Cloud scaling from the meter to the basin

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GOES East, 18th March 2008
Marine stratocumulus

Photograph: Gabor Vali
Marine stratocumulus
Trade cumuli, Antigua, Jan 2005

Photograph: Bjorn Stevens
Small cumuli
Midlatitude cyclones

Tropical storms

T. C. Sidr, MODIS, 14th Nov 2007
Questions

• What is the contribution to cloud cover and visible reflectance from clouds of different sizes?

• What are the implications for remote sensing?
Cloud size distribution and implications

Define $n(L)$ as the number density (per sampling length) of clouds with diameters from $L$ to $L+dL$

$$\int_{L_1}^{L_2} n(L) dL$$

is the number density of all clouds with diameters from $L_1$ to $L_2$

$$\int_{L_1}^{L_2} L n(L) dL$$

is the cloud fractional coverage from clouds with diameters from $L_1$ to $L_2$

$$n(L) = \alpha L^{-\beta}$$

if $\beta > 2$ then smallest clouds determine cover
if $\beta < 2$ then largest clouds determine cover
if $\beta = 2$ then all clouds determine cover
Cumulative contribution to cloud cover from largest clouds ($\beta < 2$)
Cumulative contribution to cloud cover from largest clouds ($\beta > 2$)
This work

- SATELLITE: 100 days of MODIS Level 2 swath cloud product
  - (Daily, global coverage, 288 granules per day with 2000x1330 km domain at ~1 km resolution)

- AIRCRAFT: 3 field programs
  - (marine Sc, Sc-Cu transition, cirrus clouds), total of 40 flights, typically 10x60km level legs per flight

- SATELLITE#2: CALIOP lidar, Level 2, 330m
  - non-polar oceans, low clouds only ($z_{top}<3$ km)
Observations over 4 orders of magnitude

\[ n(L) \sim L^\beta \exp\left[-\left(\frac{L}{L_*}\right)^2\right] \]

with \( L_* = 2100 \text{ km} \)

Wood and Field (J. Climate, 2011)
Contribution to cloud number, length (fraction) and reflectance from clouds larger than L

Approximate contribution to cloud cover
L < 1 km (5%)
1 < L < 10 km (10%)
10 < L < 100 km (20%)
100 < L < 1000 km (40%)
L > 1000 km (20%)
Visible reflectance as a function of cloud size

big clouds are brighter

MODIS only
Global cloud size map

$L_{50}$

Cloud diameter [km] for which larger clouds contribute 50% to cloud cover

km

10 20 50 80 100 150 200 300 400 500 600 800 1000 1200
Seasonal cycle of $L_{50}$
Small variations in power law exponent explain large variations in $L_{50}$

Stratocumulus, Cirrus shields.
Bounded cascade model

uniform field

transfer some fraction
Cloud size distribution exponent controlled by field scaling exponent $H$

$\beta$ vs $H$

1. Wood and Taylor (2001)
2. Nastrom and Gage (1985)
4. Davis et al. (1999)

Wood and Field (2011, J. Climate)
Water vapor scaling exponent $H$

Small $H$ in tropics
$\Rightarrow$ larger $\beta$ $\Rightarrow$
smaller clouds dominate (trade Cu)

Large $H$ in subtropics and midlatitudes
$\Rightarrow$ smaller $\beta$ $\Rightarrow$
larger clouds dominate (St, Sc)

AIRS data, 925 hPa, Pressel and Collins (2012, J. Climate)
.....also Kahn et al. (2011)
Consequences?

Approximately 50% of low clouds globally are optically thin or broken at the CALIOP footprint scale (90 m)

Leahy et al. (2012, *J. Geophys. Res.*)
Conclusions

• Clouds with a remarkable variety of spatial scales contribute significantly to cloud cover, since scaling exponent $\beta=1.7$ ($\sim 2$) over four orders of magnitude from 100 m to $>1000$ km

• Globally, 50% of cloud cover, and 60-70% of cloud visible reflectance is from clouds larger than $\sim 200$ km, but small clouds are important over trades

• Scaling exponent related to underlying moisture Hurst exponent

• Approximately 50% of marine low clouds are optically thin or broken at the 90 m scale
Is the cloud size distribution sensitive to sensor resolution?

