Ph.D. Dissertation Defense

Ozone Retrieval Errors Associated with Clouds in Total Ozone Mapping Spectrometer (TOMS) Data

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November 15, 2002
List of Publications


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- Errors resulting from assuming opaque Lambertian clouds and employing a partial cloud model
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- Analysis of ozone anomaly occurrence
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- Future directions
Introduction

- Tropospheric ozone plays a very important role in chemical processes and climate.

- Two methods derive tropospheric ozone from TOMS cloudy/clear ozone difference.
  - CCD [Ziemke et al., 1998] and CCP [Newchurch et al., 2002].
  - Accurate ozone retrieval over cloudy areas is critical.

- The presence of clouds complicates satellite remote sensing of ozone as well as other atmospheric constituents.
Cloud Treatment in the TOMS V7 Algorithm

- Determines cloud-top pressure ($P_c$) from monthly mean ISCCP.
- Assumes cloud reflection to be angularly independent
- Assumes optically thick clouds to be opaque. The total ozone consists of 2 parts: directly retrieved ozone above clouds and added ozone below clouds.
- Employs a partial cloud model to determine effective cloud fraction
  - 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 following:

$$I_{\text{meas}} = I_{c,\text{calc}} (R_c = 80\%, P_c) f_c + I_{g,\text{calc}} (R_g = 8\%, P_g)(1 - f_c)$$
Potential Ozone Retrieval Errors Associated with Clouds

 photons penetrate into the clouds, enhancing ozone absorption because of multiple scattering.

A TOMS partial cloud scene might be total cloudy with R < 80% (e.g., only 40%) or might be broken clouds.

- Incorrect cloud heights
- Non-Lambertian
- Non-opaque
- Incorrect cloud fraction
Errors Due to Incorrect Cloud-top Heights

Three cloud-height-related errors:

- Radiation interpolation error
- Error in ozone above clouds
- Error in ozone below clouds

Tools

- Forward model: TOMRAD
- TOMS V7 algorithm

Errors in cloud-top pressure range from −300 mb for high-altitude clouds to 150 mb for low-altitude clouds.
Errors Due to Incorrect Cloud-top Heights

- $\Delta \Omega_{\text{rad}}$: Retrieve ozone with correct CTP.
- Positive between 0.4 and 1 atm within 2 DU; Above 0.4 atm, negative error increases in magnitude with increasing cloud-top heights and viewing geometry.
- $\Delta \Omega_{\text{ozac}}$: Retrieve ozone at CTPs different from the actual CTP.
- Retrieved ozone usually increases with decreasing CTP because of decreasing air mass factor. Error decreases with increasing viewing geometry.
- $\Delta \Omega_{\text{ozbc}}$: just the ozone between actual and assumed CTPs.
- The overall error caused by incorrect cloud-top heights is dominated by the error in ozone below clouds.
OREs Due to Assuming Opaque Lambertian Cloud Surfaces: Methodologies

- **Tools**
  - Plane-parallel Gauss-Seidel RTM (PPGSRAD) [Herman et al., 1995]
  - TOMRAD and TOMS V7 algorithm

- **Model setups**
  - Same input parameters between PPGSRAD and TOMRAD.
  - Radiance difference within $0.2 \pm 0.06\%$ on average at 312 nm for clear sky.
  - Horizontally and vertically homogeneous clouds.
  - Use Mie and Ray tracing codes to calculate cloud optical properties.
  - Base case: a water cloud of optical thickness 40 at 2-12 km; L275
  - Perform sensitivities to cloud types, CODs, cloud locations, inter-cloud ozone amount and distribution, and atmospheric ozone profiles.

- **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°
Divide the overall effect into four effects:

- Lambertian: angularly-independent (Lambertian effect)
- Partial Cloud Model: incorrect cloud fraction (PCM effect)
- In-cloud Ozone Absorption Enhancement (ICOAEN effect)
- Below-cloud Ozone Absorption (BCOA effect)

For the time being, I will consider forward overcast conditions.
Lambertian-PCM Effect

- **Method:** No ozone below cloud-tops in forward calculation to simulate opaque clouds in terms of ozone absorption.

