Retrieving cloud properties in a fully 3D environment using scanning radar and zenith radiances

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1. Motivation

- **Boundary layer clouds are fundamental to Earth's radiation budget and remain a key source of uncertainty in climate projections.**
- **Observations of their 3D microphysical properties are sorely needed to improve our understanding of processes that are difficult to observe with profiling instruments, in particular for analysing cloud radiative effects.**

5. Summary

- **We have developed a novel method for obtaining high resolution 3D cloud fields in overcast and broken cloud conditions**
- **Retrieves 3D fields of LWC and effective radius and 2D fields of N_d – critical observables for studying cloud processes and aerosol indirect effects**
- **Evaluations against retrievals from microwave and other zenith-only based methods show good agreement**

2. Method - Synergy of scanning radar and shortwave radiance using an Iterative Ensemble Kalman Filter (IEnKF)

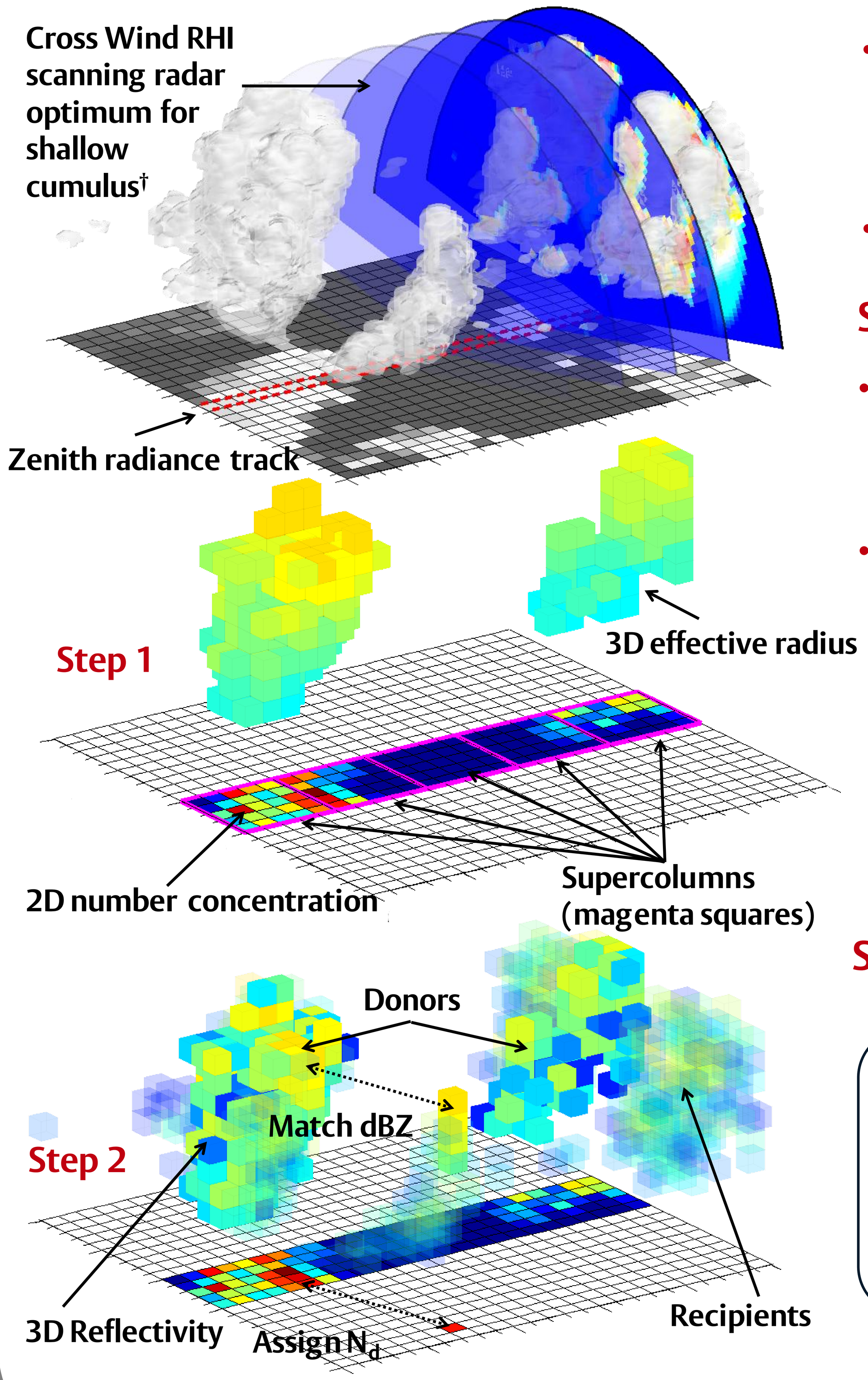


Fig 1. Retrieval method schematic

- Retrieves 3D cloud effective radius and liquid water content (LWC) and 2D (constant with height) cloud droplet number concentration (N_d)
