Constraining sub-grid cloud variability in 3D radiative transfer models with EarthCARE

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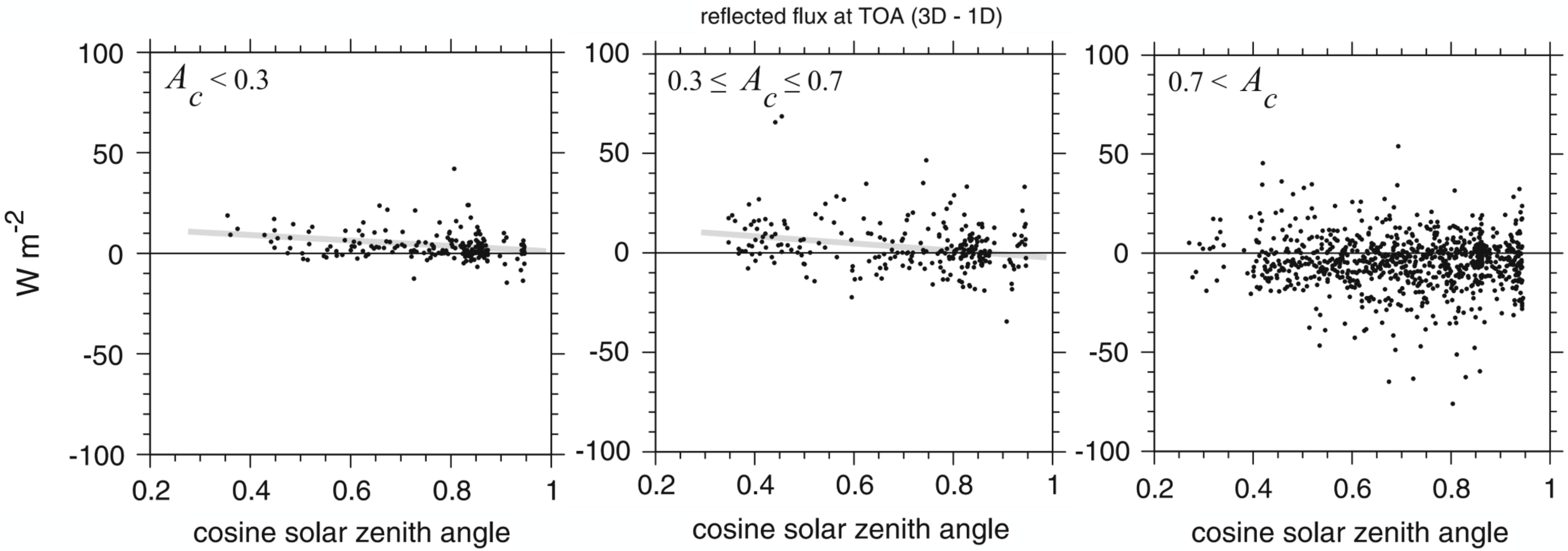
Why 3D radiative transfer matters

- **Real clouds are 3D** – most RT codes assume independent columns (ICA/1D)
- **1D bias**: ~3 W m^{-2} annually at TOA globally (Singer et al. 2021), locally >10 W m^{-2} in broken-cloud regimes (Barker et al. 2012)



Barker et al. 2012

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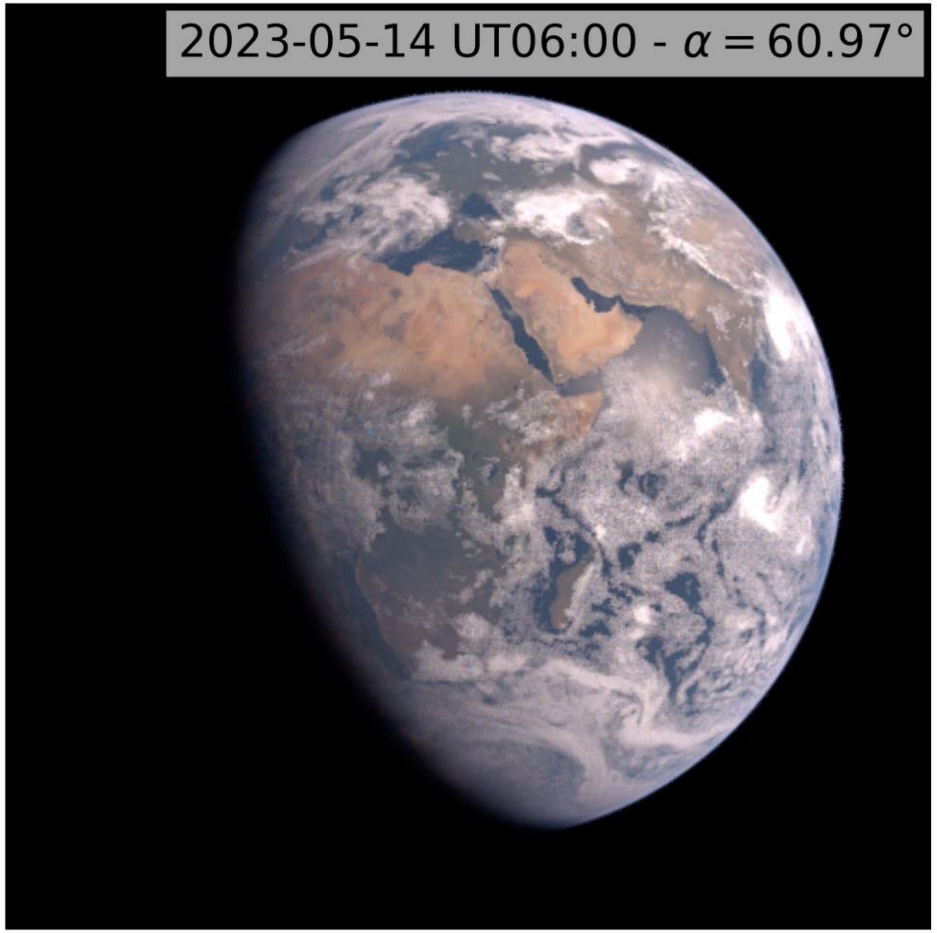
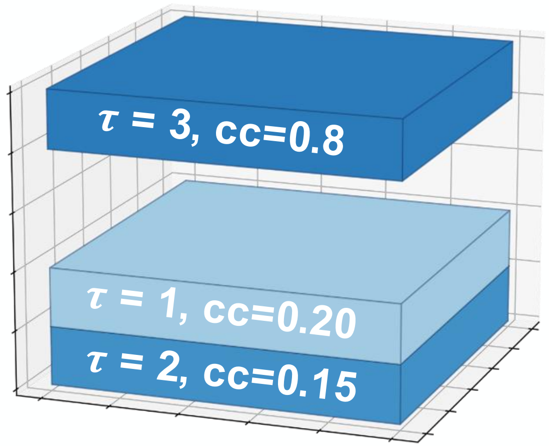
- **Earth as an exoplanet:** 3D cloud overlap over ocean glint modulates disk-integrated reflectance and polarization, key for exoplanet characterization

