Advanced radiative transfer capabilities in support of far-infrared based remote sensing of ice clouds, aerosols, and snow

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Cirrus (Ci)  Cirrostratus (Cs)  Cirrocumulus (Cu)

Altocumulus (Ac)  Altostratus (As)

Stratocumulus (Sc)  Stratus (St)  Cumulus (Cu, Fairweather)

Global Ice Cloud Coverage

One year (2012) of level-2 MODIS Collection 6 cloud products

Importance of far-IR radiation
The current RRTM-G neglects the scattering effect in LW bands
TOA Upward Flux Biases

Areas containing large biases
- Intertropical Convergence Zone (ITCZ)
- Pacific warm pool
- Tibetan Plateau

Large biases (up to 12 W/m²)

Positive biases mean that the TOA upward fluxes are overestimated when LW scattering is ignored

Surface Downward Flux Biases

Areas containing large biases
- Dry and high regions
- Tibetan Plateau
- Antarctic
- Greenland

Large biases (~-3.6 W/m²)

Negative biases mean that the surface downward fluxes are underestimated when LW scattering is ignored

Flux Biases

MLS(2xCO2) – MLS(1xCO2)

(Clough and Iacono, 1995)
Spectral Analyses

Contributing biases > 40%

Main LW emission bands
(1000 ~ 15.9 μm)
Spectral Analyses

Atmospheric Window (14.3 ~ 7.2 μm)
Spectral Analyses

Less LW emitted fluxes

Gas absorption

(7.3 ~ 3.1 μm)

**Left:** The far infrared brightness spectra for a nadir view at air craft level (20km) under clear sky conditions as well as for cirrus clouds having different visible optical thicknesses. The clouds are located at 10 km altitude, have a 1-km geometrical thickness, and an effective size of $D_e=50 \, \mu m$. **Right:** The far-IR brightness spectra for 4 effective particle sizes for optically thick ice clouds, where the visible optical thickness $\tau = 10$. 
Nonsphericity Effect of Ice Crystals on Broad-band Solar Albedo of Cirrus Clouds
**Scattering Geometry**

Incident beam

Scattering object

Scattering plane

Scattering angle

Amplitude scattering matrix

\[
\begin{pmatrix}
E^s_s \\
E^s_s
\end{pmatrix}
= \frac{e^{ikr}}{ikr}
\begin{pmatrix}
S_2 & S_3 \\
S_4 & S_1
\end{pmatrix}
\begin{pmatrix}
E^i \\
E^i
\end{pmatrix}
\]
Stokes vector-Phase matrix/Mueller matrix formulation

The electric field can be decomposed into components:

\[ E = E_{\parallel} l + E \ r \]

\[ I = E_{\parallel} E_{\parallel}^* + E \ E^* \]
\[ Q = E_{\parallel} E_{\parallel}^* E \ E^* \]
\[ U = E_{\parallel} E^* + E^* E_{\parallel} \]
\[ V = i(E_{\parallel} E^* - E^* E_{\parallel}) \]

The four component Stokes vector (Stokes, 1852) can be defined. They are all real numbers and satisfy the relation

\[ I^2 = Q^2 + U^2 + V^2 \]

The phase matrix, \( P \), (for a single-scattering event) or Mueller matrix, \( M \), (for a multiple scattering event, or radiative transfer process) relates the incident and scattered Stokes vectors.

\[
\begin{pmatrix}
I^s \\
Q^s \\
U^s \\
V^s
\end{pmatrix} = \begin{pmatrix}
M_{11} & M_{12} & M_{13} & M_{14} \\
M_{21} & M_{22} & M_{23} & M_{24} \\
M_{31} & M_{32} & M_{33} & M_{34} \\
M_{41} & M_{42} & M_{43} & M_{44}
\end{pmatrix} \begin{pmatrix}
I^i \\
Q^i \\
U^i \\
V^i
\end{pmatrix}
\]
Planktons as seen through "regular" vision

As seen when placed between two crossed linear polarizing filters

(a) Left-circular polarizer in front of camera;
(b) Right-circular polarizer in front of camera.

A photograph of the beetle without a polarizer in front of camera is similar to (a)


Squids developed polarization vision to help detect plankton and other organisms whose transparent bodies might make them otherwise invisible.

http://www.polarization.com/octopus/octopus.html#Ref%204
Finite-difference Time Domain (FDTD) Method  
(Yee 1966; Taflove and Hagness 2000; Yang and Liou, 1996; …)

Second order central difference scheme applied to the time-dependent Maxwell curl equations:

\[ \nabla \times \mathbf{H}(\mathbf{r}, t) = \frac{\varepsilon}{c} \frac{\partial \mathbf{E}(\mathbf{r}, t)}{\partial t} + \frac{4\pi}{c} \sigma \mathbf{E}(\mathbf{r}, t), \]

\[ \nabla \times \mathbf{E}(\mathbf{r}, t) = -\frac{1}{c} \frac{\partial \mathbf{H}(\mathbf{r}, t)}{\partial t}, \]

Locations of various field components on a cubic cell, (Yee, 1966).

