New measurements from ENCORE (as promised) - 3D fields of cloud effective radius for studying aerosol impacts on warm low clouds

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Why do we need 3D observations of warm low clouds?

- Clouds are rarely stratiform
- ‘Soda straw’ has limited view
- Cloud structure affects radiative transfer
- Help provide observational constraints for realistic cloud and radiation parameterizations in global circulation models.

How can we observe clouds in 3D?

- **Problem:** Scanning cloud radar provides cloud structure but not well-constrained droplet size
- **Solution:** combine scanning cloud radar (Ka/W-band) with spectral (shortwave) zenith radiances
  – Exploit relationship between radiance and optical depth, but also account for 3D effects

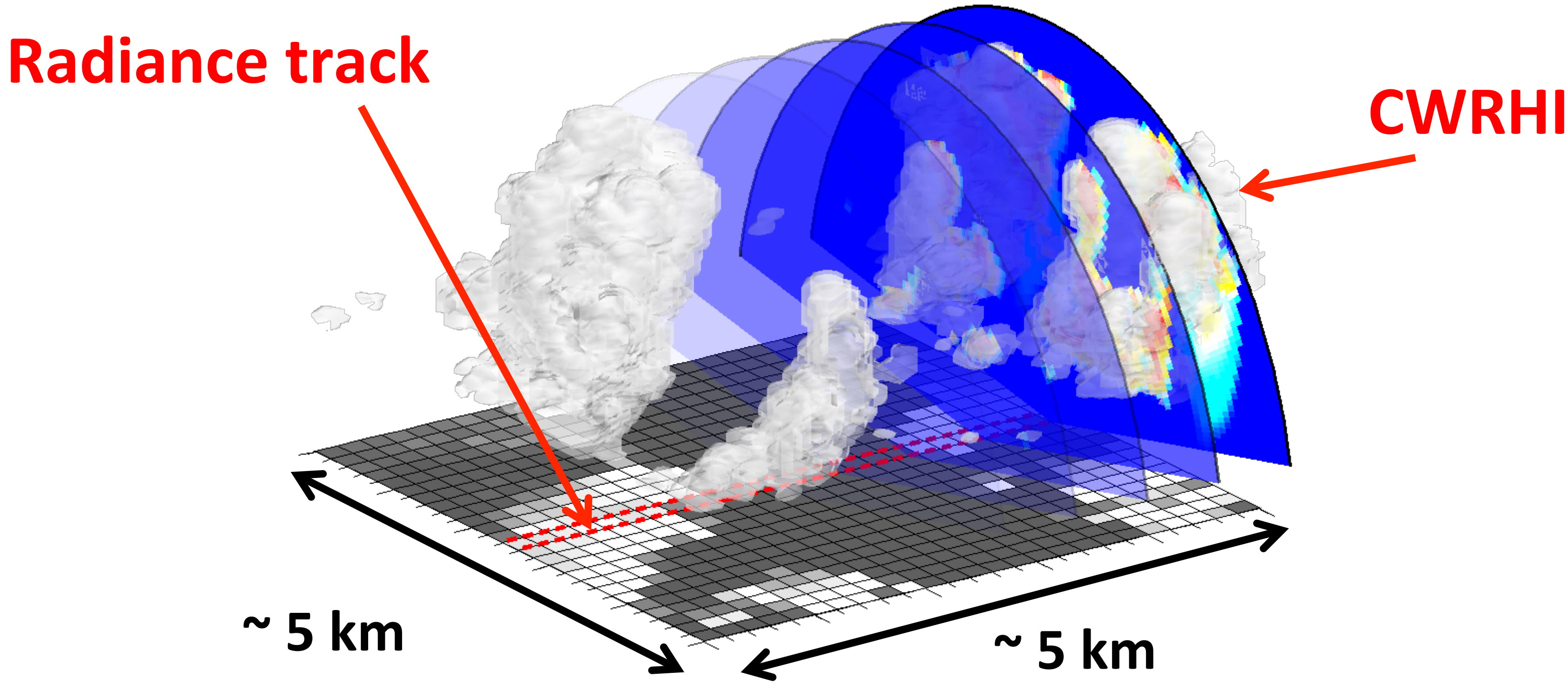
Scanning cloud radar

Spectroradiometer

ENCORE novelty

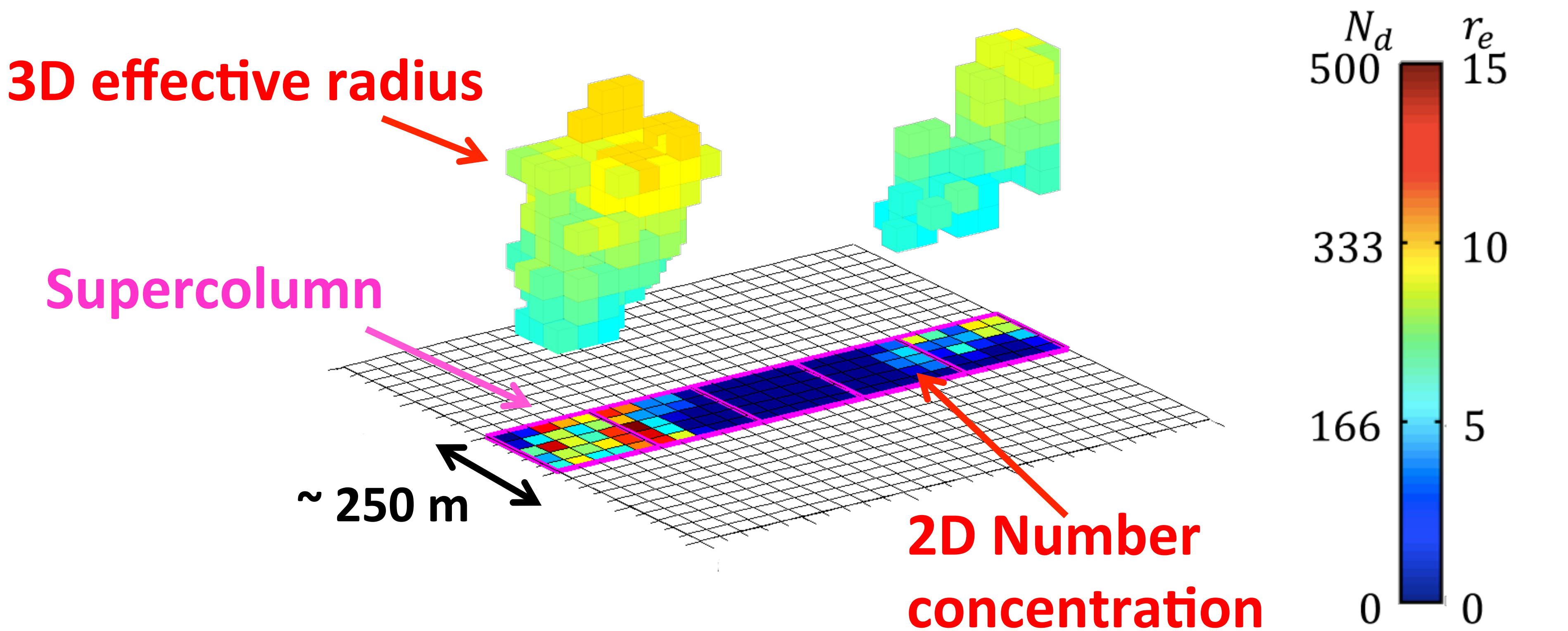
- First cloud retrieval to combine ground-based radar and zenith radiances
- First cloud retrieval to include 3D radiative transfer as a forward model
- First cloud retrieval to use the Iterative Ensemble Kalman Filter as an optimal estimation framework

3D ENCORE (ENsemble ClOud REtrieval) Method



- Zenith radiances mainly constrained by overhead cloud properties -> two step approach

ENCORE – Step 1 (Retrieve within ‘Supercolumn’)



- **Problem:** Would like to use 3D radiative transfer as a radiance forward model