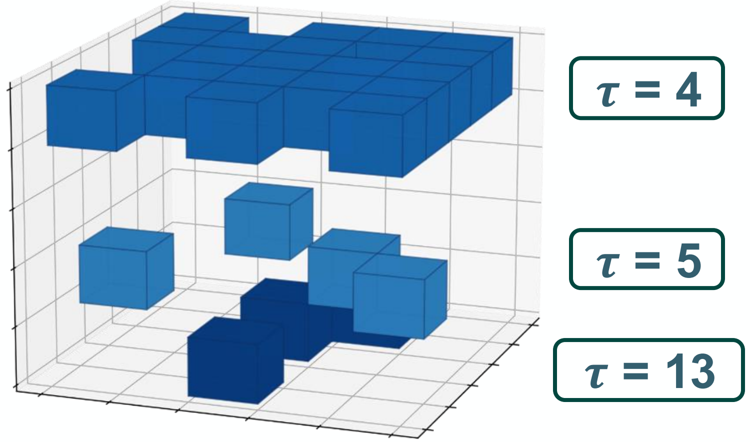


Roccetti et al. 2025

Cloud Generator

- Large-scale models have gridded clouds but **no sub-grid 3D structure**
- A cloud generator **stochastically reconstructs 3D structure** from column-mean properties
- I adapted the Hogan & Bozzo (2018) cloud generator, available in ECMWF radiation schemes, using exponential-random overlap statistics
- Missing horizontal correlations among pixels (next step)





EarthCARE

EarthCARE can be used to constrain the sub-grid cloud structures. No prior dataset has 3D cloud vertical structure + co-located broadband radiance:

- **CPR + ATLID:** cloud phase, LWC/IWC, r_{eff} along track
- **BBR:** nadir SW and LW radiances
- **MSI:** cross-track 3D cloud mask

Scope:

1. validate 1D-ICA vs 3D-MC against BBR at SW and LW
2. use EarthCARE profiles to constrain cloud generator per regime

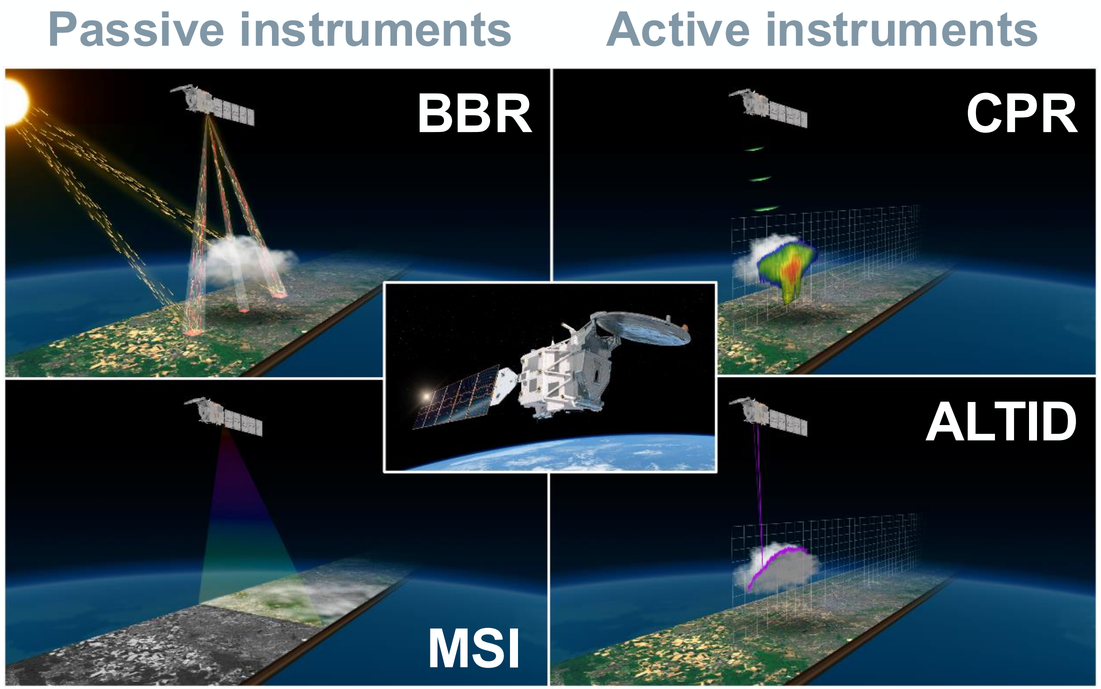


Image credits: ESA

3D cloud scene reconstruction

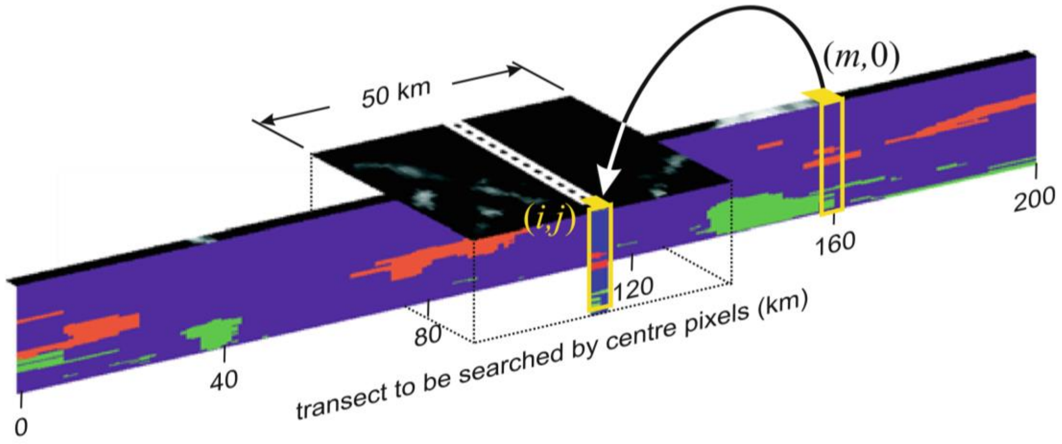
RT simulations: disort (1D) and MYSTIC (3D Monte Carlo) – Mayer & Kylling 2005, Emde et al. 2016

Input data for the RT simulations:

- **ACM_COM_2B**: atmospheric and aerosols profiles + surface albedo
- **ACM_CAP_2B**: cloud vertical profiles along the track
- **MSI_COP_2A**: cloud optical thickness, extended across track
- Combining these, reconstruct the 3D cloud field (Barker et al. 2012, Qu et al. 2023) over the 10km x 10km regions on which BBR measures the radiance.

