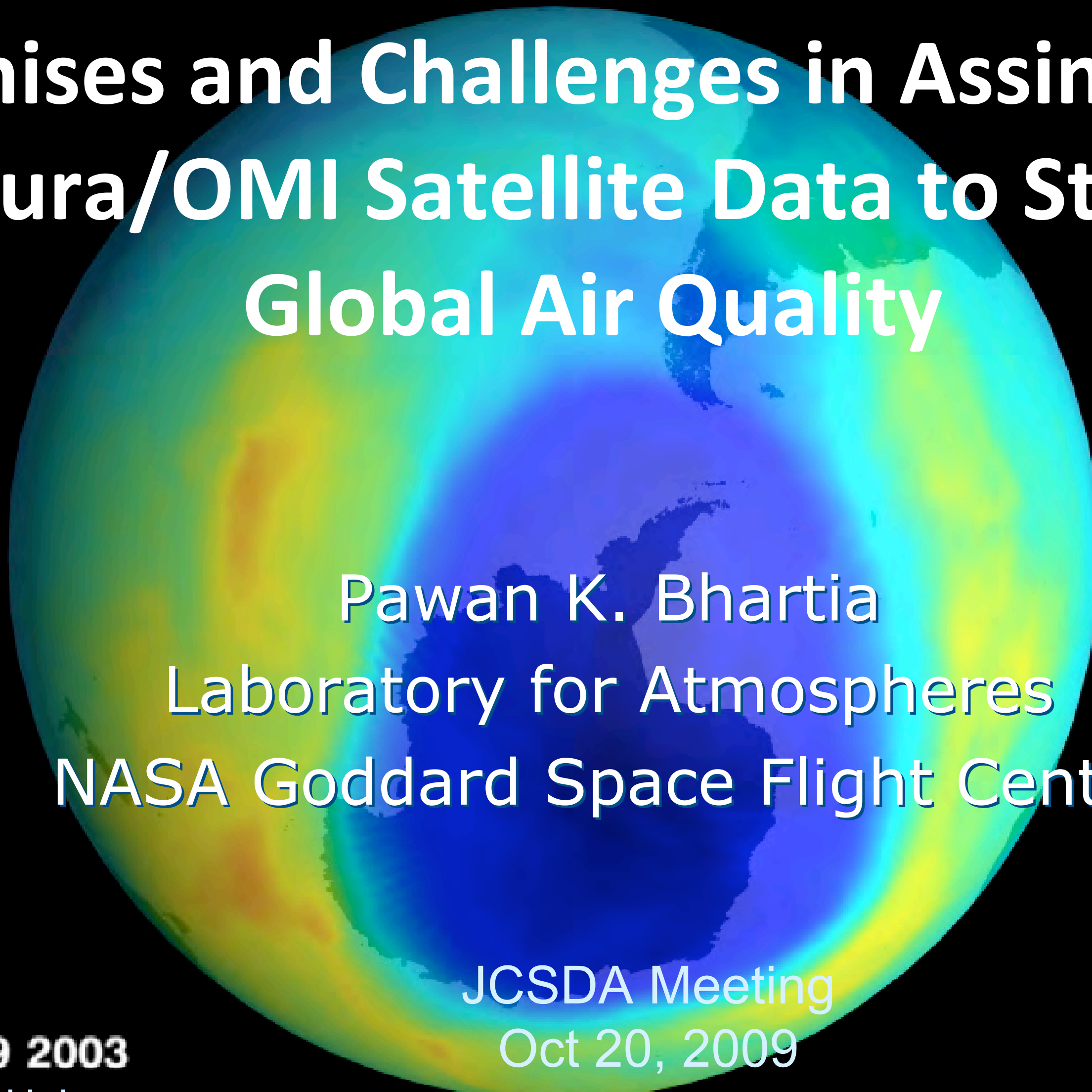
Promises and Challenges in Assimilating Aura/OMI Satellite Data to Study Global Air Quality



