Results from the TOMS V9 total ozone algorithm: Implications for GEMS

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Motivations for GEO Total Ozone Measurement

– *Model evaluation*

Improved knowledge of Tropospheric O_3 and Radiative forcing when combined with MLS O_3 and OMI OCP data (Joiner et al., 2009).

– *Data assimilation: O_3 knowledge improves analyses of lower stratosphere dynamics*

- Operational NWP: NCEP, ECMWF
- Regional (E. Asian!) dust and chemical weather models
- Chemistry & climate models: GEOS-CHEM, GEOS-5, MERRA
- Total column provides important model constraint

– *Dynamical studies*

Tracer for short-term variability and dynamical events in lower stratosphere.

Motivations for GEO Total Ozone Measurement

– *Tropospheric studies*

O_3 mixing ratios in Deep Convective Clouds, independent of stratospheric information (Ziemke, 2009) and classic residual methods.

– *Relationship with SO_2*

Expect SO_2 column to be derived accurately in TOMS V9

– *Learn more about the algorithm*

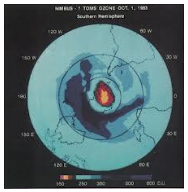
Unique viewing conditions, potential Volcanic eruptions

Increased spatial and temporal resolution in GEO to provide more information and new opportunities (some yet unimagined).

Backscatter UV Total O_3 Algorithms

Based on Dave & Mateer (1967)
SBUV V1-6 TOMS V1-8 OMI (NASA algorithm) Suomi/NPP OMPS Mapper (same as TOMS V8)
Spectral Fitting Algorithms
SBUV continuous scan (Joiner & Bhartia, 1997) GOME-DOAS OMI-DOAS WFDOAS BOAS BIRA/Direct Fit
Optimal Estimation Algorithms
GOME & OMI (Liu et al., 2005, 2010) SBUV V8.6 (Bhartia et al., 2012) Suomi/NPP OMPS NP (same as SBUV V8.6) TOMS V9 (similar to SBUV V8.6)

Current and Historical TOMS Missions



TOMS
Nimbus-7

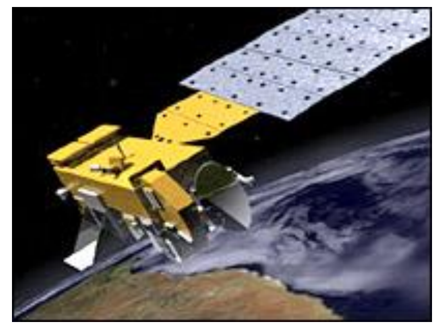
1978-1993

TOMS
Meteor-3

1992-1994

TOMS
EarthProbe

1996-2005



OMI
EOS Aura

2004 – pres.

OMPS
Suomi NPP

2011- pres.

TOMS V9 in a Nutshell

- Simple algorithm (but not simplistic).
- Goal: quality as good as V8, within error bars
- Long heritage.
- Focuses on one thing: O_3 measurement.
- Profile integrated to get O_3 column.
- Algorithm is flexible (unlike V8).