Observed radiances:

- **BMA_FLX_2B**: BBR radiances over regions 10km x 10km



Barker et al. 2012

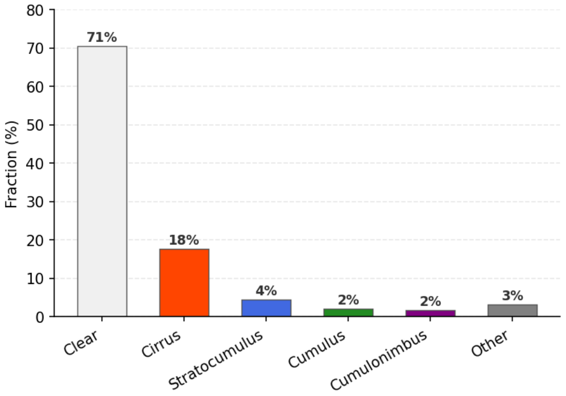
3D cloud scene reconstruction

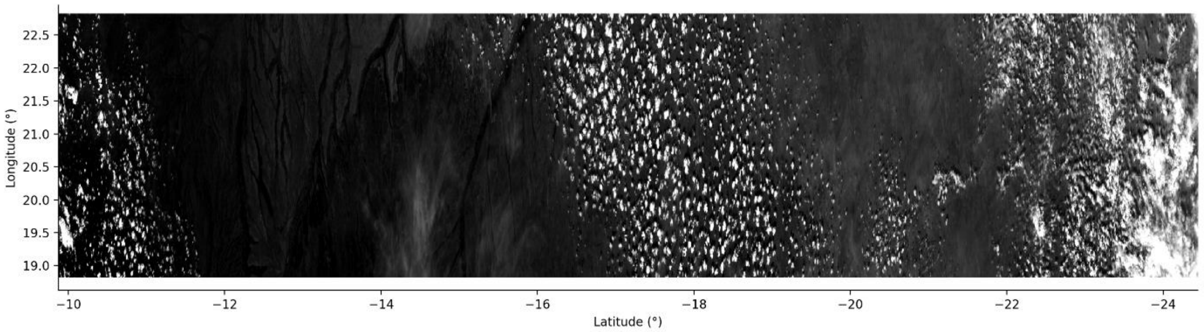
Two scenes selected with different surface and cloud properties

Sparse clouds - Angola and Namibia

Orbit: 01891
Date: 2024-09-27
Latitudes: [-10, -24]

