Optimal Estimation of Cloud Drop Effective Radius

R. Furrer¹, G. Feingold², P. Pilewskie³, L. Remer⁴, Q. Min⁵ and H. Jonsson⁶

¹NCAR & Colorado School of Mines ²NOAA/ESRL ³University of Colorado, Boulder ⁴NASA/GSFC ⁵SUNY, Albany ⁶NPS/CIRPAS

AAAR, Oct. 18th 2005

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)

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)

\[
\begin{array}{c}
\text{Height, km} \\
0 & 1 & 2
\end{array}
\begin{array}{c}
\text{Time, h (UTC)} \\
12 & 14 & 16 & 18 & 20 & 22 & 24
\end{array}
\]

\[
\begin{array}{c}
\text{dBZ} \\\-40 & -36 & -33 & -29 & -25 & -22 & -18 & -14 & -10 & -7 & -3 & 1 & 4 & 8
\end{array}
\]

- Shadowband radiometer (derived \( r_e \))

\[
\begin{array}{c}
\text{Time, h (UTC)} \\
18.0 & 18.5 & 19.0 & 19.5 & 20.0 & 20.5 & 21.0
\end{array}
\begin{array}{c}
r_e, \mu m \\
3 & 4 & 5 & 6 & 7 & 8
\end{array}
\]
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)
- Flux radiometer
- In situ probe (derived $r_e$)

Data Summary

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Sampling period (s)</th>
<th>Sampling volume/Footprint</th>
<th>Uncertainty in $r_e$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud radar</td>
<td>20</td>
<td>700 m$^3$</td>
<td>15 - 20</td>
</tr>
<tr>
<td>Shadowband radiometer</td>
<td>300</td>
<td>Circle of radius 1 km</td>
<td>13</td>
</tr>
<tr>
<td>MODIS</td>
<td>$10^{-4}$</td>
<td>2 km $\times$ 4.8 km</td>
<td>5 - 10</td>
</tr>
<tr>
<td>Flux radiometer</td>
<td>1</td>
<td>Circle of radius 2.7 km</td>
<td>15 - 20</td>
</tr>
<tr>
<td>In situ probe</td>
<td>1</td>
<td>7 cm$^3$</td>
<td>15 - 20</td>
</tr>
</tbody>
</table>

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 $s$ by

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

Mean zero Gaussian error process $Z$ with a complex variance structure.

Combine the different types of retrievals by accounting within $Z$ for
- sampling period,
- sampling volume,
- and retrieval uncertainty

to derive weighted least squares estimates for $\theta_1$ and $\theta_2$.

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 x 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 $r_e(h,t,s)$:
  - 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 and for transmission

Addendum: IE

Simultaneously measure cloud and aerosol properties at surface

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

$r_e$: 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

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.

<table>
<thead>
<tr>
<th></th>
<th>LWP g m$^{-2}$</th>
<th>30-75</th>
<th>75-113</th>
<th>113-169</th>
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<tbody>
<tr>
<td>MFRSR</td>
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<td>All</td>
<td>-0.38</td>
<td>-0.23</td>
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<td>$r_e$, N$_{PCASP}$</td>
<td>All</td>
<td>0.85</td>
<td>0.03</td>
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<td></td>
<td>All</td>
<td>0.99</td>
<td>0.39</td>
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<tr>
<td></td>
<td>May 8</td>
<td>0.09</td>
<td>0.09</td>
<td></td>
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<tr>
<td></td>
<td>May 13</td>
<td>0.70</td>
<td>0.68</td>
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<td></td>
<td>May 17</td>
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<td>0.33</td>
<td>0.19</td>
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<tr>
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<td>All</td>
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<td>0.26</td>
<td>0.14</td>
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<tr>
<td></td>
<td>May 8</td>
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<td>-0.02</td>
<td>0.05</td>
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<tr>
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<td>May 13</td>
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<td>-0.16</td>
<td>0.10</td>
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<td></td>
<td>May 17</td>
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<td>-0.16</td>
<td>-0.24</td>
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<td>0.80</td>
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<td>$r_e$, N$_{PCASP}$</td>
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<td>-</td>
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<td>2.00</td>
<td>1.06</td>
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<tr>
<td></td>
<td>May 17</td>
<td>0.05</td>
<td>0.22</td>
<td>0.36</td>
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