Lecture 11

Applications of passive remote sensing using extinction and scattering: Remote sensing of ozone in the UV region

Objectives:

1. The principle of interaction.
2. Theoretical foundation of the TOMS ozone retrieval algorithm. TOMS Aerosol Index.

Required reading:

G: 6.2, 6.5

Additional/advanced reading:

G: 3.6;

TOMS Data Products User's Guide is available at

http://toms.gsfc.nasa.gov/index.html

NOTE: We will be working with the TOMS data in Computer Lab 6.

1. The principle of interaction.

Consider an atmospheric layer that can reflect and transmit the incident radiation.

Let's rewrite the definitions for **reflection** $R(\vec{\Omega},\vec{\Omega}')$ **and transmission** $T(\vec{\Omega},\vec{\Omega}')$ **functions of diffuse radiation** (see Eqs.[10.9]-[10.10]) in the general form

$$I_{reflected}(\vec{\Omega},\vec{\Omega}') = R(\vec{\Omega},\vec{\Omega}')I(\vec{\Omega}')d\Omega' \qquad [11.1]$$

$$I_{transmitted}(\vec{\Omega},\vec{\Omega}') = T(\vec{\Omega},\vec{\Omega}')I(\vec{\Omega}')d\Omega' \qquad [11.2]$$

where $I_{\lambda}(\vec{\Omega}')$ is the incident intensity in the direction $\vec{\Omega}'(\mu',\phi')$.

NOTE: Recall that we introduced similar $R(\vec{\Omega},\vec{\Omega}')$ to characterize BRDF of the surfaces (see Lecture 5).

If the atmopsheric layer illumitated by many sources of radiation from below and above with $I_\lambda(\vec{\Omega}'_k)$ of the *k*-th source below and $I_\lambda(\vec{\Omega}'_j)$ of the *j*-th source above, then the intensity emerging from the layer in the direction $\vec{\Omega}$ is

$$I(\vec{\Omega}) = \sum_j R(\vec{\Omega},\vec{\Omega}'_j) I(\vec{\Omega}'_j) d\Omega'_j + \sum_k T(\vec{\Omega},\vec{\Omega}'_k) I(\vec{\Omega}'_k) d\Omega'_k \quad [11.3]$$

Principle of interaction:

The resulting intensity emerging from the surface of the layer is a superposition of reflected and transmitted intensities.

NOTE: Eqs.[10.5]-[10.6] for the first order scattering were derived for non-reflecting surfaces (called black surfaces). The principle of interaction enables the incorporation of radiances reflected from the surfaces.

2. Theoretical foundation of the TOMS ozone retrieval algorithm.

Total Ozone Mapping Spectrometer (TOMS) :

- **TOMS on board of the NIMBUS-7 Satellite (TOMS/ NIMBUS-7):**
  data from October 1978 to May 1993
- **TOMS on board of the Earth Probe Satellite (EP-TOMS):**
  data from July 1996 to present

NOTE: TOMS also has flown on the ADEOS and Meteor-3 Satellites

EP-TOMS measures both incoming solar energy and backscattered UV radiation at six different channels: 360.4 ± 0.2 nm, 331.3 ± 0.1 nm, 322.4 ± 0.1 nm, 317.6 ± 0.1 nm, 312.6± 0.1 nm, and 308.6 ± 0.1 nm.

Current orbital characteristics (as of 12/13/97): Altitude : 740 km; Inclination : 98.385^0 Period : 99.65 min , EP-TOMS FOV at nadir: 39 km latitude x 39 km longitude , IFOV varies.