Using the Iterative Ensemble Kalman Filter as a Gauss-Newton method

- Typically, Gauss-Newton methods use the error covariance and observation operator matrices explicitly to minimize a cost function:

$$J(\mathbf{x}) = (\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}_b) + (y - H(\mathbf{x}))^T \mathbf{R}^{-1} (y - H(\mathbf{x}))$$

X = 3D field of cloud effective radius, 2D field of number concentration

Y = Zenith Radiance, Radar reflectivity

H = lognormal cloud droplet distribution, 3D radiative transfer

- Solution: Use Iterative Ensemble Kalman Filter. Each ensemble member is individually forward modelled and their gradient in state space is used to minimize cost function

Key points of the ensemble method

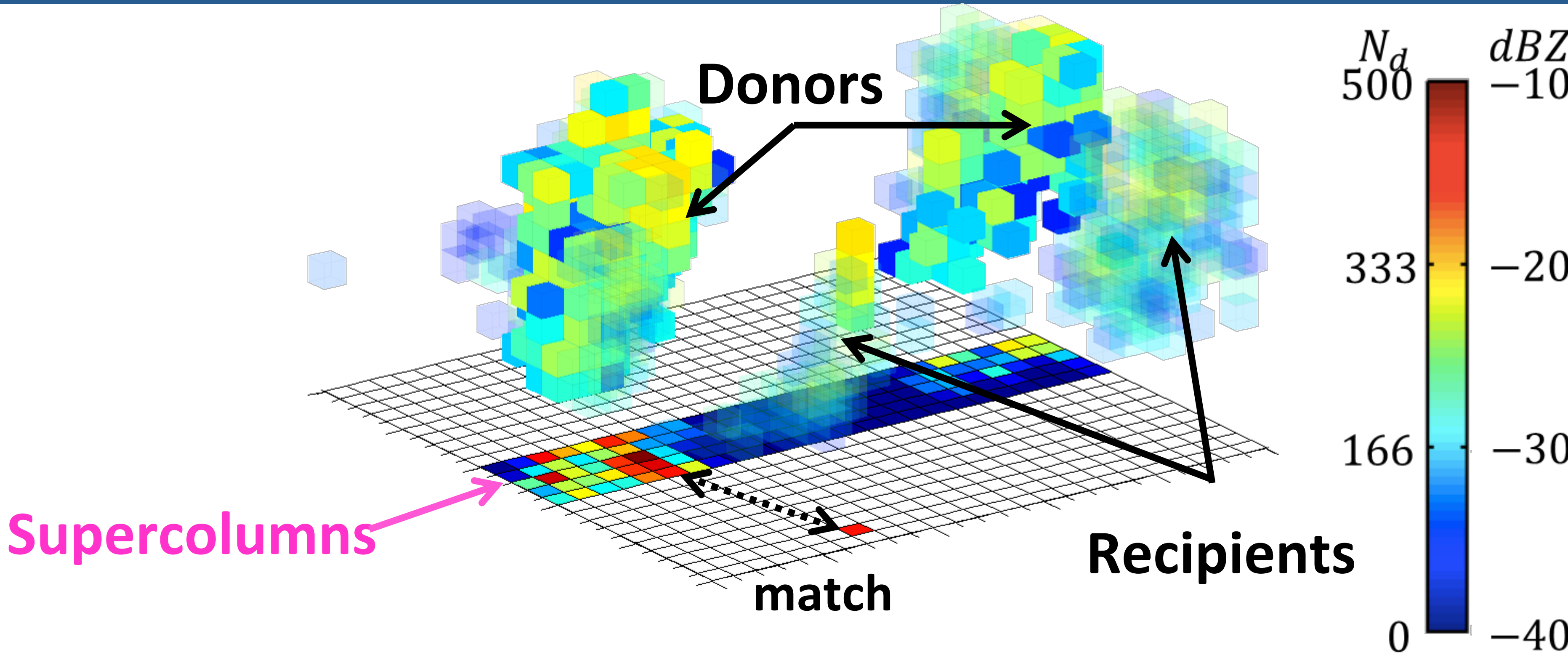
Pros

- Ensemble retains error statistics
- Does not require adjoint of forward model
- Easy to implement
- Potentially avoids local minima in non-linear problems by approximating gradient over a spread of points

