Retrieving cloud microphysical properties in a fully 3D environment using active and passive sensors

Mark Fielding

Robin Hogan, Christine Chiu

With thanks: Graham Feingold

Atmospheric System Research

University of Reading

Why do we need 3D observations of (warm) clouds?

- Clouds are fundamental to Earth's radiation budget
- Need 3D observations to unravel processes e.g., cloud structure affects radiative transfer
- Help provide observational constraints for realistic cloud and radiation parameterizations in global circulation models.

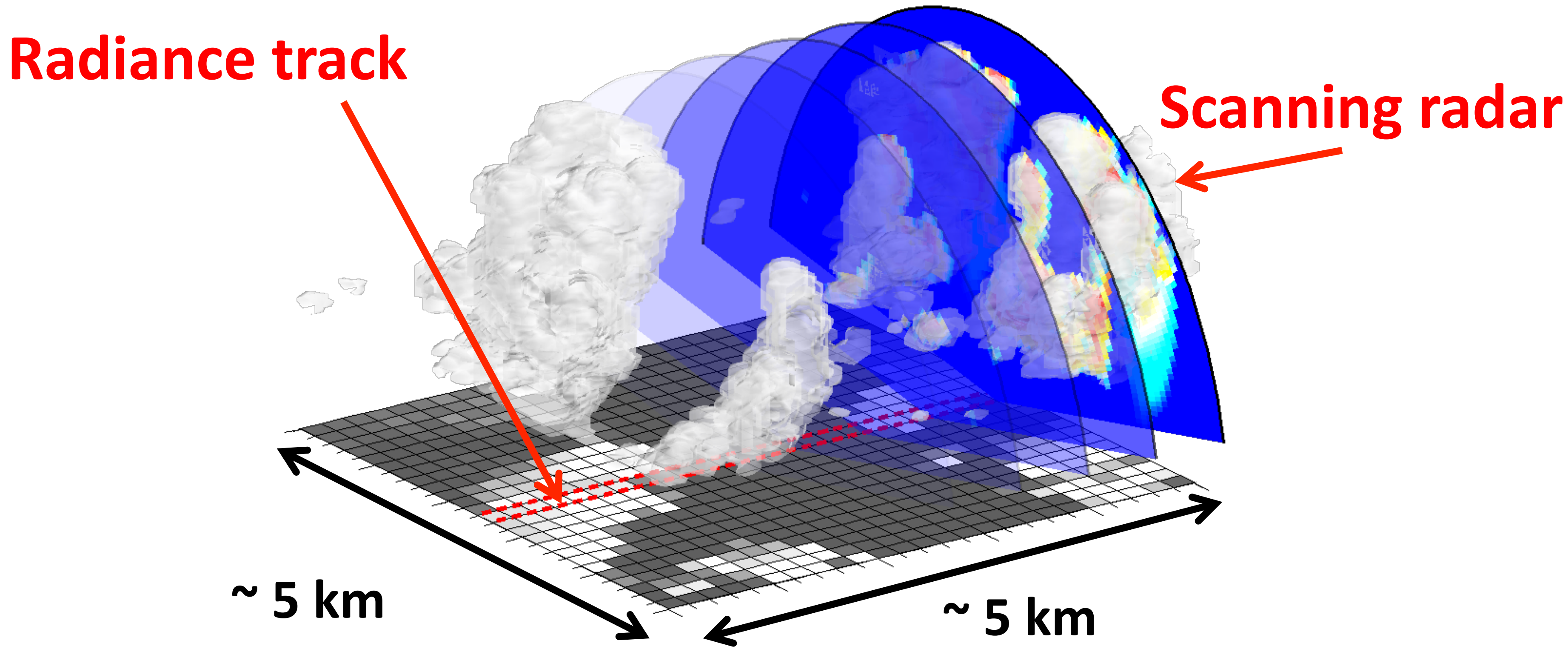
How can we observe clouds in 3D?

- **Problem:** Scanning cloud radar provides cloud structure but not 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

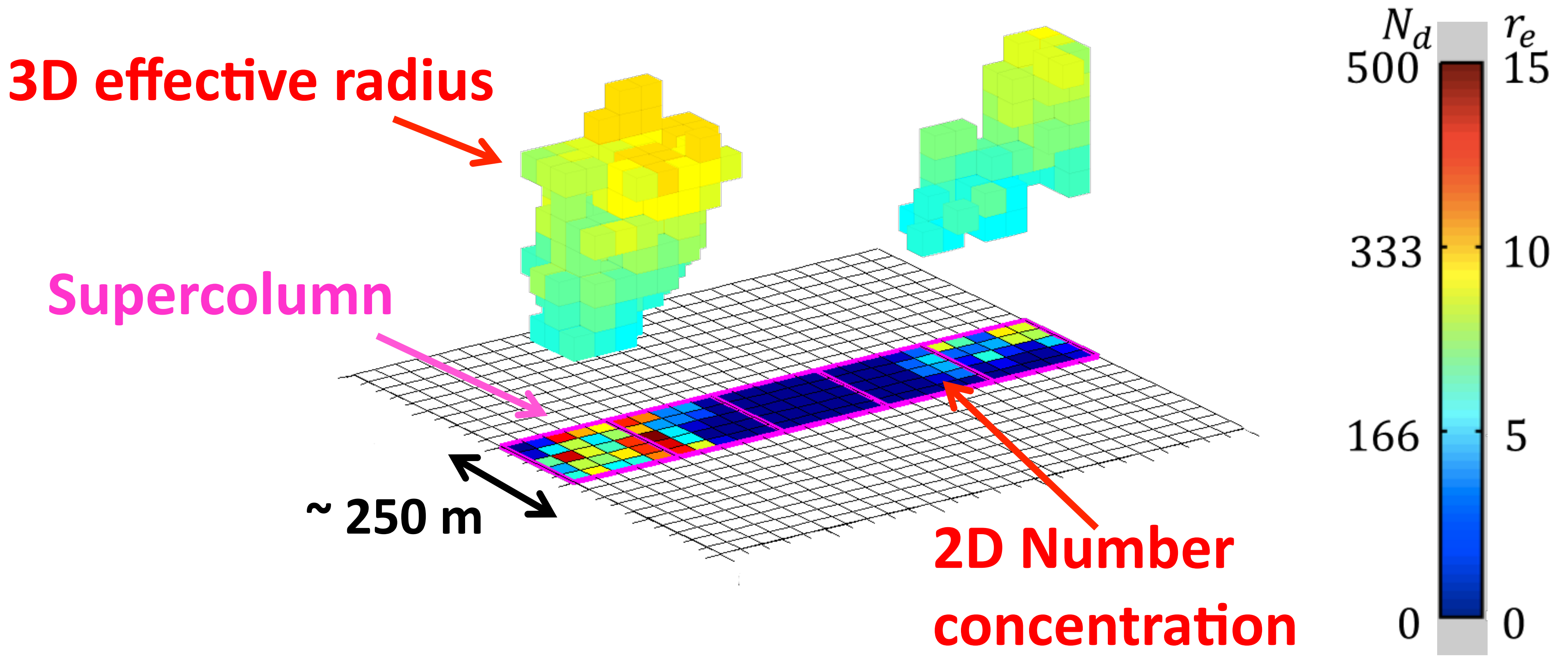
Method – Grid observations



- Allow clouds to advect across observation site
- Cross-Wind RHI scan optimum for shallow cumulus*

* *Fielding et al.*, 2013, JGR

Method – Step 1 ('Supercolumn' retrieval)



- Supercolumn size limited to area of domain constrained by the track of radiances

Define state, observations and forward models

X = 3D field of cloud effective radius, 2D field of number concentration (assume constant with height).

