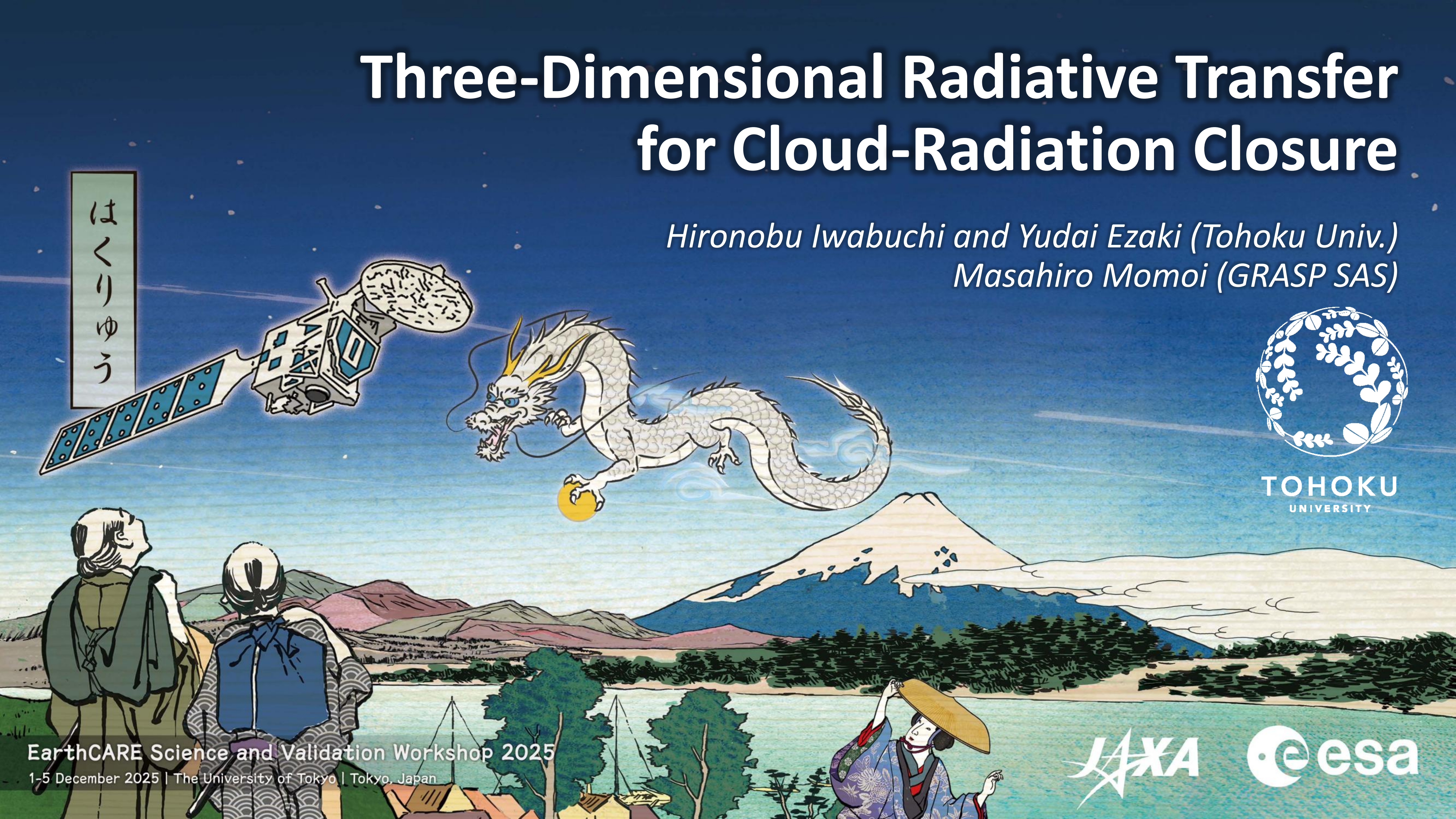
Three-Dimensional Radiative Transfer for Cloud-Radiation Closure

Hironobu Iwabuchi and Yudai Ezaki (Tohoku Univ.)
Masahiro Momoi (GRASP SAS)



TOHOKU UNIVERSITY

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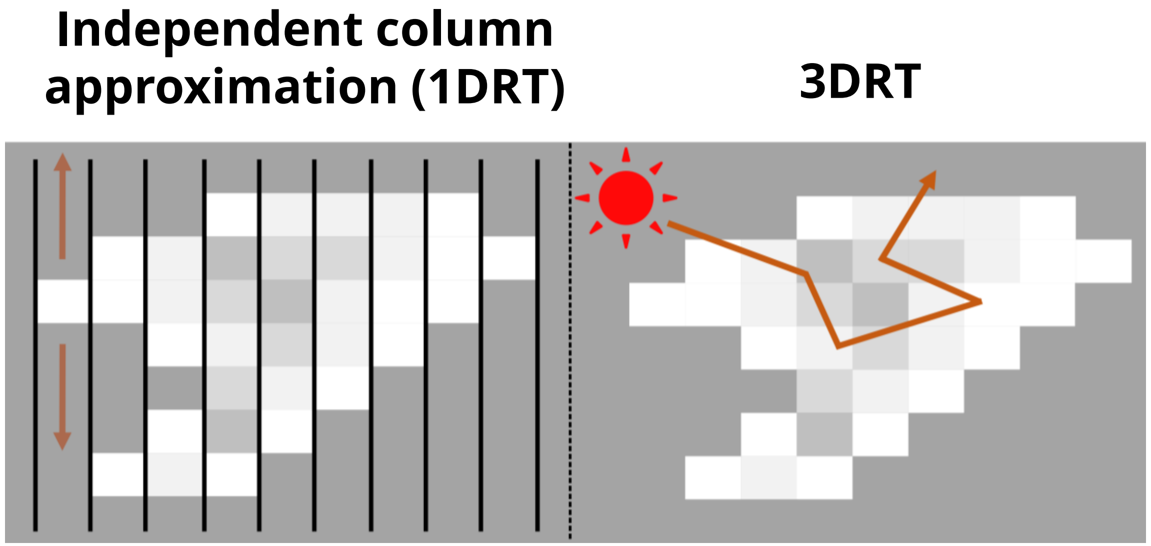
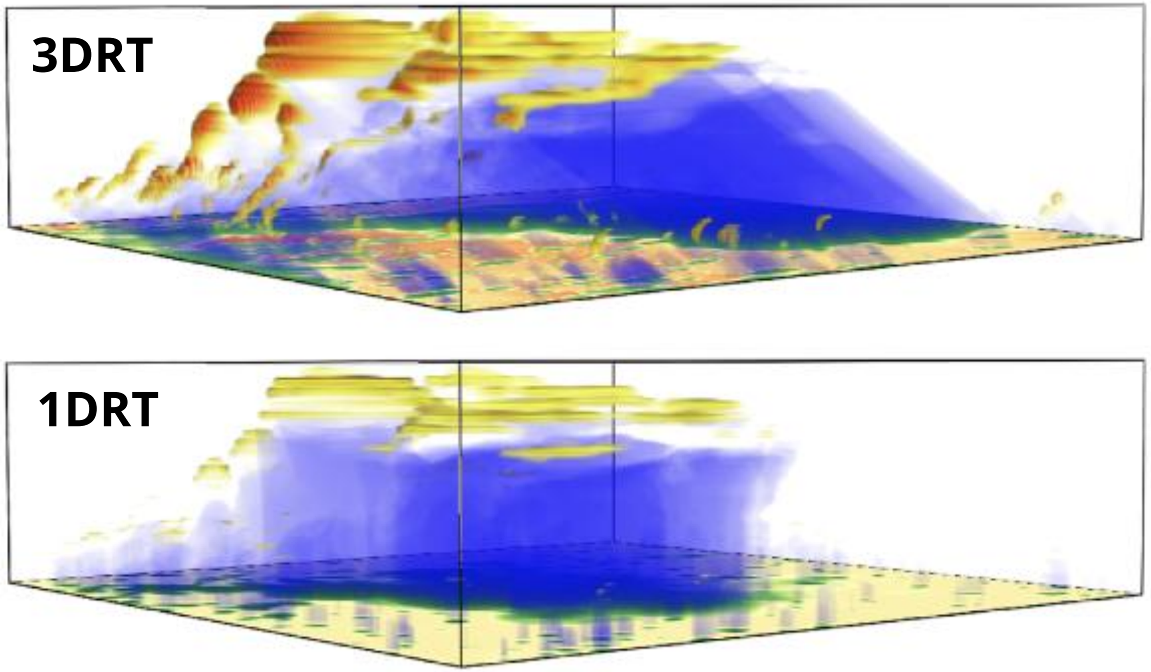
Background: 3DRT effects

- Radiation biases arising from the neglect of horizontal radiative transport (in 1DRT), which can introduce non-negligible errors in estimates of Earth's radiative budget and cloud dynamics.