Objectives for TOMS V9

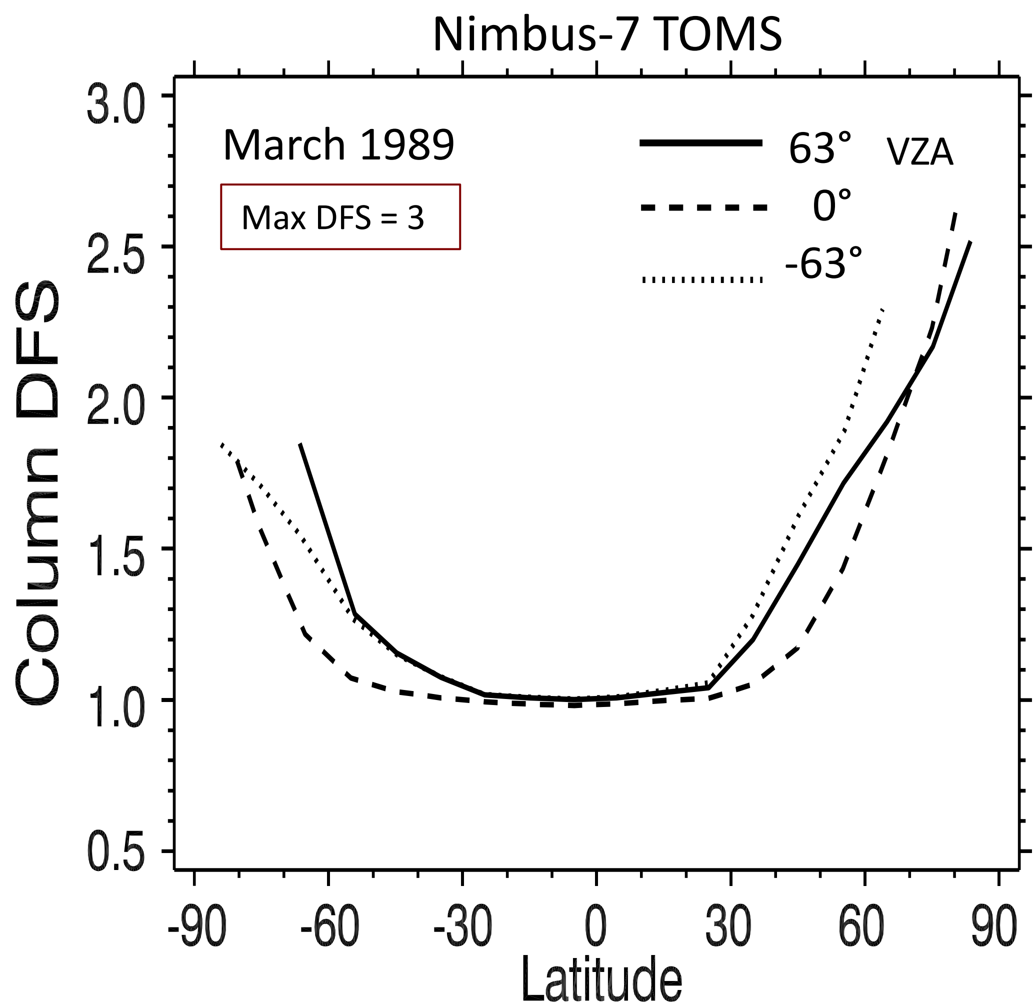
- Provide Error Bars to users. Frequent request
- Extend retrievals to 88° SZA
  - Report errors on challenging retrievals
  - Improve quality of these retrievals
- Supply information to estimate systematic error
- Simplify the entire algorithm
  - V8 performed well, but execution was far from seamless
  - Pair switching & complex correction for profile effect @ high SZA
  - 1512 a priori profile scheme tedious to construct/update
- Rodger's Optimal Estimation a good choice
  - Originally considered just for high SZA, worked well elsewhere

Simple = Fast

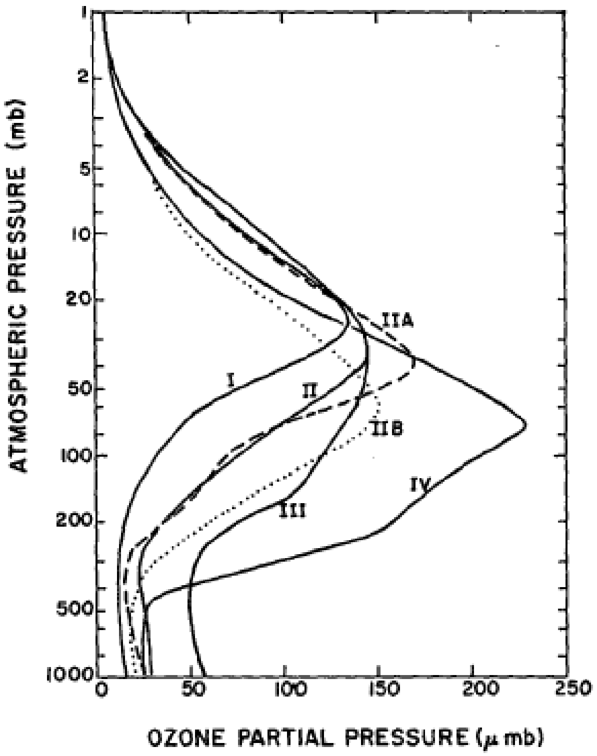
- Using selected wavelengths as opposed to range of λ in spectral fit or B/DOAS greatly reduces computer time.
- Speedy performance with 0.1% radiance accuracy achieved using radiance tables instead of on-line RTM in operational use.
- Good TOMS first guess quickly linearizes the retrieval so few if any iterations are necessary.

