network based on this improved representation of vertical cloud structure?

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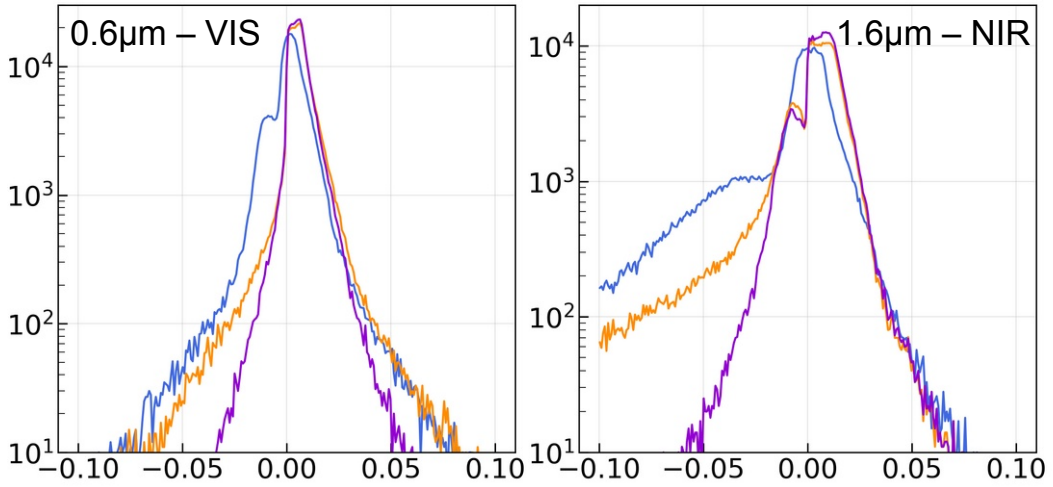

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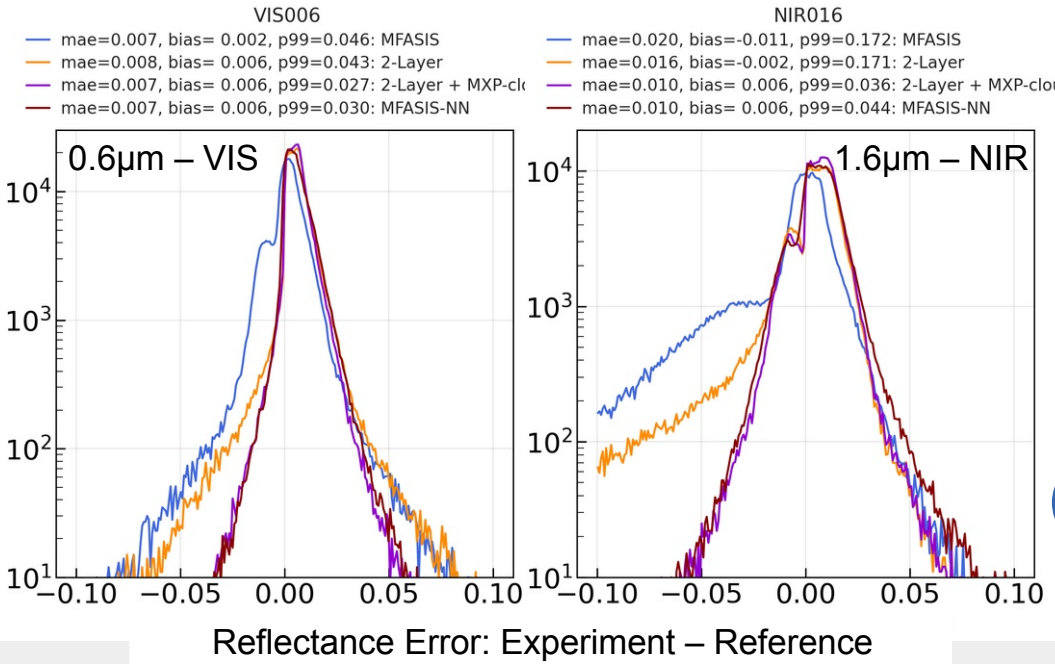
0.016	0.171	**2-Layer**
0.010	0.036	**2-Layer + MX-Cloud**

Train a first Neural-Network with improved the vertical cloud structure

Neural Network hardly increases error compared to 2-Layer + MX-Cloud

- ➔ 6 hidden Layers ; 30 Nodes per Layer
- ➔ NIR Results are only slightly worse than VIS results

