Recent Practical Applications of Radiative Transfer in Satellite Remote Sensing

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Background

- Radiative transfer used for cloud remote sensing for decades
- Climate impact of clouds has been main focus
  - how do we represent them in climate models?
  - what are their radiative effects?
- Minimal use for weather and other practical applications
  - recent incorporation of CO2-slicing cloud heights in NWP models
- Why not more use? Need near real time!
  - cloud property retrievals computer intensive
  - calibrations of visible channels highly uncertain
  - no sales
What’s New?

• Computers & networks are now very fast
  - satellite data available nearly anywhere minutes after acquisition
  - complex programs run quickly near-real time possible
  - display of results easy and informative

• Cloud retrievals more mature
  - more confidence in retrievals
  - most operational satellites have necessary channels for more info

• Calibration more reliable
  - self-calibrated MODIS et al. calibrate operational imagers

• Demand
  - modelers see benefits, can use more data now
  - new applications will find users
Aircraft Icing

- Aircraft structures act as ice nuclei in supercooled clouds
  - ice collects, weight increases, plane falls
- Pilots need to know where and when icing can occur
  - PIREPS are first order
    - sparse, aircraft dependent, location uncertain
  - weather forecasts
    - freezing levels, cloud expectations
  - radar => precipitation
- All combined in NCAR/FAA/NOAA/NASA program to provide Current Icing Potential (CIP) & Future Icing Potential (FIP) products to pilots
  - some inadequacies remain
    - NWP uncertainties, intensity, altitude of icing, etc.
Remote Sensing of Icing Conditions

ICING CONDITIONS ARE DETERMINED BY CLOUD

- liquid water content, $LWC$  \hspace{1cm} positive w/ intensity
- temperature, $T(z)$ \hspace{1cm} negative w/ intensity
- droplet size distribution, $N(r)$ \hspace{1cm} $r$ positive w/ intensity

SATELLITE REMOTE SENSING CAN DETERMINE CLOUD

- optical depth, $\tau$
- effective droplet size, $re$
- liquid water path, $LWP$
- cloud top temperature, $Tc$
- thickness, $h$

IN CERTAIN CIRCUMSTANCES
Radiative Transfer for Operational Remote Sensing

- For operational satellites (e.g., GOES or AVHRR), need means to represent multi-spectral radiance field for full range of expected conditions (surface, atmosphere, cloud)
  - three (four) wavelengths: 0.65, 3.8, 11.0, 12.0 µm
- LaRC approach (based on adding-doubling RTM)
  - compute 0.65 & 3.8 cloud reflectances in black vacuum, create LUTs for range of \( r_e \) and \( D_e, \tau \) over all SZA, VZA, RAA
  - parameterize effective emissivity of clouds at 3.8, 11.0, 12.0 µm
  - create LUT of Rayleigh scattering at 0.65 µm
  - parameterize AD code using LUTs and surface reflectance => TOA reflectances, \( R_i \)
  - apply simple layer RT for 3.8, 11.0, 12.0 µm using gaseous absorption/emissivity based on correlated k-dist computed using NWP soundings => TOA brightness temperatures, \( T_i \)
- Find closest match between \( R_i(r_e/D_e,\tau,p) \) & \( R_i(\text{obs}) \); \( T_i((r_e/D_e,\tau,p) \) & \( T_i(\text{obs}) \)
Scattering Phase Functions for Clouds Used in LaRC LUTs

Ice
Hexagonal columns

Water
Var = 10%

Minnis et al., JAS 98
AD Results for reflectance

0.65 µm

3.75 µm

Minnis et al., JAS 98
AD Results for diffuse albedo

0.65 µm

3.75 µm

Fig. 9. Diffuse albedos for model clouds at $\lambda = 0.65\ \mu m$.

Fig. 10. Diffuse albedo for model clouds at $\lambda = 3.75\ \mu m$. [Note scale differences between (a) and (b).]