Sparse clouds
Complex surface

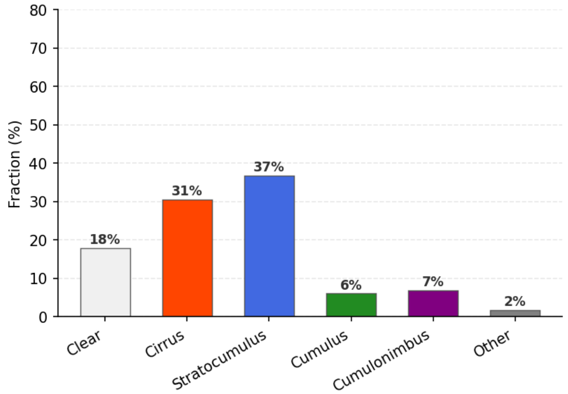


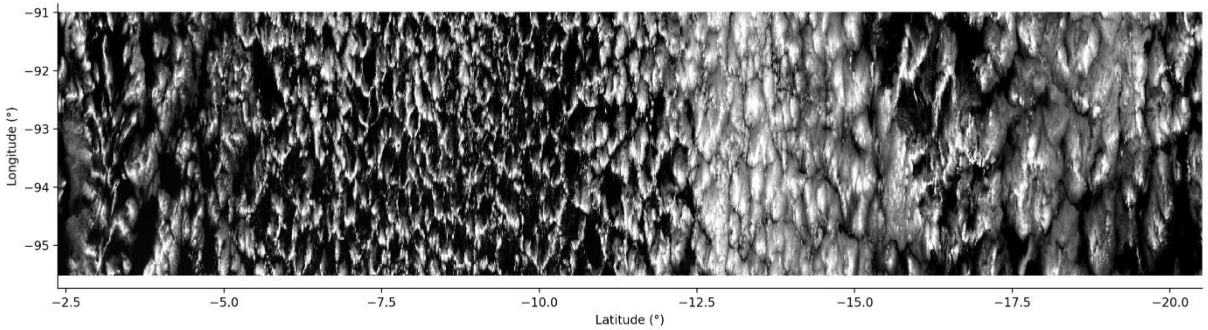


Stratocumulus - SE Pacific

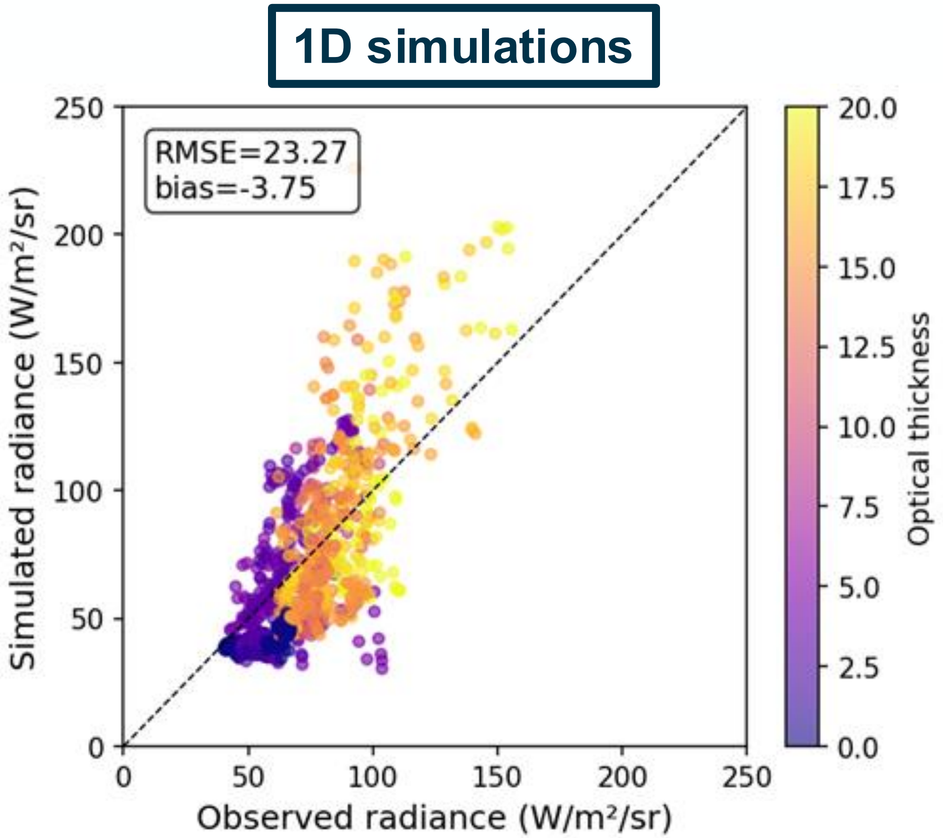
Orbit: 01087
Date: 2024-08-06
Latitudes: [-2.5, -20]