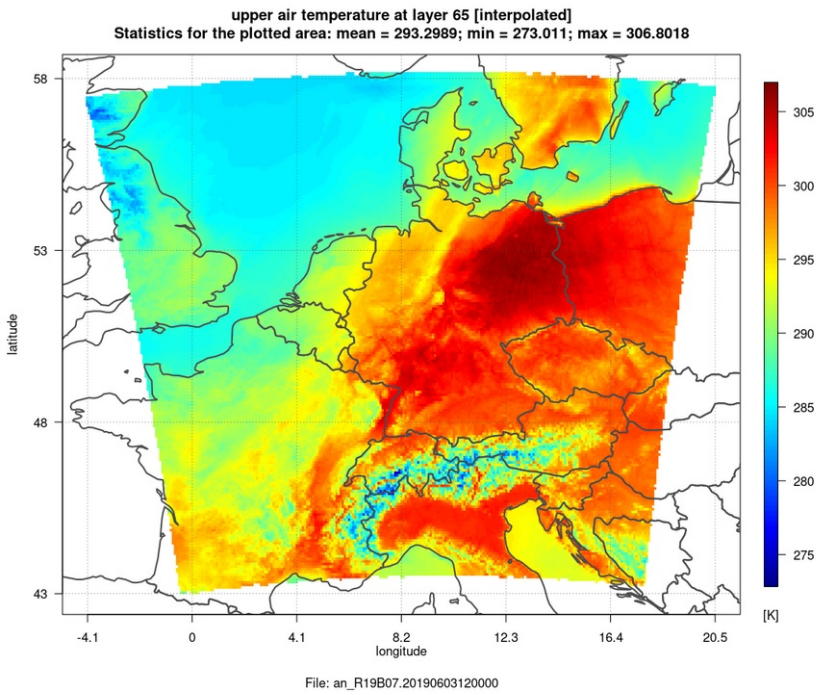
	Mean absolute error	99%-ile absolute error
MFASIS	0.007	0.046
2-Layer	0.008	0.043
2-Layer + MX-Cloud	0.007	0.027
NN	0.007	0.030



Mean absolute error	99%-ile absolute error	
0.020	0.172	MFASIS
0.016	0.171	2-Layer
0.010	0.036	2-Layer + MX-Cloud
0.010	0.044	NN

First application of MFASIS-NN on ICON-D2 hindcasts – 1.6µm

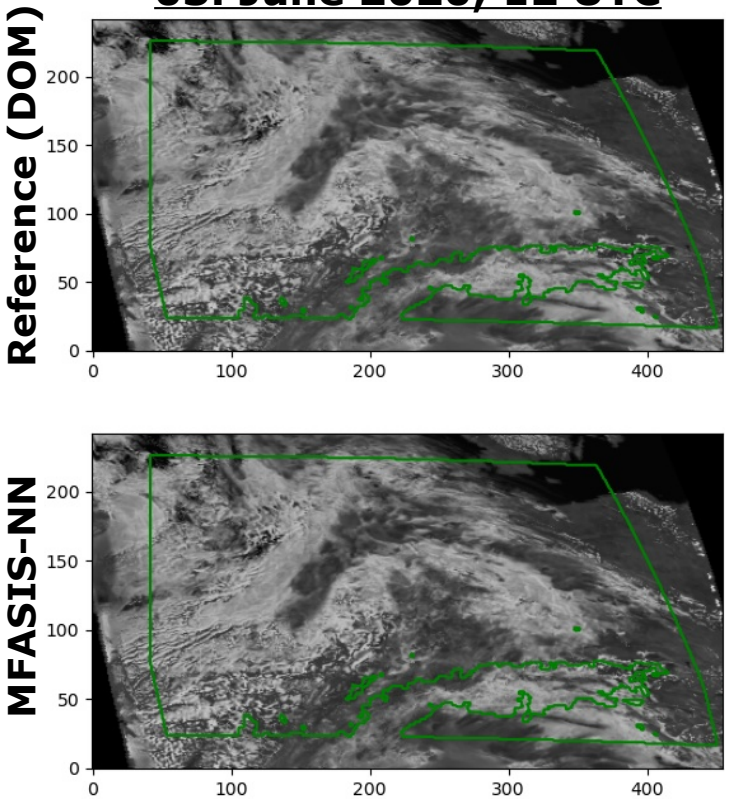
ICON-D2 Domain



- Domain: Central Europe
- 2-Moment microphysics scheme provides prognostic particle numbers and sizes
- Period: 01. June 2020 – 30. June 2020