For example, the finite-difference analog of Maxwell’s curl equation for the magnetic field:

\[ \mathbf{H}^{n+\frac{1}{2}}(\mathbf{r}) = \mathbf{H}^{n-\frac{1}{2}}(\mathbf{r}) - c\Delta t \nabla \times \mathbf{E}^n(\mathbf{r}). \]
Finite-difference Time Domain (FDTD) Method


As of 10/10/2018: 8,131 citations
Discrete Dipole Approximation (DDA) Method
(Purcell and Pennypacker 1996; Draine and Flaux 1994; Yurkin and Hoekstra 2011;...)

\[ \mathbf{P}(\mathbf{r}) = \mathbf{E}(\mathbf{r}) \]

The Clausius-Mossotti (or Lorentz-Lorenz) relation (Lorentz 1880, Lorenz 1880):

\[ \mathbf{P}_i = \sum_{i \neq j} \mathbf{A}_{ij} \cdot \mathbf{P}_j \]

\[ \sigma_{\text{ext}} = \frac{4\pi k}{|E_0|^2} \sum_{j=1}^{N} \text{Im}(\mathbf{E}_{0,j}^* \cdot \mathbf{P}_j) \]

where

\[ d = \text{dipole length} \]

\[ d = d^3 \frac{3}{4} \frac{m^2}{m^2 + 2} \]

Edward Mills Purcell
Nobel Laureate 1952
Conventional Geometric Optics Method


- Constant extinction efficiency, 2
- Singularity
- Artificial separation of contributions by diffraction and geometric rays

Wendling et al. 1979; Cai and Liou, 1982; Takano and Liou, 1989; Mack 1993; Macke et al. 1996; and many others
Applicability of Light-Scattering Computational Methods

- Rayleigh Scattering (analytical solution)
- FDTD/DDA
- Sphere (Lorenz-Mie)
- Conventional Geometric Optics Method

Gap (at least $x > 200$)
Breakthrough in Light-scattering computation
Invariant Imbedding T-matrix Method (II-TM)

Maxwell’s equations

\[ \vec{E}(\vec{r}) = \vec{E}_{\text{inc}}(\vec{r}) + k^2 \left( m^2 - 1 \right) \vec{G}(\vec{r} - \vec{r}') \times \vec{E}(\vec{r}') d^3 \vec{r}' \]

Volume Integral Equation

\[ T_{mnmn}(r + dr) = Q_{11}^m(r + dr) + \left[ I + Q_{12}^m(r + dr) \right] \left[ I - T_{mnmn}(r) Q_{22}^m(r + dr) \right] \left[ I + Q_{12}^m(r + dr) \right]^{-1} T_{mnmn}(r) \]

Johnson (1988); Bi and Yang (2014)
In the ADDA simulation, 1056 orientations with 128 scattering planes are set to achieve the randomness. Bi and Yang (2014).
II-TM is different from the conventional T-matrix method (Extended Boundary Condition Method, EBCM)

EBCM:


\[
\begin{align*}
\vec{E}^{\text{inc}}(\vec{r}') &= -\int_S ds \{ i \omega \mu_0 [\hat{n} \times \vec{H}(\vec{r})] \cdot \vec{G}(\vec{r}, \vec{r}') + [\hat{n} \times \vec{E}(\vec{r})] \cdot [\nabla \times \vec{G}(\vec{r}, \vec{r}')] \}, \quad \vec{r}' \in V_1 \\
\vec{E}^{\text{sca}}(\vec{r}') &= \int_S ds \{ i \omega \mu_0 [\hat{n} \times \vec{H}(\vec{r})] \cdot \vec{G}(\vec{r}, \vec{r}') + [\hat{n} \times \vec{E}(\vec{r})] \cdot [\nabla \times \vec{G}(\vec{r}, \vec{r}')] \}, \quad \vec{r}' \in V_0 \\
T &= R g Q [Q]^{-1}
\end{align*}
\]

Surface Integral Equations

Physical-Geometric Optics Method (PGOM)