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Laboratory for Atmospheres

NASA Goddard Space Flight Center

JCSDA Meeting

Oct 20, 2009

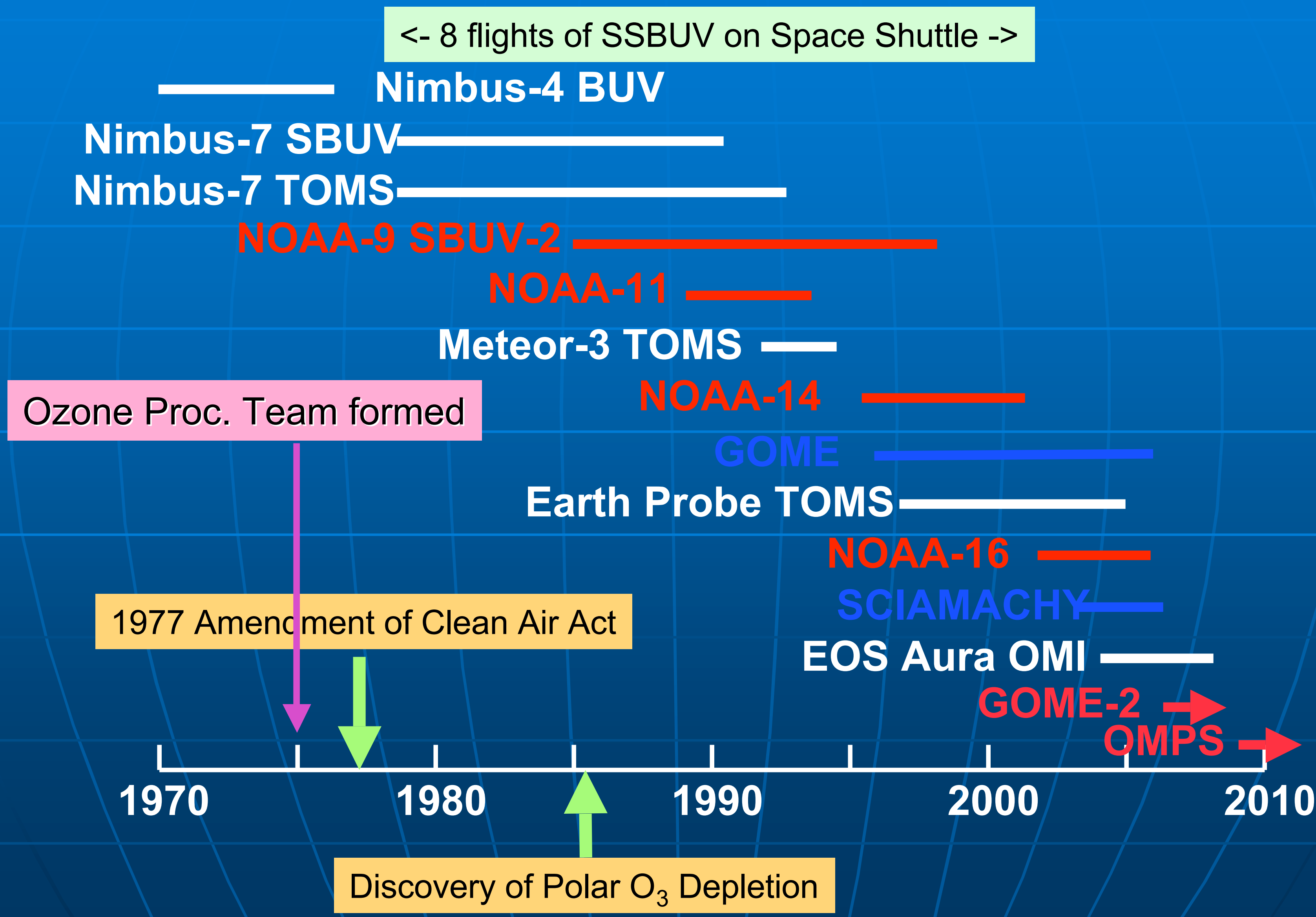
Sep 29 2003

Ozone Hole

1^{st} generation Instruments

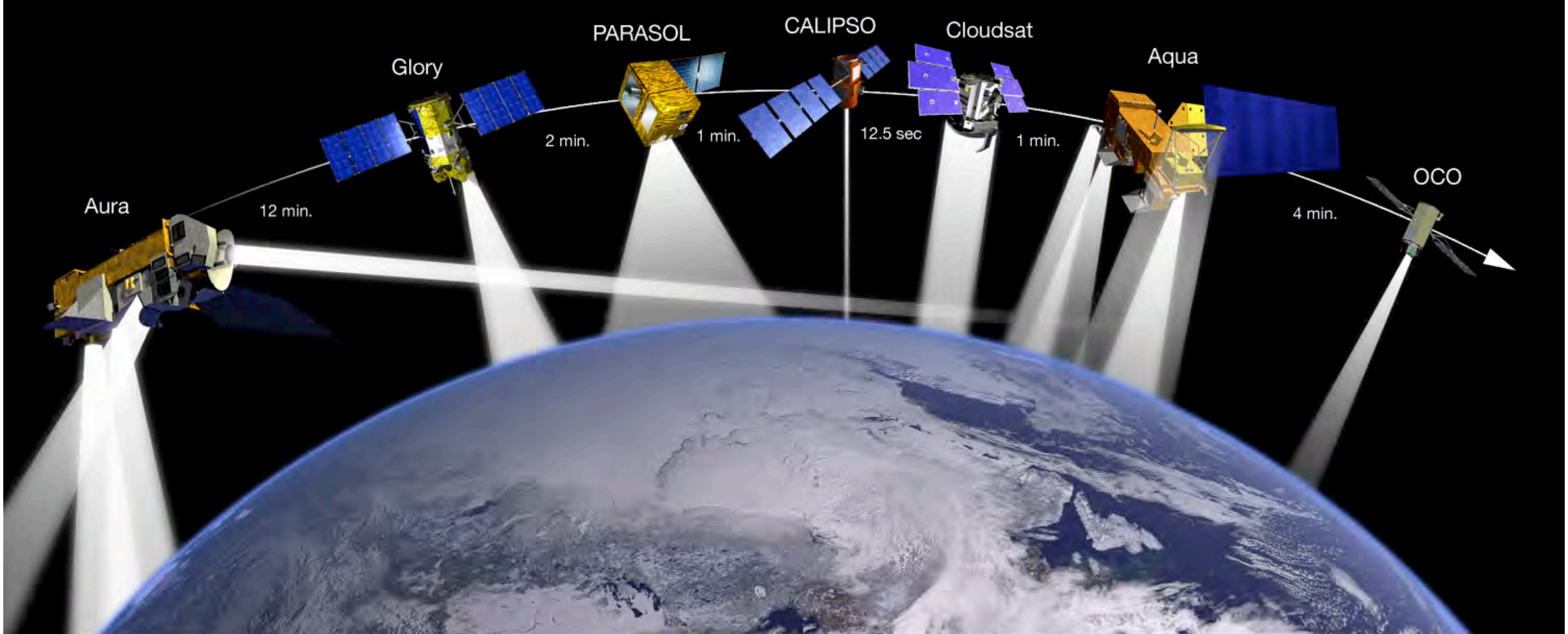
- Backscattered UV (BUV, SBUV, SBUV/2)
  - 12 discrete λs (250-340 nm), 1nm bandpass
  - Nadir only, 11° IFOV (~200 km)
  - Product: O_3 profile at 6-25 km vert resolution
- Total O_3 Mapping Spectrometer (TOMS)
  - 6 discrete λs (312-380 nm), 1 nm bandpass
  - 102° x-track scan (2600 km swath), 3° IFOV (~50 km).
  - Designed for total column O_3 only but yielded unexpected dividends.

40 Years of BUV Observations



National Aeronautics and Space Administration

The Afternoon Constellation "A-Train"



Composite: Alex McClung
Earth image: Reto Stockli

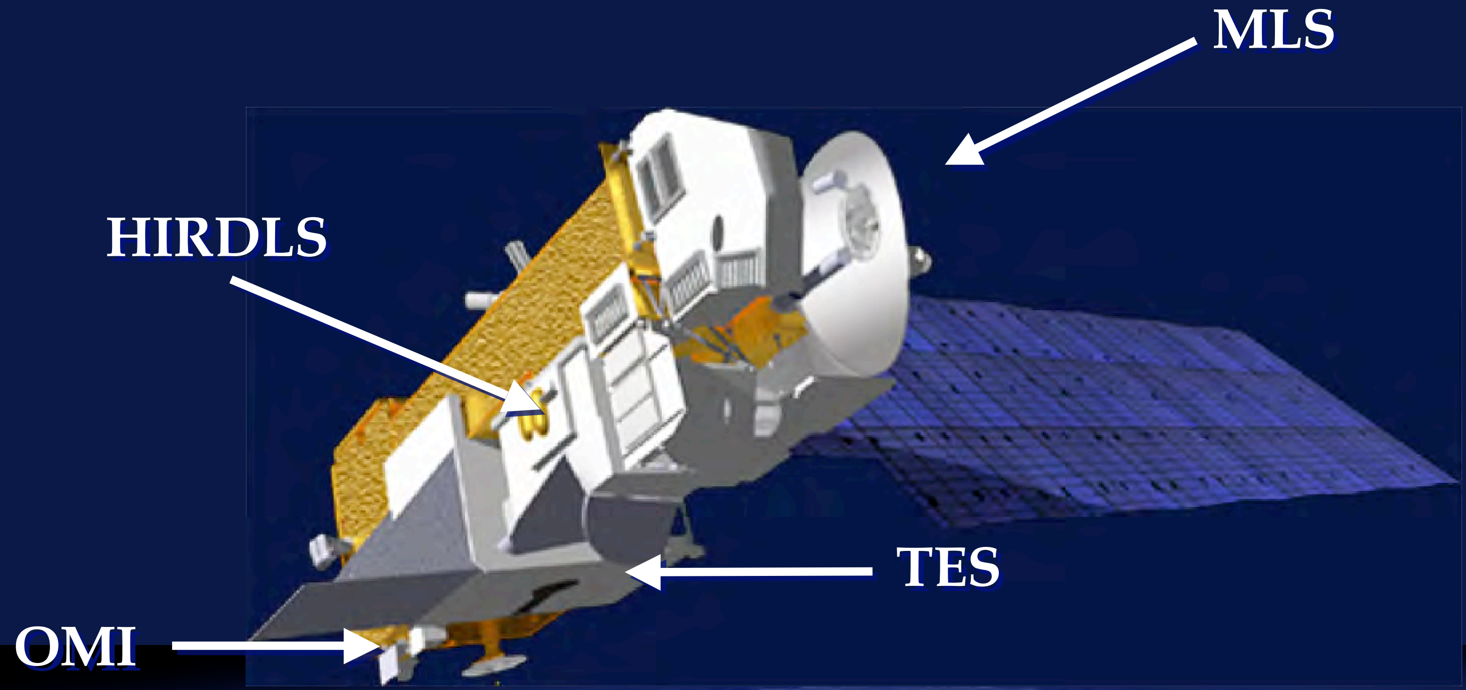
The Afternoon Constellation consists of 7 U.S. and international Earth Science satellites that fly within approximately 30 minutes of each other to enable coordinated science. The joint measurements provide an unprecedented sensor system for Earth observations.

United States · Brazil · Canada · Finland · France · Japan · Netherlands · United Kingdom

www.nasa.gov

EOS AURA

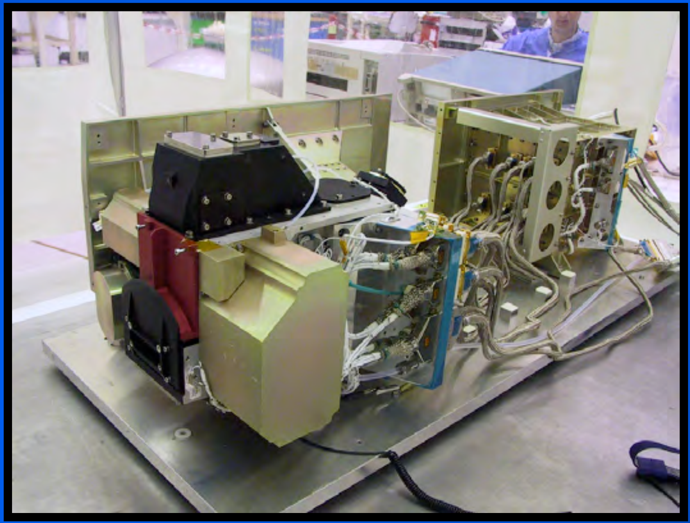
- Orbit: Polar: 705 km, sun-synchronous, 98° inclination, ascending 1:45 PM +/- 15 min. equator crossing time.
- Launch Vehicle: Delta 7920 from VAFB, July 15, 2004
- AURA follows AQUA in the same orbit by 15 minutes.
- Six Year Spacecraft Life

