TOMS Ozone Retrieval Errors Associated with Clouds

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Outline

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- Cloud Treatment in the TOMS Operational Algorithm and Potential Ozone Retrieval Errors
- Methodology
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Motivation

- Driven by deriving accurate tropospheric ozone from TOMS data.
  - Accurate ozone retrieval over cloudy areas is critical to tropospheric ozone derivation.
- Significant TOMS total ozone excesses of 10-15 DU are found over tropical high-reflectivity clouds compared to neighboring clear-sky observations. Approximately 4-9 DU ozone excesses over cloudy scenes remain unexplained [Newchurch et al., 2001].
- The presence of clouds complicates satellite/ground retrieval of ozone as well as other atmospheric components.
Cloud Treatment in the TOMS V7 Algorithm

- Opaque Lambertian cloudy surfaces.
- Cloud-top pressure \( (P_c) \) from monthly mean ISCCP.
- Lambertian-equivalent reflectivity derived from 380-nm (or 360-nm) radiance \( (I_{\text{meas}}) \).
- If \( I_{\text{meas}} \geq I_{c,\text{calc}}(R_c = 80\%, P_c) \) then Full Cloudy
  If \( I_{\text{meas}} \leq I_{g,\text{calc}}(R_g = 8\%, P_g) \) then Clear Sky
- Otherwise, partial cloudy. Determine cloud fraction using the pixel independent approximation.

\[
I_{\text{meas}} = I_{c,\text{calc}}(R_c = 80\%, P_c) f_c + I_{g,\text{calc}}(R_g = 8\%, P_g)(1 - f_c)
\]

- Adding climatological ozone below clouds to complete the total ozone column.
Potential Ozone Retrieval Errors Associated with Clouds

- Non-Lambertian Cloud Surface: Photon penetrates into clouds, and path length is enhanced through multiple scattering, resulting in enhanced ozone absorption.

- Assumed Lambertian Cloud Surface: TOMS partial cloud scene might be total cloudy with $R < 80\%$ (e.g. only 40%), or might be broken clouds.

- Actual Cloud Top: Cloud-top Height Error

- Incident Light

- Ice Clouds

- Water Clouds

- Cloudy Sky

- Partial Cloud

- Clear Sky

- Ground Surface
Methodologies


- Use the TOMS V7 algorithm for ozone retrieval. The difference between the retrieved ozone and the forward input ozone indicates ozone retrieval errors.

- Ozone profiles, ozone absorption and rayleigh scattering coefficients, and other settings are the same between PPGSRAD and TOMRAD (TOMSV7 forward model). The radiance difference is within 0.2% on average for clear sky. The corresponding retrieved ozone difference is 0.6 DU on average.

- Clouds are assumed horizontally and vertically homogeneous. Typically, a cloud of optical thickness 40 at 2-12 km is used as a base case to represent tropical-high reflecting clouds. Optical properties are calculated using Mie code for water clouds and Ray tracing code for hexagon column ice crystals and polycrystals.

- Viewing geometry:
  - Solar zenith angle $\theta_o$: 0°, 15°, 30°, 45°, 60°, 70°, 75°;
  - Satellite view zenith angle $\theta$: 0° to 70° every 5°;
  - Relative Azimuthal Angle $\phi$: 0° to 180° every 30°
Methodologies

- Separate different effects on ozone retrieval
  - Lambertian Assumption (Lambertian effect)
  - Partial Cloud Model (PCM effect)
  - In-cloud Ozone Absorption Enhancement (ICOAEN effect)
  - Below-cloud Ozone Absorption (BCOA effect)

\[
\begin{align*}
\Delta O'_{3,t} &= O'_{3,\text{total}} - O_{3,\text{total}} \\
\Delta O'_{3,a} &= O'_{3,\text{ozac}} - O_{3,\text{ozac}} \\
\Delta O'_{3,b} &= O'_{3,\text{ozbc}} - O_{3,\text{ozbc}}
\end{align*}
\]
Lambertian and PCM Effects

- Dependent on $\theta_o$, $\theta$, and $\phi$.
- Error in total ozone ranges from -4.1 to 4.4 DU. Avg. = $0.7 \pm 1.1$ DU.
- Large error in ozone above cloud occurs at small effective cloud fraction.
Lambertian and PCM Effects

- Positive errors in ozone above clouds and negative errors in ozone below clouds tend to cancel each other.

- Modify the TOMSV7 algorithm to force the effective cloud fraction to be 1 to obtain the Lambertian effect.

- Lambertian effect: -4.1 --- 4.4 DU

The error in ozone below clouds is almost 0 except at large viewing geometry due to the profile difference between forward calculation and retrieval.

- PCM effect: present in both errors in ozone above and below clouds.
Lambertian and PCM Effects

- PCM and Lambertian effects vary with phase function
- Average Ozone Retrieval Error: -0.8 --- 1.4 DU
## Lambertian and PCM Effects

<table>
<thead>
<tr>
<th>Cloud Type</th>
<th>Profile</th>
<th>Cloud OD</th>
<th>Location (km)</th>
<th>PCM &amp; Lambertian Effects</th>
<th>Lambdaertian Effect</th>
<th>PCM effect</th>
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<tbody>
<tr>
<td>Base Case</td>
<td>WC</td>
<td>L275</td>
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<td>-4.1 – 4.4</td>
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<td>POLY</td>
<td>L275</td>
<td>40</td>
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<tr>
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<td>-0.5 ± 1.1</td>
<td>-4.9 – 3.0</td>
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</table>
In-Cloud Ozone Absorption Enhancement

- A priori 20.8 DU in cloud in the forward calculation.
- Large errors (effective ozone) at small solar zenith angle and view zenith angles. About 19 DU at nadir.
- Azimuthally independent.
Excellent comparison indicates that TOMSV7 retrieves almost all the ozone absorption of reflected radiation in clouds.