Yang and Liou (1996)
PGOMS – Surface-integral equation based

Yang and Liou (1997)
PGOMV – Volume-integral equation based

New improvements by our research group using computer graphics techniques
Comparison of the phase matrix elements computed by PGOMS and IITM. The particle is a hexagonal column with aspect ratio 1. The refractive index is $1.2762 + i0.4133$, the ice refractive index at 12 $\mu$m wavelength. The inset plots show the $P_{11}$ element for 170° - 180° scattering angles. The size parameter is $kL=300$. 
Extinction efficiency ($Q_e$), single-scattering (SSA), and asymmetry factor ($g$) computed by II-TM and PGOM. The particle is a hexagonal column with aspect ratio 1. The refractive index is $1.2762 + i0.4133$ that is the ice refractive index at 12 µm wavelength.
Breakthrough: A combination of II-TM and PGOM can accurately cover the entire size parameter region.
MODIS Ice Particle Models
(Collections 4, 5, 6)

References: King et al. 2004, Baum et al. 2005, Platnick et al. 2017
CERES ice particle models *(Editions 2-4, and a two-habit model for future Edition 5)*

References: Minnis et al. 1993, 2011; Loeb et al. 2017
Comparison of the phase functions at wavelength 0.86 µm based on (a) MODIS Collection 4, 5, and 6; (b) CERES Edition 2, 4, and the Two-habit model; and (c) MODIS Collection 6 and the Two-habit model. Diagrams (d), (e), and (f) in bottom rows are counterpart of (a), (b), (c) at wavelength 2.13 µm. Effective radius is fixed at 30 µm.
Comparison of the asymmetry parameter at wavelength 0.86 µm based on (a) MODIS Collection 4, 5, and 6; (b) CERES Edition 2, 4, and the Two-habit model; and (c) MODIS Collection 6 and the Two-habit model. Diagrams (d), (e), and (f) in bottom rows are counterpart of (a), (b), (c) at wavelength 2.13 µm. Effective radius is fixed at 30 µm.
The similarity relation at a non-absorptive wavelength (van de Hulst 1971, 1974)

\[(1-g) \tau = (1-g') \tau'\]

Thus

\[g_{C6} \equiv g_{THM} \quad \text{leads to} \quad \tau_{C6} \equiv \tau_{THM}\]

\[g_{C5} > g_{C6} \quad \text{leads to} \quad \tau_{C5} > \tau_{C6}\]
Comparison of retrieved optical thickness values from the shortwave technique (the Nakajima-King bi-spectral method)

(a) Ice sphere and Two-habit model (CERES Edition 5 model), (b) CERES Edition 4 model and Two-habit model, (c) MODIS Collection 6 model and Two-habit model, and (d) CERES Edition2 model and Two-habit model.
Spectral consistency

- Nakajima-King bispectral method based on two solar bands
- Split window technique based on thermal infrared bands

Retrievals based on the two methods should be consistent!
Comparison of retrieved optical thickness values from a shortwave method (the Nakajima-King bi-spectral method) and a longwave method (the split-window technique). (a) Ice sphere, (b) CERES Edition 4 model, (c) MODIS Collection 6 model, and (d) Two-habit model (Potential CERES Edition 5 model).
Cloud Optical Depth Difference (Wm$^{-2}$)

- Overall optical depth difference is -2.3 (-28% of Global Mean) and RMS difference is 2.8 (32% of GM).
- Overall effective radius difference is -3.9 $\mu$m (16% of GM) and RMS difference is 5.2 $\mu$m (16% of GM).


**Cloud Property Differences at Aqua Overpass Time**

*(THM minus Smooth)*

**SW TOA Flux Difference at Aqua Overpass Time**

\((\text{THM(Retrieval)}/\text{THM(Downstream)} \text{ minus Smooth(Retrieval)}/\text{Smooth(Downstream)})\)

- Overall regional RMS difference is \(~1\%\). However, in some locations regional differences reach \(3\%\).
- Differences tend to be positive in tropics and negative in midlatitudes.
Findings by Loeb et al. (2018): radiative fluxes derived using a consistent ice particle model assumption throughout provide a more robust reference for climate model evaluation compared to existing ice cloud property retrievals.