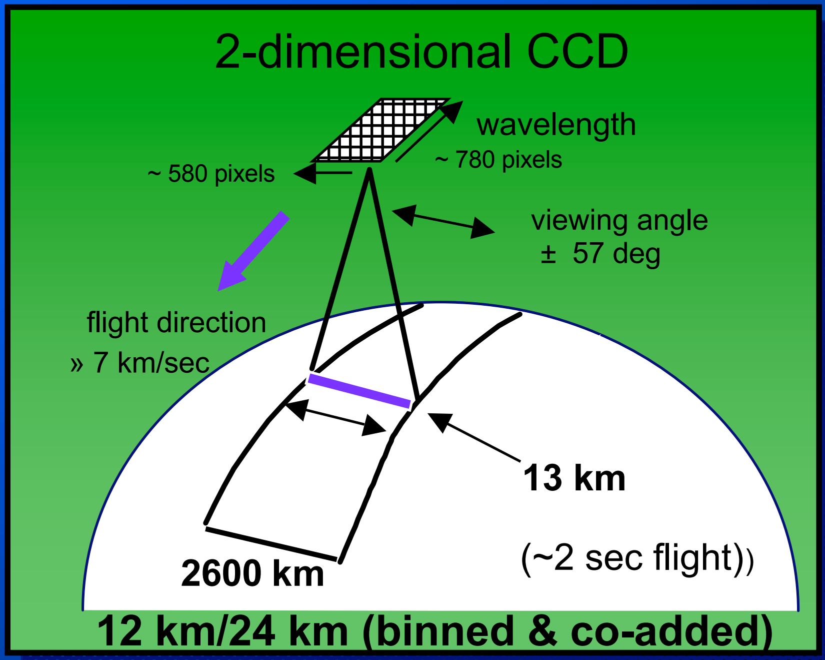


OMI

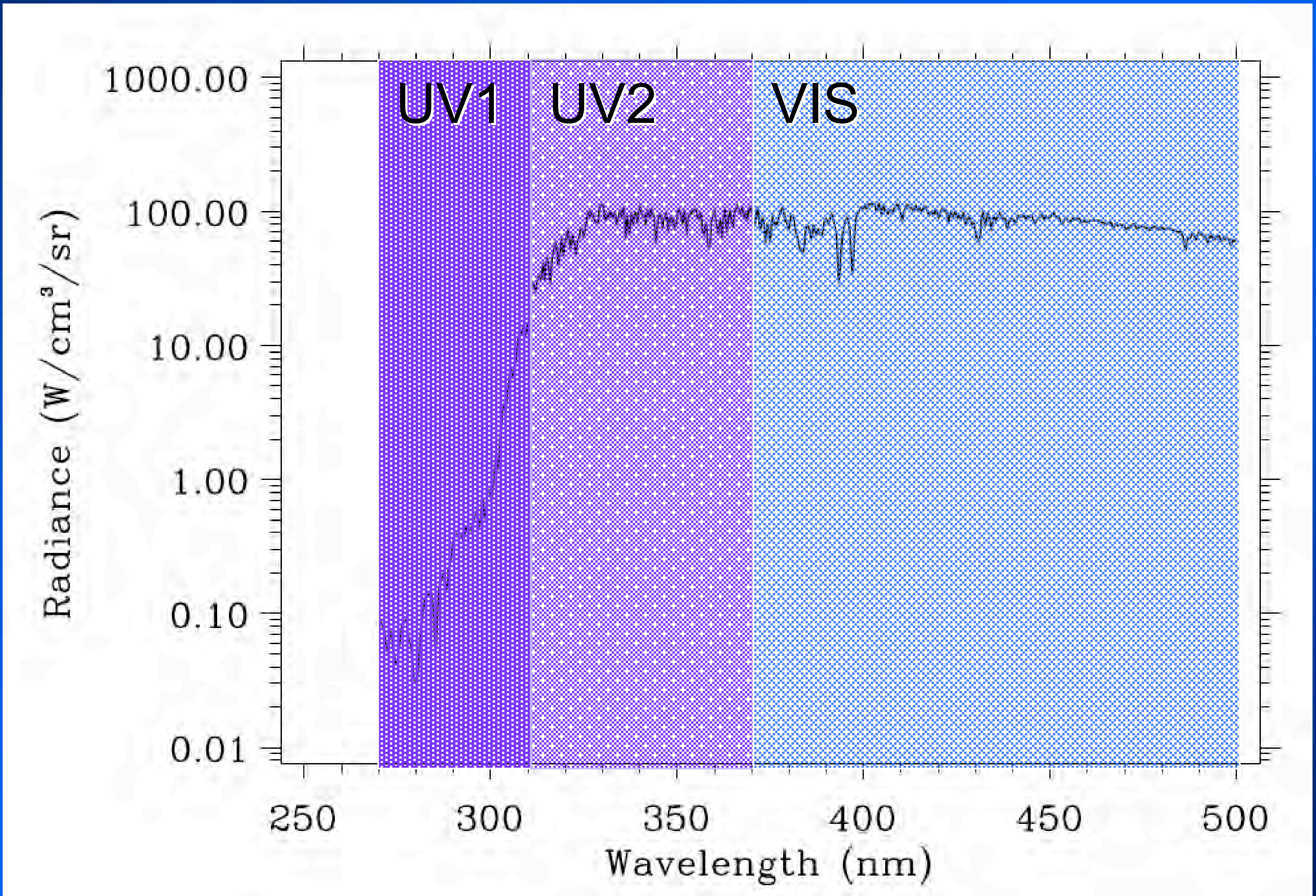
Ozone Monitoring Instrument

- Joint Dutch-Finish Instrument with Duch/Finish/U.S. Science Team
  - PI: P. Levelt, KNMI
  - Hyperspectral wide FOV Radiometer
    - 270-500 nm
    - 13x24 km nadir footprint
    - Swath width 2600 km
  - Radicals: Column O_3, NO_2, BrO, OClO
  - O_3 profile ~ 5-10 km vert resolution
  - Tracers: Column SO_2 , HCHO
  - Aerosols (smoke, dust and sulfates)
  - Cloud top press., cloud coverage
  - Surface UVB
  - Tropospheric ozone





Typical OMI Spectrum



Ozone Products from OMI

1. Total O_3 Column (3)
2. Partial O_3 columns (2)
3. O_3 MR vs pressure (2)
4. Trop O_3 column (3)

*Numbers in the parenthesis are the number of different algorithms that currently exist. Additional algorithms are being planned!

OMI Total O_3 Column Algorithms

- TOMS Version 8.5
  - Based on TOMS V8. Uses cloud optical centroid pressure derived from Raman filling-in (Ring effect), instead of IR-based climatology.
- DOAS
  - Developed at KNMI/NL. Uses cloud effective pressure derived from O_2-O_2 absorption. Differs from MetOp/GOME-2 DOAS algorithm.
- Optimal Estimation
  - By integrating retrieved O_3 profiles. Similar to SBUV.

Data Assimilation Issues

- What information does total O_3 contain?
- How important is the knowledge of O_3 profile to retrieve total O_3?
- How do clouds affect the retrieval?
- How do aerosols affect the retrieval?
- Can we assimilate radiances instead and avoid all these problems?

What information does total O_3 column contain?

- Facts:
  - Total O_3 is poorly correlated with O_3 at or above the altitude where the O_3 density peaks (~22 km), thought it contains ~50% of the total column.
  - Outside the tropics ~70% of the variation in total O_3 comes from 10-20 km that contains only ~25% of the column.
  - In the tropics ~50% of the variation in total O_3 is caused by the troposphere that contains only ~10% of the column.

Total Ozone Estimation Using the BUV Technique

JOURNAL OF THE ATMOSPHERIC SCIENCES

A Preliminary Study on the Possibility of Estimating Total Atmospheric Ozone from Satellite Measurements

J. V. DAVE AND CARLTON L. MATEER

National Center for Atmospheric Research, Boulder, Colo.

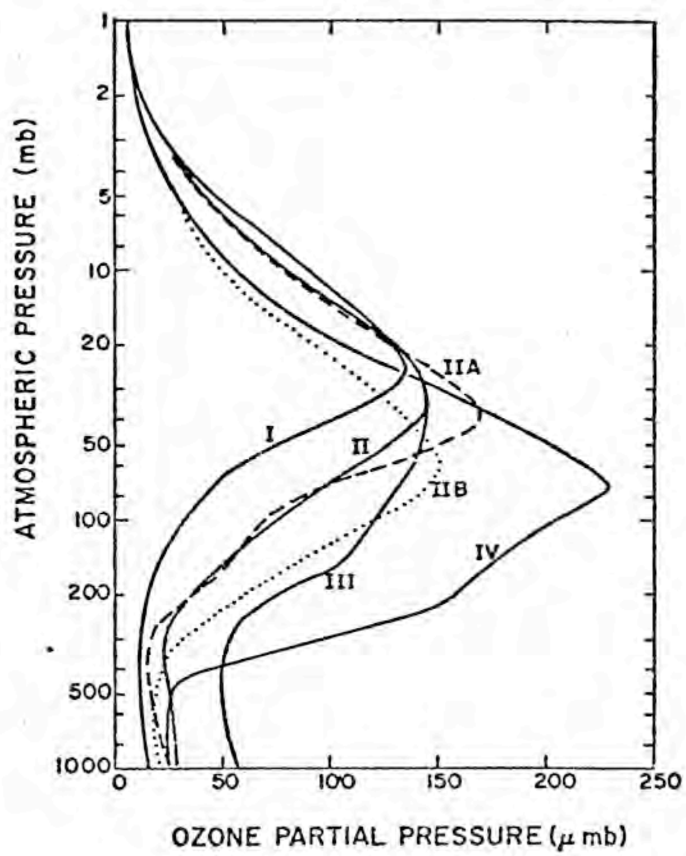
(Manuscript received 31 October 1966, in revised form 6 March 1967)

