Optimal Estimation of Cloud Drop Effective Radius

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Motivation

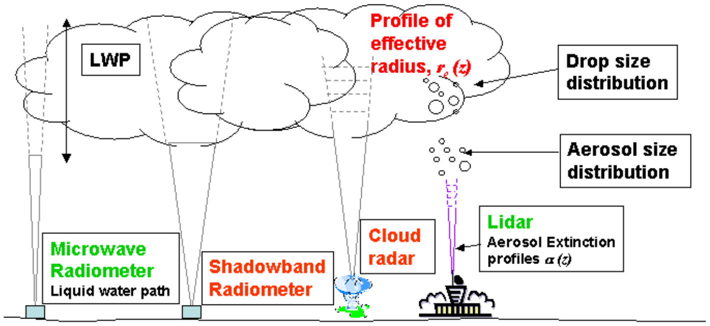
First aerosol indirect effect (IE):
increase in the number of cloud condensation nuclei
generates a cloud with smaller drops (all else being equal).

To quantify IE, measure simultaneously cloud and aerosol properties:
(a) cloud drop effective radius (r_e) and
(b) cloud condensation nuclei (CCN) proxies.

Cloud drop radius r_e can be retrieved with different measurements:
(a) Is there agreement between the techniques?
(b) What is the "best" overall estimate of r_e?

Remote Sensing: Surface-based

Cloud radar, shadowband radiometer,
(microwave radiometer, lidar, nephelometer)



LWP

Profile of effective radius, $r_e(z)$

Drop size distribution

Aerosol size distribution

Lidar
Aerosol Extinction profiles $\alpha(z)$

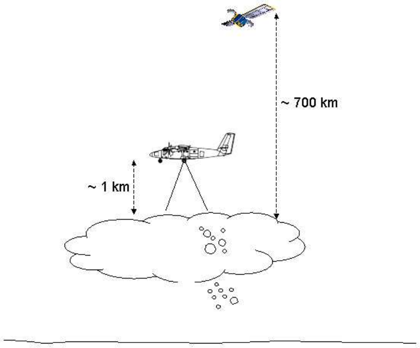
Cloud radar

Microwave Radiometer
Liquid water path

Shadowband Radiometer

Remote Sensing: Space, Airborne

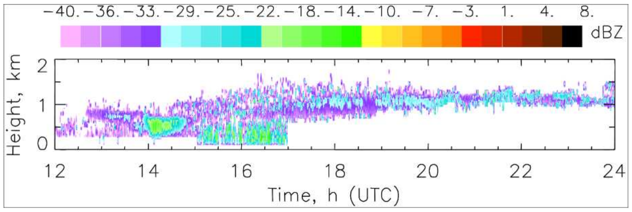
MODIS, flux radiometer, in situ probe



Relevant Data for Optimal Estimation

On May 17 2003, single event during 'Intensive Operations Period' when 5 remote and in-situ drop size retrievals were available for comparison:

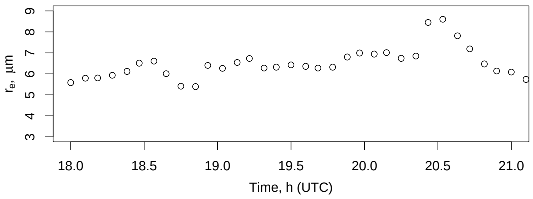
- Cloud radar (reflectivity)



Relevant Data for Optimal Estimation

On May 17 2003, single event during 'Intensive Operations Period' when 5 remote and in-situ drop size retrievals were available for comparison:

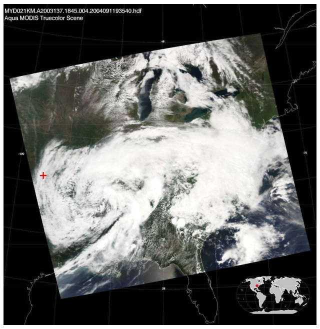
- Cloud radar
- Shadowband radiometer
  (derived r_e)