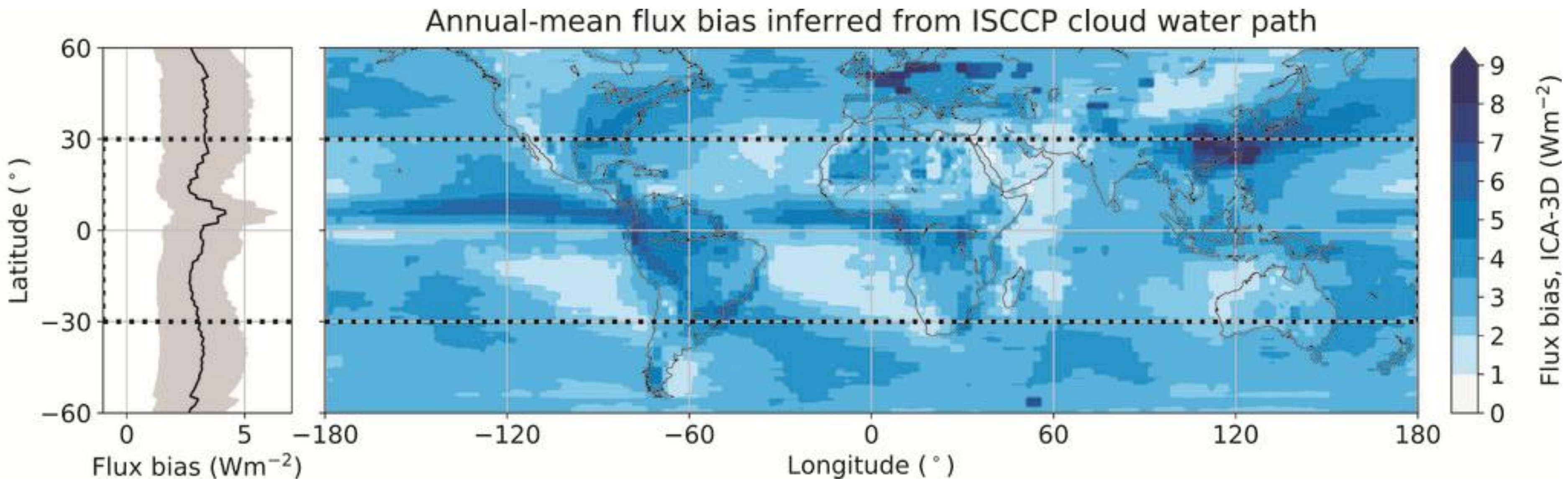
Jakub and Mayer, 2015

3DRT effect for radiation budget and cloud dynamics

Singer et al. 2021

Zonal-mean tropical flux bias is estimated to be 3.1 ± 1.6 W m^{-2}

SW flux bias = ICA - 3D (W/m²)



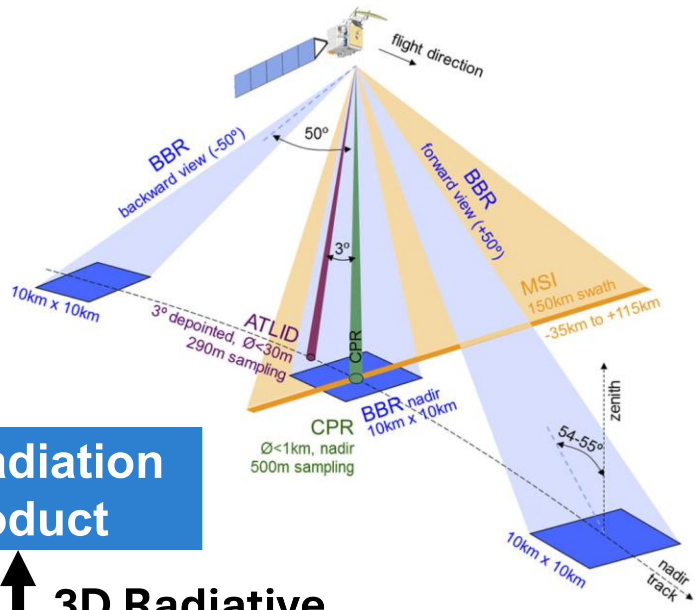
Objectives

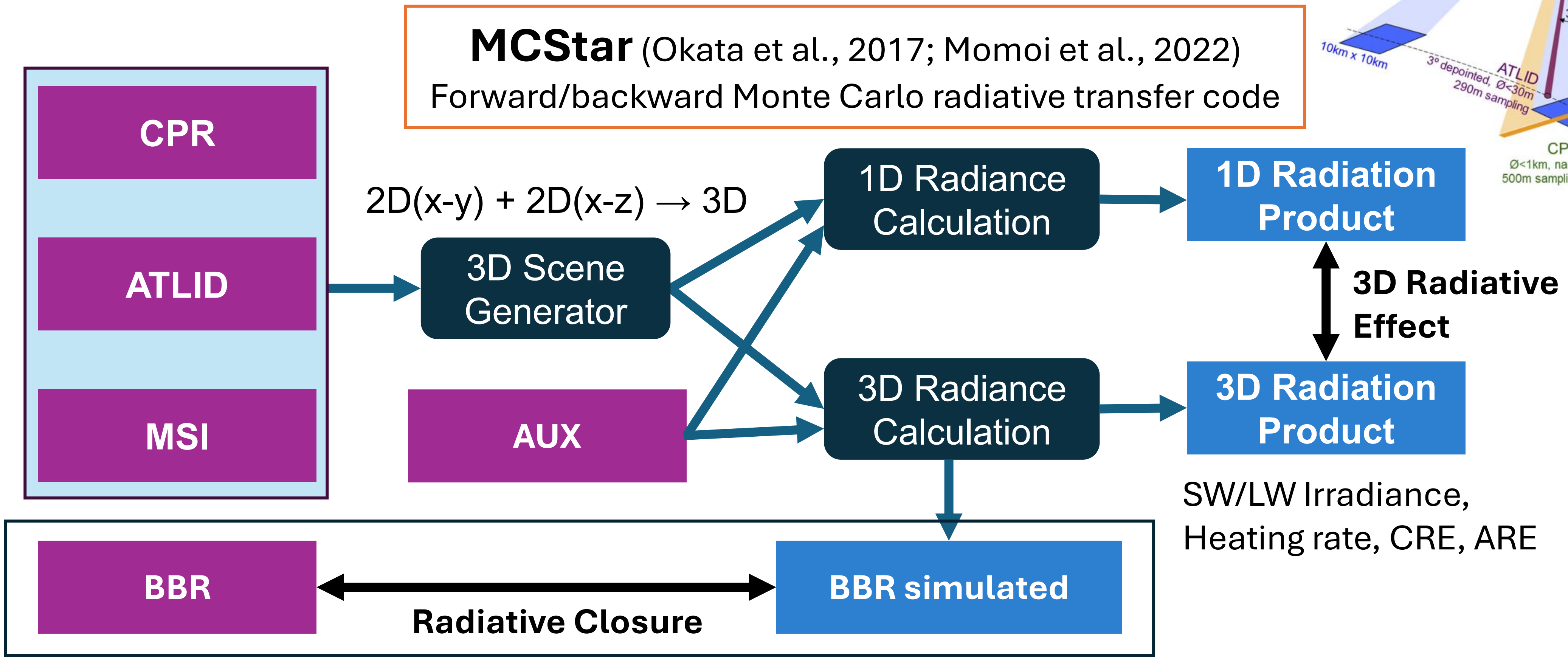
- Radiative closure by EarthCARE's multi-sensor observations
- To evaluate SW/LW 3D radiative transfer effects on global radiation budget
- Key developments are 3D scene generator module using EarthCARE L2 data and 3D radiative transfer module

3D Radiation Algorithm

1. Compute radiances from the reconstructed 3D atmosphere and compare them with BBR observations (“Radiative closure”)
2. Perform 1D and 3D radiative transfer simulations and compare them to evaluate the impact of 3DRT effects.