Y = Zenith Radiance, Radar reflectivity

H = lognormal cloud droplet distribution, 3D radiative transfer

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:

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

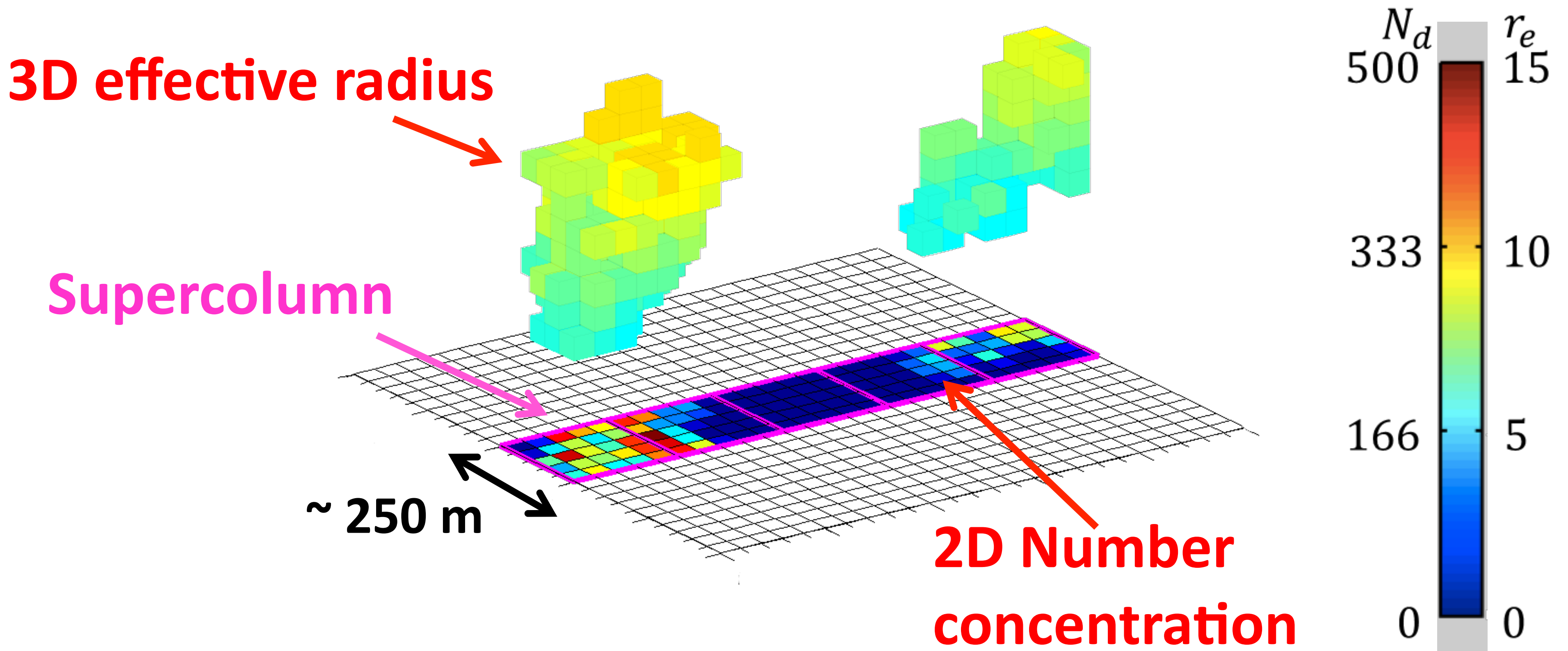
Pros

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

Cons

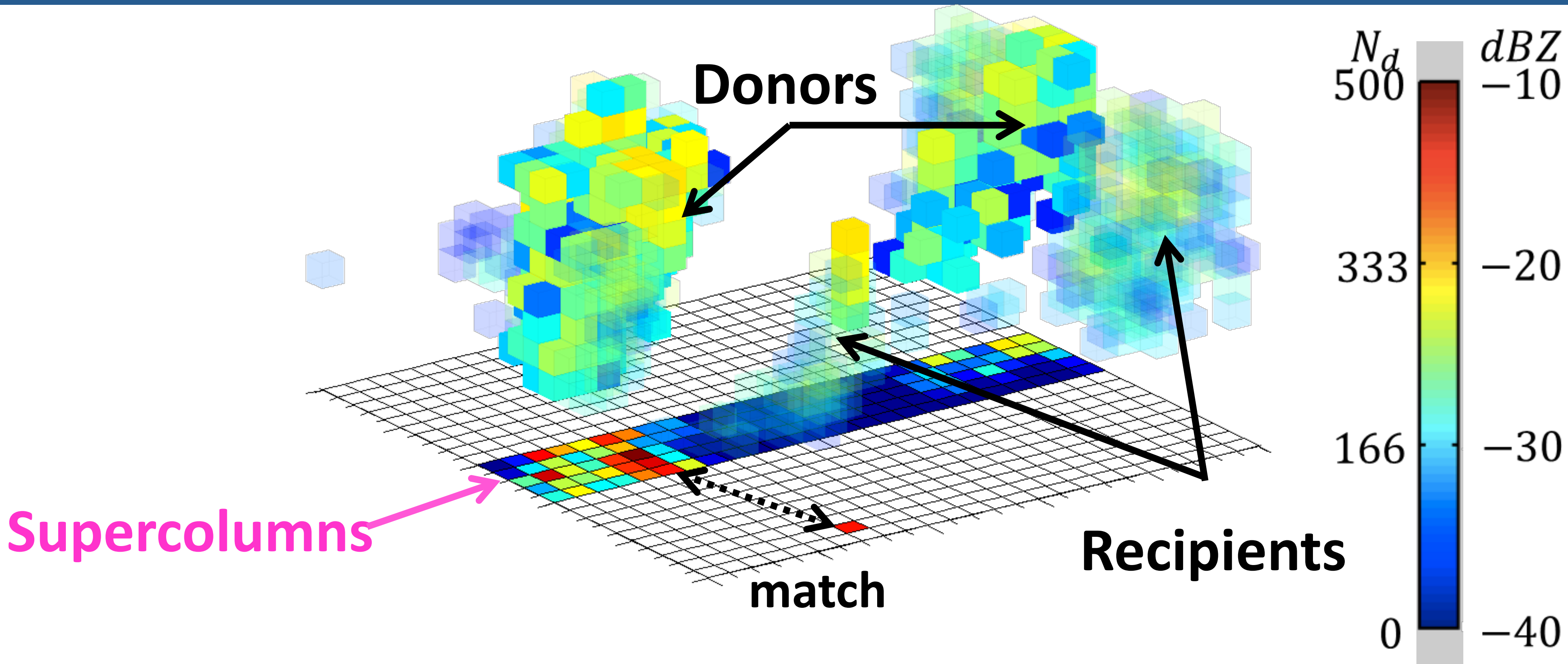
- Expensive (requires a forward model calculation for each ensemble member at each iteration)