Basic TOMS V9 Ozone Retrieval

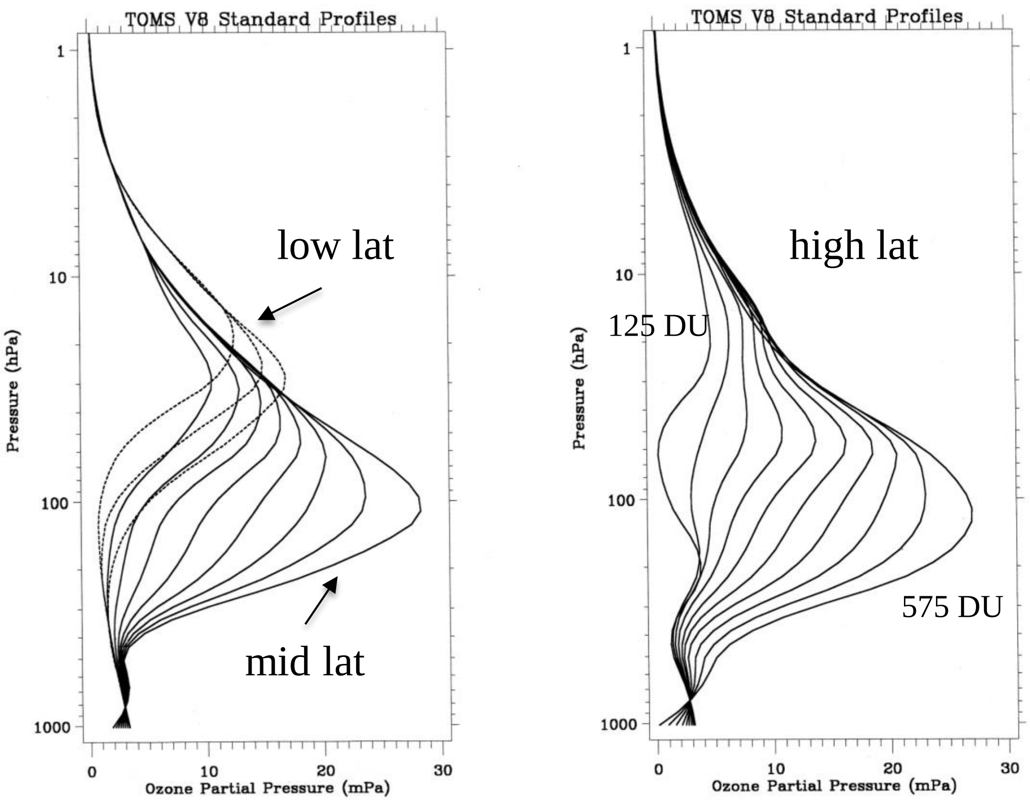
- Total O_3 by integrating profile
- Uses 3 λ Optimal Estimation
  - 312.5, 317.5, 331 nm
- Optimal estimation provides
  - Error bars
  - Efficiency factors / Error Kernels
  - DFS
- Use Brion et al. O_3 abs X-secs



TOMS Total O_3 Standard Profiles



Original Mateer profiles



V8 Profiles

Method works extremely well for retrieving total O_3 from variety of algorithms

New TOMS standard profiles

- The “TOMS standard profiles” consist of 21 profiles and vary with total column ozone and are used to create the radiance tables for TOMS, OMI, SBUV and OMPS total ozone and profile algorithms.

Tropics	0-30˚	225, 275, 325 DU (3)
Mid-Latitudes	30˚-60˚	225, 275…, 575 DU (8)
High Latitudes	60˚-90˚	125, 175…, 575 DU (10)

Note: Data from both hemispheres are combined in creating these profiles.

- Current profiles constructed > 2 decades ago from SBUV/SAGE and ozonesonde data. Ozone partial columns currently reported in 11 Umkehr layers.
- V9 TOMS profiles constructed using MLS and ozonesonde data, consistent with McPeters & Labow (ML). New profiles constructed as O_3 MR at Z* levels, extending from 0-80 km (in Z*).

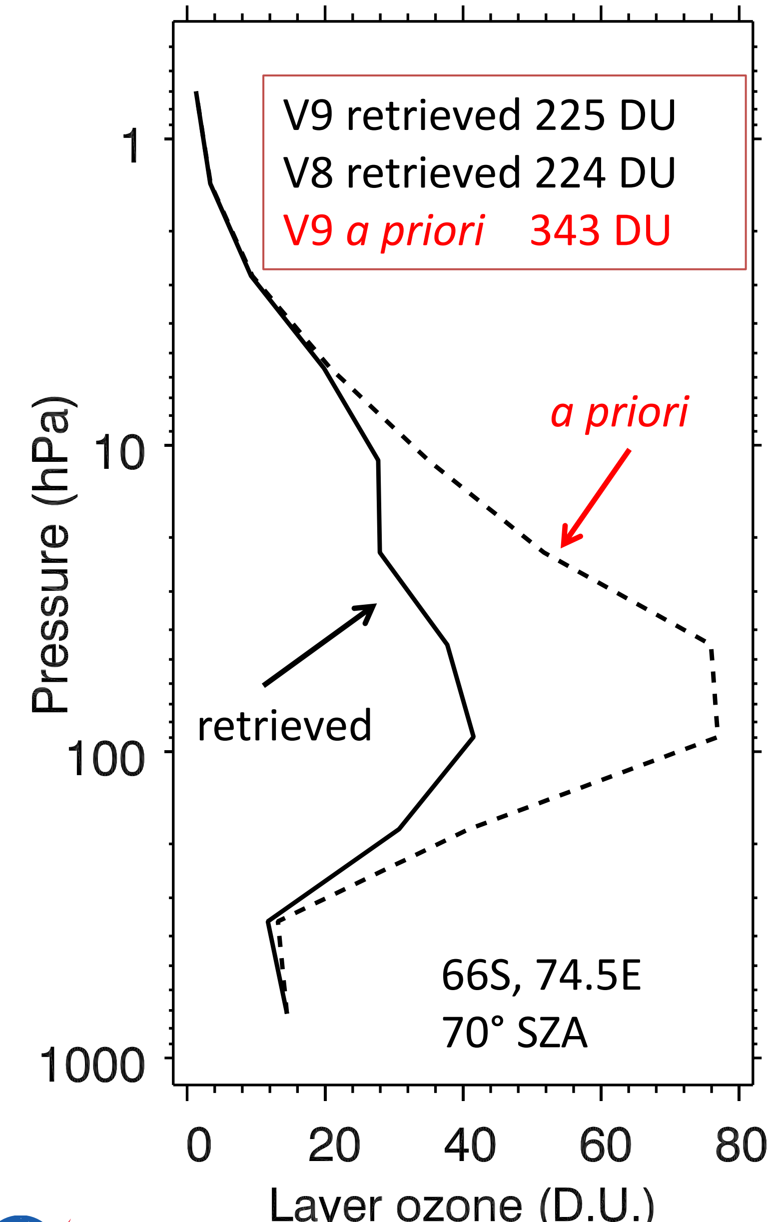
Dynamical O_3 Climatology from Residuals