Relevant Data for Optimal Estimation

On May 17 2003, single event during ‘Intensive Operations Period’ when 5 remote and in-situ drop size retrievals were available for comparison:

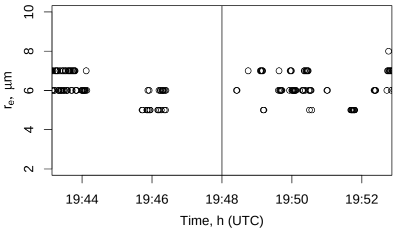
- Cloud radar
- Shadowband radiometer
- MODIS (cloud cover)



Relevant Data for Optimal Estimation

On May 17 2003, single event during ‘Intensive Operations Period’ when 5 remote and in-situ drop size retrievals were available for comparison:

- Cloud radar
- Shadowband radiometer
- MODIS
- Flux radiometer (derived r_e)



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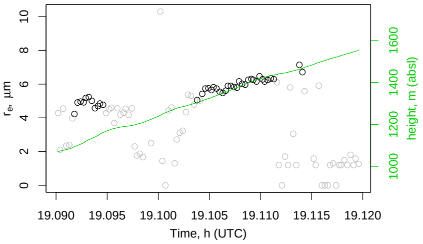


Data Summary

	Sampling period (s)	Sampling volume/ Footprint	Uncertainty in r_e (%)
Cloud radar	20	700 m^3	15 - 20
Shadowband radiometer	300	Circle of radius 1 km	13
MODIS	10^{-4}	2 km × 4.8 km	5 - 10
Flux radiometer	1	Circle of radius 2.7 km	15 - 20
In situ probe	1	7 cm^3	15 - 20

Take into account: different sampling period
different sampling volume
different retrieval uncertainty

Best-estimate of r_e

Assume that for sufficiently small spatial and temporal scales, r_e does not change systematically.

Model r_e at height h, time t and horizontal location $\mathbf{s}$ by

$$r_e(h,t,\mathbf{s}) = \theta_1 + \theta_2 h^{1/3} + \mathcal{Z}(h,t,\mathbf{s})$$

Mean zero Gaussian error process $\mathcal{Z}$ with a complex variance structure.

Combine the different types of retrievals by accounting within $\mathcal{Z}$ for
– sampling period,
– sampling volume,
– and retrieval uncertainty
to derive weighted least squares estimates for θ_1 and θ_2.

Numerical Example

Data:

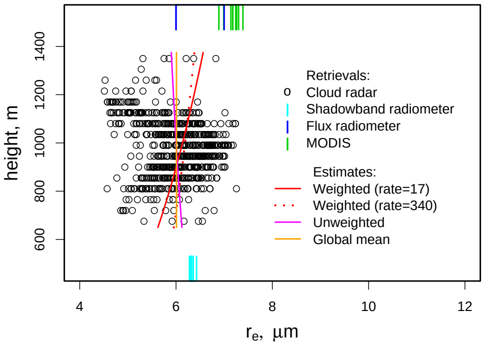
Cloud radar:	688 data points between 19:20 and 19:50 (91 columns retrievals)
Shadowband radiometer:	6 data points between 19:20 and 19:50
MODIS:	3×3 square pixels centered at SGP site
Flux radiometer:	3 data points between 19:47 and 19:49

Weighting functions for spatial aggregation:

Cloud radar:	none, no spatial aggregation
Shadowband radiometer:	constant
MODIS, flux radiometer:	exponential with rates 17 or 340

