Bluing of Aerosols near Clouds: Results from a Simple Model and MODIS Observations

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What happens to aerosol in the vicinity of clouds?

All observations show that aerosols seem to grow near clouds or (to be safer) “most satellite observations show a positive correlation between retrieved AOT and cloud cover”, e.g.:

- from Ignatov et al., 2005
- from Loeb and Manalo-Smith, 2005
- from Zhang et al., 2005
What happens to aerosol in the vicinity of clouds?

All observations show that aerosols seem to grow near clouds.

However, it is not clear yet how much grows comes from

- “real” microphysics, e.g.
  - increased hydroscopic aerosol particles,
  - new particle production or
  - other in-cloud processes.
- (“artificial”) the 3D cloud effects in the retrievals:
  - cloud contamination,
  - extra illumination from clouds
How do clouds affect aerosol retrieval?

Both
• cloud contamination (sub-pixel clouds)
• cloud adjacency effect (a clear pixel with in the vicinity of clouds) may significantly overestimate AOT.

But they have different effects on the retrieved AOT: while cloud contamination increases “coarse” mode, cloud adjacency effect increases “fine” mode.
The Ångström exponent and the cloud fraction vs. AOT

- Atlantic ocean, June-Aug. 2002; each point is aver. on 50 daily values with similar AOT in 1° res.;
- for AOT < 0.3, as AOT increases CF and the Ångström exponent also increase;
- the increase is due to transition from pure marine aerosol to smoke (or pollution);
- the increase in AOT cannot be explained by cloud contamination but rather aerosol growth.

from Kaufman et al., IEEE 2005
More clouds go with larger AOT and larger (not smaller!) Ångström exponent

- one month of data: 25 $1^\circ \times 1^\circ$ in each $5^\circ \times 5^\circ$ region over ocean (off the cost of Africa) are subdivided into two groups with
  \[
  \tau_a < \langle \tau_a \rangle
  \]
  and
  \[
  \tau_a > \langle \tau_a \rangle
  \]
- meteorology has been checked as similar for two groups

from Loeb and Schuster (JGR, 2008)
The Ångström exponent increases with distance to the nearest cloud while the AOT increases from Koren et al., GRL, 2007
Airborne aerosol observations in the vicinity of clouds

From airborne extinction rather than scattering observations, 3D effects decrease AOT rather than increase it.

Courtesy of Jens Redemann
Aerosol-cloud radiative interaction (a case study)

Collocated MODIS and ASTER image of Cu cloud field in biomass-burning region in Brazil at 53° W on the equator, acquired on Jan 25, 2003

Wen et al., 2006
ASTER image and MODIS AOT

Thick clouds

Thin clouds

from Wen et al., JGR, 2007
Cloud effect at 90-m resolution

Thin clouds, $\langle \tau \rangle = 7$

Thick clouds, $\langle \tau \rangle = 14$

$AOT_{0.66} = 0.1$

Enhancement:

$\Delta \rho = \rho_{3D} - \rho_{1D}$

$\Delta \rho \sim 0.0046$

$\Delta \tau \sim 0.05 \approx 50\%$

$\Delta \rho \sim 0.014$

$\Delta \tau \sim 0.14 \approx 140\%$

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Alexander Marshak
Conceptual model to account for the cloud enhancement (at 0.47 μm)

from Wen et al., JGR 2008:
molecule (82%)  
+ aerosol (15%)

aerosol or molecule

surface (3%)
Assumption for a simple model

Molecular scattering is the main source for the enhancement in the vicinity of clouds

thus

we retrieve larger AOT and fine mode fraction
How to account for the 3D cloud effect on aerosols?

The *enhancement* is defined as the difference between the two radiances:

- one is reflected from a broken cloud field with the scattering Rayleigh layer above it
- and one is reflected from the same broken cloud field but with the Rayleigh layer having extinction but no scattering
Stochastic model of a broken cloud field

Clouds follow the Poisson distr. and are defined by
• average optical depth, $<\tau>$
• cloud fraction, $A_c$
• aspect ratio, $AR = \text{hor./vert.}$

AR = 2

AR = 1

$A_c = 0.3$
Stochastic model of a broken cloud field

Clouds follow the Poisson distr. and are defined by
• average optical depth, <\tau>
• cloud fraction, $A_c$
• aspect ratio, $AR = \text{hor./vert.}$
Cloud-induced enhancement at 0.47 μm

LUT:
The enhancement vs $\langle \tau \rangle$ for $AR = 1$. $A_c = 1$ corresponds to the pp approximation.
Cloud-induced enhancement: our simple model and 3D RT calculations

The enhancement vs $<\tau>$ for $A_c = 0.6$ and 3 cloud AR = 0.5, 1 and 2. Different dots are from Wen et al. (2007) MC calculations for the thin and thick clouds.
Ångström exponent vs $\langle \tau \rangle$ for $A_c = 0.5$ and AR = 2. Three cases: clean, polluted and very polluted.