Cons

- Expensive (requires a forward model calculation for each ensemble member at each iteration)

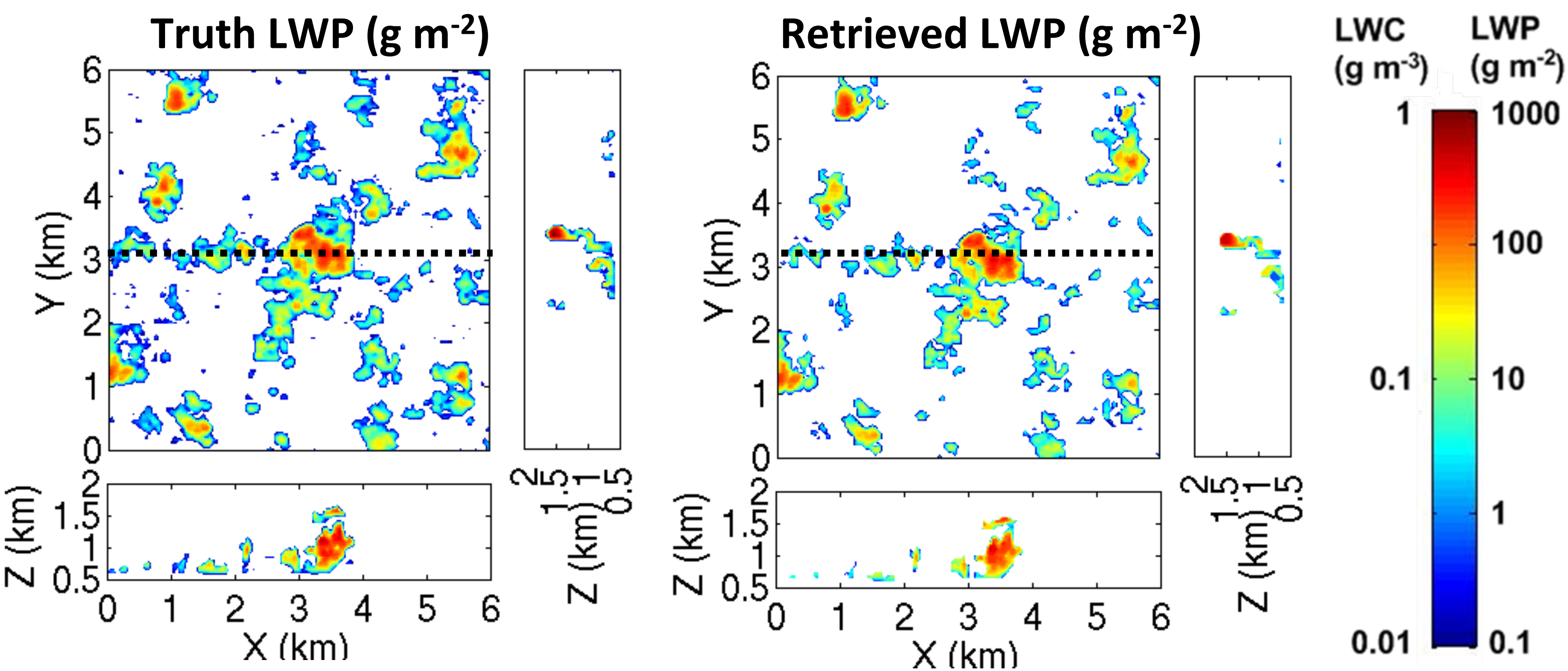
ENCORE – Step 2 (Reflectivity matching)