In other words, the same ice model must be consistently used in forward remote sensing implementation (look-up tables) and downstream radiative forcing assessment.
Ice Water Path (IWP),
Optical Thickness (tau)
Effective Particle size ($D_{\text{eff}}$)

$IWP = \text{constant} \cdot \tau \cdot D_{\text{eff}}$
Global (blue), tropical (30° N–30° S; red) and extratropical (>30° N,S; yellow) spatial mean values of cloud ice-water path (kg m⁻²) for 23 GCM simulations (adapted from Waliser et al., 2009). Note that the blue (yellow) bars of GISSEH and GISSER that extend above the top of the plot have values of 0.21 and 0.22 (0.34 and 0.36), respectively. Observations are shown in the CERESMODIS-Terra column.
A new database of the optical properties of ice crystals

The particle surfaces are assumed to be smooth, moderately rough, or severely rough (Yang et al. 2013)
TAMUice 2013 (ADDA+PGOM)

TAMUice2016 (II-TM+PGOM)
Spectral coverage and temperature ranges of available datasets. The thick lines show datasets obtained at unique temperatures. The present compilation was made using datasets of the imaginary part of the refractive index obtained by Warren and Brandt (2008), Gosse et al. (1995), Toon et al. (1994), Rajaram et al. (2001), Clapp et al. (1995), Curtis et al. (2005), and Mätzler (2006). Adapted from Iwabuchi and Yang (2011).
Refractive index of ice has temperature dependence (Iwabuchi and Yang, 2011)
“Dust: Small-scale processes with global consequences” (Okin et al., 2011)

The track of a large dust storm that was followed with the SeaWIFS Satellite in 1998

Source: R. B. Husar et al, JGR, 2001
Asian Dust

MODIS RGB (0.65µm, 0.55µm, 0.47µm) Image
Mineral aerosols sample (feldspar) SEM image (Volten et al., 2001). Dust aerosols are exclusively irregular particles with arbitrary geometries.
Comparison between the phase functions computed for spherical and nonspherical dust particles (Feng, Yang, Kattawar and co-authors, 2009). The symbols indicate laboratory measurements (Volten et al. 2001).
Simulated solar reflectance at the top of a dusty atmosphere. Spherical and nonspherical shapes are assumed for dust particles (Yang et al., 2007).

These results indicate that the equivalent sphere approximation leads to an underestimate of the albedo of a dusty atmosphere. This underestimate has an important implication to the study of the effect of airborne dust on the radiation budget within the atmosphere.
MODIS RGB image on March 2, 2003, showing a dust plume over West Africa. The area indicated by the small red box is used to retrieve dust AOD in the present sensitivity study (Feng, Yang, Kattawar and co-authors, 2009).
Upper panels: the retrieved dust AOD based on the nonspherical and sphere models.

Lower left panel: retrieved dust AOD based on the sphere model versus those based on the nonspherical model.

Lower right panel: the relative differences of the retrieved AOD (Feng, Yang, Kattawar and co-authors, 2009).
Dust Simulations

METHODOLOGY (Stegmann and Yang 2017)

- 46 Journal Articles
- 3 Reference Books

Optical Character Recognition Program

Digital Data
Computed refractive index of dust from the Northern Sahara, and West Asia (Gobi desert). The particle size is 15 µm.
VARIATION WITH GRAIN SIZE
(Stegmann and Yang 2017)

Dust Simulations

NORTH SAHARAN DUST

Real Part Refractive Index $n$

Wavelength $\lambda$ (µm)
Eight examples of the randomly distorted hexahedral particles

Yang, P., J. Ding, K. N. Liou, G. W. Kattawar, and M. I. Mishchenko (in preparation)
Single-scattering properties

Compared with lab measurement-olivine

The spheroid ensemble model has aspect ratios 1.7 for both prolate and oblate spheroids. The hexahedra ensemble model has aspect ratio 1.7.
Application to remote sensing

PARASOL data over red sea
Application to remote sensing

Compared the simulation with PARASOL data (865 nm band)
Application to remote sensing

Aerosol Optical Thickness

Effective radius

Asia dust model

Sahara dust model
Multiple scattering

Ice cloud particle with effective radius 30 μm, at 865 nm wavelength
Multiple scattering

Two-component method:
• Small-angle approximation (SAA)
• Adding-doubling (AD)

\[ u \frac{\partial I(t, u, f)}{\partial \theta} = I - \frac{v}{4} \int_{-1}^{1} du' \int_{0}^{2} d \theta' I(t, u', \theta') P(t, u', \theta', u, f) B(T(\theta')) \]

\[ P(\theta) = P^f(\theta) + P^d(\theta) \]

\[ I(t, m, f) = I^f(t_f, m_f) + I^d(t_d, m_d, f) \]

SAA

Numerical Solution

Gas absorption

Regression-based method

<table>
<thead>
<tr>
<th>Previous methods</th>
<th>Present method</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_n ) ( P_n ) ( u_n )</td>
<td>( T_n ) ( P_n ) ( u_n )</td>
</tr>
<tr>
<td>( T_3 ) ( P_3 ) ( u_3 )</td>
<td>( T_3 ) ( P_3 ) ( u_3 )</td>
</tr>
<tr>
<td>( T_2 ) ( P_2 ) ( u_2 )</td>
<td>( T_2 ) ( P_2 ) ( u_2 )</td>
</tr>
<tr>
<td>( T_1 ) ( P_1 ) ( u_1 )</td>
<td>( T_1 ) ( P_1 ) ( u_1 )</td>
</tr>
</tbody>
</table>