The cloud adjacency effect increases the Ångström exponent from Marshak et al., JGR, 2008.
MODIS observations

(Várnai and Marshak, 2008, in preparation)

- Collection 5 MOD02, MOD06, MOD35 products
- 2 weeks in Sep. and March in 2000-2007 (2x2 weeks in 8 years)
- North-East Atlantic (45° -50° N, 5° -25° W), south-west from UK
- Viewing zenith angle < 10°

Pixels included in plots:
- Ocean surface with no glint or sea ice
- MOD35 says “confident clear”, all 250 m subpixels clear
- Highest cloud top pressure nearby > 700 hPa (near low clouds)
- Nearby pixels are considered cloudy if MOD35 says definitely cloud.
Example of the region: Sep 22, 2005
Average reflectance vs. dist. to clouds for 0.45, 0.65, 0.87, and 2.1 μm
Reflect. Diff from Values at 10 km vs Cloud Optical Depth

- COD
- 1-2
- 2-7
- 7-13
- 13-30

Reflect. diff. from values at 9 km (2.1 μm)
dist from clouds (km)

2.10 μm
Reflect. Diff from Values at 10 km vs Cloud Optical Depth

COD

0.009
0.006
0.003
0

0 2 4 6 8 10

1-2
2-7
7-13
13-30

Refl. diff. from values at 9 km (0.65 μm)
dist from clouds (km)

0.65 μm
Reflect. Diff from Values at 10 km vs Cloud Optical Depth

Reflect. diff. from values at 9 km (0.47 μm) vs dist from clouds (km)

COD

0.47 μm

1-2
2-7
7-13
13-30

dist from clouds (km)
Asymmetry with respect to the sun

Average 0.47 µm reflectance

Distance to nearest cloud (km)

illuminated side of the nearest cloud

shadowed side of the nearest cloud

0.47 µm
Latency effect for 2.1 \( \mu m \)

![Graph showing latency effect for 2.1 \( \mu m \)](image)
Point spread function effect for 0.53 μm
(preliminary results)

with Jack Xiong
Cloud contamination in 0.47 µm
(preliminary results)

- latency effect removed (red curve);
- assumed that at 2.1 µm the increase is due to undetected subpixel clouds (blue curve);
- assumed that 2.1 µm has the same point spread function as 0.53 µm (green curve)

with Jack Xiong
Research in progress

with Norman Loeb and Lorraine Remer

- select a few MODIS subscenes with
  - broken low Cu;
  - retrieved AOT;
  - over ocean with no glint, etc;
- analyze AOT, CF, average COT over many 10 x 10 km areas;
- use a simple stochastic model and RT to estimate upward flux;
- use CERES fluxes to convert BB to spectral fluxes;
- use ADM to determine spectral fluxes from MODIS radiances;
- estimate cloud enhancement and compare the results;
- use a simple linearization model.
Conclusions

• No clear understanding from satellites alone of what happens to aerosols at the vicinity of clouds.

• Accounting for the 3D cloud-induced enhancement helps.

• For certain conditions, 3D cloud enhancement $\Delta \rho = \rho_{3D} - \rho_{1D}$ only weakly depends on AOT. Molecular scatt. is the key source for the enhancement.

• The enhancement increases the “apparent” fraction of fine aerosol mode (“bluing of the aerosols”).

• MODIS observations confirm that the cloud induced enhancement increases with cloud optical depth.

• Retrieved AOT can be corrected for the 3D radiative effects.
More clouds go with larger AOT and larger (not smaller!) Ångström exponent

- 25 1°x1° in each 5°x5° region over ocean (over the entire globe) are subdivided into two groups with
  \[ \tau_a < \langle \tau_a \rangle \]
  and
  \[ \tau_a > \langle \tau_a \rangle \]

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from Loeb and Schuster (JGR, 2008)