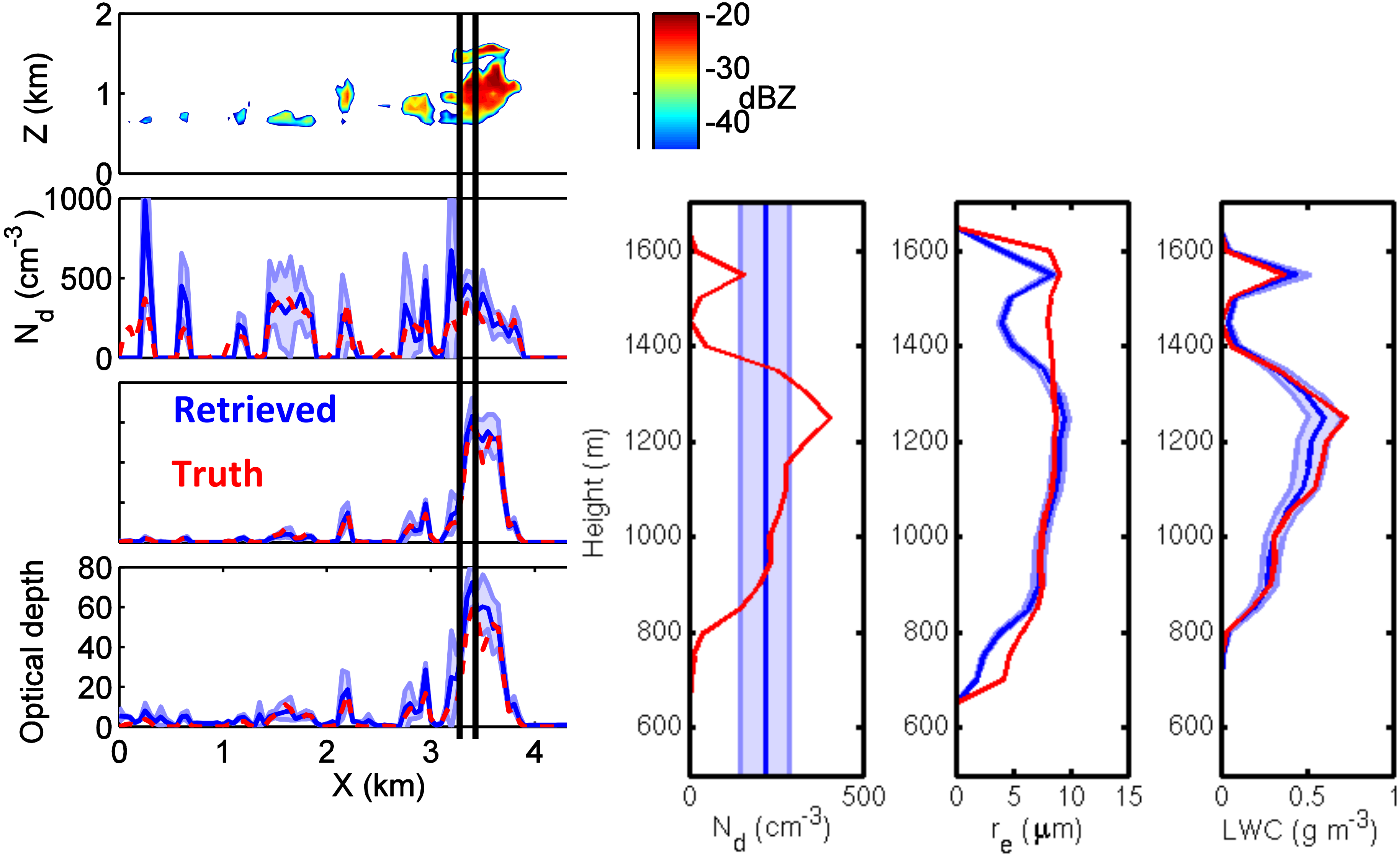
- Similar to *Barker et al.* 2011, match columns of radar reflectivity outside the supercolumn (recipients) to columns inside supercolumn (donors).
- Assign donor column's number concentration to recipient column.