KEY IDEAS

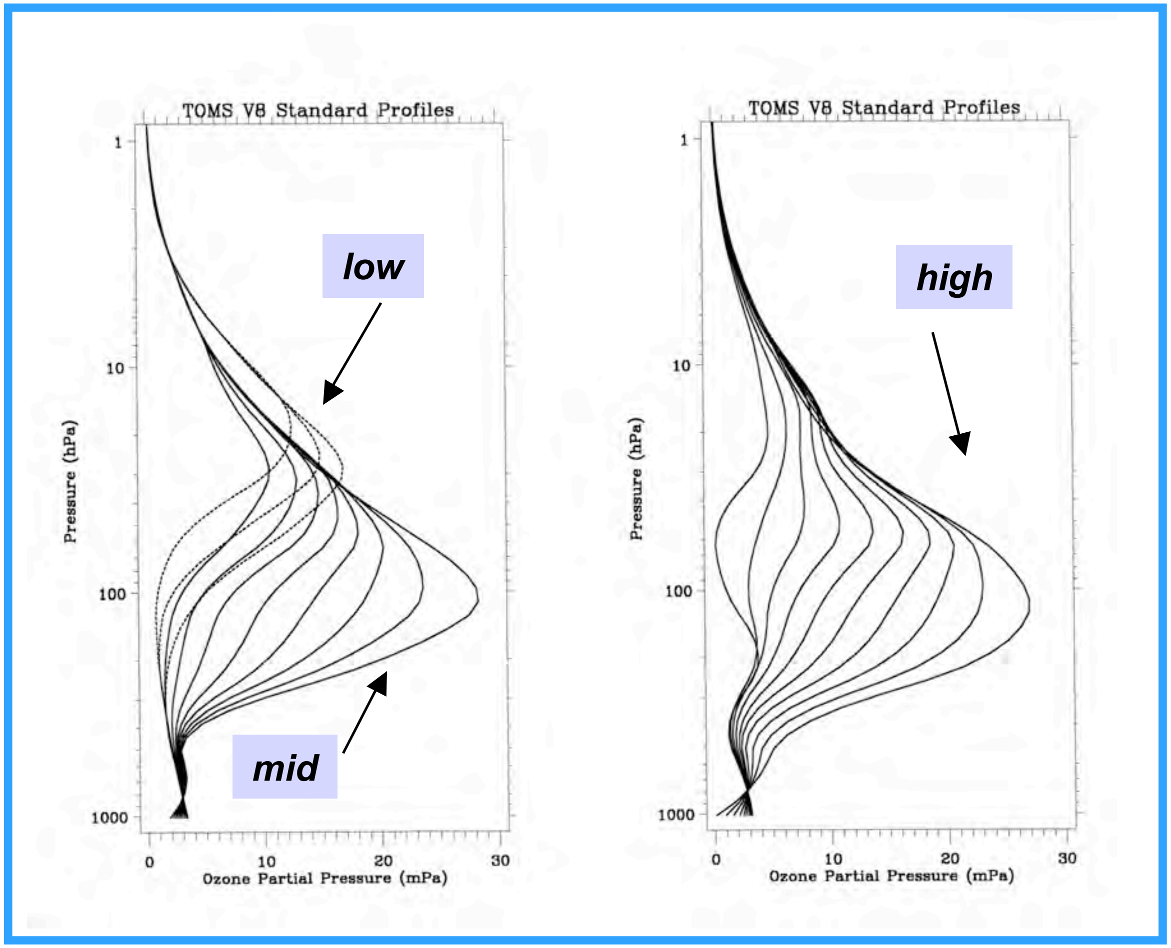
- ***Use Multiple Wavelengths Pairs***
- ***Standard Ozone Profiles- defined by total O_3***
- ***Treat Cloud and Aerosols as Opaque Lambertian Surface (LER model)***

Total Ozone Dependent Standard Profiles

ORIGINAL VERSION



MODERN VERSION

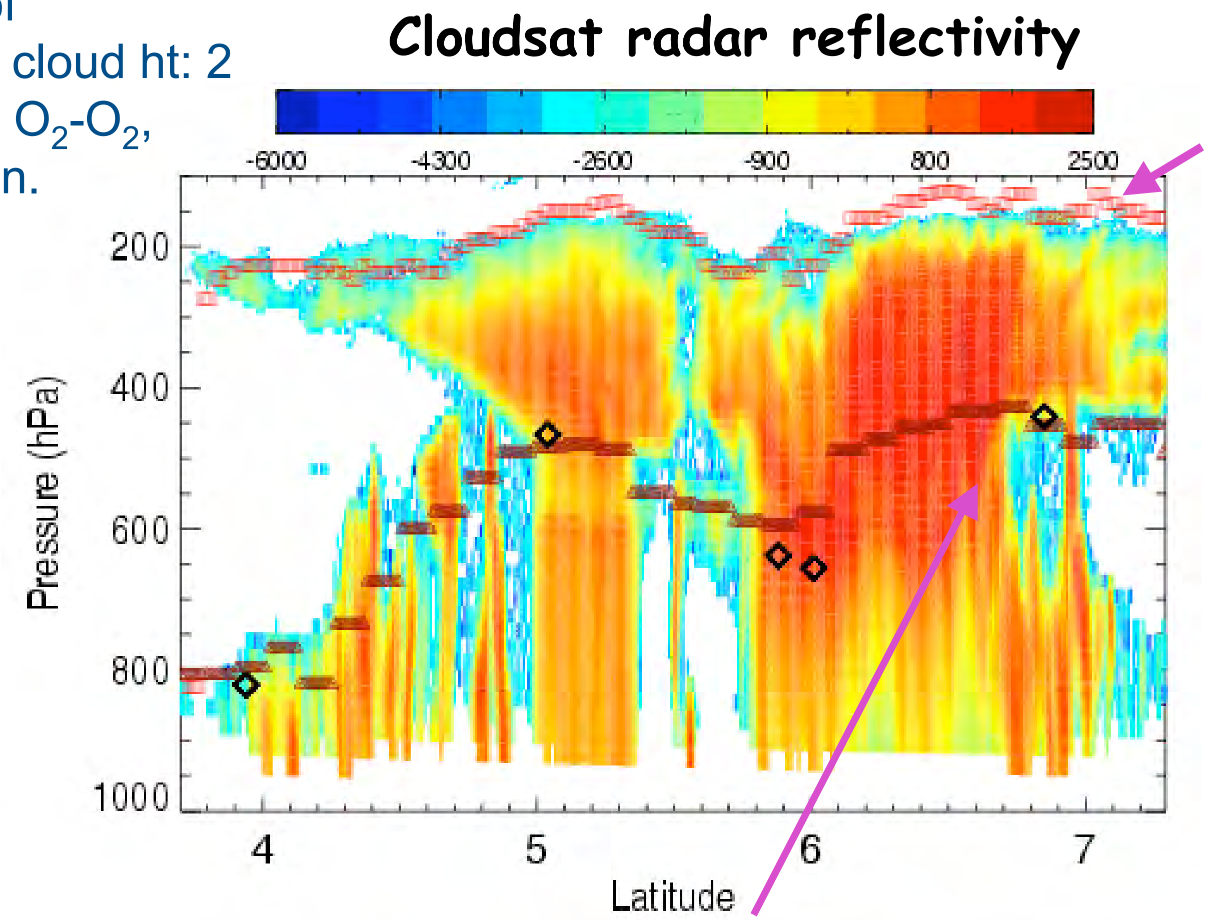


How important is the knowledge of profile to derive total O_3?

- Not very important (up to SZA ~80˚) if one uses TOMS "standard" profiles that vary with total O_3 and latitude.
- Climatological profiles that vary with month/lat and are proportionally adjusted with total column can produce large errors @ SZA>60˚.
- Use of TOMS standard profiles would very likely improve retrieval of total O_3 from IR sounders (TOVS, AIRS, IASI, CrIS).

Multi-phase/Multi-layer Cloud Effects

There are 5 different methods of estimating cloud ht: 2 TIR, O_2-A, O_2-O_2, and Raman.