Experimental. Goal is to use correlation between total ozone and the ozone tropopause to capture dynamical profile information in TOMS a priori. Create *a priori* that changes from pixel to pixel.

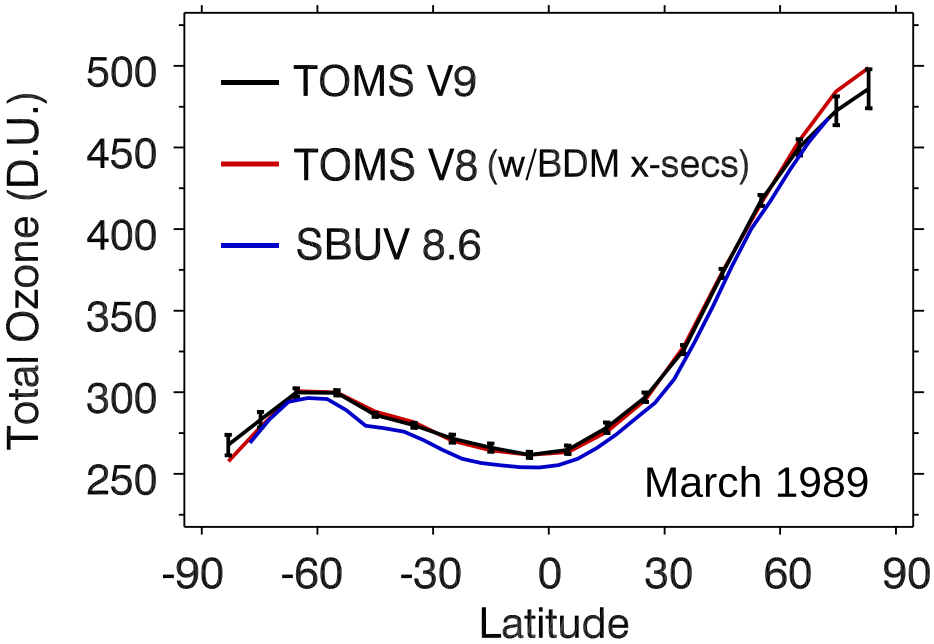
Important for short term dynamic variability (a GEO strength).

1. Calculate variance of the residuals obtained after subtracting TOMS std. profiles from the original profile data.
2. New climatology is avg. of residuals in 18 lat. x 12 mo.
3. Add residuals to standard profile matching F.G. total column. This only changes the profile, not the column amount.
4. Variances for *a priori* constructed similarly. **They are reduced**.
5. Expect results from this total O3 driven a priori at least as good as those driven by external NCEP Temp / PV.