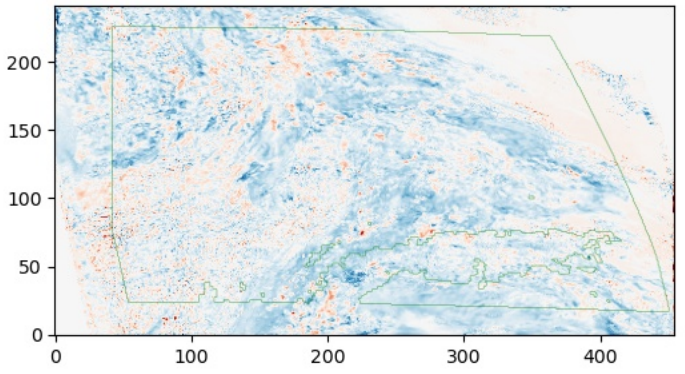
MFASIS-NN applied on ICON-D2 03. June 2020 – 1.6µm

03. June 2020; 12 UTC



- Domain: Central Europe
- 2-Moment microphysics scheme provides prognostic particle numbers and sizes
- Cloudy regions involving ice-phase show underestimation of Reflectance (**blue**)

MFASIS-NN – Reference

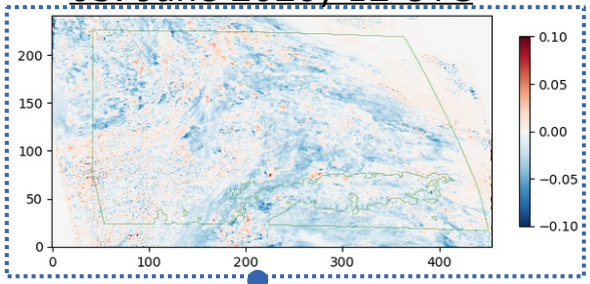


	Mean absolute error	99%-ile absolute error
NWPSAF	0.010	0.044
ICON-D2 03. June	**0.015**	**0.049**

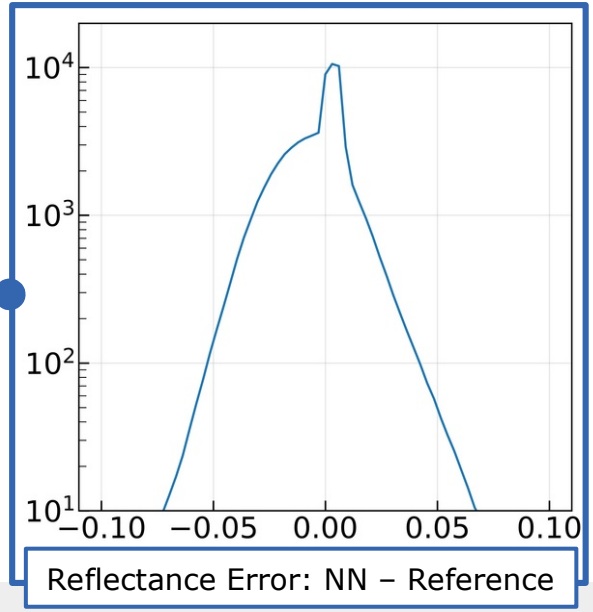
MFASIS-NN applied on 30 Days of ICON-D2 hindcasts – 1.6µm

- Period: 01. June 2020 – 30. June 2020 ; 12 UTC
- Shape of error-histogram similar to NWPSAF-Data
- Mean & 99th percentile of absolute errors similarly small as for NWPSAF-Profiles
- First step towards using the 1.6µm-channel in Data Assimilation

03. June 2020; 12 UTC



	Mean absolute error	99%-ile absolute error
NWPSAF	0.010	0.044
ICON-D2 1 Day	0.015	0.049
ICON-D2 30 Days	**0.011**	**0.047**



Summary and Outlook

1.6 µm NIR-channel:

- Improved description of vertical cloud-structure removes largest errors
- Errors for NIR are now in the range of VIS
- First Neural-Networks are very promising

➔ **Next steps:**

- Application for model evaluation and data assimilation
- Implementation in RTTOV-v13.2