Credit: ESA, Airbus DS





3D scene construction

Based on the pixel-matching approach of Barker et al. (2011); Qu et al. (2023), with several improvements, we calculate microphysical properties(e.g., effective radius, extinction coefficient) for liquid, ice, cirrus clouds individually.

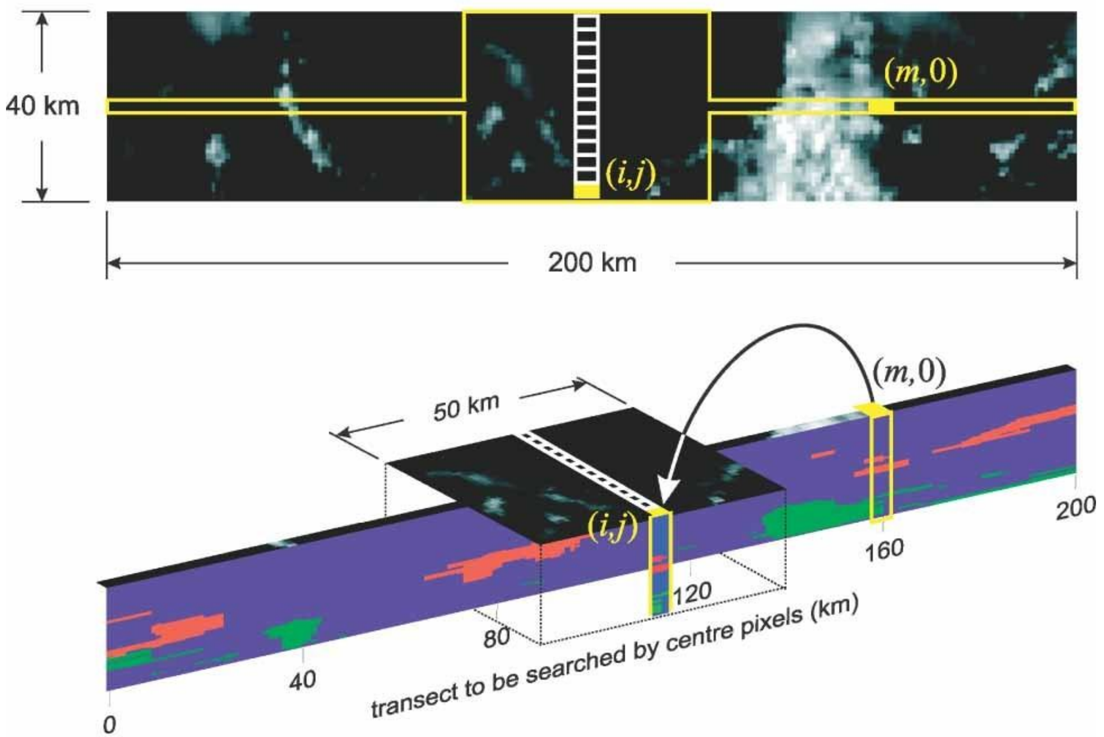
$$\arg\min F(i, j; m)$$

$$F(i, j; m) = \sum_{k=1}^{K} w_k \left[\frac{r_k(i, j) - r_k(m, 0)}{r_k(i, j)} \right]^2$$

$$: m \in [i - m_1, i + m_2]$$

KDTree is used for quick pixel matching.

Schematic of construction algorithm



- AC__CLP
- MSI_RGR
- MSI_CLP
- AUX_2D

Liquid/Ice/Cirrus
- Cloud optical thickness (x, y, z)
- Water content (x, y, z)
- T(z), P(z)
- Gas property (z)

BBR radiance simulations vs. observation

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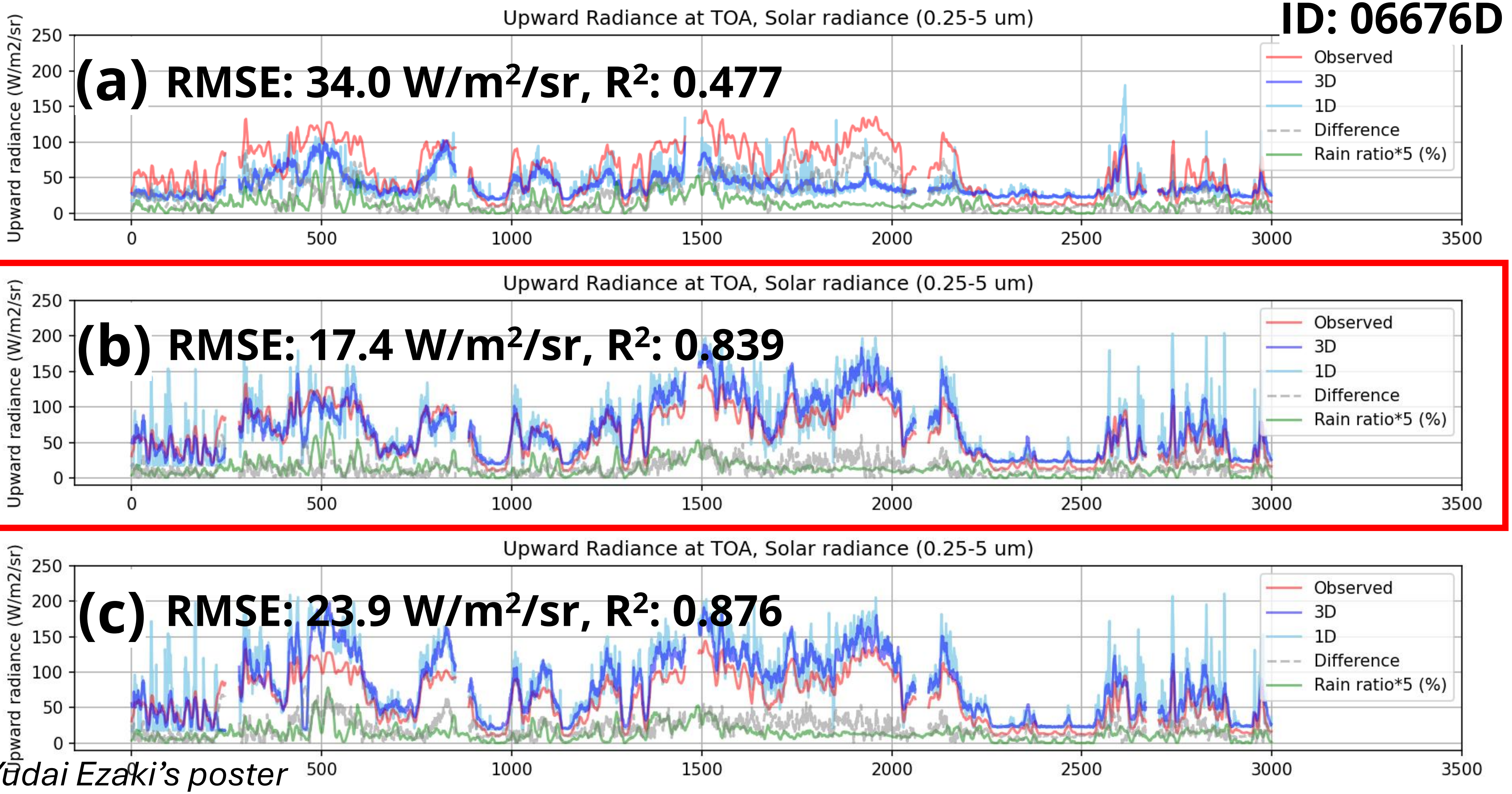