Koren et al. (2008, ACP) How small is a small cloud?
Effect of pixel resolution on scaling exponent $\beta$

- Coarsening resolution has only small effect on cloud size scaling exponent provided domain size is $> 1000$ times the pixel scale
- Studies showing significant effect of resolution (e.g. Koren et al. 2008) have too small a domain
Consequences: finding clear sky

![Graph showing the relationship between mean cloud fraction and probability of clear footprint, with different footprint sizes represented by various symbols and a red dashed line indicating MODIS Aerosol.](image-url)
Satellite inferred aerosol indirect effects
(Quaas et al. method)

1° ≈ 100 km

aerosol retrieval ‘pixel’

cloud
Large clouds dominate cloud cover and reflectance....

.....but only just

GOES East, 18th March 2008
On the physicality of scale breaks

\[ \beta = 1.88 \]

\[ \beta = 3.18 \]
Studics of high resolution (10-50 m) satellite data

Table 1. Past Studies on Cumulus Macrophysical Properties Using 2-D High-Resolution Images

<table>
<thead>
<tr>
<th>Reference</th>
<th>Instrument</th>
<th>Domain, km²</th>
<th>Spatial resolution, m</th>
<th>Location</th>
<th>Number of Scenes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plank [1969]</td>
<td>camera on aircraft</td>
<td>16 × 32</td>
<td>NR&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Florida Coast</td>
<td>12</td>
</tr>
<tr>
<td>Wielicki and Welch [1986]</td>
<td>MMS&lt;sup&gt;e&lt;/sup&gt;</td>
<td>170 × 185</td>
<td>57</td>
<td>United States, tropical western Atlantic, western Arkansas, Gulf of Mexico</td>
<td>4</td>
</tr>
<tr>
<td>Cahalan and Joseph [1989]</td>
<td>MMS</td>
<td>170 × 185</td>
<td>57</td>
<td>Pacific, South America, Florida coast</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>TM&lt;sup&gt;f&lt;/sup&gt;</td>
<td>65 × 65</td>
<td>28.5</td>
<td>Pacific, South America, Florida coast, tropical Atlantic, Gulf of Mexico, United States, France</td>
<td>19</td>
</tr>
<tr>
<td>Sengupta et al. [1990]</td>
<td>MMS</td>
<td>170 × 185</td>
<td>57</td>
<td>tropical Atlantic, Gulf of Mexico, United States, France, tropical western and central Pacific, Maldives, Somali coast, Coral Sea, Caribbean Sea</td>
<td>10</td>
</tr>
<tr>
<td>Benner and Curry [1998]</td>
<td>MAS&lt;sup&gt;g&lt;/sup&gt;</td>
<td>37 × 37</td>
<td>50</td>
<td>tropical western and central Pacific, Maldives, Somali coast, Coral Sea, Caribbean Sea</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>space shuttle</td>
<td>110 × 145</td>
<td>30</td>
<td>tropical western and central Pacific, Maldives, Somali coast, Coral Sea, Caribbean Sea</td>
<td>5</td>
</tr>
<tr>
<td>Gotoh and Fujii [1998]</td>
<td>TM</td>
<td>65 × 65</td>
<td>28.5</td>
<td>Japan</td>
<td>1</td>
</tr>
<tr>
<td>This study</td>
<td>ASTER</td>
<td>60 × 60</td>
<td>15</td>
<td>tropical western Atlantic</td>
<td>152</td>
</tr>
</tbody>
</table>

The total cloud fraction of trade wind cumulus was 0.086, half of which was contributed from clouds smaller than 2 km in equivalent area diameter.

Zhao and Di Girolamo (J. Geophys. Res. 2007)
2000 km

1-D segments

clear

clouds
Cloud size distributions in fair weather cumulus

Fig. 12. Number density and sky cover histograms, and corresponding equation plots, for the typical population samples of Blackmore and Serebreny (1962). It should be noted that the $N$ and $S$ values plotted here are four times larger than those of the Florida histograms, because of the different normalized class widths employed.

Cloud size distributions in 156 trade cumulus scenes (Zhao and Di Girolamo 2007)

Size distribution follows a power law of the form

\[ n(L) = \alpha L^{-\beta} \]

where \( n(L)\,dL \) is the number of clouds with diameters from \( L \) to \( L + dL \)

\[ \beta = 1.88 \]

Scale ‘break’

\[ \beta = 3.18 \]
Tropical cloud clusters

Visible radiance scaling

\[ \beta = 2 \]

\[ \beta = \frac{3}{2} \]

\[ \beta = 1 \]

Extending cloud size distribution down to $L_{\text{min}} = 10 \text{ m}$
Cloud area size distribution (MODIS)

similar scaling to that for cloud chord length

\[ \beta = 1.87 \pm 0.03 \]