Evaluation using trade wind shallow cumulus generated by large eddy simulation

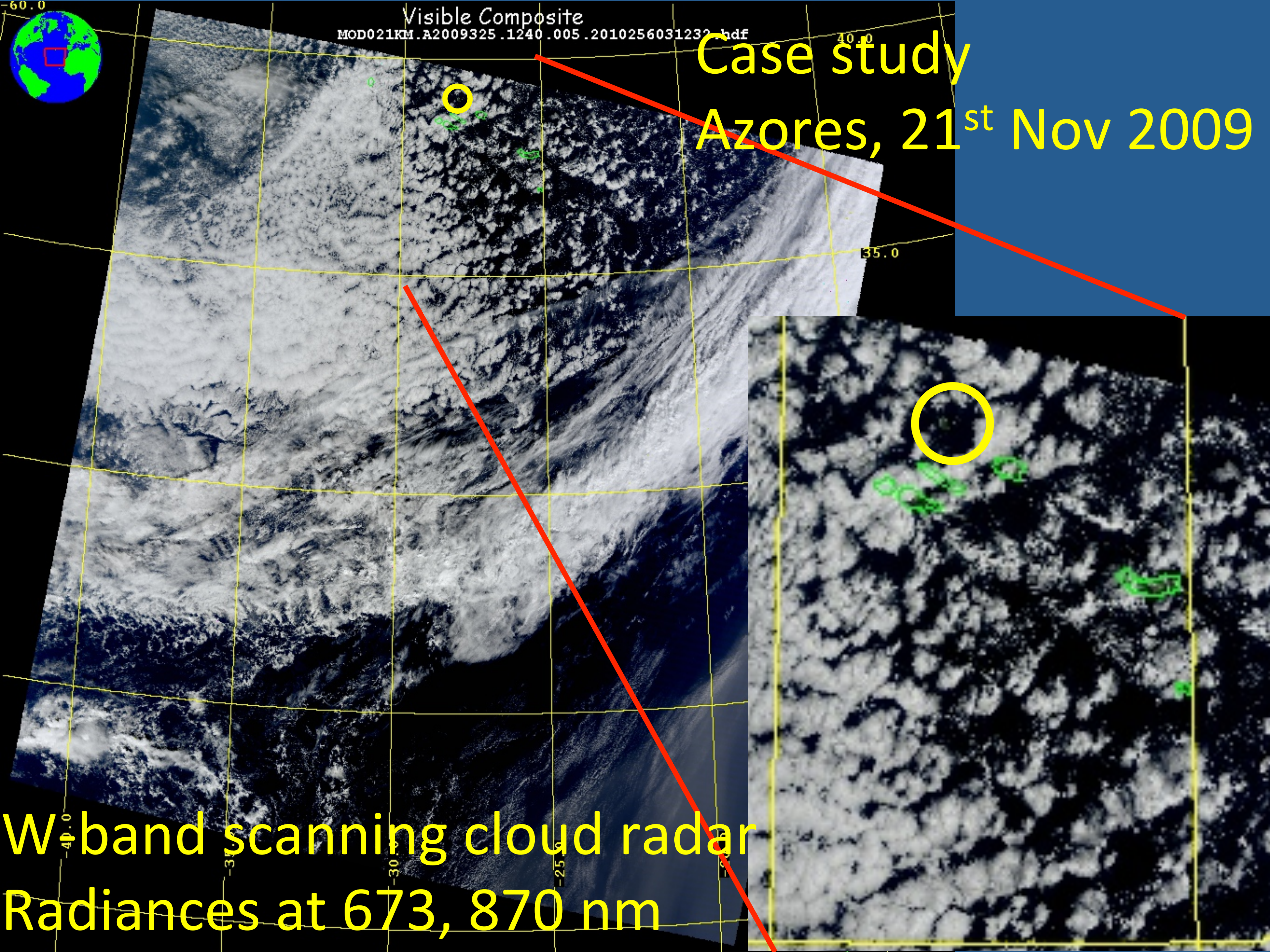
- Retrieval performs well, RMSE in LWP ~20 g m^{-2}
- Adding water-absorbing wavelength (e.g., 1640 nm) improves retrieval