V9 TOMS Retrieved Profiles

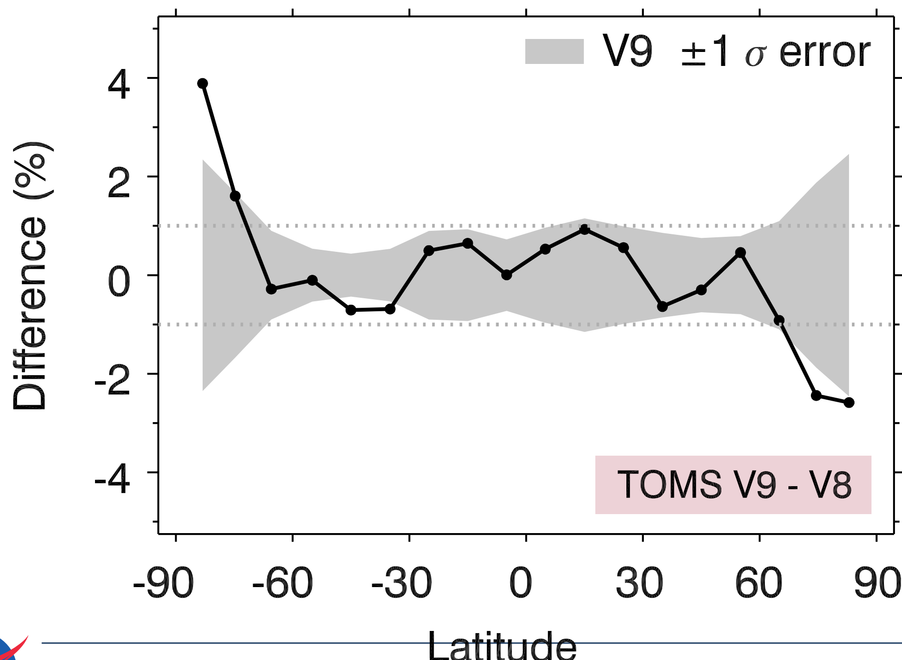


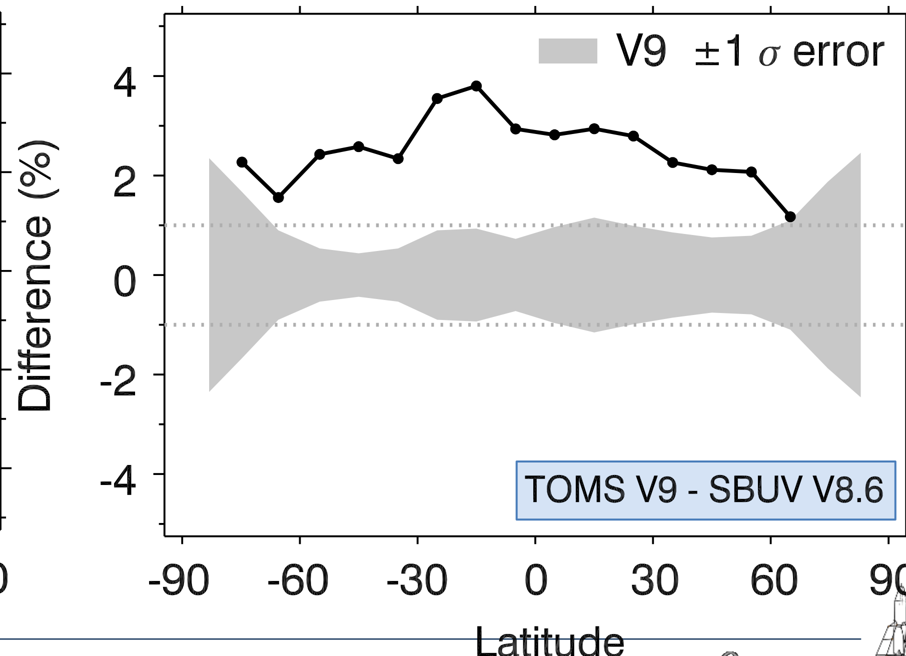
- Profiles (x_j) retrieved as O_3 in 11 layers
- Provides total ozone with a consistent profile
- Profile retrieval reduces profile shape related error – affects shorter wavelengths, benefits SO_2, UV-B estimates.



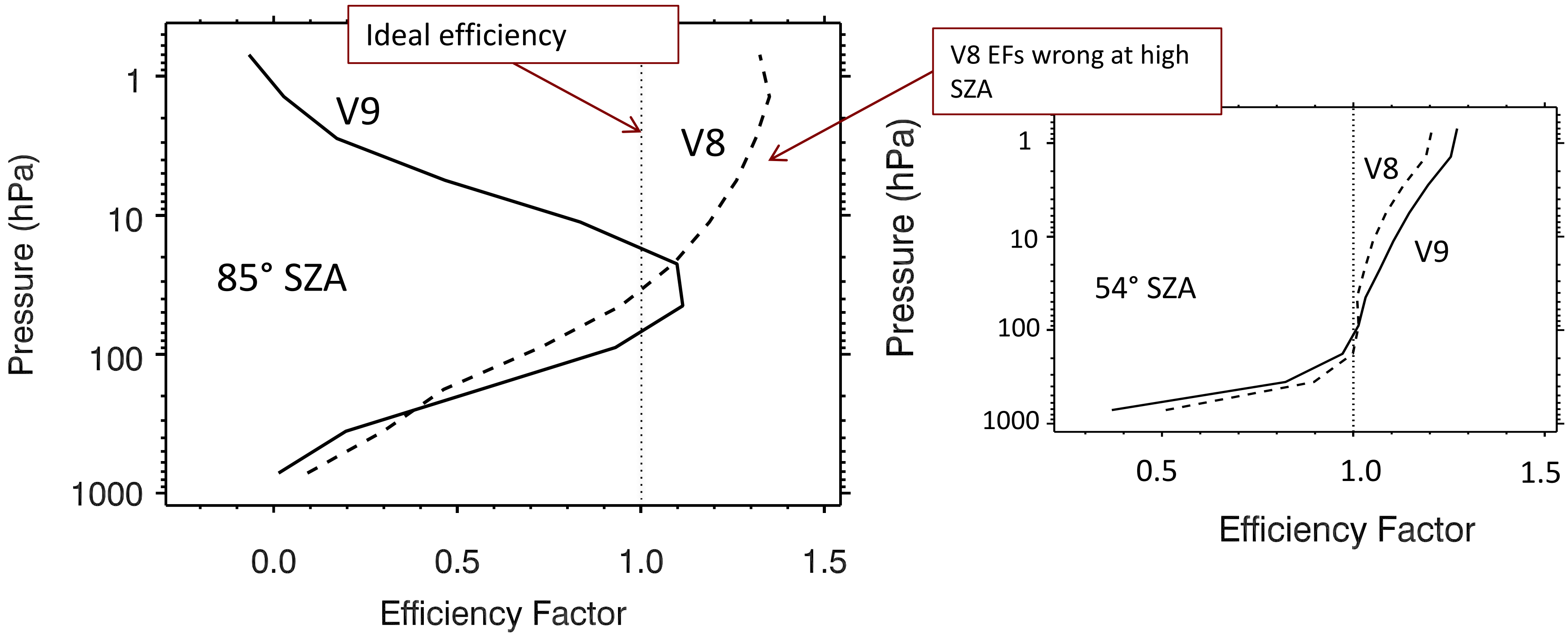
Total Ozone Comparisons with TOMS V8 and SBUV V8.6 in March 1989