- **Dependent on SZA, VZA, and AZA.**

- **Error in total ozone ranges from -4.1 to 4.4 DU with an average of -0.8 ± 1.1 DU.**
Lambertian and PCM Effects

Positive errors in OZAC and negative errors in OZBC tend to cancel each other.

Method: Modify the TOMS V7 algorithm by forcing the effective cloud fraction to be 1 to obtain the Lambertian effect.

- Lambertian effect: -4.1 to 4.4 DU with an average of \(-0.2 \pm 1.3\).

- PCM effect: positive errors in OZAC and negative errors in OZBC, offsetting each other and leading to overall negative errors.

- When the cloud optical thickness is smaller, the error will become significant.
### Lambertian and PCM Effects

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**Note:** Errors are provided with ± one standard deviation (s.d.)
In-Cloud Ozone Absorption Enhancement

- **Methods:** Simulate 2 sets of radiances with and without inter-cloud ozone, retrieved ozone difference from these 2 sets of radiances indicates the ICOAEN effect or effective inter-cloud ozone (EICO).

- Azimuthally independent but strongly dependent on SZA and VZA.

- Large EICO at small SZAs and VZAs. About 18 DU at nadir.
In-Cloud Ozone Absorption Enhancement

- ICOAEN effect is strongly dependent on the amount of inter-cloud ozone.
- The ratio of retrieved to actual inter-cloud ozone slightly decreases with increasing inter-cloud ozone.
In-Cloud Ozone Absorption Enhancement

ICOAEN vs. COP (COD=40, L275, 2-12 km)

Generally, ICOAEN effect decreases with increasing COD.

Even at COD 500, the EICO is still significant at small viewing geometry, 11 DU at nadir view.

Slight variation among different COPs.

WCHG > \approx WC > \approx HEX > \approx POLY

The larger asymmetry factor, the deeper photons penetrate, and the greater EICO will be.

ICOAEN vs. COD (L275, 2-12 km)

Generally, ICOAEN effect decreases with increasing COD.

Even at COD 500, the EICO is still significant at small viewing geometry, 11 DU at nadir view.
In-Cloud Ozone Absorption Enhancement

Three profiles:
1. Homogeneous (20.8 DU)
2. Linearly increasing (20.8 DU)
3. Linearly decreasing (20.8 DU)

The ICOAEN effect is strongly dependent on ozone distribution in the clouds.

Ozone distributed in the upper part of the clouds usually contributes more to the ICOAEN effect.
Below-Cloud Ozone Absorption

Ozone absorption below clouds depends mainly on the cloud optical thickness and the amount of ozone below clouds.
Overall Ozone Retrieval Errors

- Two retrievals:
  - $f_c = 1$, consistent with forward calculation
  - TOMS V7 PCM ($R_s = 80\%$)

- At COD 1, using the correct cloud fraction leads to large positive error, while the TOMS V7 algorithm retrieves the about correct total ozone.

- At COD 40, these two retrievals converge, both containing large positive errors.
The TOMSV7 PCM also retrieves approximately correct results for more realistic 2-3 km and 11-12 km clouds with COD 1.
- At small CODs, negative PCM effect almost offsets other positive effects.
- Using PCM is good because of compensating errors.
- With increasing COD up to 20-40, the negative PCM decreases more dramatically than the positive effects, so the overall positive error increases.
- At COD > 20, the error is dominated by the ICOAEN effect. Then the overall positive error slightly decreases with the further increase of COD.
OREs Associated with Forward Partial Clouds

- **Methods:** Apply independent pixel approximation to simulate radiance for partial clouds.

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

- **Errors are approximately proportional to forward cloud fractions.**

- **Errors for forward full clouds apply to forward partial clouds as well but weighted by forward cloud fraction.**
Effects of OREs on Tropospheric Ozone Derivation

- Cloudy/clear total ozone difference without any correction: -9 to 7 DU.
- Correct incorrect cloud-top heights, incorrect tropospheric climatology, and imperfect ozone retrieval efficiency.
- Dynamic and chemical effects are estimated to be negligible in the tropics.
- ICOAEN effect: 1 to 7 DU over the Pacific Ocean, and 5 to 13 DU over the Atlantic Ocean and Africa.
- Error in stratospheric ozone: 5 to 11 DU over the western Pacific Ocean and 9 to 19 DU over the Atlantic Ocean and Africa.