Numerical Example: Best-Estimate

Superposition of all measurements and best-estimate profile of r_e

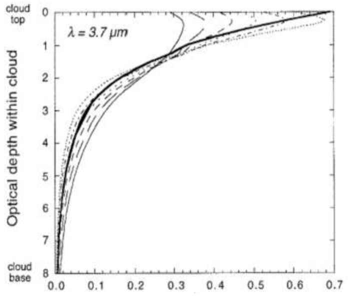


Summary

- Comparison of five r_e retrieval methods on May 17 2003
- Methodology for deriving best-estimate of $r_e(h, t, \mathbf{s})$:
  - four remote sensors (shadowband radiometer, cloud radar, MODIS, flux radiometer)
  - incorporates uncertainties, weighting, different sampling volumes
- Calculation of IE for different r_e retrievals and different CCN proxies (radar, shadowband radiometer and lidar, nephelometer, PCASP):
  - even though r_e retrievals are similar, estimates of IE differ considerably
  - low statistics when binning by LWP

Weighting functions

Vertical weighting for reflectance



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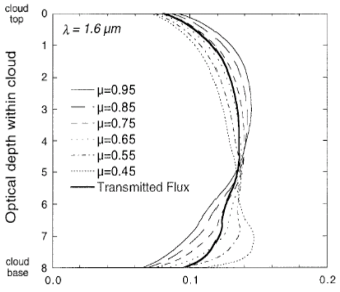


Addendum: IE

Simultaneously measure cloud and aerosol properties at surface

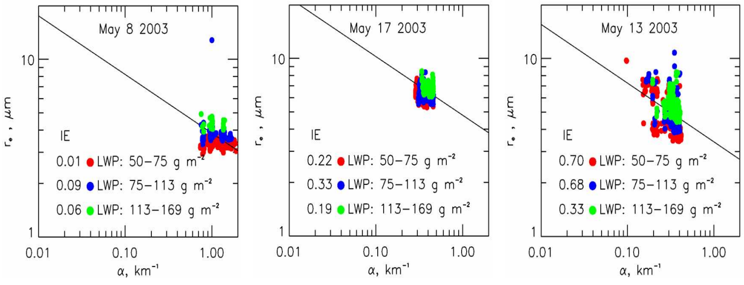
$$\text{IE} = -\frac{d\ln(r_e)}{d\ln(\text{CCN})} \qquad 0 < \text{IE} < 0.33$$

r_e:
- Shadowband radiometer and microwave radiometer
- Cloud radar and microwave radiometer

CCN proxy:
- lidar extinction (355 nm; 350 m)
- Nephelometer scattering (550 nm; surface)
- PCASP aerosol concentration (>0.15 μm; surface)

Addendum: IE

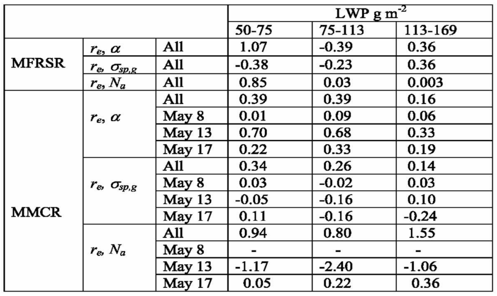
IE for 3 days with cloud radar and lidar extinction for CCN proxy



Addendum: IE

Calculations of IE for 3 LWP bins based on shadowband radiometer (MFRSR) or cloud radar (MMCR) and various CCN proxies.

IE values should lie between 0 and 0.333. Note numerous excursions and even negative IE, when nephelometer is used as CCN proxy.



			LWP g m^{-2}		
			50-75	75-113	113-169
MFRSR	r_e, α	All	1.07	-0.39	0.36
	r_e, $\sigma_{sp,g}$	All	-0.38	-0.23	0.36
	r_e, N_a	All	0.85	0.03	0.003
MMCR	r_e, α	All	0.39	0.39	0.16
		May 8	0.01	0.09	0.06
		May 13	0.70	0.68	0.33
		May 17	0.22	0.33	0.19
	r_e, $\sigma_{sp,g}$	All	0.34	0.26	0.14
		May 8	0.03	-0.02	0.03
		May 13	-0.05	-0.16	0.10
		May 17	0.11	-0.16	-0.24
	r_e, N_a	All	0.94	0.80	1.55
		May 8	-	-	-
		May 13	-1.17	-2.40	-1.06
		May 17	0.05	0.22	0.36