Minnis et al., JAS 98
Fig. 3. Schematic diagram of scattering and absorption processes for a three-layer atmosphere with no clouds (left) and with one cloud layer (right).
Visible Parameterization

**AD Lite**

\[ R_{TOA} = (R_a + \Delta R) \exp(-\tau_{gas}(1/\mu + 1/\mu_0)) \]

where

\[ \Delta R = a_0 + \sum_{i=1}^{3} a_i \mu^i_0 + \sum_{i=1}^{3} b_i \mu^i + \sum_{i=1}^{6} c_i \Theta^i \]

\[ \tau_{gas} = \sum_{i=1}^{3} |T_{12}(\mu)| + |T_{12}(\mu)| \]

and \( T_{12} \) is the direct Rayleigh transmission as defined by Minnis et al. (1983), and the numeric indices refer to a layer or combination of layers. The downward transmittance of the two layers is

\[ T_{12} = D_1[T_2 + t_{2}(\mu)] + T_2 t_{1}(\mu), \]

where

\[ T_2 = 1 - \alpha_{t2} t_{2}(\mu), \]

and \( t_{2} \) is the direct transmittance of the cloud (Minnis et al. 1993).

The combined reflectance for the three layers is

\[ R_{123} = R_{12} + (1 - \alpha_{t2} D_2 T_{12} + \rho_{t2} t_{2}(\mu) t_{1}(\mu) + S_2) t_{1}(\mu), \]

where

\[ D_2 = T_{12} (1 + S_2), \]

\[ S_2 = Q_2 (1 - Q_2), \]

\[ Q_2 = \alpha_{t2} T_{12} \]

\[ R_{12} = \alpha_{t1} + (1 - \alpha_{t2}) D_1 \alpha_{tcd} + t_{1}(\mu) \alpha_{tcd} t_{1}(\mu) + S_1, \]

and

\[ U_{12} = (1 - \alpha_{t2}) (1 + S_2). \]

The downward transmittance for the three layers is

\[ T_{123} = D_2[T_3 + t_{3}(\mu)] + T_2 t_{1}(\mu), \]

where

\[ T_3 = 1 - \alpha_{t3} t_{3}(\mu). \]

The combined atmosphere and surface reflectance is

\[ R_{T0A} = R_{123} + \alpha_{t0} T_{123} + D_3 + t_{123}(\mu) t_{123}(\mu) t_{123}(\mu), \]

where \( \alpha_{t0} \) and \( \rho_{t} \) are the diffuse surface albedo and surface bidirectional reflectance, respectively,

\[ t_{123}(\mu) = t_{12}(\mu) t_{12}(\mu) t_{12}(\mu), \]

\[ D_3 = T_{123} (1 + S_3), \]

\[ S_3 = Q_3 (1 - Q_3), \]

\[ Q_3 = \alpha_{t3} T_{123}, \]

\[ T_{123} = T_{12} + U_{12} (1 - \alpha_{t3}), \]

\[ U_{12} = (1 + S_3) (1 - \alpha_{t3}), \]

\[ S_3 = R_{12} t_{12}(\mu) t_{12}(\mu) t_{12}(\mu), \]

\[ R_{123} = \alpha_{t0} + D_{123} T_{123} + [S_3 + \alpha_{t3} t_{12}(\mu)] t_{12}(\mu) t_{12}(\mu), \]

and

\[ R_{T0A} = R_{123} + \alpha_{t0} T_{123} D_3 + t_{123}(\mu) t_{123}(\mu) t_{123}(\mu), \]

The combined atmosphere and surface reflectance is

<table>
<thead>
<tr>
<th>( \alpha_{t0} ) (%)</th>
<th>new parameterization</th>
<th>old parameterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-10</td>
<td>-0.01 ± 0.53 %</td>
<td>-0.08 ± 5.1 %</td>
</tr>
<tr>
<td>10-50</td>
<td>-0.01 ± 0.67 %</td>
<td>-0.14 ± 7.0 %</td>
</tr>
<tr>
<td>50-90</td>
<td>0.03 ± 1.04 %</td>
<td>-4.3 ± 12.4 %</td>
</tr>
</tbody>
</table>

Values for \( \alpha_{t0} \) and \( \rho_{t} \) are estimated from the estimated clear-sky diffuse albedo \( \alpha_{t0} \) (Minnis et al. 1993) and the observed clear-sky reflectance, \( \rho_{t0} \).