TOMS ozone retrieval algorithm:

Consider an atmosphere bounded below by a Lambertian surface of reflectivity R_{sur}. The radiance measured by a TOMS instrument at the top of the atmosphere (TOA), I_{TOA}, is the sum of purely atmospheric backscattered radiance, I_A, and reflection from the incident radiation from the reflecting surface, I_s,

$$I_{TOA}(\lambda,\theta,\varphi,\theta_0,\varphi_0,u_{o3},P_0,R_{sur}) = I_A(\lambda,\theta,\varphi,\theta_0,\varphi_0,u_{o3},P_0) + I_s(\lambda,\theta,\varphi,\theta_0,\varphi_0,u_{o3},P_0,R_{sur}) \quad [11.4]$$

where

λ is the wavelength (central value of a particular TOMS channel); (θ, ϕ) is the satellite viewing angle; (θ_0, ϕ_0) is solar angle; $\boldsymbol{P_o}$ is the surface pressure and $\boldsymbol{u_{03}}$ is the column ozone amount.

The surface reflection term can be expressed as follows

$$I_s(\lambda,\theta,\varphi,\theta_0,\varphi_0,u_{o3},P_0,R_{sur}) = \frac{R_{sur} I_{dd}(\lambda,\theta,\varphi,\theta_0,\varphi_0,u_{o3},P_0)\, f(\lambda,\theta,\varphi,P_0)}{1 - R_{sur} S_b(\lambda,u_{o3},P_0)} \quad [11.5]$$

where

$\boldsymbol{S_b}$ is the fraction of radiation reflected from surface that atmosphere reflects back to space;

$\boldsymbol{I_{dd}}$ is the total amount of direct and diffuse radiation reaching the surface at $\boldsymbol{P_o}$;

$\boldsymbol{f}$ is the fraction of radiation reflected toward satellite in the direction (θ, ϕ) that reaches the satellite.

NOTE: The denominator in the above equation accounts for multiple reflection between the ground and the atmosphere.

The **N-value** is defined as

$$N = -100 \log_{10}\left(\frac{I_{TOA}}{F}\right) \quad [11.6]$$

Steps of TOMS ozone retrieval algorithm:

a) Using a radiative transfer code, pre-calculate N-values at TOMS channels that should be measured for different ozone amounts, given the location of the measurement, viewing conditions, and surface properties.

b) The initial estimate of O_3 is derived from N-values of a pair of wavelengths (one with strong O_3 absorption and another without O_3 absorption).

c) Construct **the residues** as $\Delta N = N_{meas} - N_{calc}$. Using the **residues** at a properly chosen **triplet wavelength**, it is possible to simultaneous solve for the ozone amount and for contribution to the radiances that is linear with wavelengths (e.g., from wavelength dependence of the surface reflectivity or instrument calibration).

Table 11.1 Pair/triplet wavelength of EP-TOMS

Pair/Triplet designation	O3 sensitive Wavelength (nm)	O3 insensitive Wavelength (nm)	Reflectivity wavelength (nm)
A	312.6	331.3	360.4
B	317.6	331.3	360.4
C	322.4	331.3	360.4

To carry out the above calculations (i.e., to calculate I_{TOA}, I_A, I_{dd}, f and S_b in Esq.[11.4]-[11.5]), the following information is required:

1) Ozone absorption coefficients as a function of temperature at the TOMS wavelengths;

2) Rayleigh scattering coefficients;

3) Climatological temperature profiles;

4) **Climatological ozone profiles**

(each standard profile represents a yearly average for a given total ozone and latitude based on ground-based and ozonesonde data; Profiles have been constructed for three latitude bands: low latitude (15^0)- 6 profiles, mid-latitude (45^0) - 10 profiles, and high latitude (75^0) – 10 profiles (total 26 O_3 profiles).

5) Solar position, satellite viewing angle and IFOV
(EP/TOMS makes 35 measurements every 8 seconds, strung along a line perpendicular to the motion of the satellite. This results in an instantaneous satellite field of view (or a footprint) of 39x39 km at nadir to 70x140 km at the extreme off-nadir)

6) Pressure at the reflecting surface

(TOMS algorithm assumes that reflected radiation can come from two levels: ground and cloud. The average ground terrain heights are from NOAA NMC provided in km for 0.5x0.5 degree latitude and longitude grid. Heights are converted to the surface pressure and interpolated to TOMS IFOVs. Also the algorithm uses a monthly snow/ice climatology. For cloud heights, a climatology based upon ISCCP (see Computer Lab 9)).