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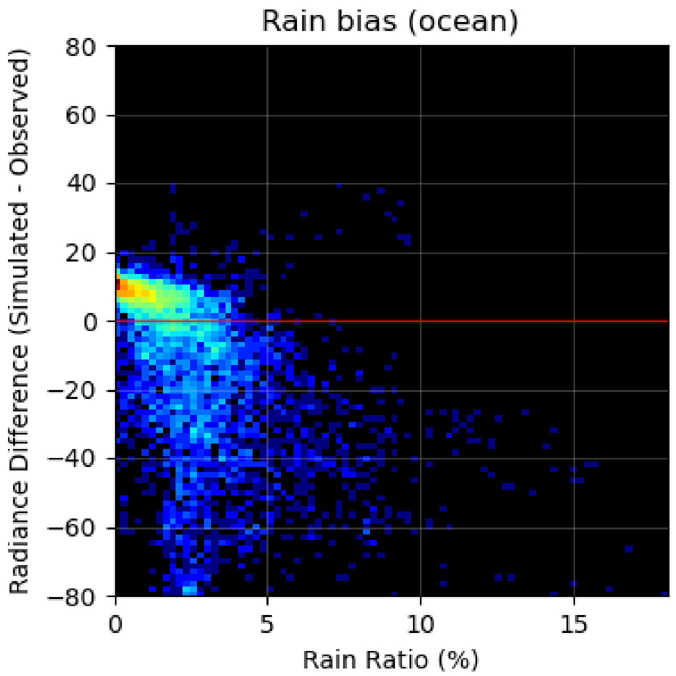
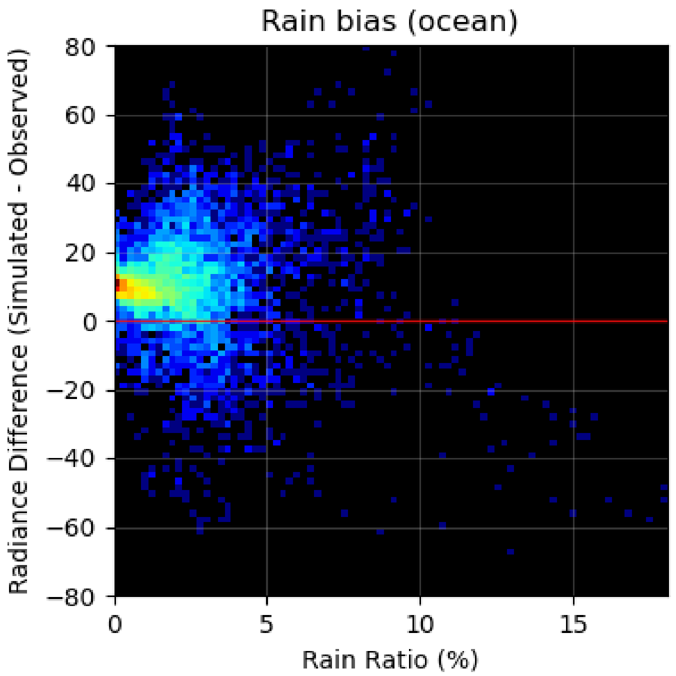
Correction by MSI cloud optical thickness

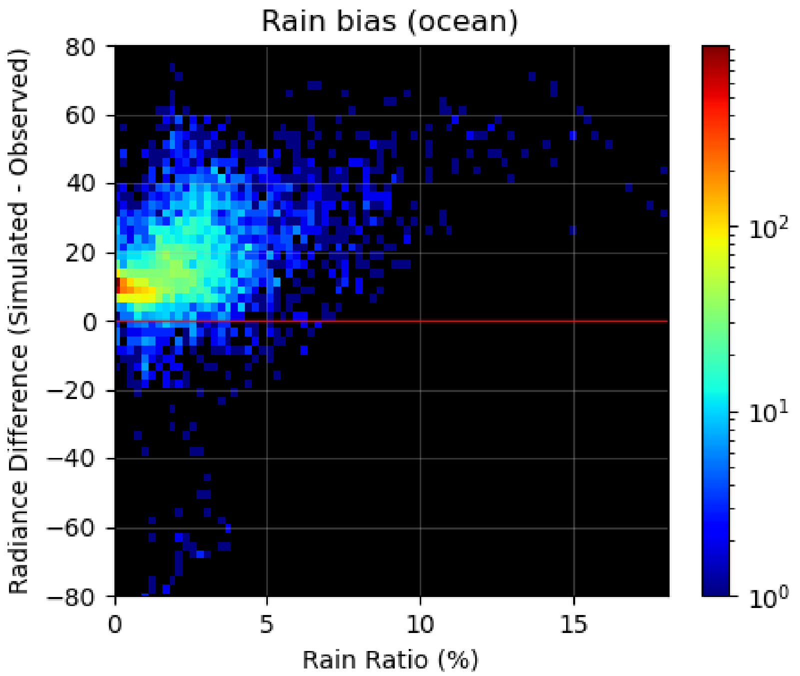
(Shortwave, nadir, ocean)



(a) RT with optical thickness from AC_CLP(vBa) products



(b) Corrected (rain/snow/drizzle) grid (AC_CLP) by MSI_CLP OT



(c) RT with optical thickness scaled by MSI_CLP (zCa) OT

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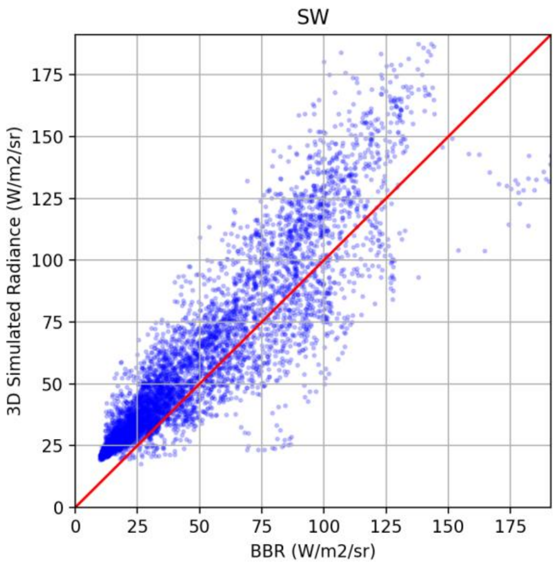
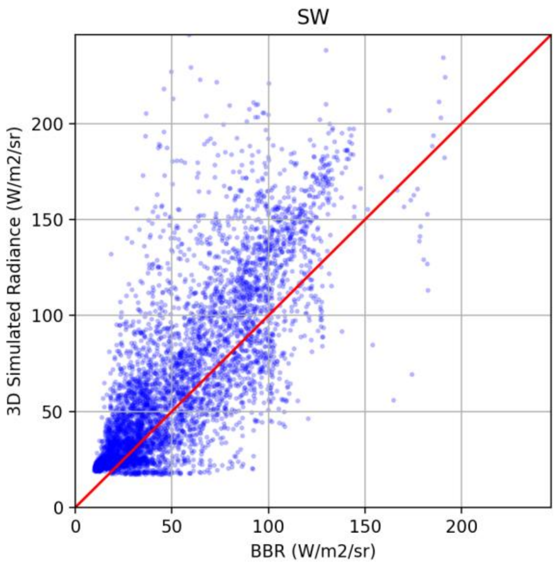
Radiative closure by BBR radiance

SW radiance (10km*10km)