Method – Step 1 (‘Supercolumn’ retrieval)



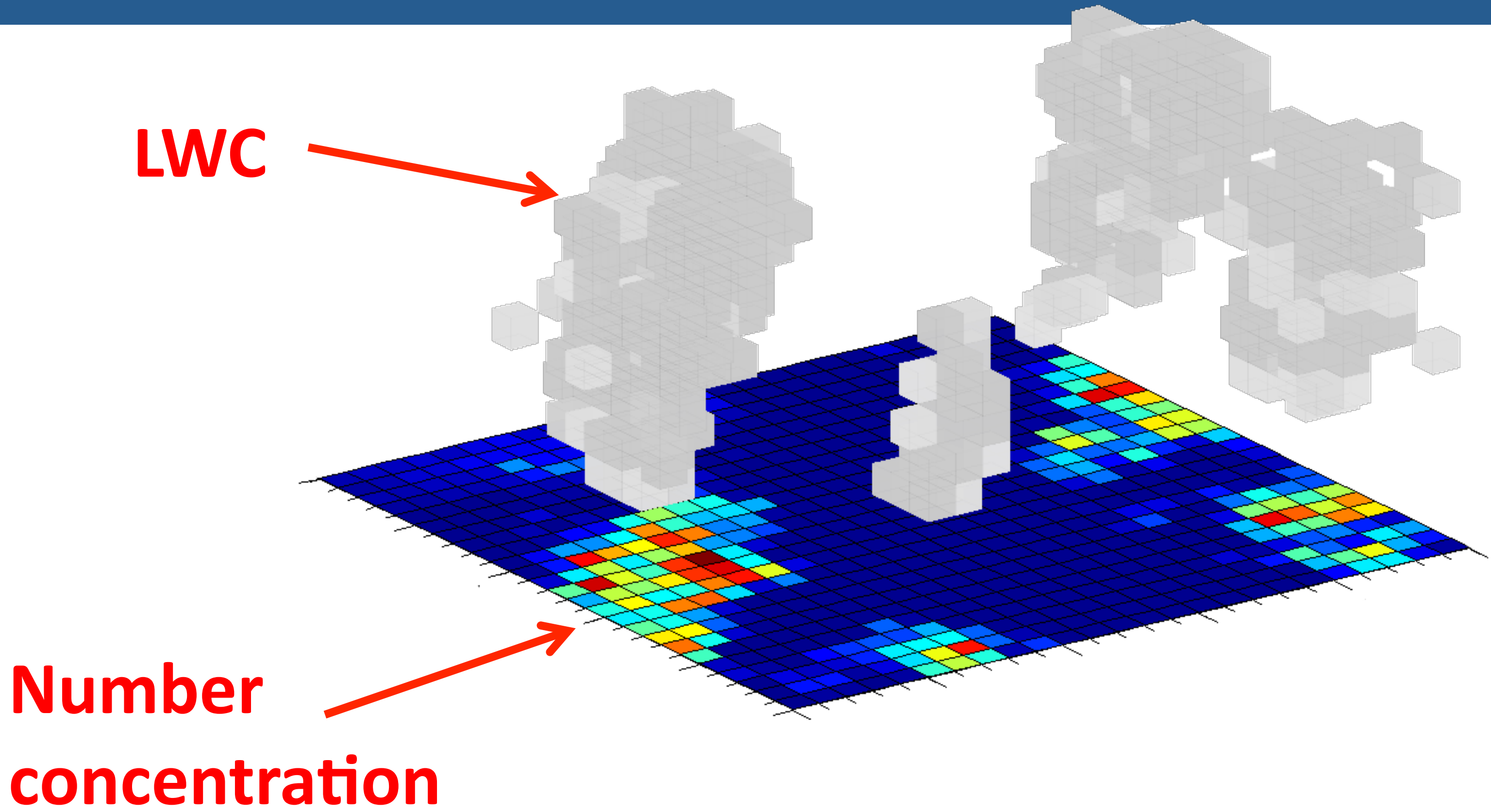
- Supercolumn size limited to area of domain constrained by the track of radiances
- Supercolumn size limited by computational cost

Method – 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.

Method – Step 2 (Reflectivity matching)