➢ Effects of clouds on O3 retrievals

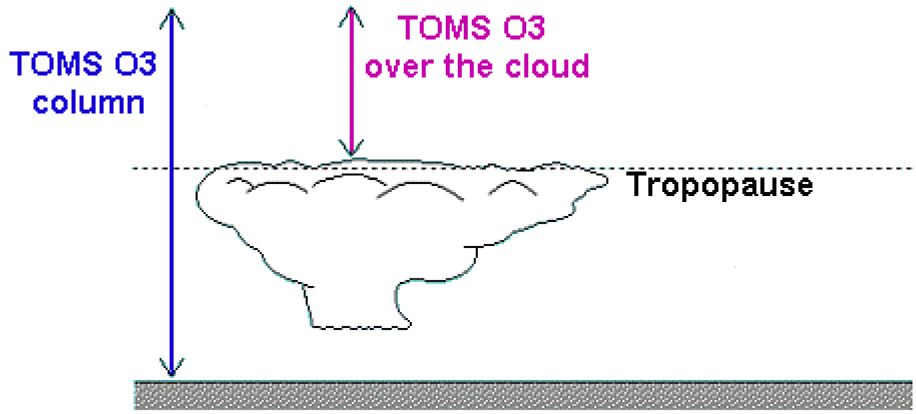
Recent studies (Newchurch et al., JGR, 2001) show:

significant total-ozone-column excess of 10-15 DU over tropical high-altitude, highly reflecting clouds compared to clear observations.

Possible causes:
• Assumption on the cloud Lambertian reflectance.
(The non-isotropic effect varies with viewing geometry, cloud optical thickness, different types of clouds (different phase function), cloud-top height, and ozone above cloud. For most conditions, the non-isotropic effect is within ±4 DU, indicating the assumption of isotropic cloud scattering is fairly good for clouds with optical thickness > 20)

•The ozone absorption enhancement is due to the in-cloud multiple scattering, which interacts with ozone absorption. The enhanced ozone depends significantly on zenith angles, ozone amount in clouds, ozone distribution in clouds, and cloud optical thickness. It also depends somewhat on different cloud types and cloud location. Positive ozone retrieval errors occur without correcting the enhanced ozone. Compared to the non-isotropic effect, the ozone enhancement in clouds is the dominating source of retrieval errors in the assumption of optically thick clouds as Lambertian surfaces.

➢ TOMS convective cloud differential (CCD) method for deriving tropospheric ozone



TROPOSPHERIC O3 = **TOMS O3** (entire column)- **TOMS O3** (over the cloud)

NOTE: Current six TOMS-based methods to retrieve tropospheric O_3 have significant method-to-method differences with a range of 10-20DU.

➢ **Effects of aerosols on O3 retrievals**

Atmospheric aerosols can scatter and absorb the UV-radiation in addition to molecular scattering and hence affect the ozone retrieval.

UV-absorbing aerosols: dust, carbonaceous, some organics, volcanic ash

- Aerosol effects on UV radiation depend on aerosol type (refractive index and particle size distribution, optical depth, and aerosol layer height.
- The presence of UV-absorbing aerosols result in the underestimation of the TOMS retrieved ozone

Aerosol Correction Scheme (Torres and Bhartia, 1999, JGR):

Assumes the linear relationship between ozone retrieval errors and TOMS Aerosol Index

Retrieval of aerosols from TOMS

TOMS aerosol product is reported in terms of an **Aerosol Index (AI)**

AI = $-100\{\log_{10}[(I_{331}/I_{360})_{meas}] - \log_{10}[(I_{331}/I_{360})_{calc}]\}$,

$$AI = -100[\log_{10}\left(\frac{I_{331}}{I_{360}}\right)_{meas} - \log_{10}\left(\frac{I_{331}}{I_{360}}\right)_{cal}] \qquad [11.7]$$

Example: Dust storm and biomass burning of April 13, 2001

SeaWiFS

TOMS AI