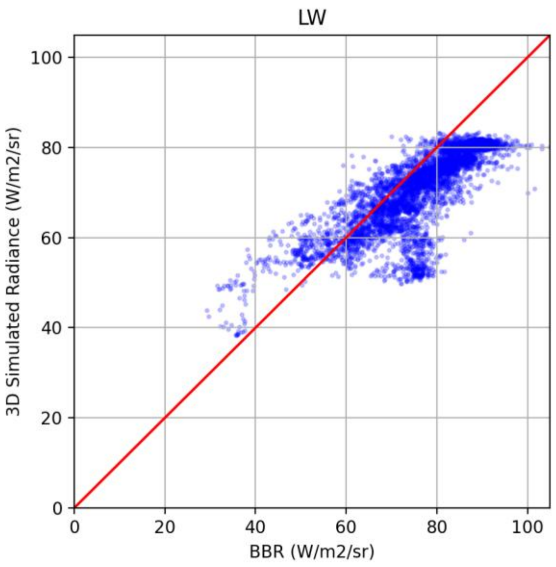
Simulation

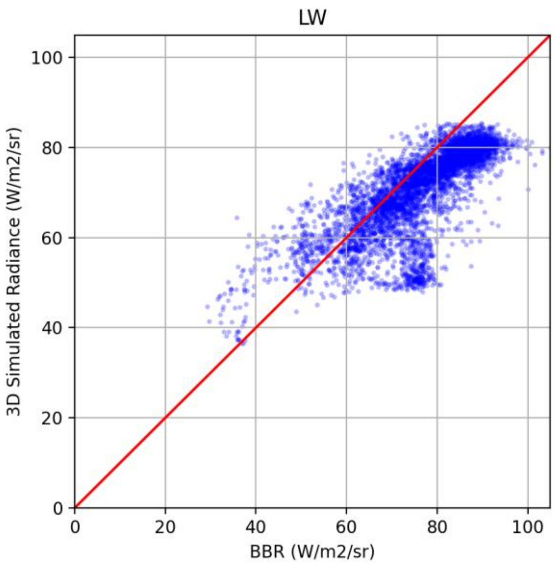




Observation

LW radiance (10km*10km)





($W/m^2/sr$)

SW 3D	SW 1D	LW 3D	LW 1D
RMSE: 16.4	RMSE: 25.7	RMSE: 8.6	RMSE: 8.9
R^2: 0.854	R^2: 0.706	R^2: 0.718	R^2: 0.663

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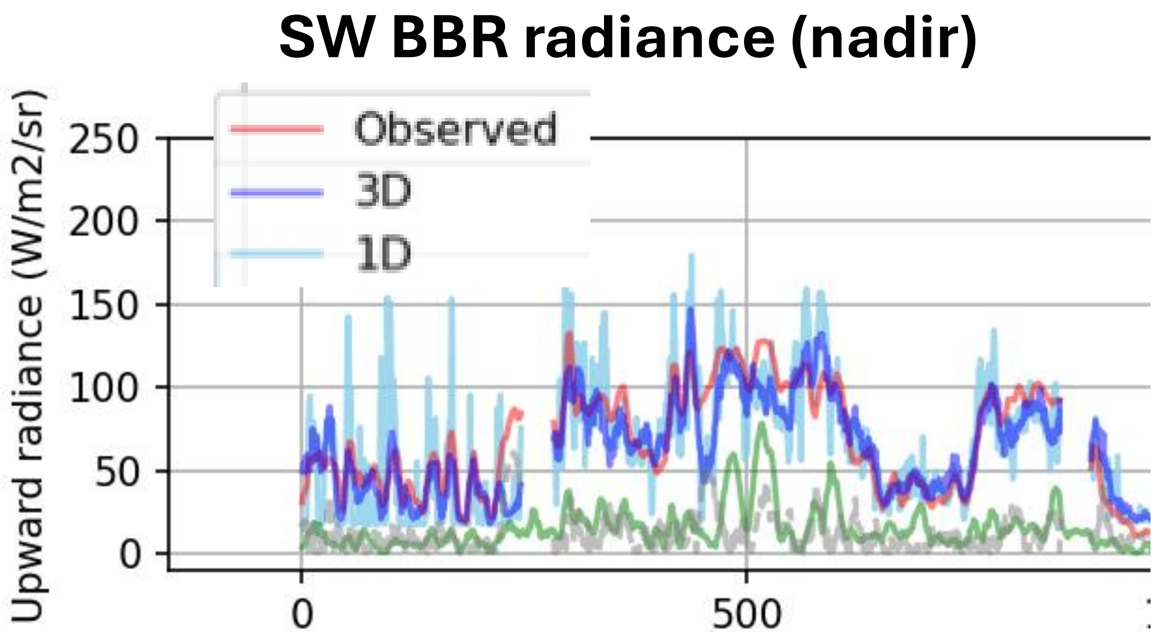
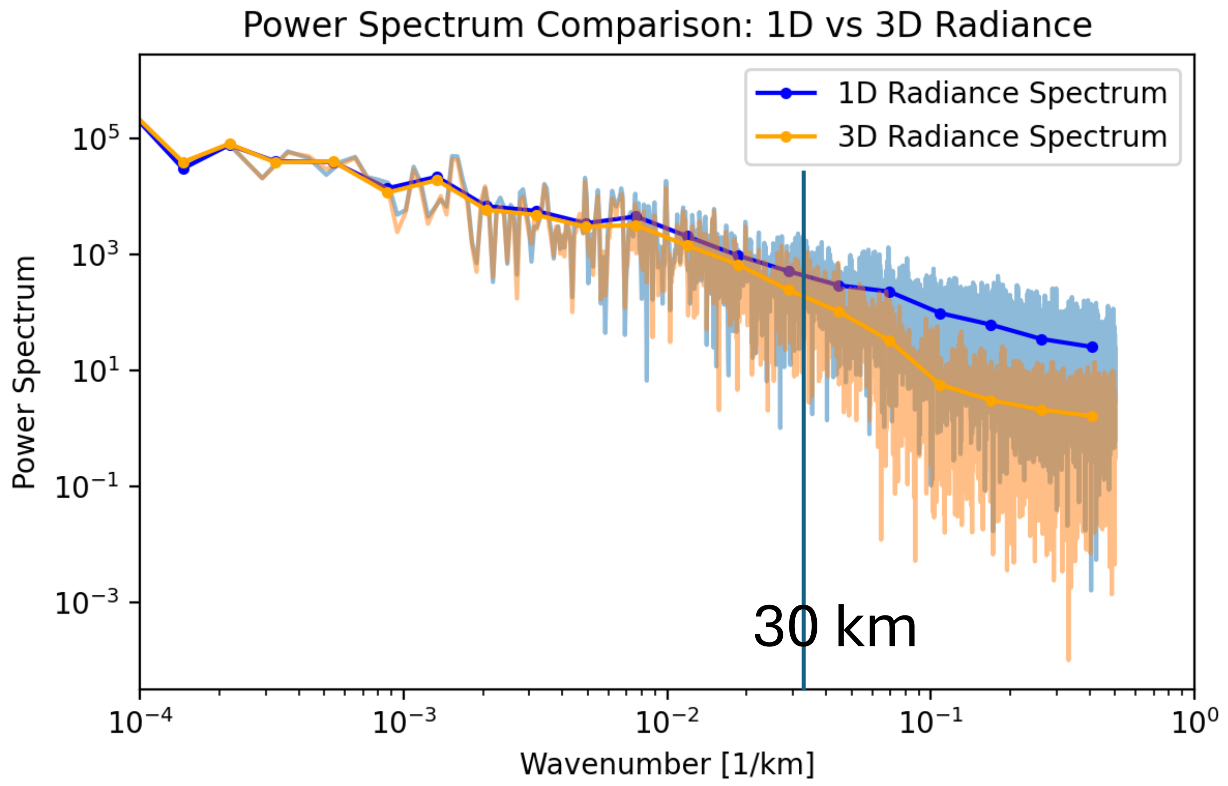
3D radiative effect: Radiative smoothing

- **Radiative smoothing** (Marshak et al. 1996), caused by multiple scattering, occurs at scales less than **30 km**, SW 3D radiance variation is smoother than 1D counterpart.