\[ \alpha_{t0} = 1.149 \alpha_{t0} - 0.033. \]

\[ \rho_{t0} = \rho_{t0} + D_{123} \exp(-\tau_{gas}/\mu), \]

and

\[ \tau_{gas} = \sum_{i=1}^{3} |T_{12}(\mu)| + |T_{12}(\mu)| \]

\[ \tau_{gas} = \sum_{i=1}^{3} a_{i} \mu_{i} + \sum_{i=1}^{3} b_{i} \mu_{i} + \sum_{i=1}^{6} c_{i} \Theta_{i} \]

\[ \Delta R = a_{0} + \sum_{i=1}^{3} a_{i} \mu_{i}^{i} + \sum_{i=1}^{3} b_{i} \mu_{i}^{i} + \sum_{i=1}^{6} c_{i} \Theta_{i}^{i} \]

Minnis et al., TGARS 08
Parameterization of Brightness Temperatures

Example of AD results, $\varepsilon$

Radiance at cloud top

$$B_\lambda(T_a) = \varepsilon_\lambda B(T_c) + (1 - \varepsilon_\lambda) B(T_b) + \mu_\lambda \mu_0 E_\lambda \delta(d),$$

Parameterization errors

<table>
<thead>
<tr>
<th>Model</th>
<th>$3.75\text{-}\mu\text{m }\Delta T$ (K)</th>
<th>$3.90\text{-}\mu\text{m }\Delta T$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All $\varepsilon &lt; 1$</td>
<td>All $\varepsilon &lt; 1$</td>
</tr>
<tr>
<td>$r_\varepsilon (\mu\text{m})$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.16</td>
<td>1.07</td>
</tr>
<tr>
<td>4</td>
<td>1.21</td>
<td>1.16</td>
</tr>
<tr>
<td>6</td>
<td>1.02</td>
<td>1.00</td>
</tr>
<tr>
<td>8</td>
<td>0.81</td>
<td>0.81</td>
</tr>
<tr>
<td>12</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>16</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td>32</td>
<td>0.22</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Parameterization of $\varepsilon$

$$\varepsilon(\zeta, \mu, \xi) = \sum_{i=0}^{2} \sum_{j=0}^{4} \sum_{k=0}^{1} d_{ijk} \zeta^i \mu^j \xi^k,$$

$\zeta = 1/\ln(\Delta T_{sc})$

$\mu = \cos VZA$

$\xi = 1/\ln(T_s)$

Minnis et al., JAS 98
Brightness Temperature Differences from Parameterization

Fig. 14. Brightness temperature differences from parameterizations for $T_s = 295$ K, $T_c = 260$ K, $\tau < 16$, and $\theta = 30^\circ$. 

Minnis et al., JAS 98
Finding a Solution, Given $R_i(\text{obs}), T_i(\text{obs})$

Try to compute solutions iteratively for (A) ice and (B) water, if $T(11) > 233$ K.

Use logic to deduce phase
- no retrieval
- $T_{\text{eff}}$
- smallest error
- agreement w/$T_{11}-T_{12}$

In most cases, no retrieval or $T_{\text{eff}}$ decides phase!

Visible Infrared Solar-infrared Split-window Technique (VISST)

Minnis et al., NASA 95
Putting Parameterizations into Near-Real-Time Operation for GOES
## Current Products

<table>
<thead>
<tr>
<th>0.65 µm Reflectance</th>
<th>3.7 µm Temperature</th>
<th>6.7 µm Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.8 µm Temperature</td>
<td>12 or 13.3-µm Temp</td>
<td>1.6 µm Reflectance</td>
</tr>
<tr>
<td>Skin Temperature</td>
<td>Optical Depth</td>
<td>Eff Radius/Diameter</td>
</tr>
<tr>
<td>Liq/Ice Water Path</td>
<td>Cloud Eff Temp</td>
<td>Cloud Top Pressure</td>
</tr>
<tr>
<td>Cloud Eff Pressure</td>
<td>Cloud Top Height</td>
<td>Cloud Eff Height</td>
</tr>
<tr>
<td>Cloud Phase</td>
<td>Cloud Bot Height</td>
<td>Cloud Mask</td>
</tr>
<tr>
<td>Cloud Bot Pressure</td>
<td>Icing Potential</td>
<td>Broadband SW Albedo</td>
</tr>
<tr>
<td>Broadband LW Flux</td>
<td>Infrared Emittance</td>
<td></td>
</tr>
</tbody>
</table>