- V9 agrees with V8 within error bars (1-2%) to 84° SZA
- V9 reduces error at SZA > 70° (compared to SBUV V8.6)
- V9 bias must be removed



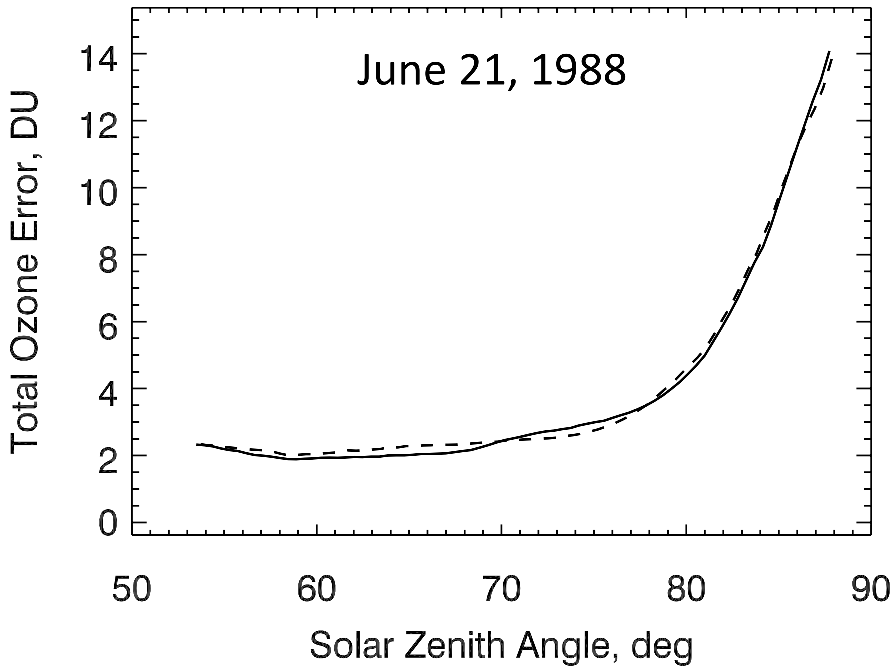


TOMS Efficiency Factors for 3 λ

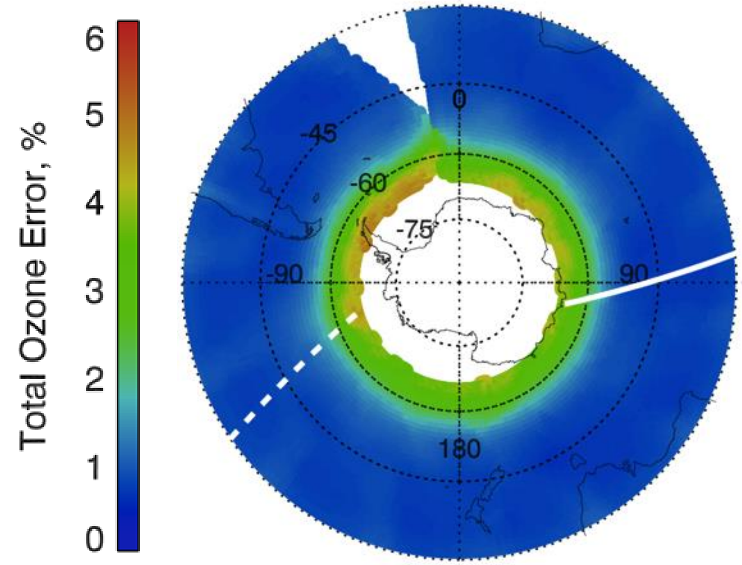


Integrating Kernel (IK)	→	**Column Integrating Kernel (CIK)**	→	**Efficiency Factors (EF)**
$\mathbf{W} = \mathbf{S}_x \mathbf{K}_1^T (\mathbf{K}_1 \mathbf{S}_x \mathbf{K}_1^T + \mathbf{S}_e)^{-1} \mathbf{K}_1$		$\mathbf{W}^C = \sum_i w_{ij}$		w_j^C
(a.k.a. Averaging Kernel)		sum over columns of IK		elements of CIK