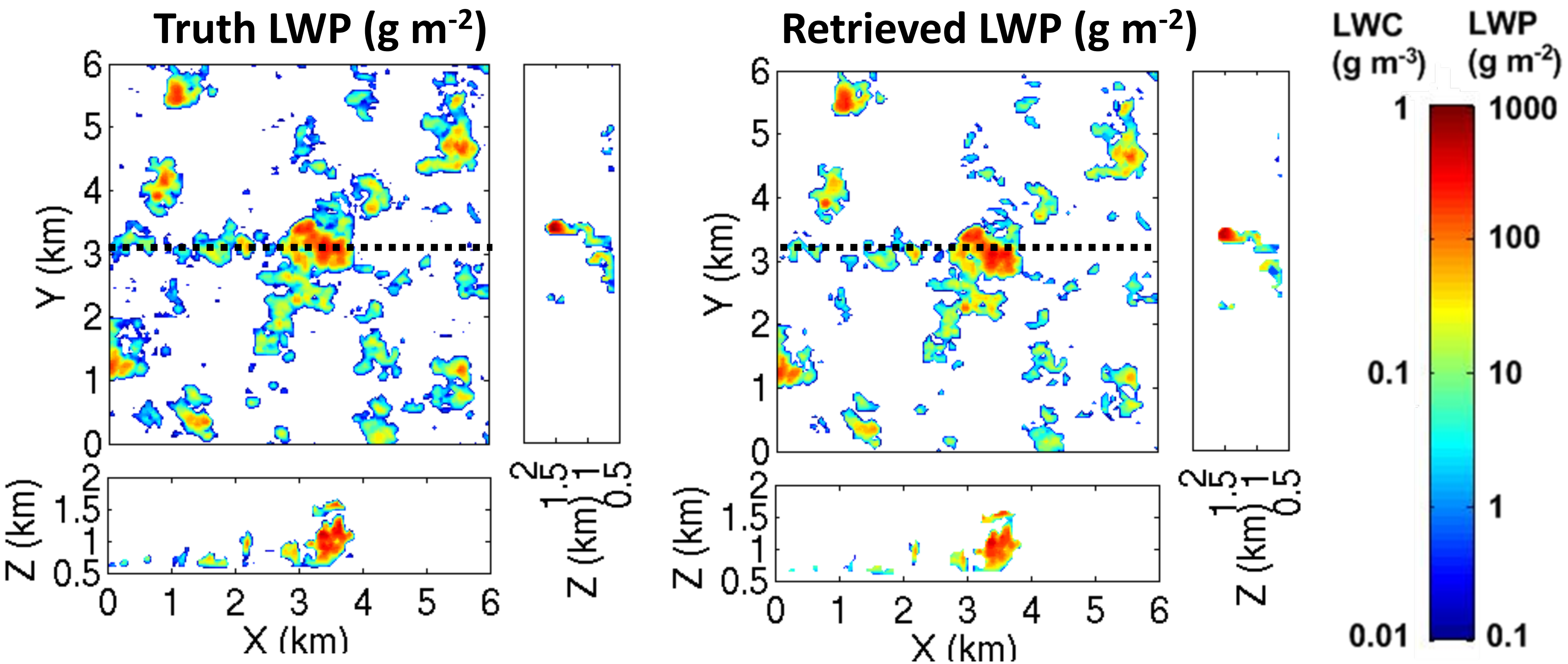
- Calculate effective radius and LWC in recipient column using assigned number concentration and recipient's reflectivity and lognormal droplet distribution assumption.

Method key points

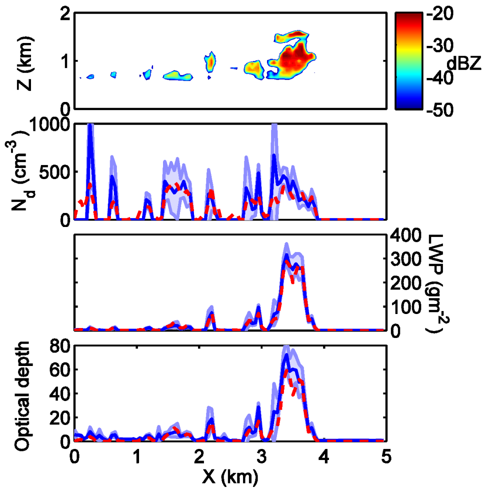
- First cloud retrieval to combine ground-based radar and zenith radiances
- First cloud retrieval to include 3D radiative transfer as a forward model
- First cloud retrieval to use the Iterative Ensemble Kalman Filter as an optimal estimation framework

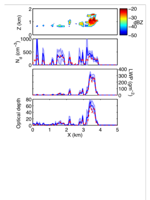
Evaluation using trade wind shallow cumulus generated by large eddy simulation

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



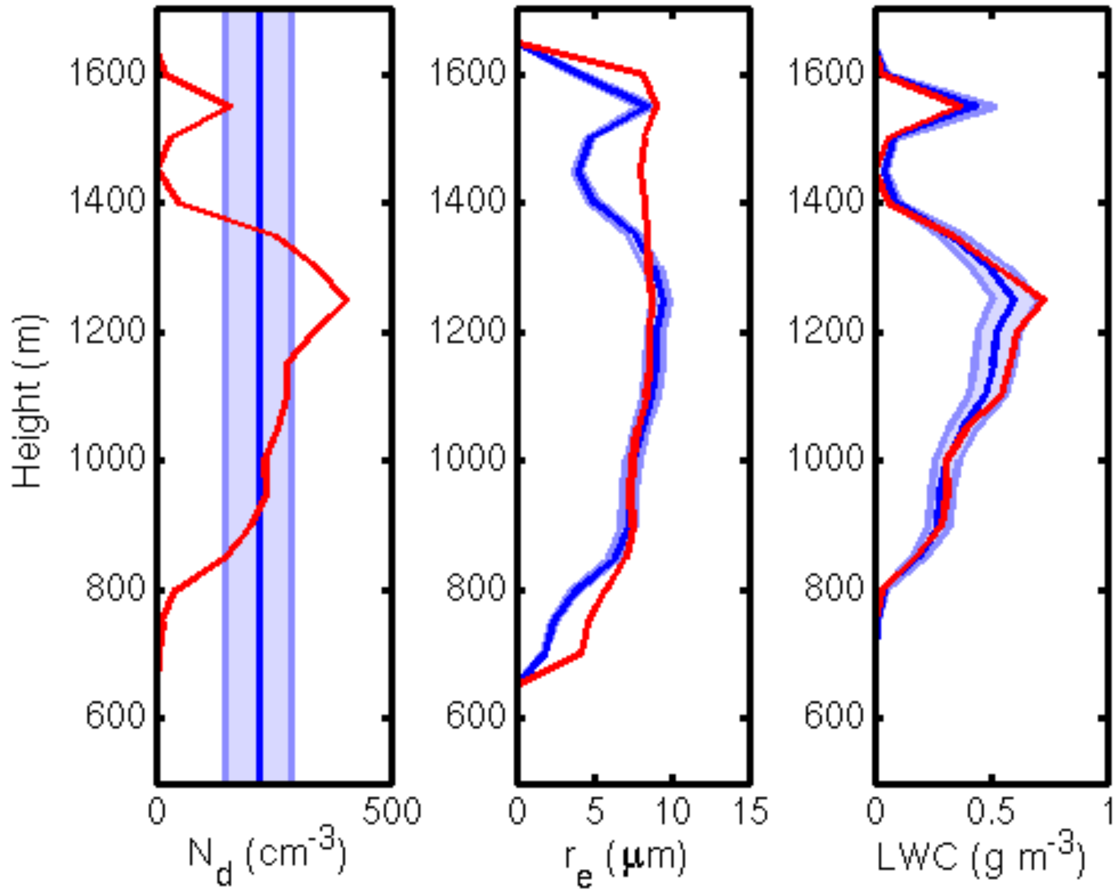
Retrieval cross-section along track of radiances