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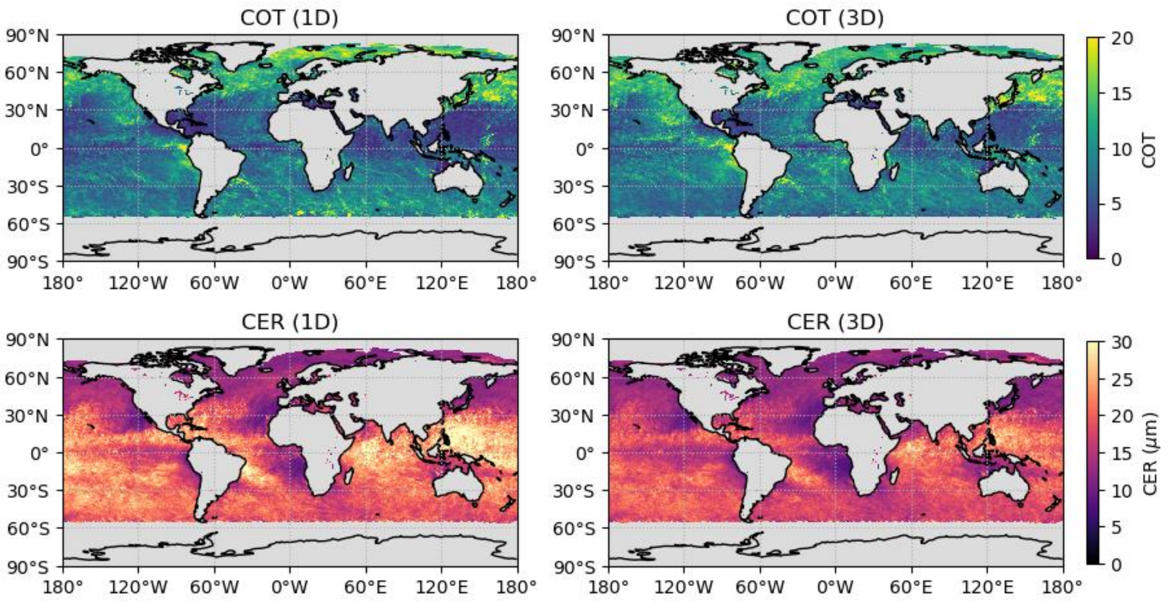
3DRT-based cloud retrieval from multispectral imager

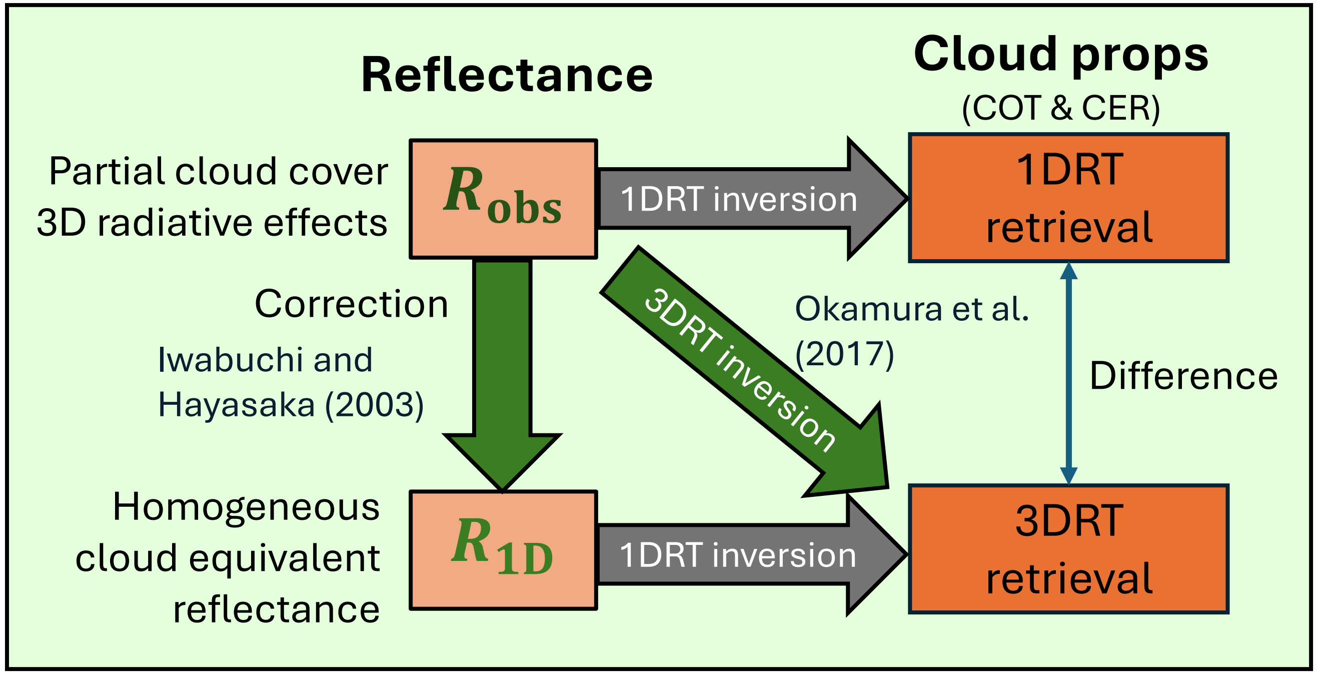
- 3D radiative effect correction (Iwabuchi and Hayasaka, 2003) has been renewed by AI trained on LES model simulations and 3DRT simulations