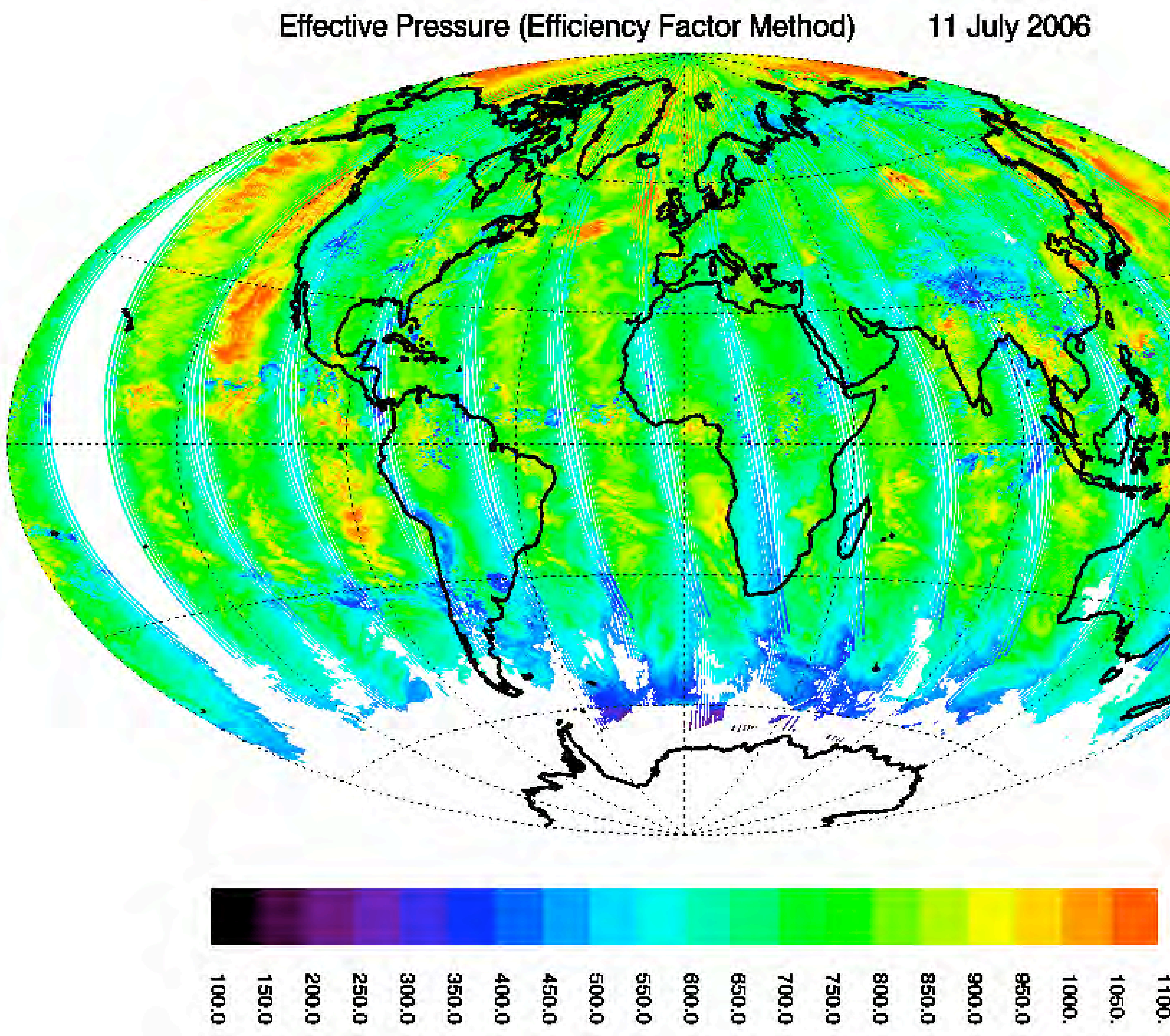


MODIS cloud-top press is insensitive to cloud vertical structure

Cloud Optical Centroid press calculated using OMI-measured Rot Raman Scattering is sensitive to cloud vert structure (ref : Vasilkov *et al*.,JGR, '08)

Summary of Cloud Effects

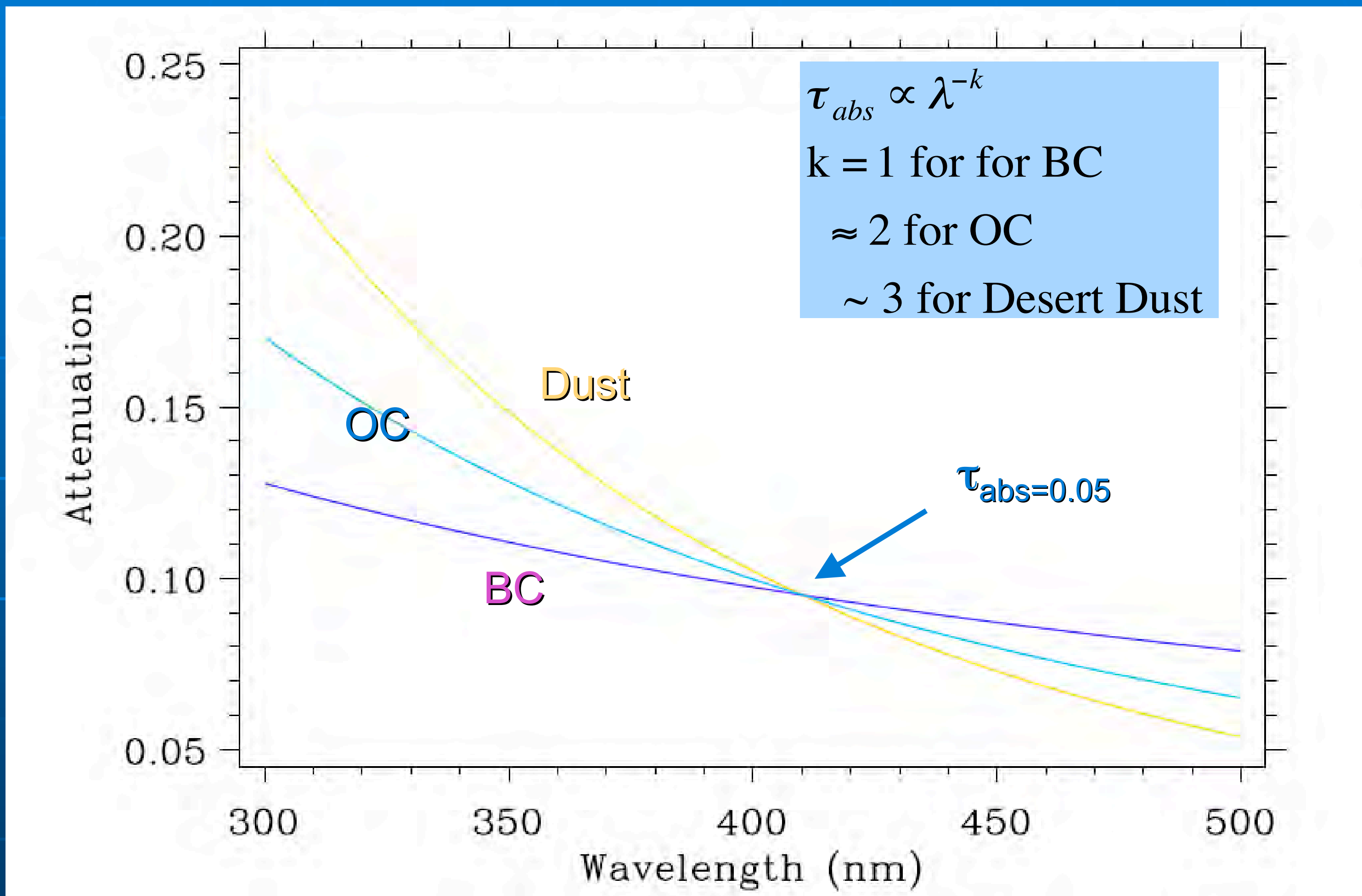
- IR cloud heights can be used only when the clouds are single-layered and <1 km thick.
- In OMI pixels ~40% of the clouds are either multi-layered or vertically extended (ref: Joiner et al., 2009). GOME-2 and OMPS pixels are likely to be worse.
- Use of optical centroid press derived from Raman filling-in (Ring effect) is currently the best way to account for clouds in UV, though, strictly speaking, the method is accurate only if O_3 is well-mixed in the troposphere.


Effective Pressure (Efficiency Factor Method)
11 July 2006
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
650.0
700.0
750.0
800.0
850.0
900.0
950.0
1000.
1050.
1100.

Summary of Aerosol Effects

- Boundary layer aerosols have no significant effect. Elevated aerosols (primarily smoke and desert dust) greatly reduce the sensitivity to O_3 below the altitude where they are located.
- Primary reason is high UV absorption of these aerosols. These aerosols also have a large (up to 30%) impact on the estimation of surface UV radiation.
- To estimate and correct for these effects we need to know τ_{abs} and aerosol centroid press. (Surface UV is not affected by aerosol ht.) We are trying to estimate both using OMI data.

How do aerosols absorb in the UV?



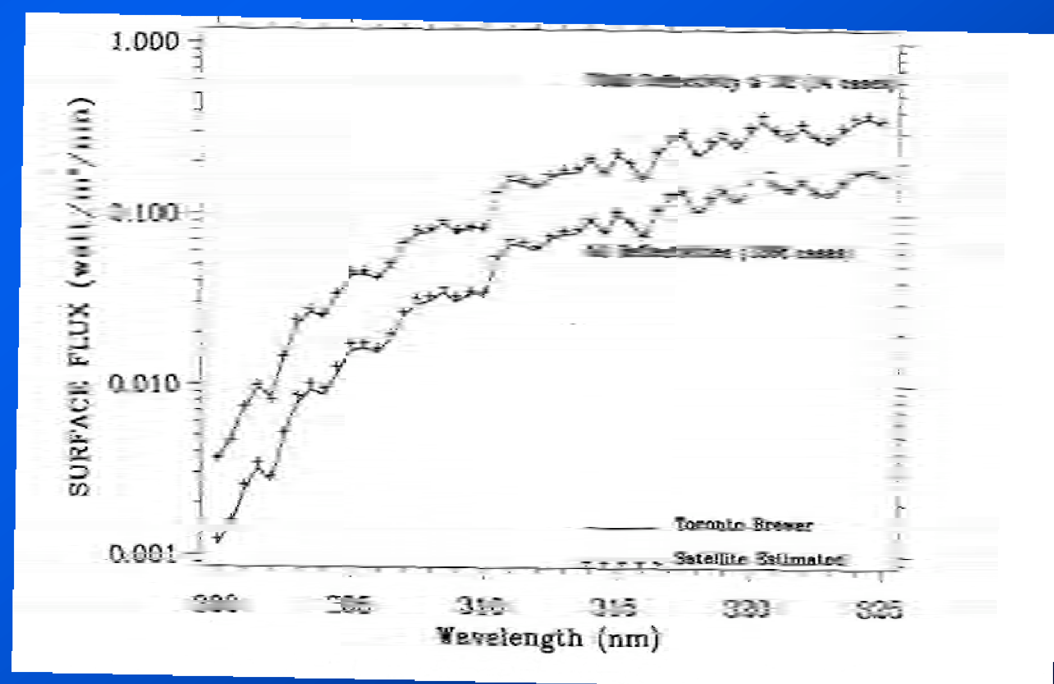
UVB Estimation Using the BUV Technique

GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 5, PAGES 611-614, MARCH 1, 1995

