Ice clouds: optical phenomena, optical properties and remote sensing

Bastiaan van Diedenhoven, GISS lunch seminar 2014

Clouds associated with Superstorm Sandy's outflow
Huntsville, AL, Oct. 30, 2012
(Earth Science Picture of the Day, Nov. 12, 2012)
Three subjects

- **Optical phenomena**
  - van Diedenhoven: *The prevalence of the 22° halo in cirrus clouds*, JQSRT, in press

- **Optical properties**

- **Remote sensing**
Clouds are made of.....

A: Cotton balls  B: Ice cream  C: Water
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22-degree halo

Sassen et al., 2003:
- 10 year statistics in Salt Lake City
- 37% of ice clouds showed 22° halo
- 6% bright and prolonged

ER-2 aircraft during PODEX campaign, NASA Dryden
22-degrees halo produced by randomly oriented smooth hexagonal ice crystals
46 degree halo

Sassen et al., 2003:
- Occurred in 0.4% of 10 year statistics in Salt Lake City
Hexagonal columns and plates are fundamental ice crystal shapes.
Freezing drops

Colin Gurganus, Alexander B. Kostinski, and Raymond A. Shaw

“Fast Imaging of Freezing Drops: No Preference for Nucleation at the Contact Line”


DOI: 10.1021/jz2004528

Cell phone pictures taken on 3 Jan. 2014

Alexey Kljatov
Cloud Particle Imager (CPI)
Cloud Particle Imager (CPI)

Sparticus campaign
Surface roughness

Scanning electron microscope images from Steven Neshyba, University of Puget Sound
No halos produced by rough ice crystals
Ray tracing and simulating roughness/distortion (e.g., Macke et al 1996)

Geometric optics

Roughness/distortion parameterization

\( \alpha = \text{maximum tilt angle} \)

\( \gamma = \text{angle of incidence} \)

\( \gamma' = \text{new angle of incidence} \)
Smooth versus rough hexagonal ice crystals

Asymmetry parameter

\[ g_{tot} = \int_{0}^{\pi} P_{tot} \cos \theta \sin \theta \, d\theta \]

- \( g = 1 \) Forward scattering
- \( g = 0 \) isotropic scattering
- \( g = -1 \) backward scattering

For cloud ice: \( g = 0.6 \text{—} 0.95 \)
Ice crystal asymmetry parameter dependence on aspect ratio and distortion.
Simulating optical properties

Breaking down complex ice into simple radiative proxies

Scattering properties mainly depend on
- Aspect ratios of hexagonal components
- Crystal distortion levels


cf. Fu et al. 1996; Fu 2007
Phase function of complex crystal is similar to phase function of its components (Fu 2007; Um & McFarquhar 2007; 2009)
In summary: Simple radiative proxies for complex ice

Complex aggregates of plate-like or column-like crystals with varying aspect ratio and distortion

Single hexagonal columns and plates with matching aspect ratio and distortion
• **Optical phenomena**
  - van Diedenhoven: *The prevalence of the 22° halo in cirrus clouds*, JQSRT, in press

• **Optical properties**

• **Remote sensing**
Ice crystal microphysical properties important for radiation

- Optical thickness
- Total projected area
- Single scattering albedo
  \[ \frac{3}{4} \times \text{Volume/Area} \]
  - "Effective radius"
- Phase function/Asymmetry parameter
  - Shape:
    - Aspect ratio
    - Distortion

cf. Fu et al. 1996; Fu 2007
2-step 2-D fitting of Ice crystal asymmetry parameter
Single scattering albedo

\[ d_e = \frac{V}{A_p}. \]

\[ \chi_{abs} = \frac{m_i V}{\lambda A_p} = \frac{m_i}{\lambda} \, d_e, \]
2-step 2-D fitting of single scattering albedo

![Graph showing 2-step 2-D fitting of single scattering albedo](image)
Projected area $A_p$

Volume $V$

Wavelength $\lambda$

Imaginary refractive index $m_i$

Aspect ratio $\alpha$

Projected area $A_p = \frac{m_i V}{\lambda}$

$\chi_{abs} = m_i V / \lambda A_p$

$\omega_{\alpha} = 1 - a_0 (1 - e^{-a_1 \chi_{abs}})$

$a_0 = 0.457593$ and $a_1 = 20.9738$

$\Delta \omega_{\alpha} = \frac{l_0}{\sqrt{2\pi} l_2 \chi_{abs}} \exp \left[ \frac{(\ln \chi_{abs} - l_1)^2}{2 l_2^2} \right]$

$l_i = \sum_{j=0}^{3} c_{i,j} \log^i \alpha$

$(c_{i,j}$ in Table 2)$

$\sigma_e = Q_e A_p$

$Q_e = 2$

$\omega = \omega_{\alpha} + \Delta \omega_{\alpha}$

$L = \frac{2 \sqrt{A_p / \pi}}{\lambda}$

$g_{\text{diff}} = 1$ when $\chi_{\text{sat}} \geq 100$

$g_{\text{diff}} = b_0 - b_1 \ln \chi_{\text{sat}} + b_2$

when $\chi_{\text{sat}} < 100$

$b_0 = -0.822315$, $b_1 = -1.201225$ and $b_2 = 0.996553$

$C_m = \frac{(m_{\nu,2} - \epsilon)}{(m_{\nu,2} + \epsilon)}$

$\epsilon = c_0 + c_1 \log \alpha$

$m_{\nu} = 1.3038$

$c_0 = 0.960251$ and $c_1 = 0.429181$ for $\alpha \leq 1$

$c_0 = 0.941791$ and $c_1 = 0.216010$ for $\alpha > 1$

$C_{w,1} = \sum_{i=0}^{5} s_i (1 - \alpha)^i$

$s_0 = 1.00014$, $s_1 = 0.666094$, $s_2 = -0.535922$, $s_3 = -11.7494$, $s_4 = 72.3690$, $s_5 = -109.940$

$C_{w,2} = u \log(\alpha) \cdot (\omega - 1) + 1$

$u = -0.213038$, for $\alpha \leq 1$

$u = 0.204016$ for $\alpha > 1$. 