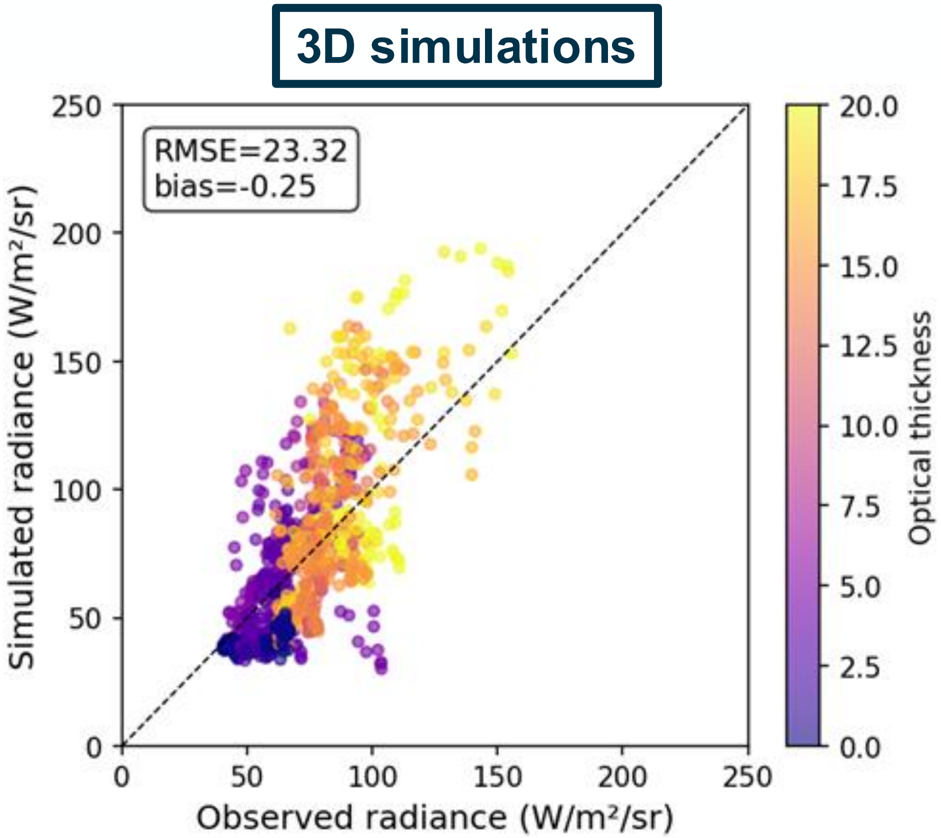
Complex clouds
Ocean surface





Sparse clouds scene - SW

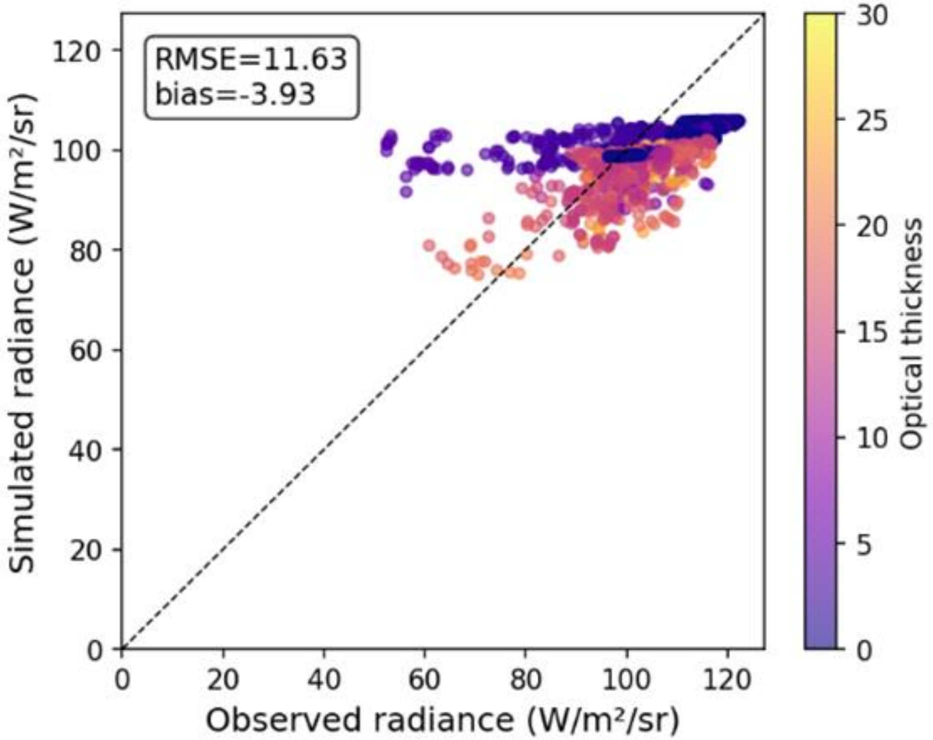




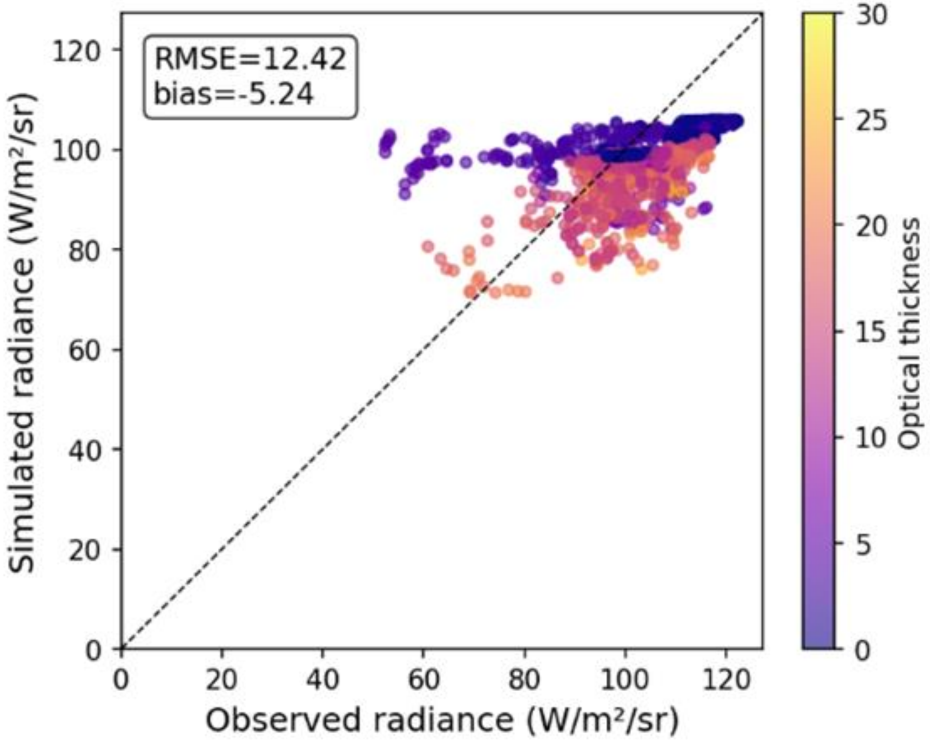
- 3D and 1D radiative closure: when horizontal structure is sparse, 3D effect is small, as expected
- Residual bias: likely thin cirrus uncertainty in ACM_CAP