Clouidy/clear
- Clouds: R ≥ 80%, THIR ≤ 300
- Clear: (R ≤ 20%)
- Time: 1979-1983 (with THIR)
Effects of OREs on Tropospheric Ozone Derivation

- Derived tropospheric ozone before correction: < 21 DU at all regions.
- Derived tropospheric ozone after correction: more consistent with the climatology.
Effects of OREs on Tropospheric Ozone Derivation

- The errors in CCD or CCP methods are much smaller.
- The higher altitude improve the retrieval only by 2 to 3 DU.
- The CCP and CCD methods select cloud fields with less ICOAEN effect or extremely low values that offset other positive errors.
Cloudy Ozone Anomaly

- Two examples with highly positive (left) and negative (right) correlation between ozone and reflectivity.

Definition of Cloudy Ozone Anomaly

- \( \geq 20 \) measurements in a 5 x 5 region.
- Reflectivity range is \( \geq 30\% \).
- Correlation coefficient \( \geq 0.5 \) (i.e., positive ozone anomaly) or \( \leq -0.5 \) (i.e., negative ozone anomaly).
Ozone Anomaly Occurrence

- Average fraction of OA occurrence is 32% in N7 TOMS data.
- Ozone anomaly is not evenly distributed on the globe.

The slope is mainly a function of latitude, ranging from 12-30 DU/100% in the tropics to 40-80 DU/100% at mid-latitudes.
Analysis of Ozone Anomaly Occurrence

Ozone anomaly after correcting incorrect CTHs

- Most tropical negative ozone anomalies are eliminated.
- A large fraction increase of positive ozone anomalies by 20-50\% occurs in the tropical convective cloudy areas.
- Tropical POAs are mainly caused by ozone retrieval errors due to the ICOAEN effect associated with deep convective clouds.
- The slopes do not change much.
Analysis of Ozone Anomaly Occurrence

- Ozone retrieval errors cannot explain the large ozone/reflectivity slope observed at mid-latitudes.

- At mid-latitudes, the slope is highest from winter to early spring (60-80DU/100%) and lowest in summer and fall with a magnitude of 30-40 DU/100%, consistent with the total ozone fluctuation found by Allen and Reck, [1997] and Stanford et al. [1996].

- Mid-latitude ozone anomalies are mainly caused by synoptic- and planetary-scale wave disturbances.

Allen and Reck [1997], Figure 1d
The slopes of POAs at marine stratocumulus regions (off the west coast of South America and South Africa) peak during September-November and are lowest during February-May.

This slope variation is consistent with tropospheric ozone variation at those regions caused by biomass burning activities.

The correlation between the slope and measured tropospheric ozone at Ascension is 0.95.
Analysis of Ozone Anomaly Occurrence

- **Simulate slopes for ozone anomalies**
  - Use monthly average tropospheric ozone profiles measured at ASCENSION
  - Assume water clouds at 1.5-2.5 km with a COD of 15, simulating marine stratocumulus clouds with reflectivity of ~55%.
  - Assume clear-sky surface reflectivity to be 5%.

- **The simulated slope can only explain ~ half the observed slope and 75% of the amplitude.**

- **Greater ozone production from frequent low-altitude clouds and rich ozone precursors may cause the remainder.**
Conclusions

- Errors caused by incorrect cloud-top heights are most significantly from the added ozone below clouds.

- Assuming Lambertian clouds is good at COD greater than 20.

- Assuming opaque clouds can introduce large ozone retrieval errors even for optically thick clouds.

- The use of TOMS PCM is good because negative PCM effect offsets other positive effects.

- The fraction of OAs in Nimbus-7 TOMS data is very high, about 32%. Some ozone anomalies are mainly caused by ozone retrieval errors and some ozone anomalies are mainly caused by geophysical phenomena.
Future Directions

- Implications of TOMS OREs for ozone/trace gas retrieval from other satellites such as OMI, GOME, and SCIAMACHY.

- Study more realistic clouds: multi-layer, inhomogeneous, and broken clouds.

- Study ozone/trace gas distribution inside clouds.

- Examine our speculation about more ozone from photochemical production over marine stratocumulus clouds off the west coast of South Africa and South America.
Thank you!