- Uses 3D radiative transfer as a forward model

Step 1 – Retrieve cloud properties *inside* 'supercolumns'

- Retrieves 3D cloud effective radius and liquid water content (LWC) and 2D (constant with height) cloud droplet number concentration (N_d)
- Use IEnKF to minimize:

$$(\mathbf{y}-H(\mathbf{x}))^T\mathbf{R}^{-1}(\mathbf{y}-H(\mathbf{x}))$$

$\mathbf{x}$: state variables (i.e., what we retrieve)
$\mathbf{y}$: observations (i.e., reflectivity and radiance)
H : forward models
$\mathbf{R}$: observation and forward model error matrix

- Typically require Jacobian of forward model, but not available for 3D radiative transfer
- Use ensemble of perturbed states – each individually forward modelled
- Gradient in state space used to update towards minimum
- Uncertainty in retrieval calculated from spread in ensemble

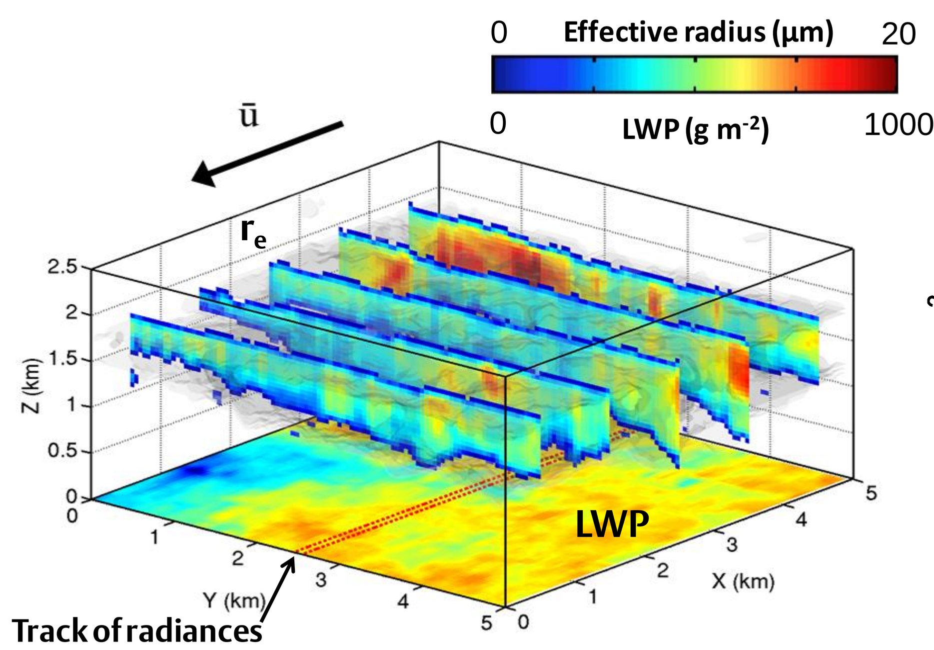
Step 2 – Retrieve cloud properties *outside* 'supercolumns'

- Donor – inside supercolumns
- Recipient – outside supercolumns
- Find the best match using reflectivity

→ Assign donor column's N_d to recipient
→ Calculate r_e and LWC using assigned N_d and recipient's reflectivity