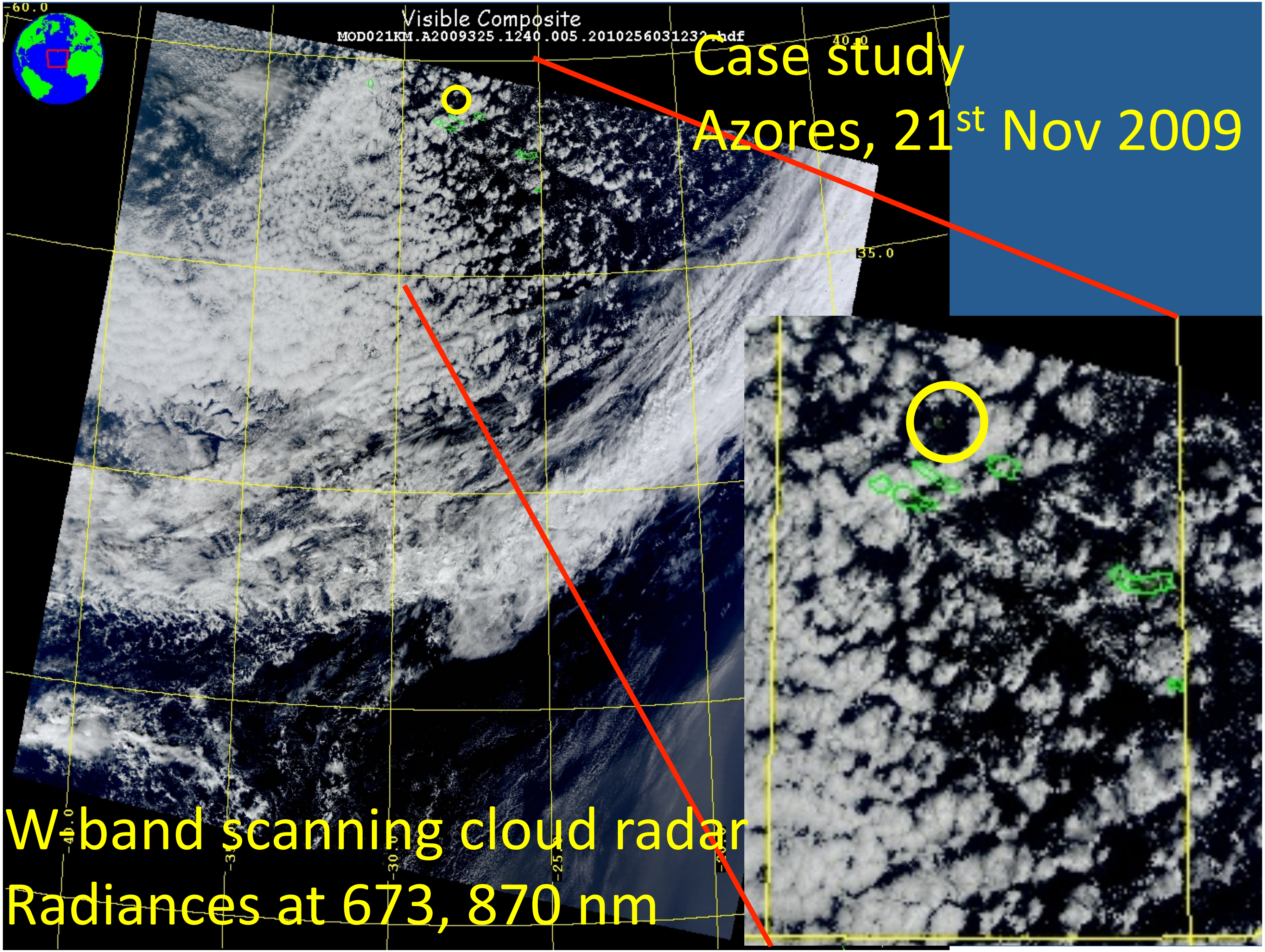


Retrieved

Truth



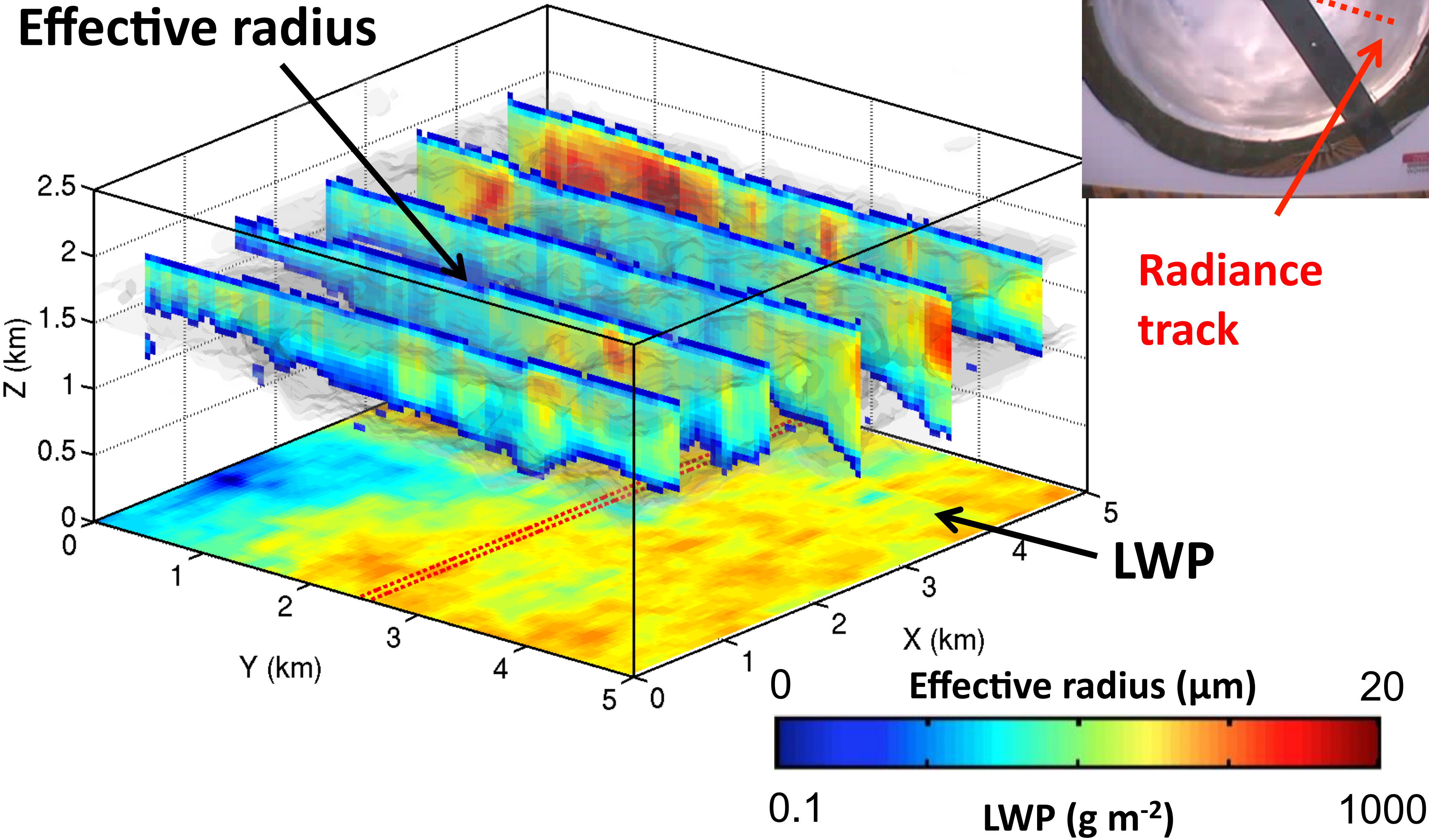
Case study Azores, 21st Nov 2009



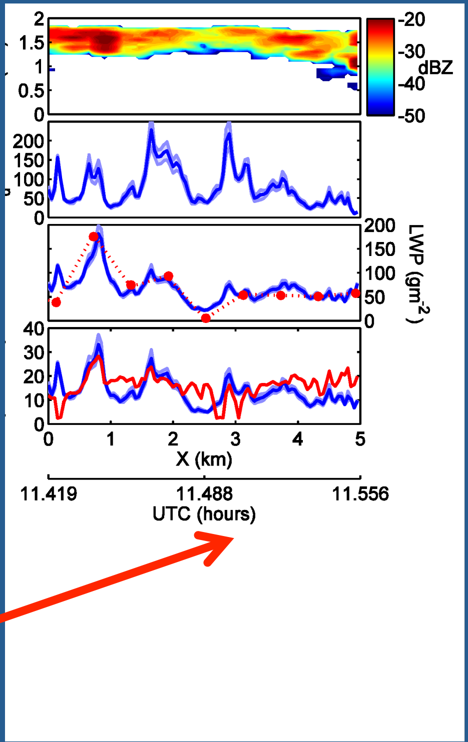
W-band scanning cloud radar

Radiances at 673, 870 nm

Example SCu

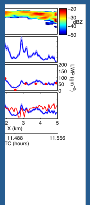