Using the triplet methods cannot reduce the errors, because the path enhancement are almost the same at all the channels.
In-Cloud Ozone Absorption Enhancement

- Photon Path Length decreases with increasing $\theta_o$ and $\theta$. TOMSV7 takes the geometrical path length into account. The effective ozone in the cloud decreases more with increasing geometrical path.

- Solar zenith angle and view zenith angle are exchangeable.
In-Cloud Ozone Absorption Enhancement

ICOAEN Effect vs. Cloud Optical Properties

- Slight variation among different cloud types.
  - WCHG > ≈ WC > ≈ HEX > ≈ POLY
In-Cloud Ozone Absorption Enhancement

ICOAEN Effect vs. Cloud Optical Thickness

- Generally, ICOAEN effect decreases with increasing optical thickness.

- The increase of ICOAEN effect with optical thickness at smaller optical thickness is due to the imperfect retrieval efficiency at smaller surface reflectivity.
ICOAEN effect is largely dependent on the amount of ozone in the cloud. The ratio of retrieved to actual ozone in cloud slightly decreases with increasing ozone in the cloud.
The ratio of retrieved O$_3$ to actual O$_3$ in the cloud slightly increases with increasing cloud altitude.
In-Cloud Ozone Absorption Enhancement

ICOAEN Effect vs. Ozone Distribution in Clouds

1. Original (20.8 DU)
2. Well-mixed (20.8 DU)
3. Homogeneous (20.8 DU)
4. Linearly increasing (20.8 DU)
5. Linearly decreasing (20.8 DU)
6. Upper 2 km (4.2 DU)
7. Lower 2 km (4.2 DU)

- ICOAEN is very dependent on ozone distribution in clouds.
- Ozone distributed in the upper part of cloud usually contributes more to ozone absorption in clouds.
In-Cloud Ozone Absorption Enhancement

Vertical Distribution of ICOAEN Effect

For upward radiance, ozone absorption peaks in the upper part of clouds. The height of the peak increases with increasing viewing geometry.

For downward radiance, ozone absorption peaks in the middle of the clouds and almost symmetric around the peak location.
In-Cloud Ozone Absorption Enhancement

Vertical Distribution of ICOAEN Effect vs. Cloud Optical Depth and Cloud Optical Properties

- E-folding depth is defined as the depth above which \( 1/e \approx 36.8\% \) of ozone absorption occurs.

- The larger the cloud optical thickness, the smaller the E-folding depth; the larger the asymmetry factor, the larger the depth.
Below-Cloud Ozone Absorption

- Ozone absorption below clouds depends on the cloud optical thickness and the amount of ozone below clouds.
Ozone Retrieval Error Associated with Clouds

- Comparison of ozone retrieval for two cases:
  - \( f_c = 1 \), consistent with forward calculation
  - TOMSV7 partial cloud model

- At smaller cloud optical thickness, using the partial cloud model gives the about correct result due to the compensating errors.
At larger cloud optical thickness, these two methods start to converge because the effective cloud fraction is either 1 or very close to 1.

Part of the in-cloud ozone can be seen by TOMS and retrieved. However, both methods add almost all the ozone below clouds, leading to positive errors.
Ozone Retrieval Error Associated with Clouds

- For a cloud of optical thickness of 1 at 2-3 km or 11-12 km, using the TOMSV7 partial-cloud model leads to the about correct retrieved ozone.

- Assuming the full-cloud minimum reflectivity as 100% gives almost the same result as 80% (i.e. the TOMSV7 partial-cloud model) due to the compensating errors.
Ozone Retrieval Error Associated with Partial Clouds

- **Pixel-independent approximation:**
  \[ I_{pc} = I_c(\tau_c) \times f_c + I_g(R_g = 8\%) \times (1 - f_c) \]

- Error is approximately proportional to cloud fraction.

### In Cloud Ozone Absorption Enhancement

- **Lambertian and PCM effects**

- tauc = 1

- tauc = 40
At smaller cloud optical thickness, using the TOMS partial cloud model retrieves the about correct results for different forward cloud fractions.

The good result occurs because of the compensating errors so that the positive error due to ozone absorption in clouds and the negative error due to using the partial-cloud model almost cancel.
Summary and Conclusions

The assumption of Lambertian cloud surface is good in ozone retrieval for cloud optical thickness $\geq 20$, with average ozone retrieval errors within 3 DU.

Ozone retrieval error due to using the partial-cloud model is usually negative if the derived effective cloud fraction is $< 1$, and the magnitude increases with decreasing cloud optical thickness due primarily to the cloud fraction being underestimated and with less ozone added below clouds.

Because the TOMS instrument can see ozone absorption in and below clouds, the algorithm assumption of an Opaque cloudy surface results in positive errors. Ozone absorption in clouds is largely dependent on ozone distribution in clouds, ozone amount in clouds, and geometrical path length, cloud thickness, and slightly dependent on cloud optical properties and cloud optical thickness.

At small cloud optical thickness, using the partial-cloud model leads to the about correct total ozone due to the compensating errors. The negative errors due to using the partial-cloud model tend to cancel the positive errors due to ozone absorption in and below clouds.

With increasing cloud optical thickness, positive errors due to ozone absorption in and below clouds slowly decrease in magnitude, while negative errors due to using the partial cloud model decrease more dramatically, leading to increasing positive errors.
Thank you!