†*Fielding et al.* (2013, JGR) 3D cloud reconstructions: Evaluation of scanning radar scan strategy with a view to surface shortwave radiation closure

4. Evaluation using Azores ARM Mobile Facility Data, 21 November 2009



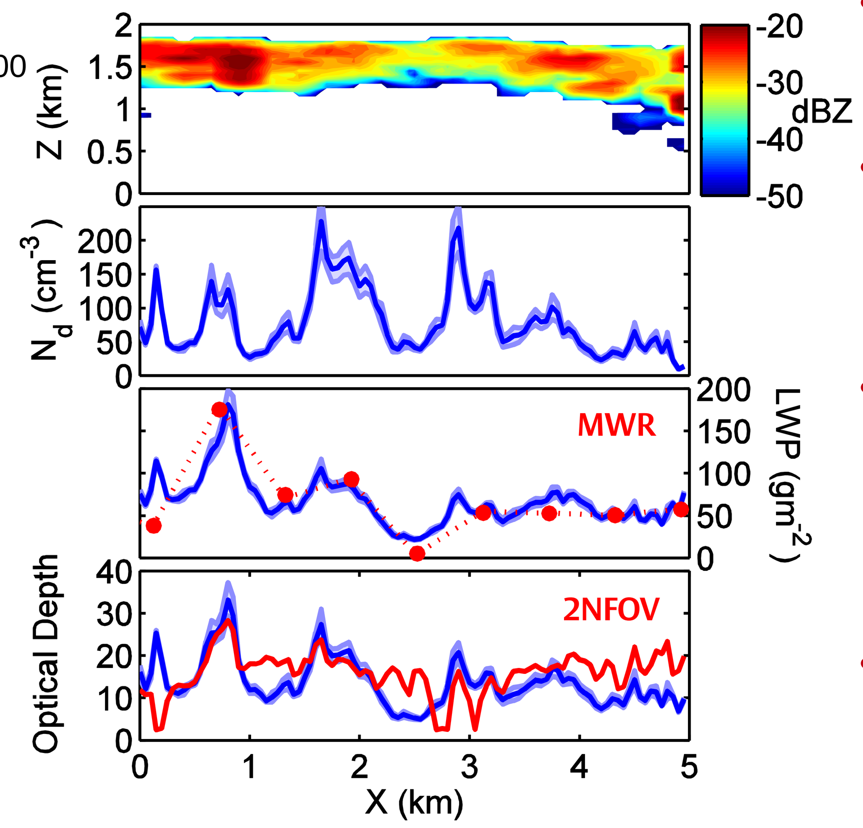


Fig 5. Retrieved cloud properties over the Azores between 1125-1135 UTC. Left shows 3D gray isosurfaces of LWC, 2D effective radius plotted along the X-axis and LWP plotted at the surface. Right shows a 2D cross section along the track of radiances at Y=2.5km. From top: Radar reflectivity, N_d, LWP and optical depth. Microwave radiometer retrieved LWP (MWR) and 2NFOV radiance-only retrieved optical depth are plotted in red.

- Observations of W-band scanning radar and 2NFOV radiances
- Nd between 50-250 cm^{-3} consistent with marine environment
- Retrieved LWP along track of radinaces agrees well with MWR retrieval, bias is < 5 g m^{-2}, RMSD is 2 g m^{-2}
- Retrieved optical depth agrees well with 2NFOV retrieval, bias is ~1 with RMSD ~ 6

3. Verification using shallow trade wind cumulus generated by large eddy simulation ‡

- Evaluated retrieval using synthetic observations derived from a challenging LES generated cumulus cloud field
- Retrieval performs well, liquid water path across whole domain has RMSE ~ 19 g m^{-2} and effective radius ~ 2 µm
- Adding a water absorbing wavelength improves retrieval, but effective radius strongly constrained by radar