Effective radius
2.5
2
1.5
1
0.5
0
Z (km)
0
1
2
3
4
5
Y (km)
0
1
2
3
4
5
X (km)
Radiance
track
LWP
0
Effective radius (μm)
20
0.1
LWP (g m-2)
1000

Example SCu



Radiance track

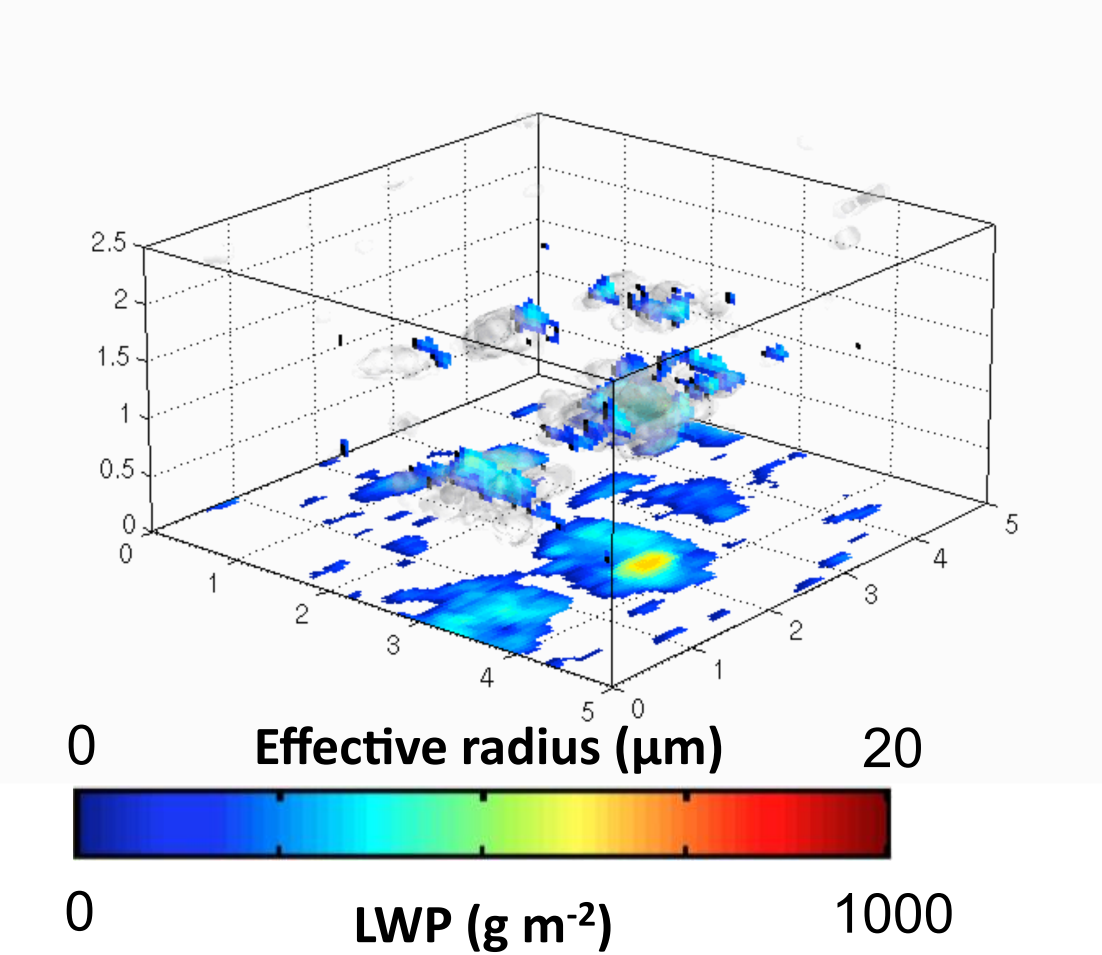
Microwave radiometer retrieval RMSD ~20 g m^{-2}