Satellite estimation of spectral UVB irradiance using TOMS derived total ozone and UV reflectivity

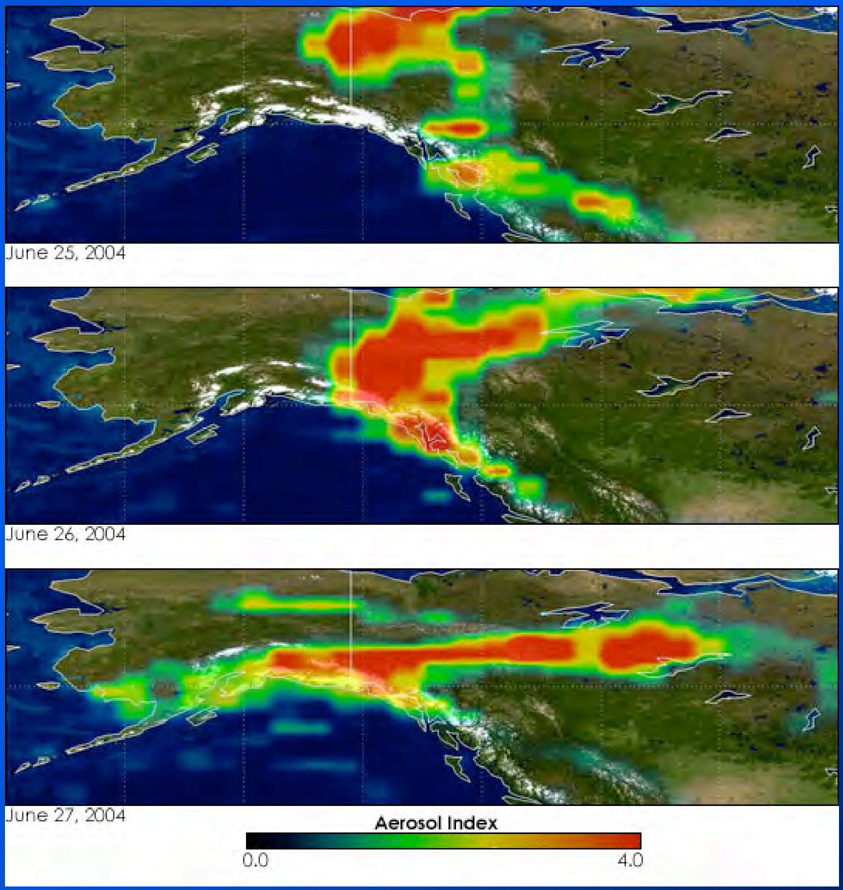
T.F. Eck [1], P.K. Bhartia [2], and J.B. Kerr [3]

Comparison of TOMS-derived UVB (symbols) with an accurate ground-based instrument (lines). The good clear-sky comparison (upper curve) was an expected result, but similar results under all-sky conditions (lower curve) were quite unexpected. Other comparisons show that aerosols can produce up to 30% errors due to their high UV absorption.



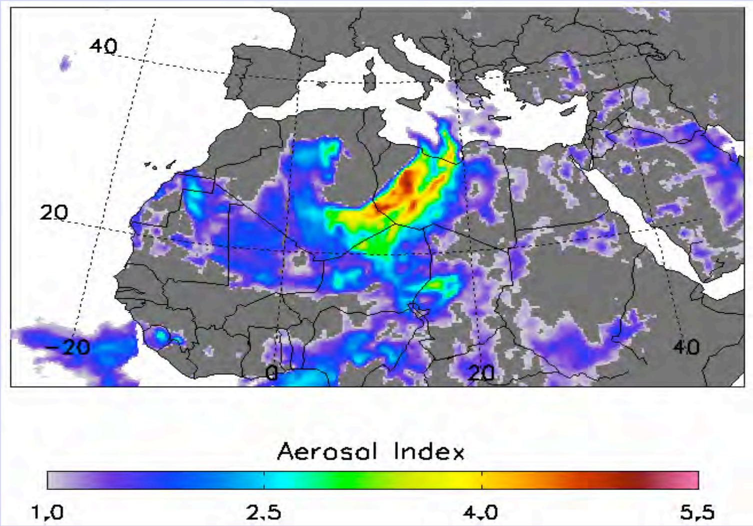
Alaska Fires, June 25-27, 2004

SeaWiFS June 27, 2004



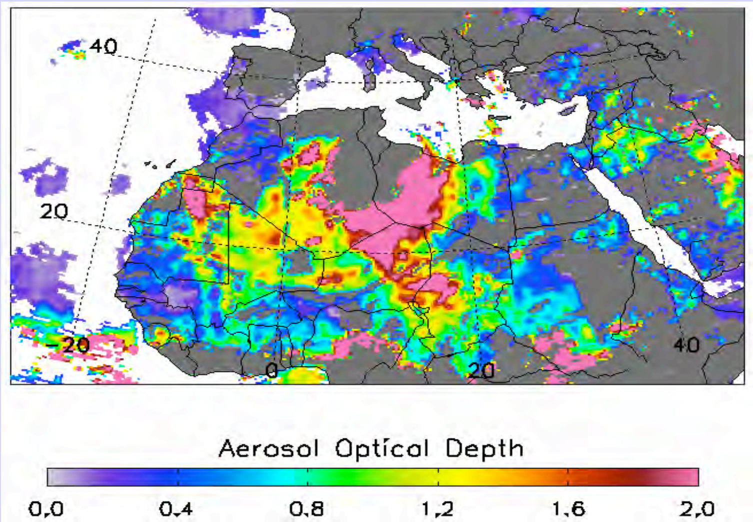
TOMS Aerosol Index

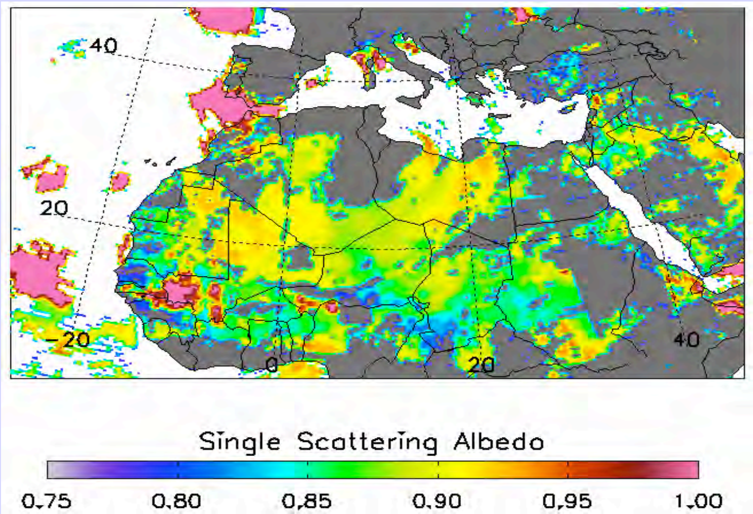
Retrieving Aerosol Absorption in the near-UV



March 9, 2007

By means of an inversion algorithm AOD and SSA are derived





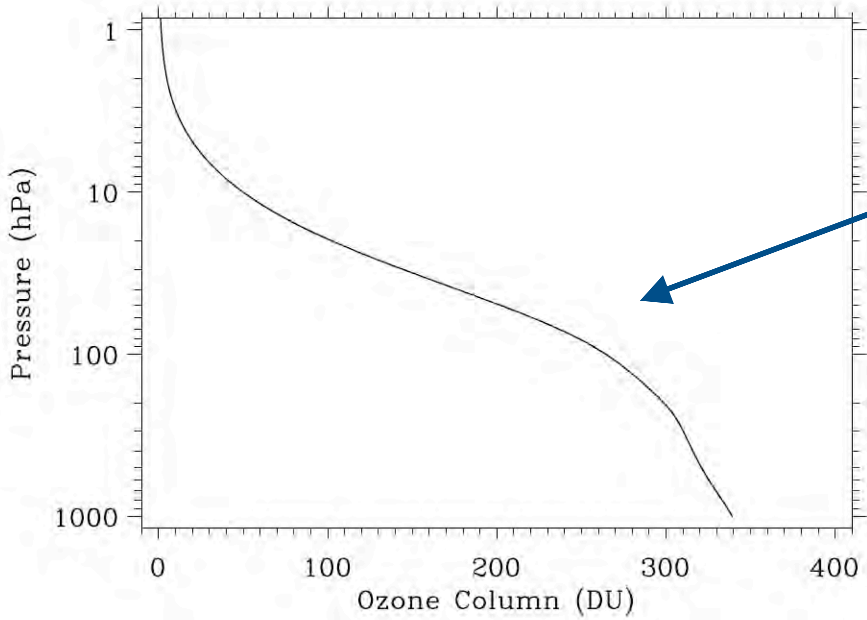
Radiance Assimilation

- Clouds and aerosols are by far the biggest issues in assimilating UV radiances. Assimilation will need to handle cloud vertical structure, aerosol absorption in UV somehow.
- Assimilation of radiance requires good knowledge of the uncertainty in the forecast profiles as a fn of altitude. Lacking such information it may be better to assimilate the profiles we provide with our total O_3 data. The worst strategy is to assume that forecast profiles have the same fractional error at all altitudes.