1DRT retrieval **3DRT retrieval**

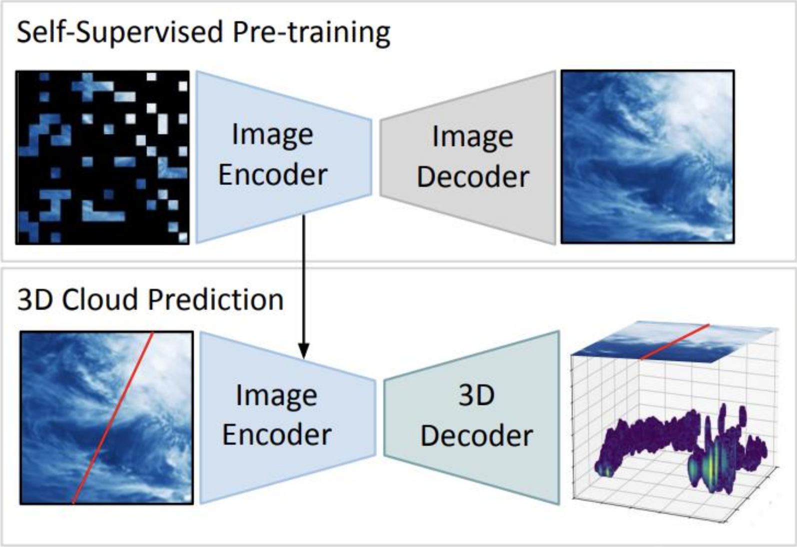


Applied to GCOM-C/SGLI measureemnts

3D radiative effect correction

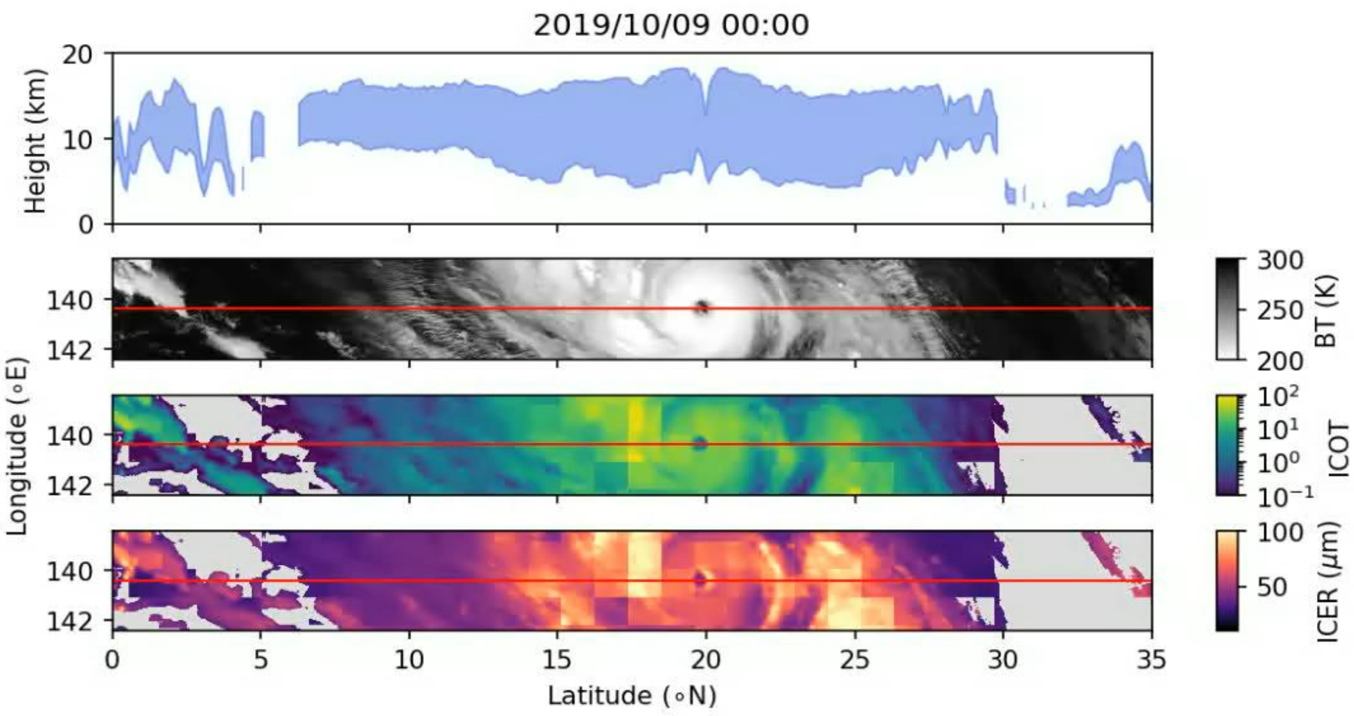


3D scene construction by AI



Girtsou et al., 2025; Brüning et al., 2024
3D cloud reconstruction using pairs of MSG/SEVIRI and CloudSat/CPR radar reflectivity profiles

ML/AI cloud retrieval trained using Himawari-8 and DARDAR (CloudSat/CALIPSO/MODIS) products (Wang et al. 2022)



Applications
1. **3D scene construction**
2. **Spatio-temporal extrapolation** by EarthCARE/geostationary satellite fusion

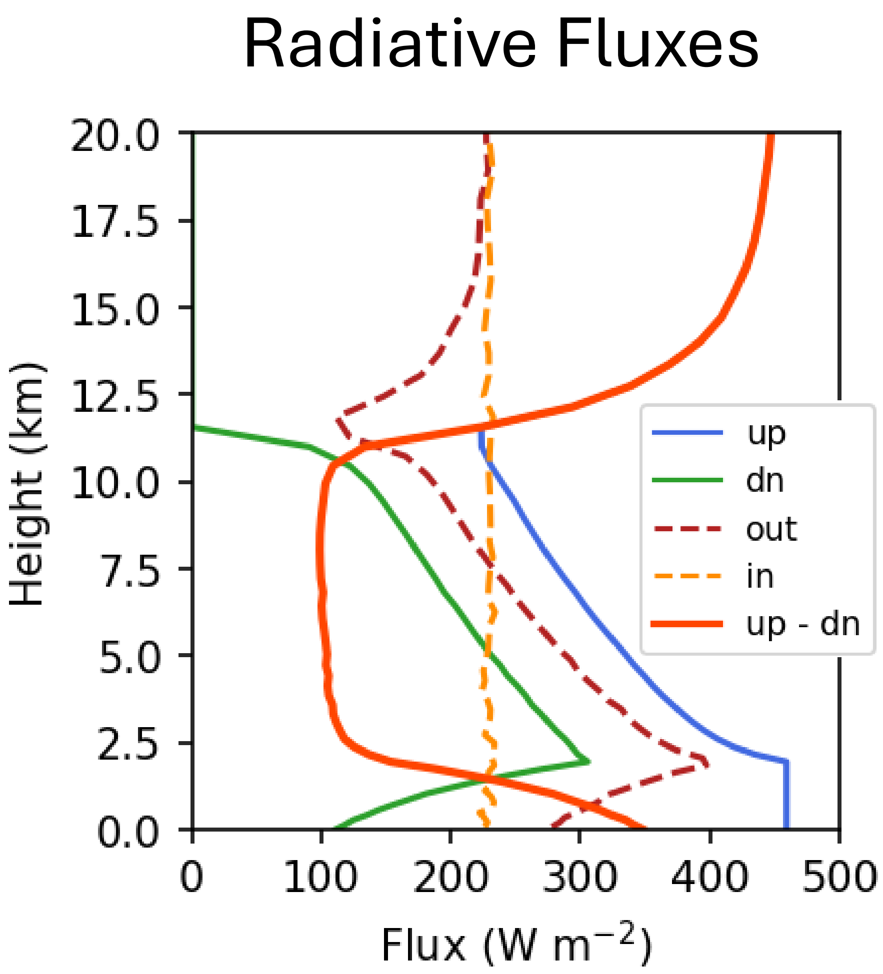
Summary

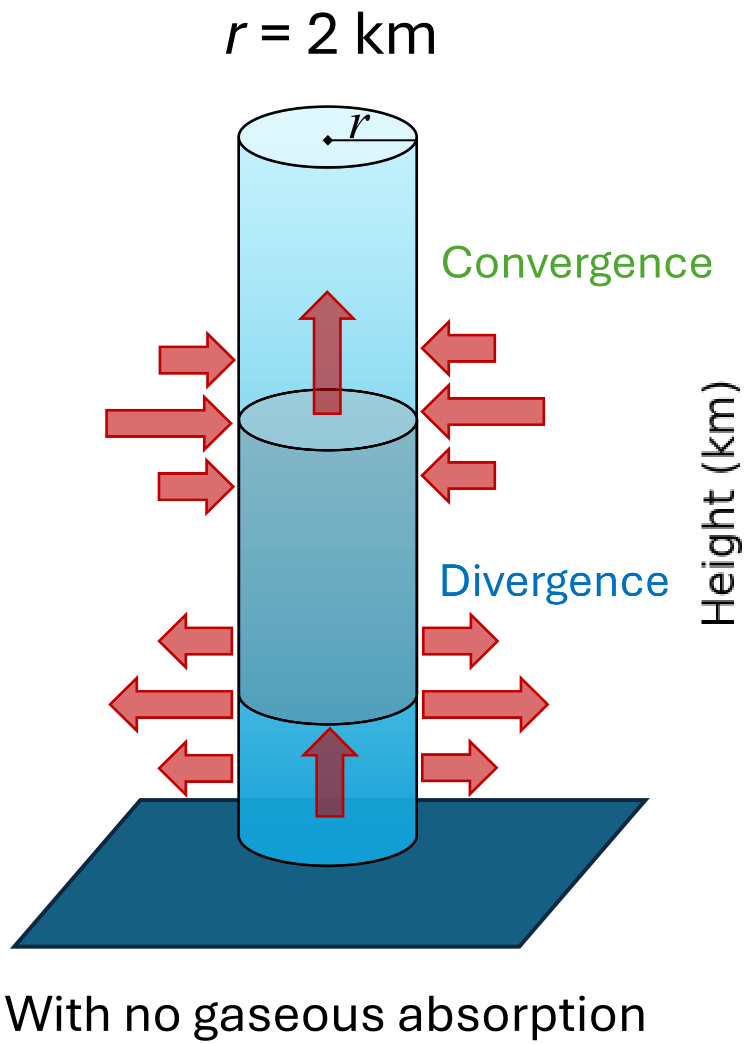
- 3D radiation algorithm is being developed,
  - for **radiative closure assessment and evaluation of 3DRT effects**, using EarthCARE multi-sensor products, pixel-matching-based **3D scene construction** and **MCStar** radiation modules.
- BBR radiance closure was tested.
  - Extinction profile from AC_CLP should be scaled by MSI COT for better SW radiance closure where rain droplets are present.
  - LW radiance is well simulated with small bias and rms error.
  - 3DRT effects are particularly pronounced at scales less than ~30 km.
- Future works:
  - To evaluate global radiative budget and assess the 3DRT effects.
  - To enhance the scene construction and radiative modules.