### New products:

- Surface Flux (Gridded)
- Multi Layer Cloud Mask & Layer Retrievals

Analysis Applied to Two Satellites to Cover USA
1645 UTC, 4 Dec 2007

Each image is analyzed and the results are combined
Combined GOES-11/12 Retrievals, 1645 UTC 4 Dec 2007

Light Blue - Supercooled
LWP = LWC * h

re = f[N(r)]

Tc & h can yield depth of freezing layer

z_t is top of icing layer

ceiling = z_t - h

IN MANY CASES, SATELLITE REMOTE SENSING SHOULD PROVIDE ICING INFORMATION
GOES SLW vs. PIREPS Icing

Compared to Positive icing PIREPS and provided there were no overcast ice clouds, LaRC GOES technique detected SLW 98% of the time (Smith et al., 2000)
Comparison of GOES Cloud Properties with PIREPS Icing Intensity
N=7800 (Jan-March, 2003)
Comparison of LWP with 18,000 PIREPS, 5 Jan -5 Apr, 2005

Day Time GDCP Liquid Water Paths vs Pirep Severity
140032 Points Plotted
No Precip

Haggerty et al., JCAM 08
Dependence of Icing on LWP and $r_e$

Major dependence on LWP, minor on $r_e$

Formulation developed for icing potential
Icing Potential from GOES Data Alone

Many indeterminate areas (white)
Integration of Cloud Products into NCAR CIP

16 UTC 16 Feb 2005

GOES Cloud Properties

CIP Icing Severity Product

Haggerty et al., JCAM 08
Finding More Icing in Indeterminate Areas
Multilayer Cloud Detection & Retrieval

- Some indeterminate cloudy pixels are overlapped ice over water clouds
  - multilayered cloud detection needed to find those areas where icing is a problem
- Need a multilayered VISST to derive low cloud properties

Use AD model to develop LUTs for ice over water clouds

Minnis et al. JGR 2007
Multilayered Cloud Reflectance Fields from AD Computations

Total WP - 200 gm$^{-2}$, Vary LWP

(a) LWP=0 gm$^{-2}$

(b) LWP=50 gm$^{-2}$

(c) LWP=100 gm$^{-2}$

(d) LWP=150 gm$^{-2}$

BRDF varies dramatically as mix of ice and water changes

Minnis et al. JGR 2007
Multi-layered Cloud Detection, 13.3/10.8 μm

1645 UTC 4 Dec 2007

Magenta areas are identified as multilayer ice-over-water
Based on simplification of Chang & Li, JGR 2000 method
Some retrieved clouds are supercooled
Multilayer retrievals pick up additional areas with icing that were formerly indeterminate

... some areas remain undetected
When upper cloud is too thick, CO$_2$ Does Not Help

...may need microwave data

Microwave radiative transfer can be used to determine cloud LWP and temperature of water clouds even when thick ice cloud is present.

Temperature derived from TMI MW 37 GHz on TRMM, 1998 for single-layer ice cloud = SST

$T_c$ derived from VIRS imager using VISST

Water cloud temperature derived from TMI MW 37 GHz on TRMM, 1998 for single-layer ice cloud

$T_c$ derived from VIRS imager using VISST

Supercooled clouds can be detected using MW data, day & night

*Minnis et al., JGR 2007*
Summary & Future Research

- Radiative transfer has enabled the development of new cloud products from real time satellite data
  - application to weather and nowcasting problems
  - proven valuable for aircraft safety products (used in CIP)
  - near-real time cloud properties & radiation budget available over many regions of the globe

- Icing product currently limited to water clouds without overlying cirrus
  - CO2-slicing with ML VISST looks very encouraging
    - limited to thin cirrus over thick water
  - MW with ML VISST works over ocean
    - need more development over land
    - real time limited because of few polar-orbiters with MW data
      - GEO MW?

- Other applications in process
  - improve icing altitude range more accurately than model
  - cloud products being assimilated into RUC (Ztop, LWP/IWP)
  - potential for ceiling estimation