\( u \): gas concentration  
\( P \): pressure  
\( T \): temperature  
\( n \): number of layers
Gas absorption

\[ u: \text{gas concentration} \]
\[ P: \text{pressure} \]
\[ T: \text{temperature} \]
\[ n: \text{number of layers} \]
\[ t_{1-n} = b_3 G_{1-n}^3 + b_2 G_{1-n}^2 + b_1 G_{1-n} + b_0 \]

\[ b_0, b_1, b_2, b_3: \text{regression coefficients} \]
\[-1_n = b_3(G_{1_n})^3 + b_2(G_{1_n})^2 + b_1(G_{1_n})^1 + b_0\]

\[G_{1_n} = \begin{cases} 
\left(\sum_{i=1}^{n} u_i\right) / \left(\sum_{i=1}^{n} u_i^{ref}\right) \\
\left(\sum_{i=1}^{n} u_i P_i\right) / \left(\sum_{i=1}^{n} u_i^{ref} P_i^{ref}\right) \\
\left(\sum_{i=1}^{n} u_i T_i\right) / \left(\sum_{i=1}^{n} u_i^{ref} T_i^{ref}\right) \\
\left(\sum_{i=1}^{n} u_i \sqrt{P_i}\right) / \left(\sum_{i=1}^{n} u_i^{ref} \sqrt{P_i^{ref}}\right)
\end{cases}\]

\(u\): gas concentration

\(P\): pressure

\(T\): temperature

\(n\): number of layers

\(ref\): reference profile
Gas absorption

TOA brightness temperature

ten thousand times faster than Line-by-line;

two times faster than 32-point CKD.
Gas absorption

Ten thousand times faster than Line-by-line
• Snow Grain Habit Mixture (SGHM) model (CERES meeting in May 2018).

• BC internal inclusions in snow particles are considered.

• Particle size distribution (PSD) is parameterized in terms of the gamma distribution based on snow sampling dataset.
### Two-layer Snow Albedo Model

<table>
<thead>
<tr>
<th>Input</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Top layer:</strong></td>
<td>• $C_{BC}$ is constant over layers</td>
</tr>
<tr>
<td>$SWE_1$, $R_{e1}$</td>
<td>• $SWE_2$ corresponds to optical thickness = 960</td>
</tr>
<tr>
<td>$C_{BC}$</td>
<td></td>
</tr>
<tr>
<td><strong>Second layer:</strong></td>
<td></td>
</tr>
<tr>
<td>$R_{e2}$, $C_{BC}$</td>
<td></td>
</tr>
</tbody>
</table>

- **Snow albedo simulations:**
  - Adding-doubling RTM (Huang et al., 2015)
  - Plane parallel homogeneous snow layers
  - Optically semi-infinite depth of second snow layer
  - Snow grain habit mixture (SGHM) model

**Variables:**
- Top layer Snow Water Equivalent ($SWE_1$)
- Effective radii ($R_{e1}$, $R_{e2}$)
- BC internal mixing ($C_{BC}$)
Comparison

Two-layer snow albedo model reproduce the observed snow albedo in Antarctica (Grenfell et al., 1994).

Our model is comparable to SNICAR model in the visible to 1.5-$\mu$m region and outperforms in the 2.0–2.5-$\mu$m region.

SNICAR model: (Flanner et al., 2007)
- Single-layer
- Effective radius = 80 $\mu$m (taken from Yasunari et al., 2012)

This study:
- Two-layer
- Effective radius = 52 $\mu$m (top), 160-$\mu$m (second)
Summary

- **Single-scattering properties of ice clouds**: we would like to develop a new database in support of far-IR based remote sensing, which will take into account the **temperature dependence of the index of refraction**. The newly developed modeling capability, *a synergetic combination of the II-TM and PGOM*, will be used.

- **Optical properties of African and Asian dust aerosols**: we will use the newly developed dust refractive indices (*Stegmann and Yang, 2017*) in conjunction with the hexahedral ensemble model for light-scattering involving dust aerosol.

- **Develop accurate and efficient radiative transfer modeling capabilities** in support of practical far-IR remote sensing implementations:
  - The Small Angle Approximation
  - Regression method for gaseous absorption
  - Spectrally Consistent cloud, dust, and snow optical property models