Dependence of Error with SZA

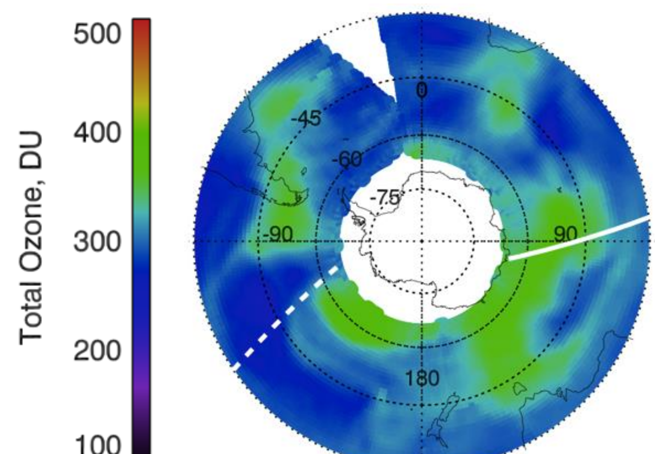


Column Error

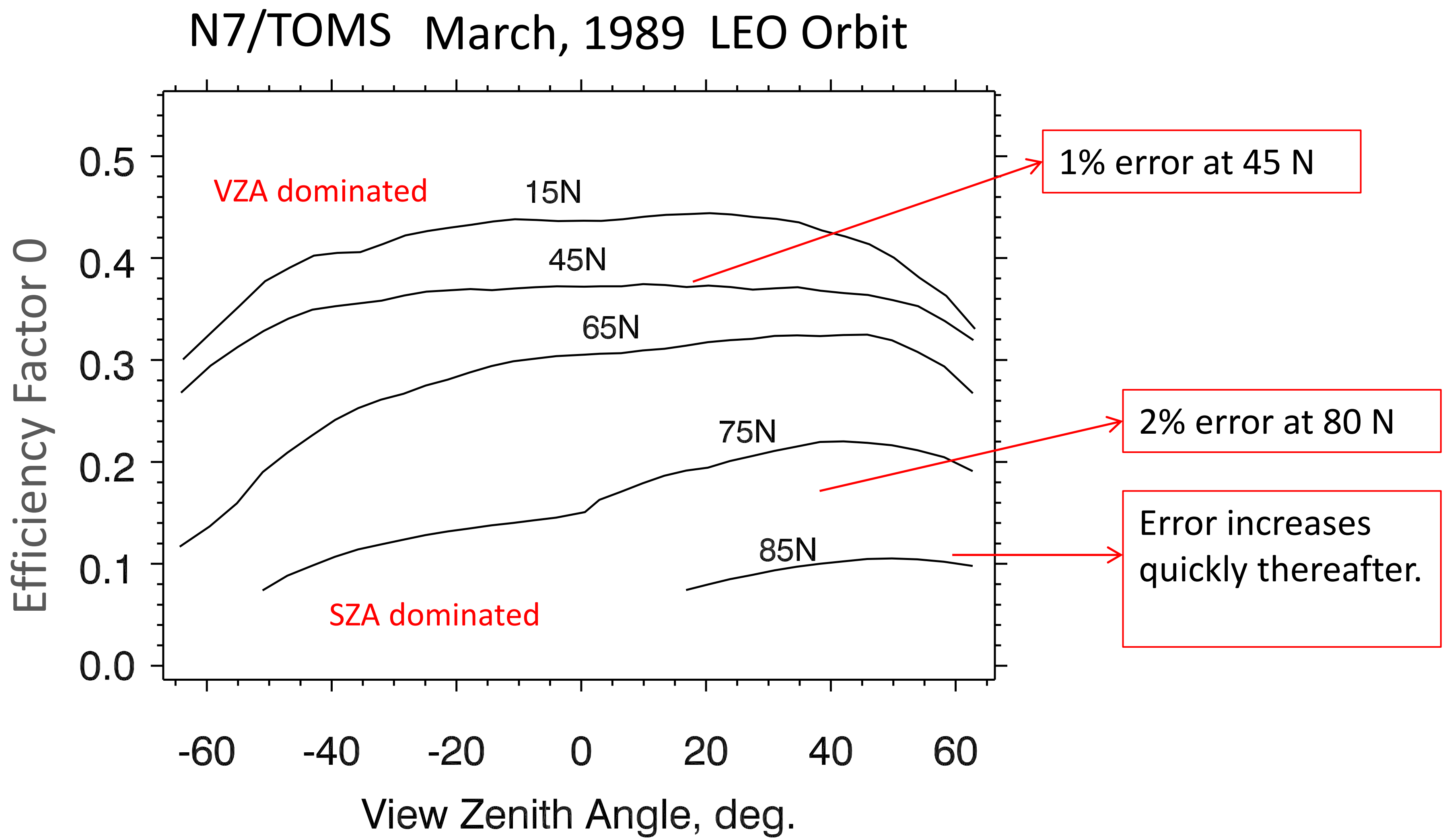


- Error varies by factor of 10.
- Most dependence is w/ SZA, not O_3, VZA.
- Reason: EFs reduce dramatically in lower atmosphere as path length increases.
- Less info. from measurements → greater reliance on *a priori* → larger uncertainty.

Column Amount



Overall Dependence of Error on Geometry



The SLER Model

For Lambertian Reflecting Surface:

$$I = I_0 + \frac{RT}{1 - RS_b}$$

$$R = \frac{(I - I_0)}{T + S_b(I - I_0)}$$

- R is called Lambert-equivalent Reflectivity (LER)
- R and its spectral dependence can be calculated from radiances measured at wavelengths where the atmospheric absorption is small. For TOMS we use 340 and 380 nm.
- The method works best when one ignores cloud height, and assumes that clouds are at the surface. (See Ahmad et at., 2004)
- Clouds/aerosols properties are treated the surface

Aerosol Correction

- If uncorrected, aerosol absorption appears as ozone enhancement.
- For low and moderate aerosol amounts, R-λ correction removes this effect
  - Retrieve LER at 340 and 380 nm
  - Linearly extrapolate R to O_3-absorbing λs
  - Retrieve O_3 with wavelength dependent R
- Approach fails for thick aerosols
  - Use more sophisticated correction or just flag data (not frequent).

Effects of cloud on TOMS

- Modifies Rayleigh/Raman scattering
  - Largely a function of cloud transmittance ($1-A_c$).
- Reduces sensitivity to ozone in lower trop
  - O_3 below cloud OCP is typically 10 DU.
- Increases sensitivity to O_3 above clouds
  - Largely a function of cloud albedo (A_c).
- Since low level clouds increase ozone absorption above ~3 km and decrease it below, the two effects largely cancel out.

Some Implications of TOMS V9 for GEMS

- Performance & accuracy make it well suited for operational GEO O_3 retrievals (demanding users).
- Algorithm should satisfy wide range of users
  - Error bars, DFS, Error Kernels useful for assimilation and inter-comparisons with models/measurements.
- OE approach is inherently flexible
  - Can increase wavelengths and layers to convert to robust profile algorithm. Apply to window and becomes spectral fit.