Sparse clouds scene - LW

1D simulations

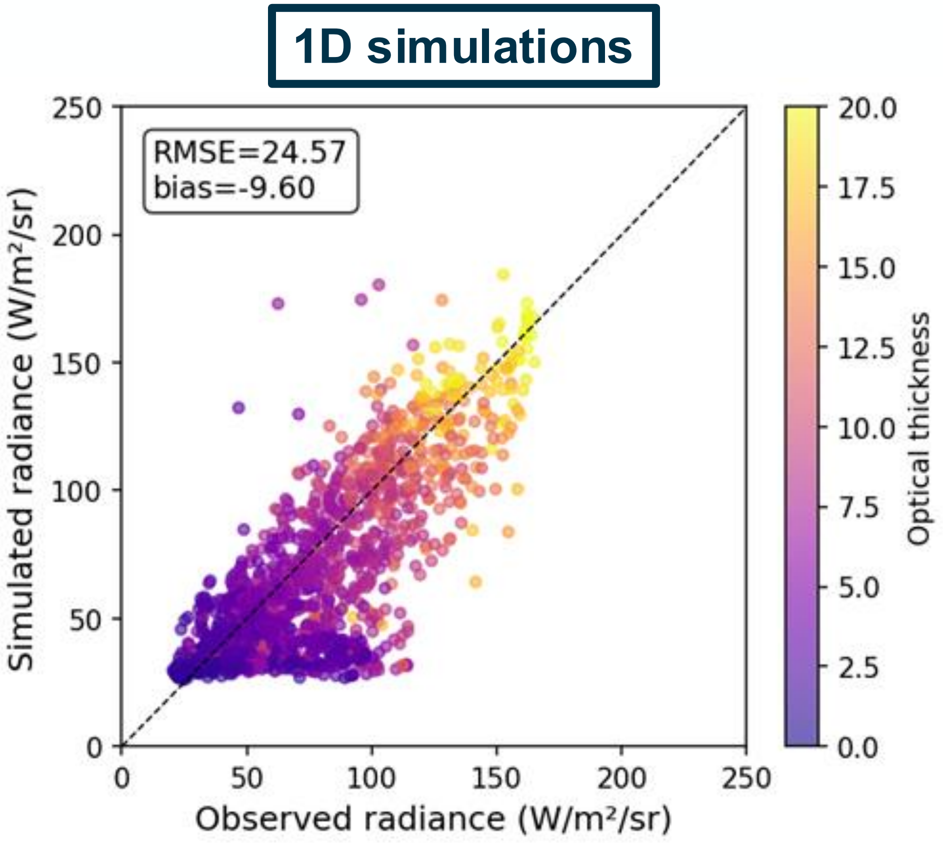


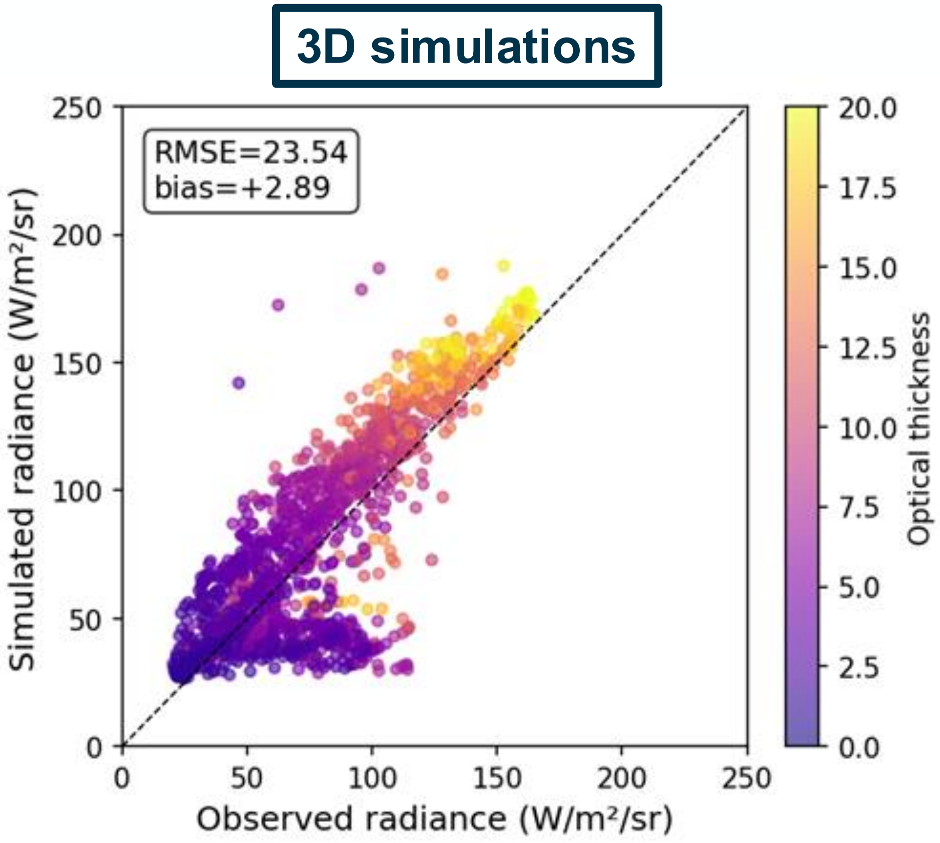
3D simulations



- Similar 1D and 3D radiative closures in longwave simulations

Stratocumulus clouds scene - SW

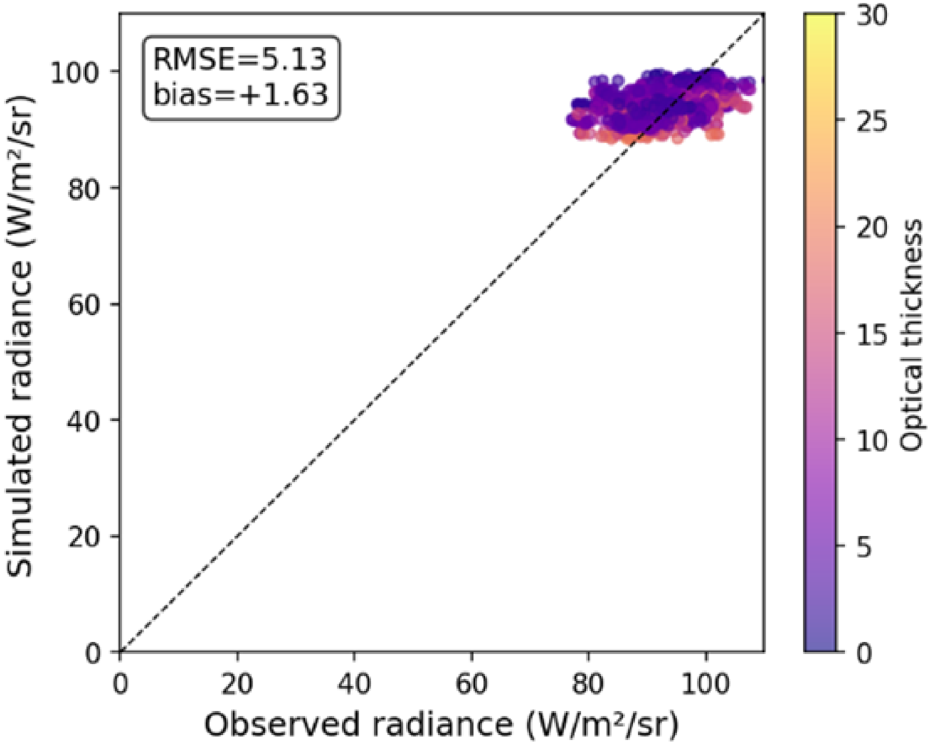




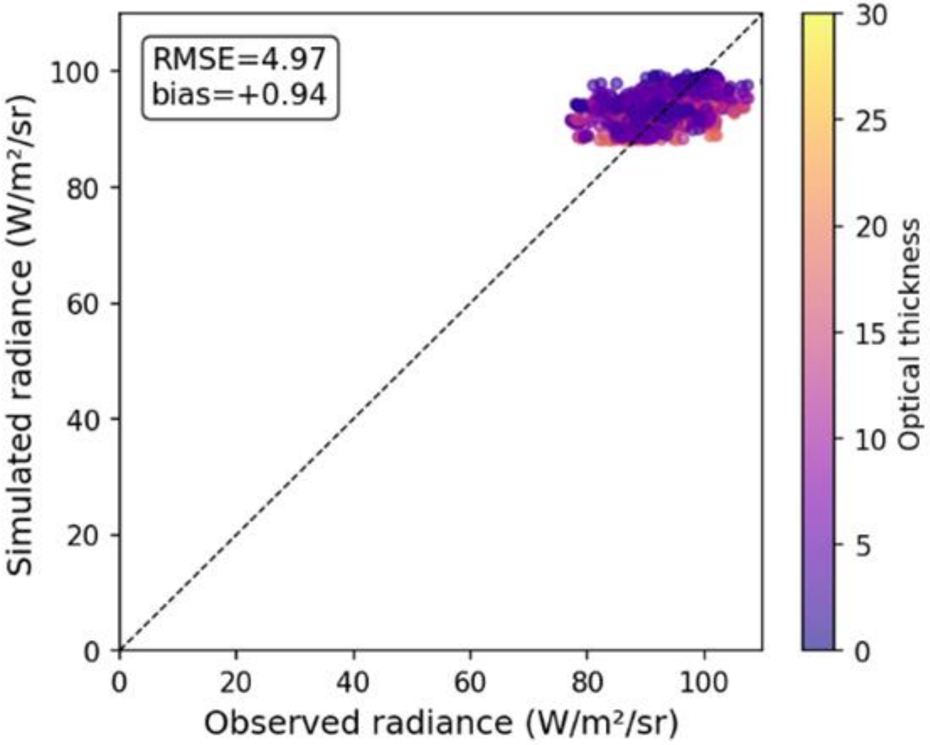
- Similar RMSE, but stronger negative 1D bias due to side illumination dominating in this broken-Sc regime
- 3D recovers the correct radiance: small bias across the full range of cloud fractions