Table 1:

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<tr>
<th>Plate</th>
<th>$a_{0,j}$</th>
<th>$a_{1,j}$</th>
<th>$b_{0,j}$</th>
<th>$b_{1,j}$</th>
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Table 2:

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</tr>
</tbody>
</table>
Simple code

- Single scattering albedo, asymmetry parameter for any
  - Volume
  - Projected area
  - Aspect ratio
  - Distortion parameter
  - Wavelength

- Being implemented in the GISS cloud resolving model (CRM)
- In GISS GCM!?
Solar Flux variations from varying size and shape

- Optical thickness = 4
- SZA = 60°

van Diedenhoven et al., “A flexible parameterization for shortwave optical properties of ice crystals”, JAS, in press
Solar Flux variations from varying size and shape

- Optical thickness $= 2$
- SZA $= 60^\circ$

van Diedenhoven et al., “A flexible parameterization for shortwave optical properties of ice crystals”, JAS, in press
• Optical phenomena
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• Optical properties
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• Remote sensing
Current knowledge on fundamental global ice cloud optical properties

Maddux et al., JAOT 2010
A little help from polarization

- Orientation of EM wave
- A single scattering event on ice crystals polarizes light
- Multiple scattering wipes out any polarization
Information from Polarization

Polarization contains info about:
- Aspect ratio (AR)
- Distortion $\delta$ (Macke et al. 1996)

Multi-directional polarized reflectance measurements conserve Single scattering features

Retrieve aspect ratio and distortion from polarization to estimate asymmetry parameter

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van Diedenhoven et al., Atmos. Meas. Tech., 2012
Ice crystal asymmetry parameter dependence on aspect ratio and distortion
Tests

Simulated data:
• Complex ice shapes (Yang et al.)
• 20 different size distributions
• Retrieval within 5% (0.04), Mean bias: 0.004

Research scanning Polarimeter:
RSP data collected during CRYSTAL-FACE

Remote sensing data and retrievals

29 July 2002

Typical cloud particle images
Towards global retrievals: POLDER/PARASOL and MODIS/Aqua

- POLDER
  - Multi-angle polarization measurements
  - up to 16 angles per pixel
  - No ice-absorbing wavelength bands

- MODIS
  - Multi-wavelength imager
  - ice-absorbing wavelength bands
  - Infrared bands to retrieve cloud height
Preliminary global results

- Only COT>5
- 3 days in January, 3 days in June
  - Tropics: $g \sim 0.76-0.8$
  - Mid-latitudes: $g \sim 0.76-0.8$
  - 10-30°: $g \sim 0.78-0.83$
- $g \sim 0.02$ greater over land
- Low aspect ratios north of 15°
- Mostly plate-like
- Highly distorted $\delta \sim 0.5$
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  • van Diedenhoven: *The prevalence of the 22° halo in cirrus clouds*, JQSRT, in press

• Optical properties
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• Remote sensing
Why are 22 degree halos so common although ice crystals seem mostly non-pristine?
Halo ratios

$h_{22} = \frac{P(22^\circ)}{P(18.5^\circ)}$
(Shcherbakov, JQSRT, 2013)
How persistent are the halo features in a mix of distorted and pristine crystals?
Just ~10% contribution of pristine crystals ($\delta < 0.15$) needed for $22^\circ$ halo, but >40% for $46^\circ$ halo.
Summary

- Simple hexagonal plates and columns serve as radiative proxies for complex ice
- Parameterization of optical properties of ice crystals for any combination of:
  - Volume
  - Projected area
  - Aspect ratio
  - Distortion
  - Wavelength
- Remote sensing of ice aspect ratio, distortion and asymmetry parameter using multi-directional polarized reflectances
- 22-degree halo is very persistent in a mix of distorted and pristine crystals
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Resources: www.atoptics.co.uk, Snowcrystals.com
Less frequently seen halos

An all sky HaloSim simulation for a 26° high sun and very well aligned cloud crystals.

Some of these halos might be expected to be visible on average more than once a year. Others are once in a lifetime sights.

Click the halo key to reach descriptions.

Fig. 5. Comparison of bulk ice cloud scattering phase functions for different effective diameters at the wavelengths of (a) 0.65 µm (left column), (b) 2.13 µm (middle column), and (c) 12.0 µm (right column). Indicated in the figure are the bulk extinction efficiency, the bulk single-scattering albedo, and the asymmetry factor of the bulk-scattering phase function.

![Figure 9](image)

**Fig. 9.** The mean and standard deviations for the relative errors in the retrieved effective diameter within different ranges of the optical thickness.

![Figure 14](image)

**Fig. 14.** Ten-year mean annual SW/LW total cloud radiative effect (unit: W m⁻²) and the differences between the II-TM+IGOM and the CGOM cases (the CGOM case minus the II-TM+IGOM case).