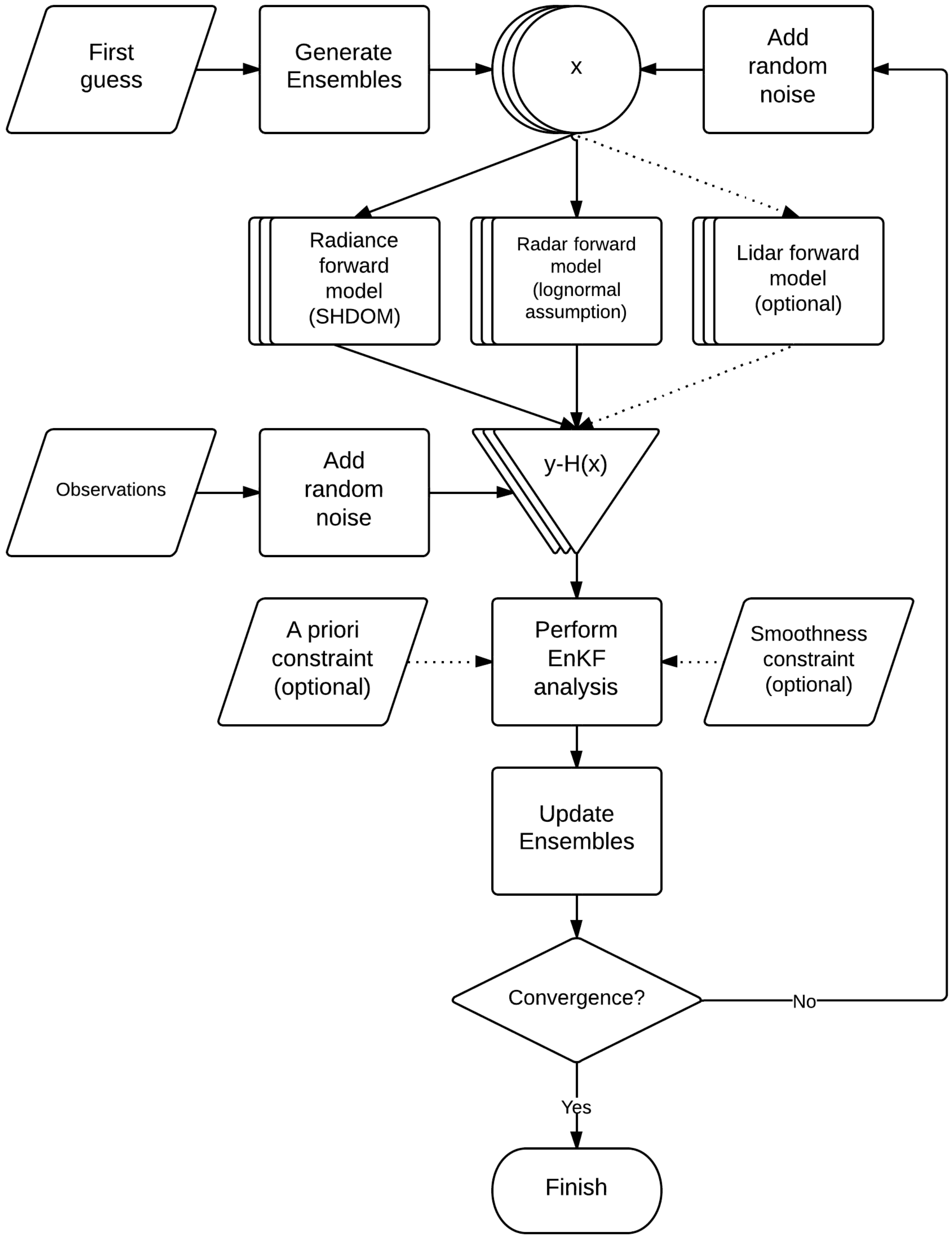


2NFOV radiance-only retrieval RMSD ~6

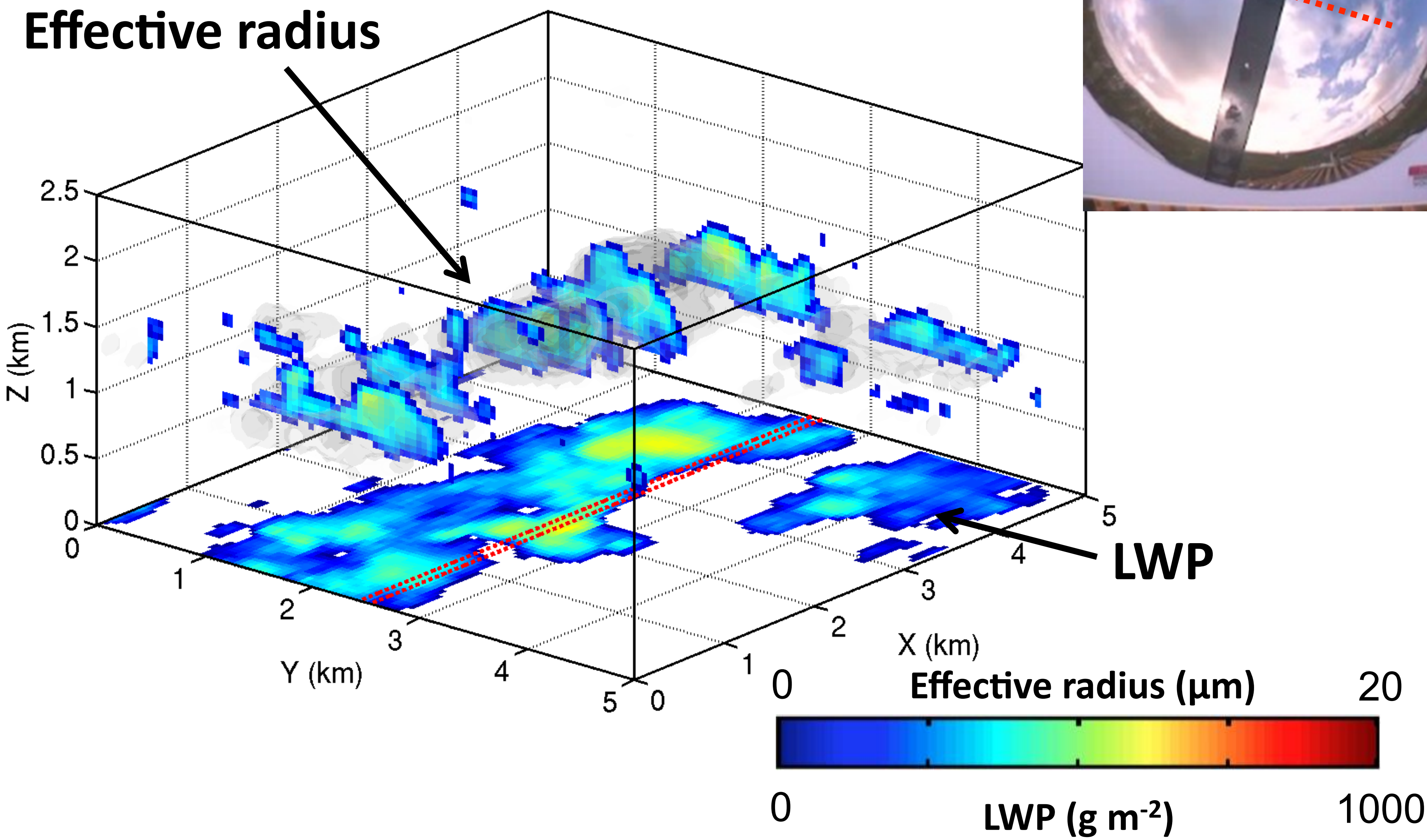
Summary

- 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



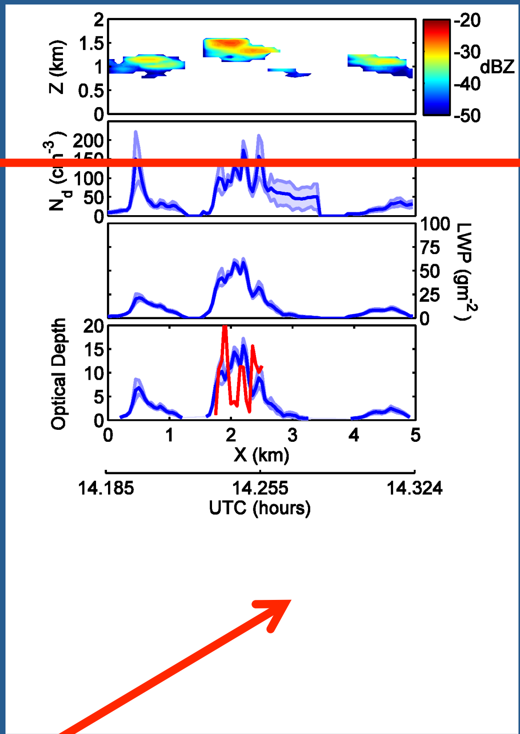

First guess
Generate Ensembles
x
Add random noise
Radiance forward model (SHDOM)
Radar forward model (lognormal assumption)
Lidar forward model (optional)
Observations
Add random noise
y-H(x)
A priori constraint (optional)
Perform EnKF analysis