Stratocumulus clouds scene - LW

1D simulations

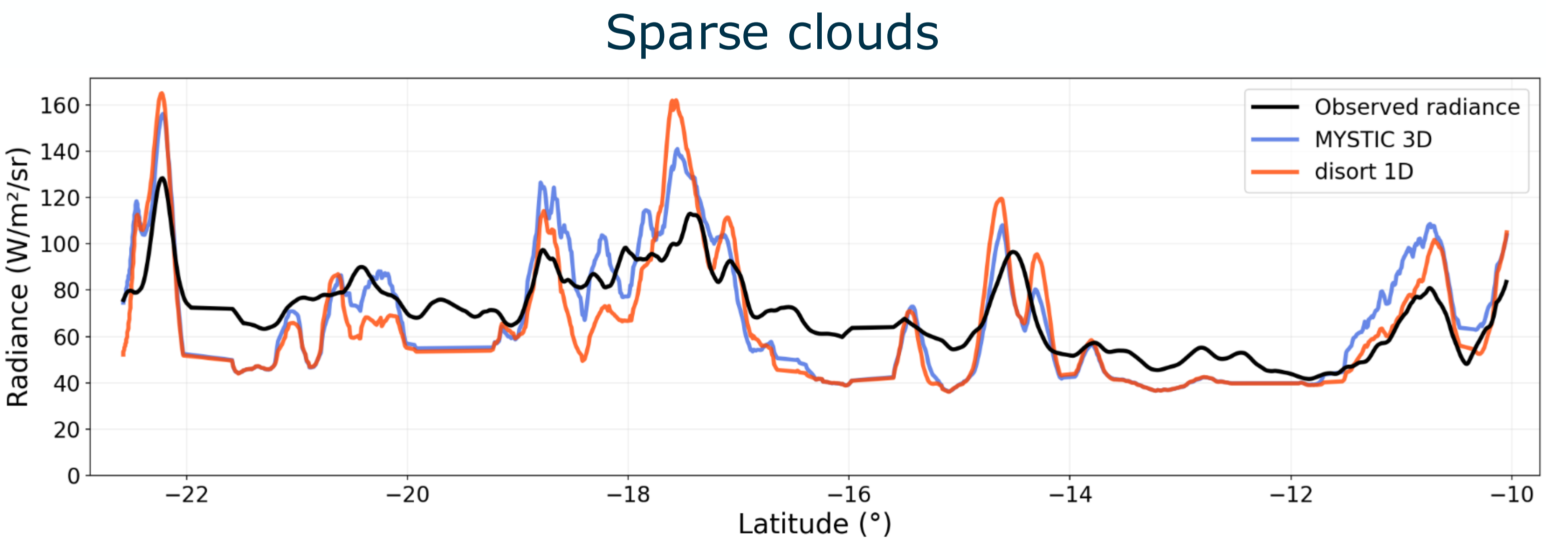


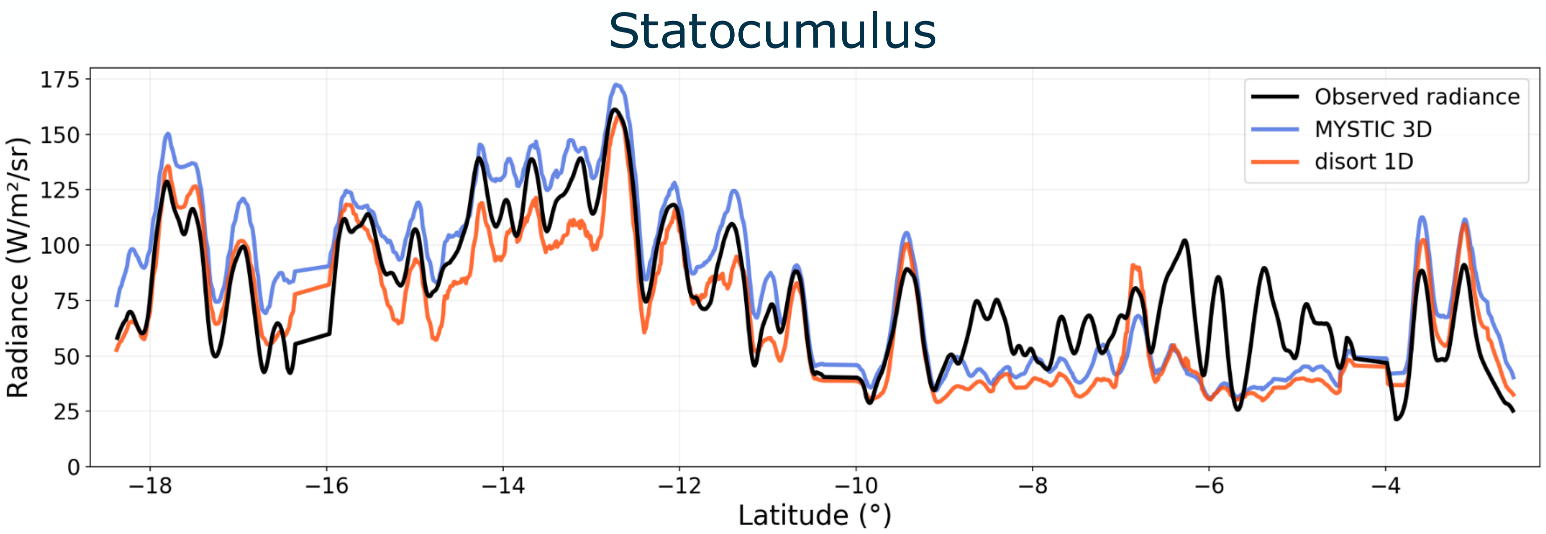
3D simulations



- Similar 1D and 3D radiative closures in longwave simulations, very small bias

Along-track structure - SW

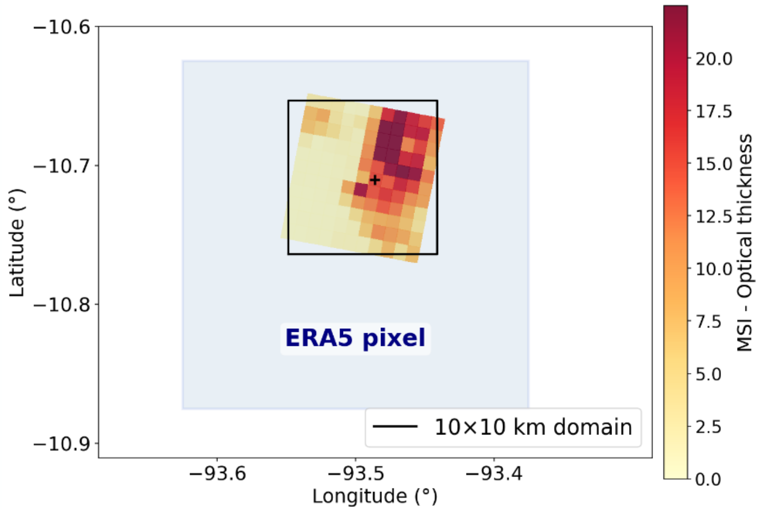


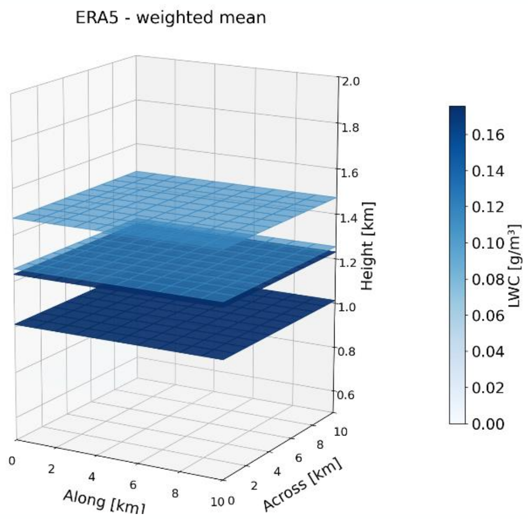


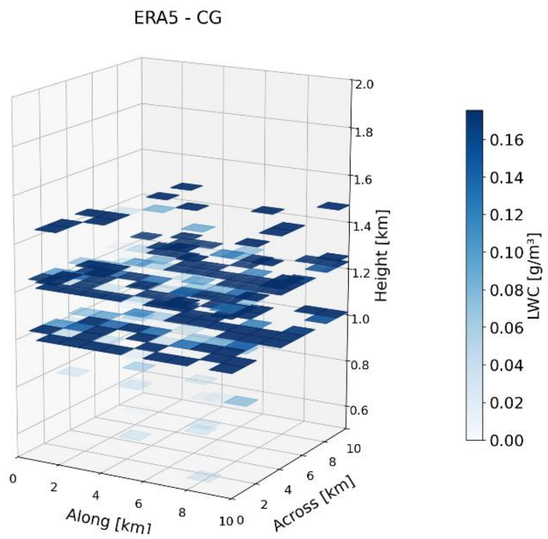
- Good agreement between simulated and observed along-track radiances.
- Cloud variability correctly reproduced in the stratocumulus scene
- disort 1D (red) systematically below MYSTIC 3D (blue)

Cloud generator applied to ERA5

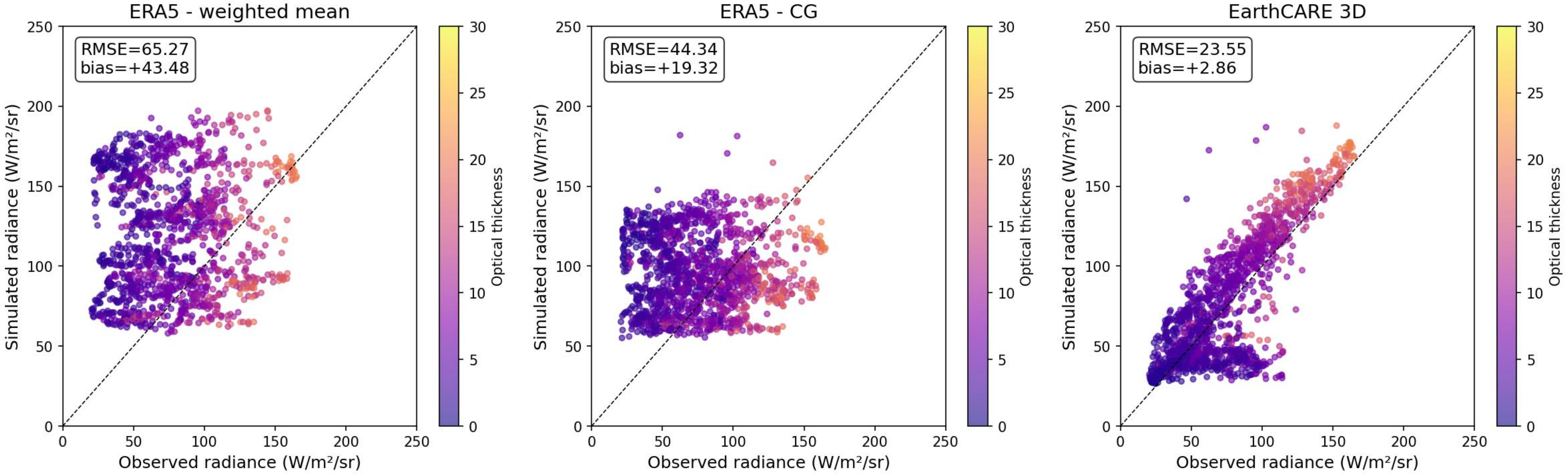
- Select the ERA5 pixels along the EarthCARE track.
- For each 10km x 10km region from which we have the BBR measurements, recover the cloud column from the larger ERA5 pixel.
- Run two sets of simulations:
    a) Use the column as it is, as well as a clear sky counterpart. Then weight the two simulations by the cloud cover of the column (**weighted-mean**)
    b) Apply the cloud generator (**CG**)







Cloud generator applied to ERA5



- The CG improves on the weighted mean, but cannot compensate for the differences in LWC
- The LWC is consistently larger in ERA5 compared to EarthCARE for SE Pacific. The bias is in the input, not only the overlap statistics
- EarthCARE profiles give the validation needed to diagnose model cloud biases

Summary & next steps

- **EarthCARE enables the first co-located 3D closure:** cloud structure + broadband radiance on the same orbit track
- **Sparse cloud scene:** SW and LW closure consistent between 1D and 3D
- **Stratocumulus clouds scene:** 3D MYSTIC achieves very good SW closure, while 1D systematically underestimates due to side illumination. LW closure consistent in both 1D and 3D.

Next steps:

- more cloud regimes, observational constraint on overlap parameters per cloud type
- ensemble-based ERA5 cloud generator validation per regime, using EarthCARE as observational constraint on sub-grid cloud structure