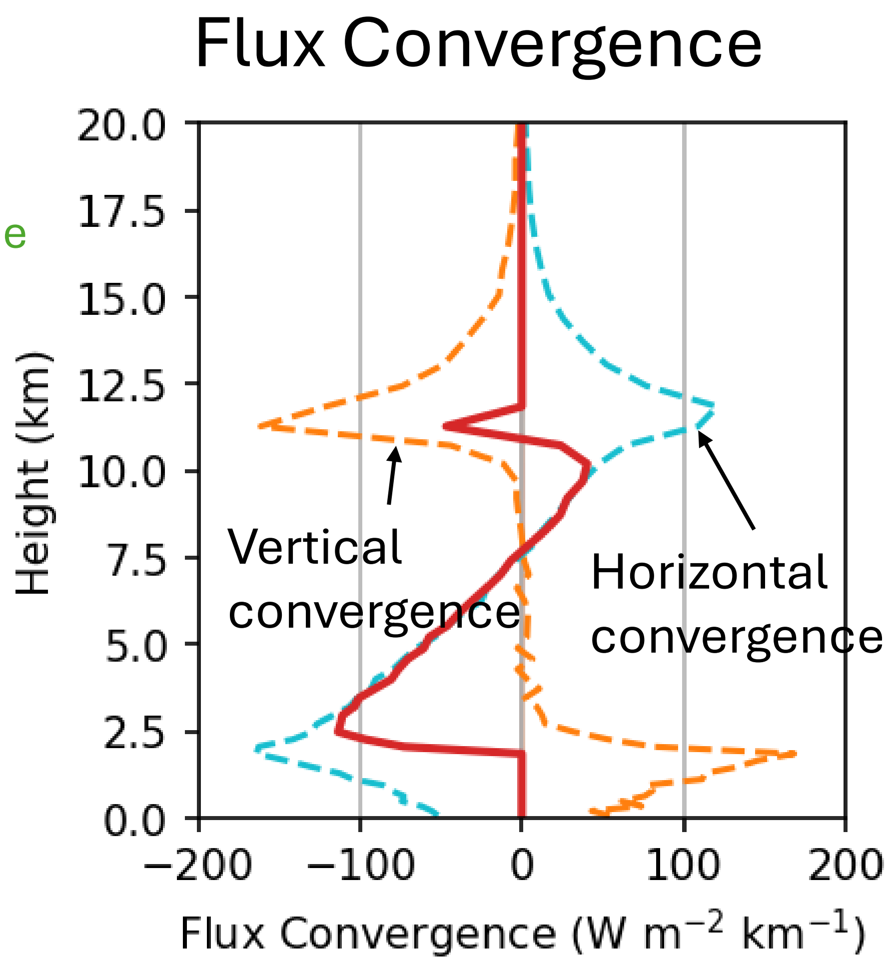
Backup

Background: LW Radiative Heating

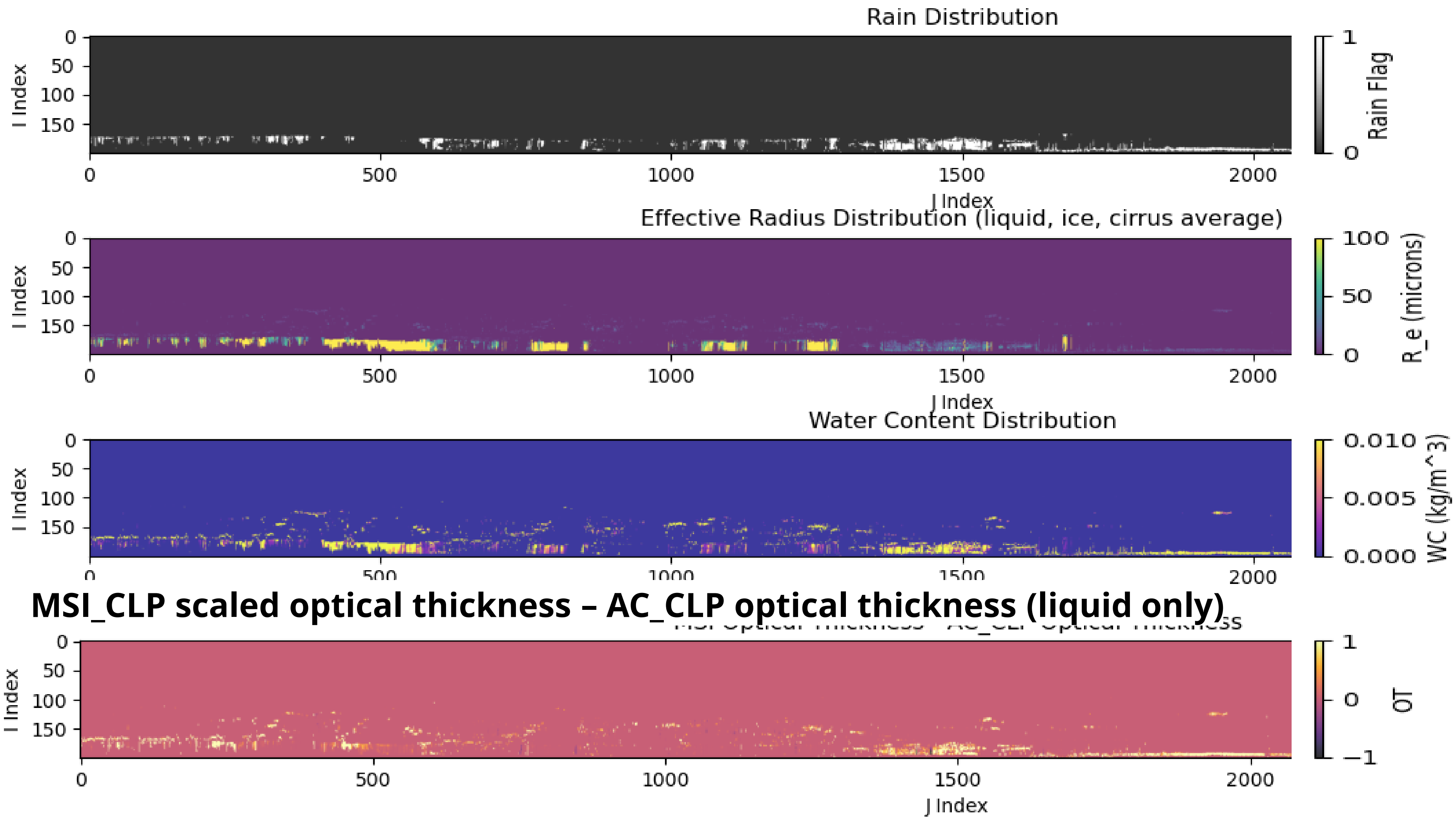
Radiation exchange through cloud sides causes convergence and divergence







Correction by MSI_CLP



MSI_CLP scaled optical thickness – AC_CLP optical thickness (liquid only)

- The cloud optical thickness derived from the Radar–Lidar product (AC_CLP) is underestimated in precipitating regions. To address this, grids flagged as rain, snow, or liquid/mixed phase drizzle (AC_CLP product) are normalized using the vertically integrated optical thickness from MSI_CLP.