Assimilation of OMI O_3 profiles

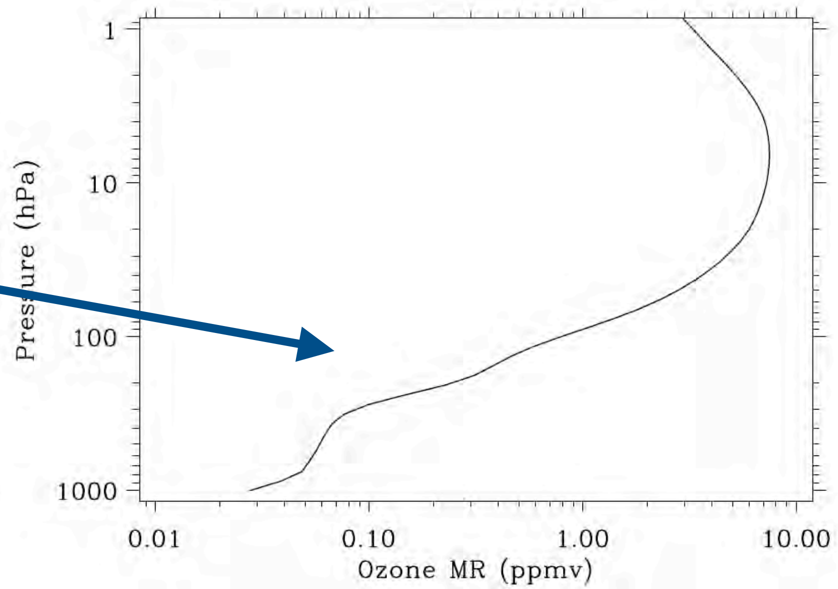
- Primary information OMI (also SBUV and GOME-2) provides is the column O_3 above pressure surfaces (~1 hPa to surface). MR is derived by differentiating this curve, which increases the error and creates large dependence on *a priori* profiles, particularly below 30 km.
- If these partial column O_3 amounts cannot be directly assimilated, they should, at least, be used for the validation of assimilated MR profiles.

Column O_3 profile



Primary information in the buv radiances. OMI retrieval precision ~1% at all pressure levels.

O_3 MR profile



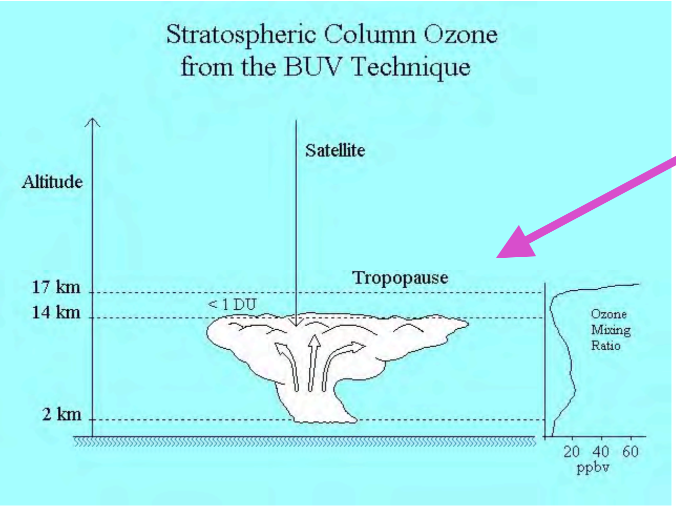
Desired information for scientific studies. Derived by differentiation. Precision varies with the slope of the upper curve. Worst in the troposphere.

Retrieval of Trop O_3 column from OMI- Methods

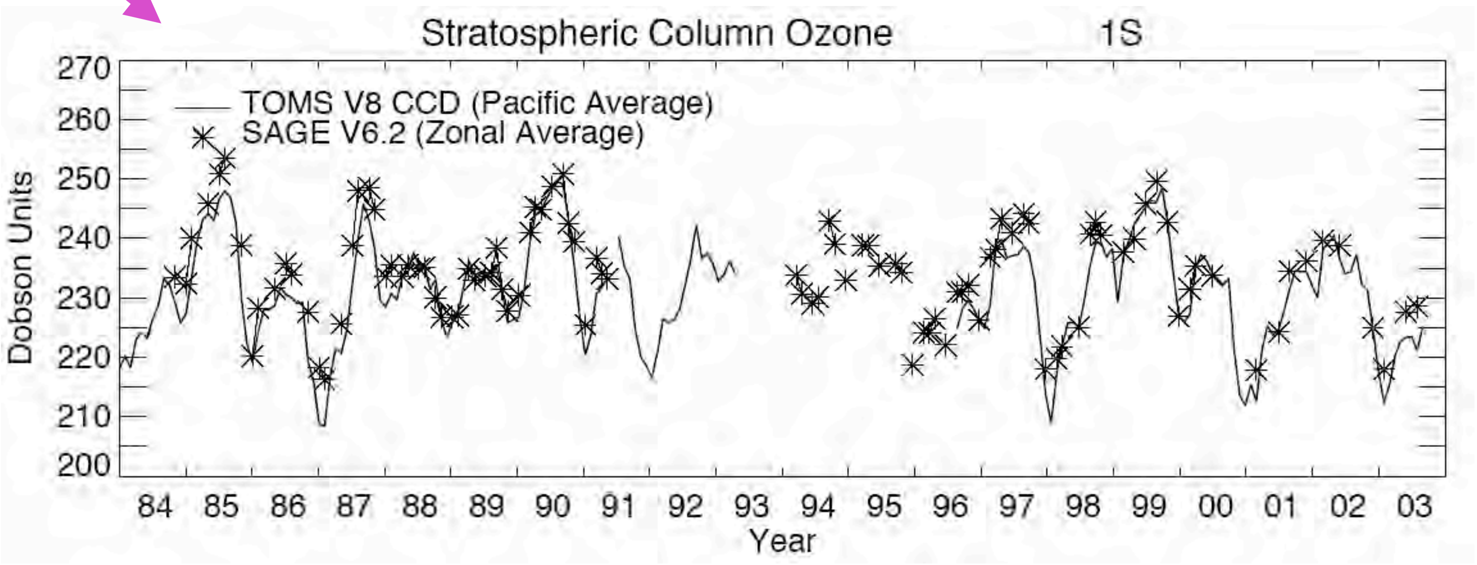
- Cloud Slicing (aka the CCD method)
  - For monthly means only. Works best in the Pacific region. Data goes back to '79.
- OMI total Column - MLS strat column
  - Relatively noisy, best for weekly/monthly means.
- Partial O_3 column estimated from profile retrieval
  - Best for producing daily maps. Monthly means may be less accurate than the methods above.

Stratospheric O_3 Column by Cloud Slicing (aka the CCD method)