Smoothness constraint (optional)
Update Ensembles
Convergence?
No
Yes
Finish

Example (2) - Cu

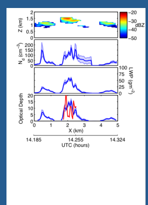

Effective radius
LWP
Z (km)
2.5
2
1.5
1
0.5
0
Y (km)
X (km)
0
Effective radius (μm)
20
0
LWP (g m-2)
1000

Example (2) - Cu

Limit of radar sensitivity

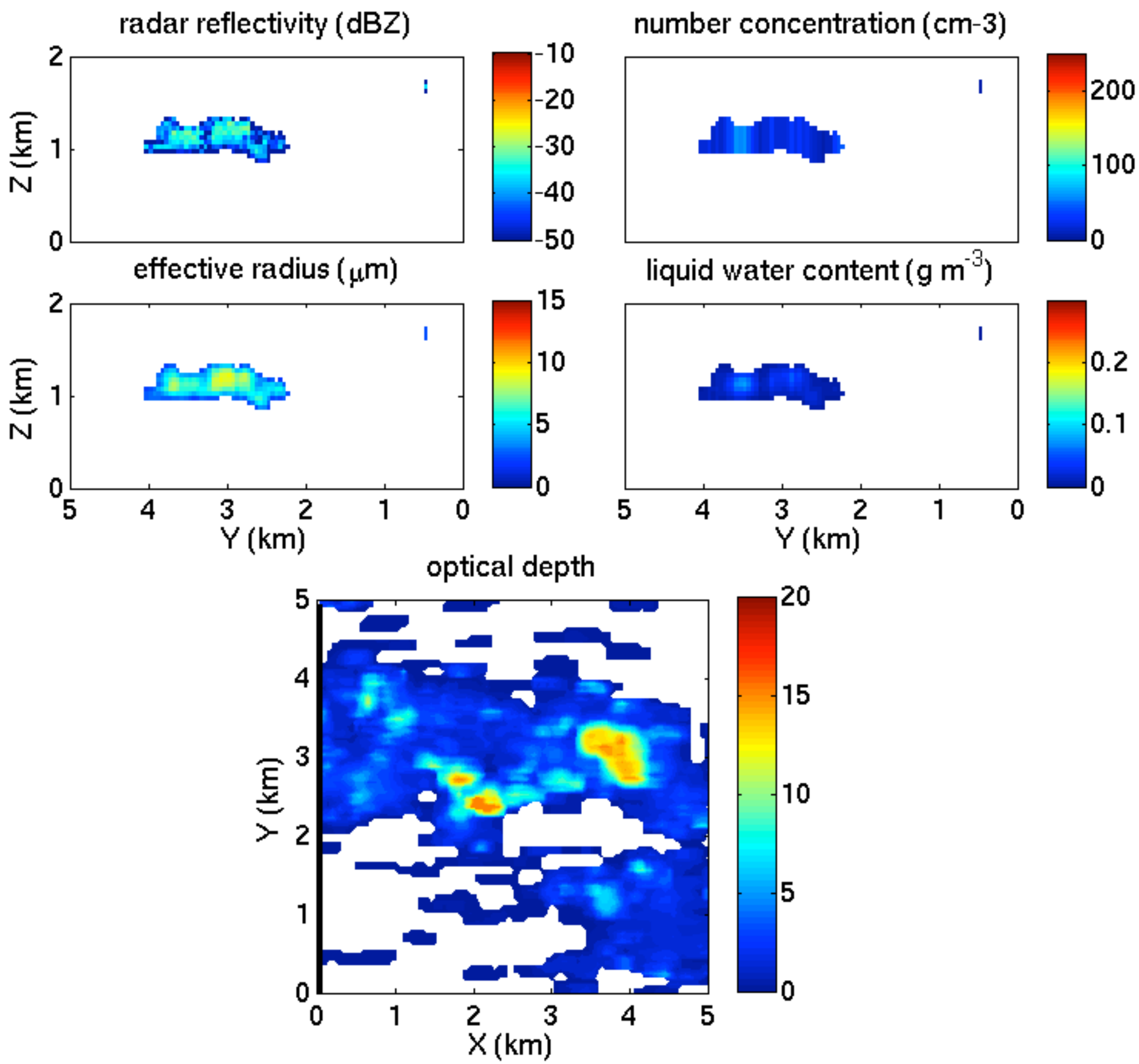


Microwave radiometer retrieval is negative



2NFOV retrieval only physical for larger Cu clouds

Cu case, Azores, 21st November 2009



Sc case, Azores, 28th November 2009