  - Dynamical a priori expected to improve response of algorithm to short term variability.

Summary

- V9 TOMS achieves comparable accuracy to V8 with OE profile retrieval and provides error bars and other info. users have wanted.
- The algorithm is efficient and well suited to operational implementation.
- Retrievals can extend to 88° SZA – useful for GEO.
- Retrieval errors originate mostly in lower atm where Rayleigh scattering limits retrieval of O_3 information.
- V9 algorithm is flexible with OE. Dynamical *a priori* under investigation.
- The SLER does very good job in estimating effect of clouds on Rayleigh.
- Linear R-λ correction can account for residual errors, ocean/land color, sea glint, and aerosols
- Shielding of trop O_3 by clouds is quite small, and doesn't require an elaborate correction method.

Backup

Thoughts on TOMS V9 and SOE

- TOMS V9 driven by need to be compatible with TOMS instruments (+OMI, OMPS).
- TOMS V9 the basis for V9 profile algorithm. With modifications, V9 and SOE may look quite similar. We'd like to add Chappuis too someday.
- Discrete band vs. spectral fit philosophy:
  – We may prefer to limit spectral info. to only what's necessary to remain fast, maintain high SNR, avoid or reduce sensitivity to calibration and Ring error.
  – Analysis of residuals is somewhat different.

Measurement at Extreme viewing geometries presents challenges

– Larger retrieval errors at high SZA (now reported)
– Larger forward model errors (RT, surface models) at greater θ_o, θ, ϕ.
– Data available to help to evaluate these issues for UV/VIS trace gas and aerosol retrievals
– OMI: afternoon orbit + large swath angles give extreme relative azimuth
– Meteor-3: 212 day orbital precession supplies high SZA conditions at lower latitudes

Total O_3 Accuracy and Precision from the TOMS Algorithm

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. D4, PAGES 5239–5247, JUNE 30, 1984

Intercomparison of the NIMBUS 7 SBUV/TOMS Total Ozone Data Sets With Dobson and M83 Results

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Key Conclusion

……TOMS instrument is producing daily global ozone maps with between 50 and 150 km resolution; each measurement on this map has accuracy and precision comparable to the best-run stations in the Dobson network.