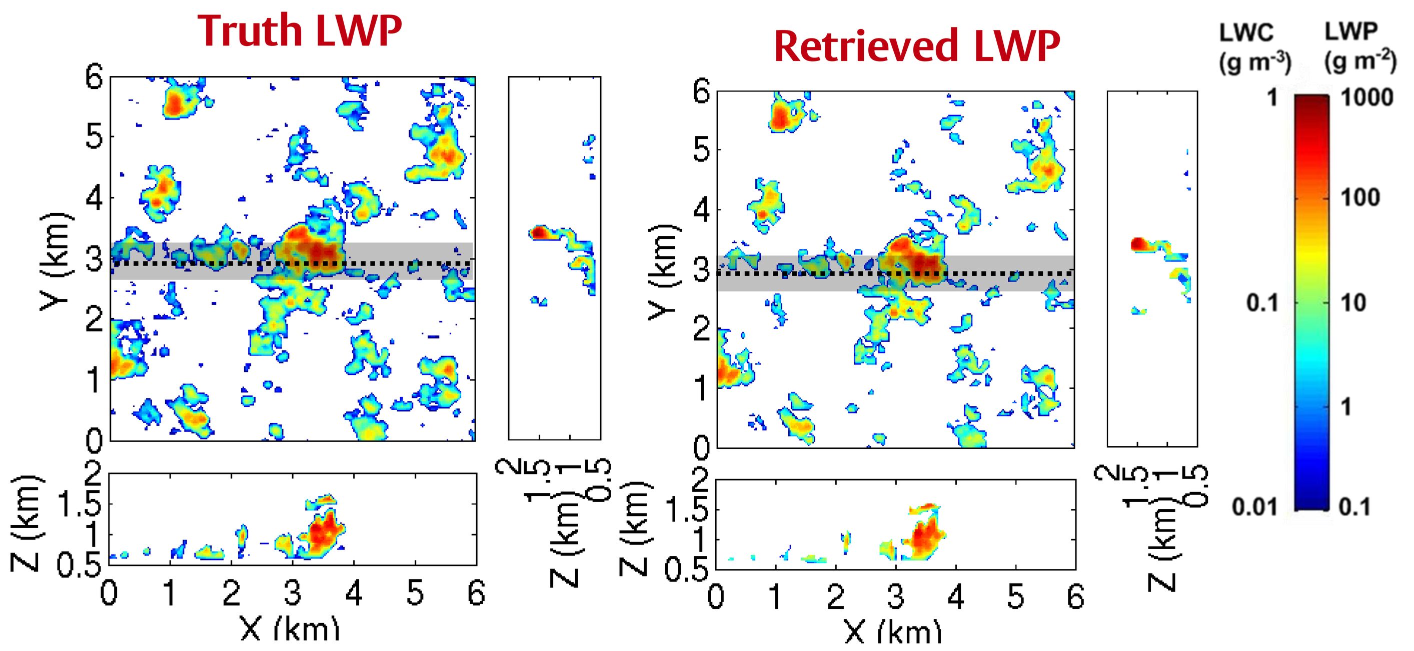


Fig 2 (above). Truth LES snapshot (left) and retrieved (right) of LWP (main square panels) and vertical cross-sections of LWC (side panels). The retrieval used radiances at 440, 870 and 1640 nm, with solar zenith angle = 30°. The black dashed line indicates the track of radiances measurements and the shading indicates the supercolumn.