Retrieval cross-section along track of radiances



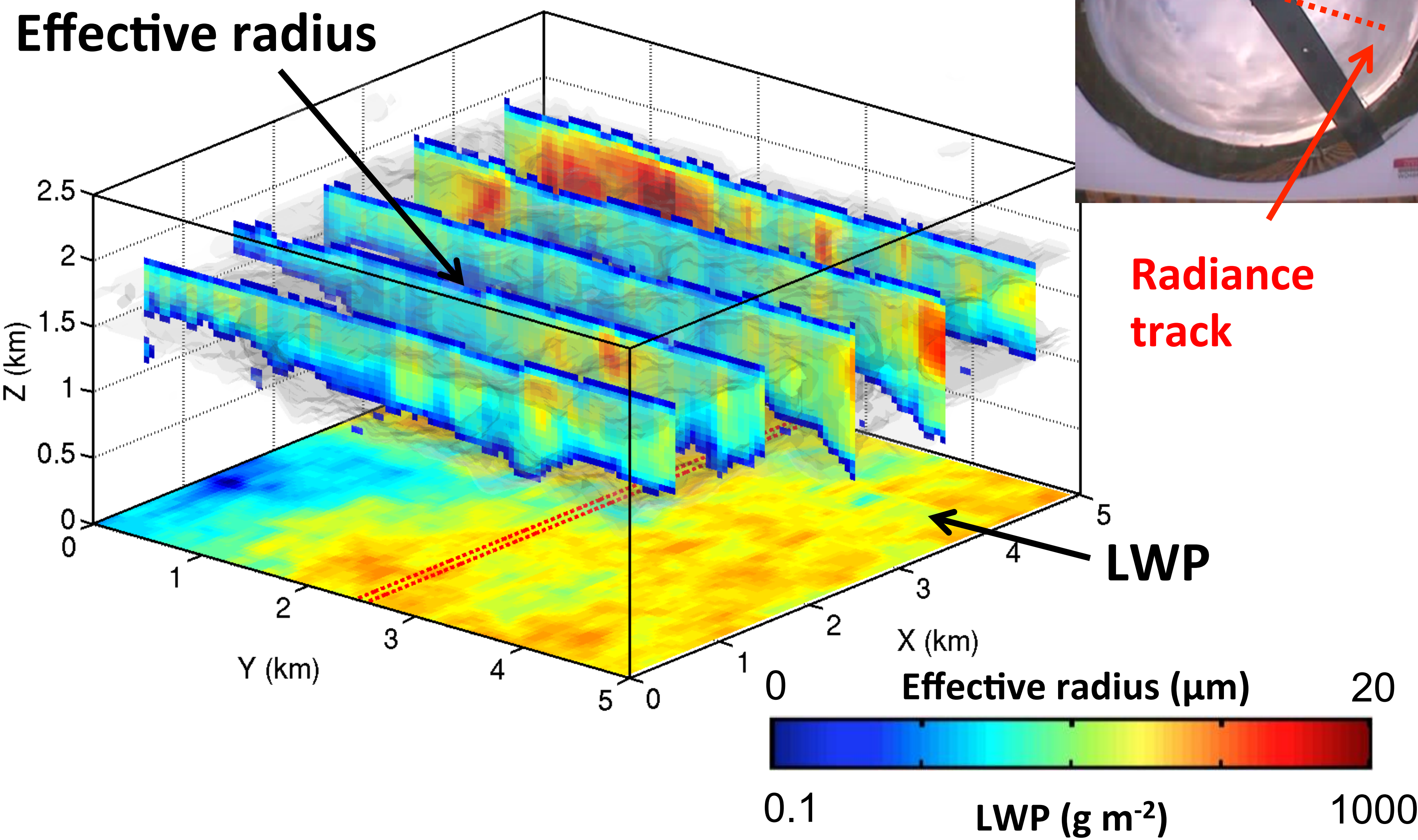
Case study
Azores, 21st Nov 2009



W-band scanning cloud radar

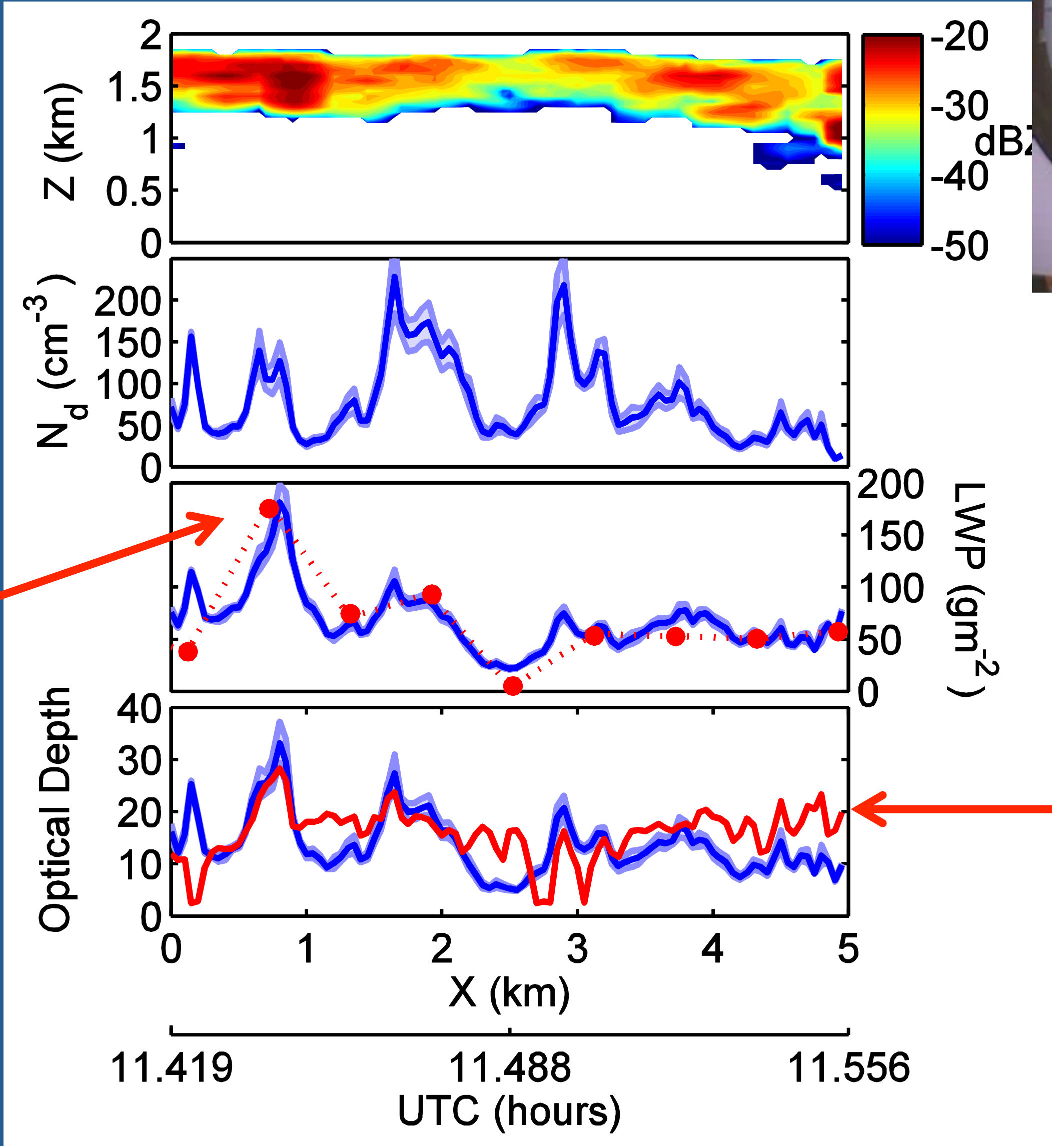
Radiances at 673, 870 nm

Example SCu


Effective radius
2.5
2
1.5
1
0.5
0
Z (km)
0
1
2
3
4
5
Y (km)
0
1
2
3
4
5
X (km)
LWP
0
Effective radius (μm)
20
0.1
LWP (g m-2)
1000


Radiance
track

Example SCu



Radiance track

Microwave radiometer retrieval RMSD ~20 g m^{-2}

2NFOV radiance-only retrieval RMSD ~6

Summary

- New method to provide 3D cloud fields in overcast and broken-cloud – key step to understand 3D effects
- Verified using LES shallow cumulus
- Good agreement with independent LWP in stratocumulus case
- Flexible ensemble optimal estimation framework