Retrieval minus truth

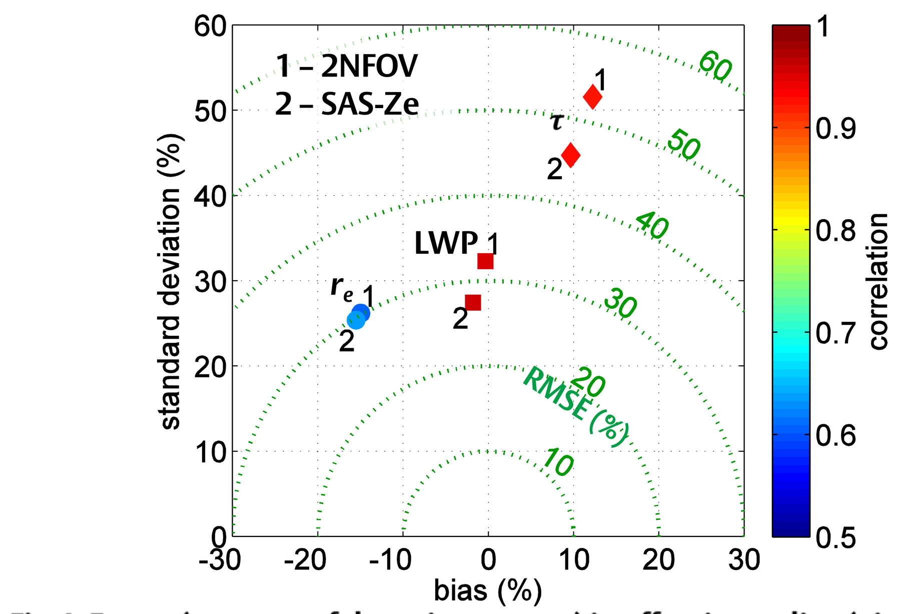


Fig 4. Errors (percent of domain average) in effective radius (circles), LWP (squares) and optical depth (diamonds) inside cloudy columns (LWP > 5 g m^{-2}) in the supercolumn. Retrievals used 1) 2NFOV radiances and 2) SAS-Ze radiances, for the truth snapshot shown in Fig. 2 with solar zenith angle = 30°.

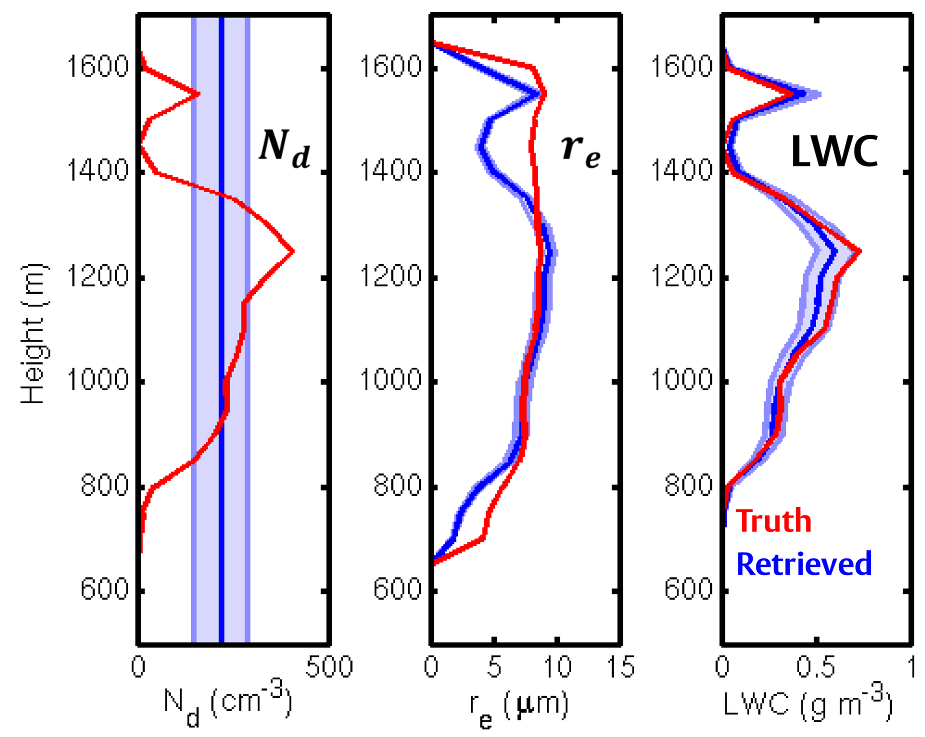


Fig 3 (right). Truth (red) and retrieved (blue) vertical profiles of cloud properties taken at X=3 km, Y=3 km from Fig. 2. The shaded blue is the error estimate from the spread of the ensemble in the IEnKF.

‡*Fielding et al.* (2014, submitted to JGR): A novel ensemble method for retrieving cloud properties in 3D using ground-based scanning radar and zenith