Can be used to estimate MM TOR in the Pacific and 15S-15N with high accuracy



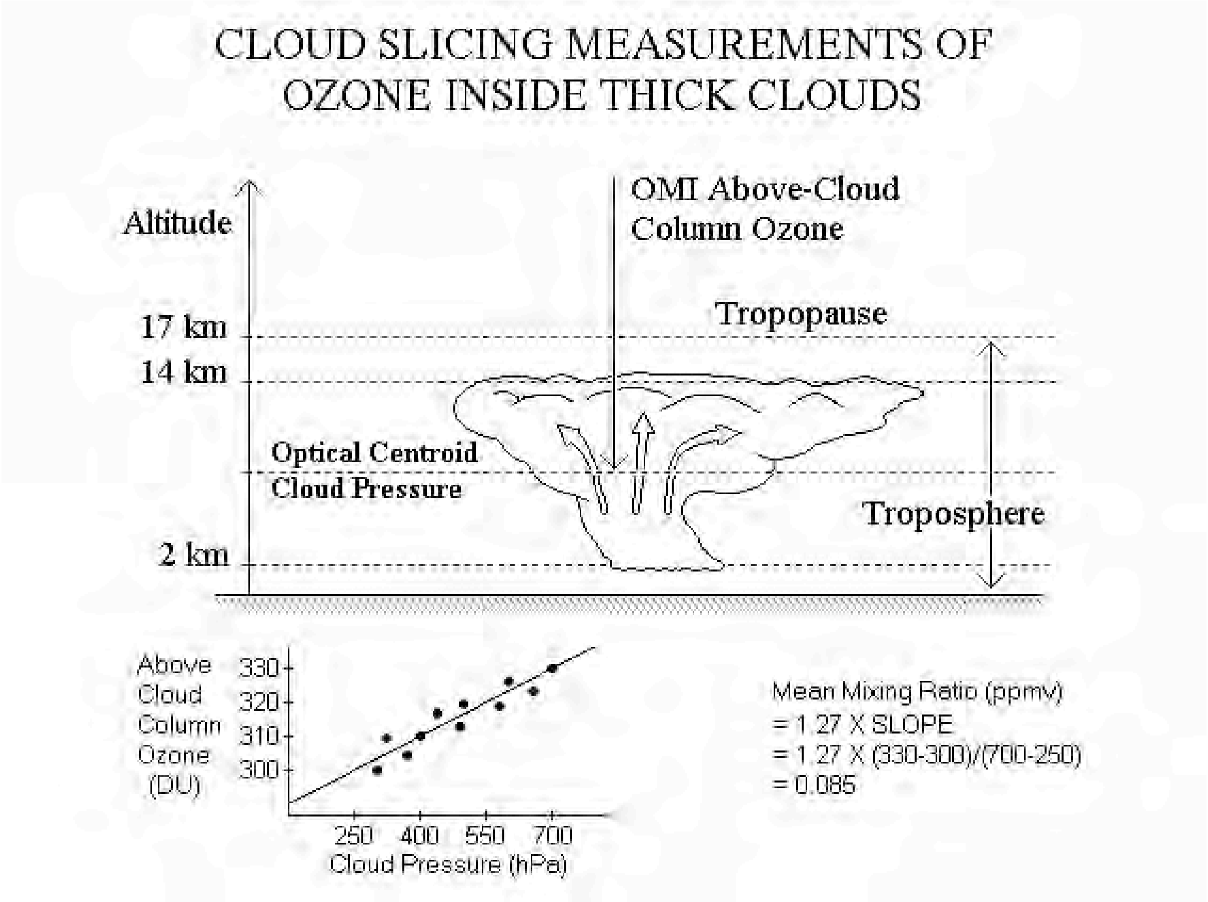
Old paradigm
Ziemke *et al*., '98



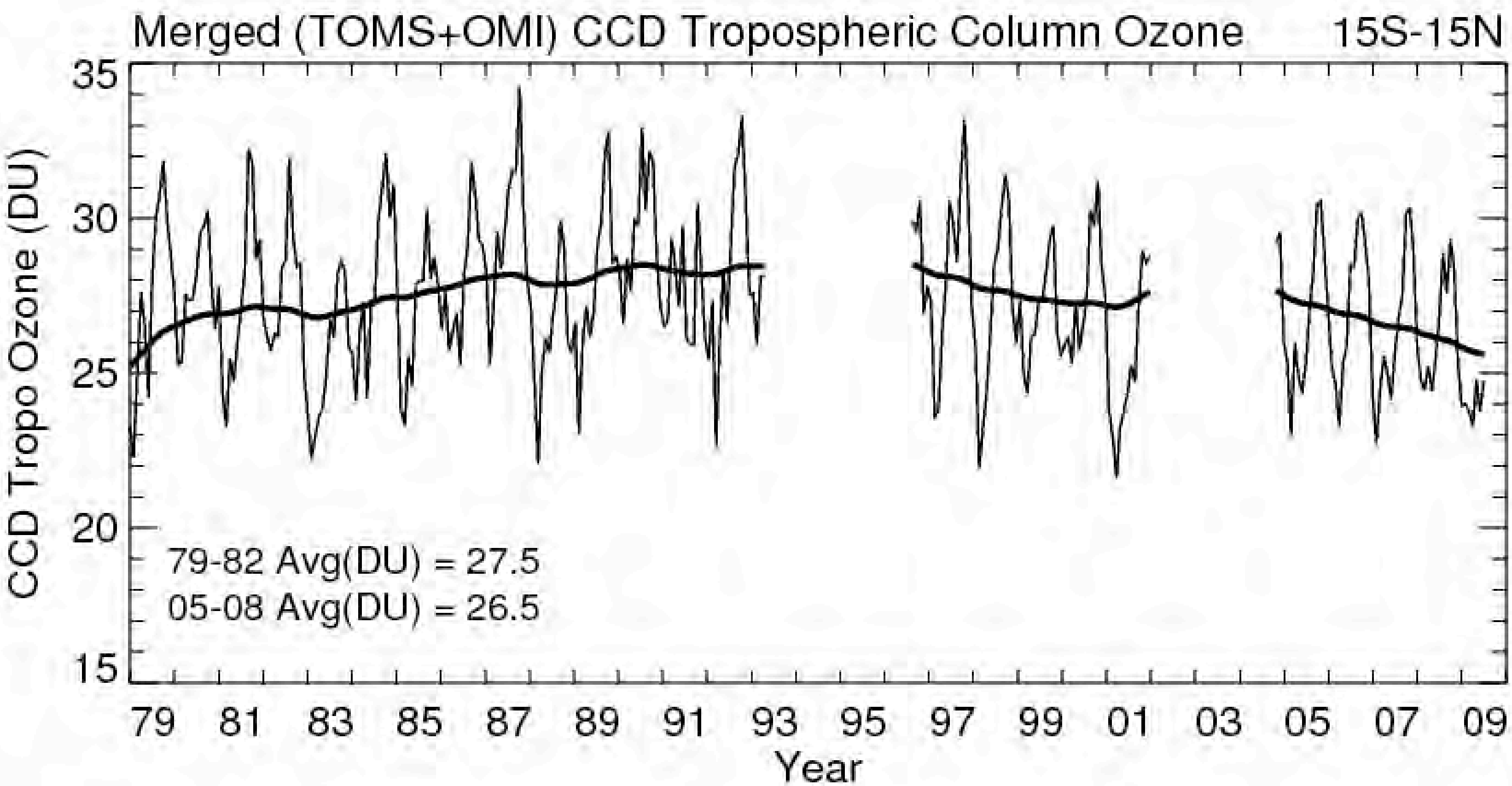
Revisiting the CCD method

Ziemke *et al.*, ACP, '09

O_3 mr in deep convective clouds in the Pacific is usually <10 ppbv.
Method doesn't work outside the Pacific since clouds are usually dirtier.



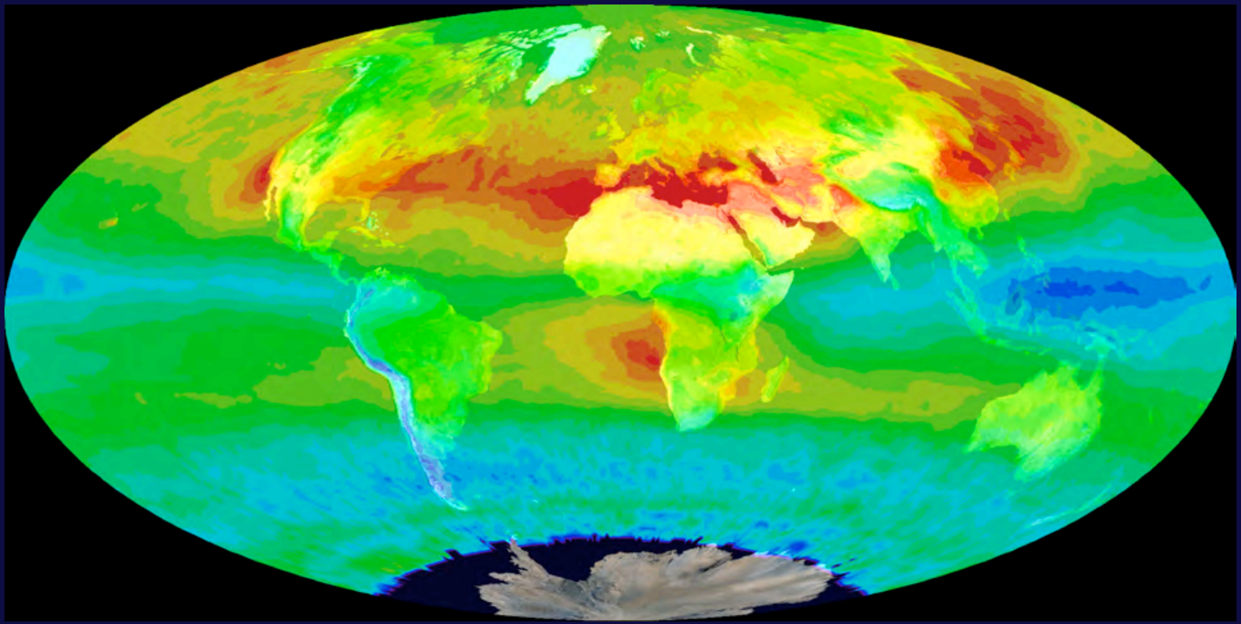
Changes in Tropical Trop O_3 Column over the past 30 years



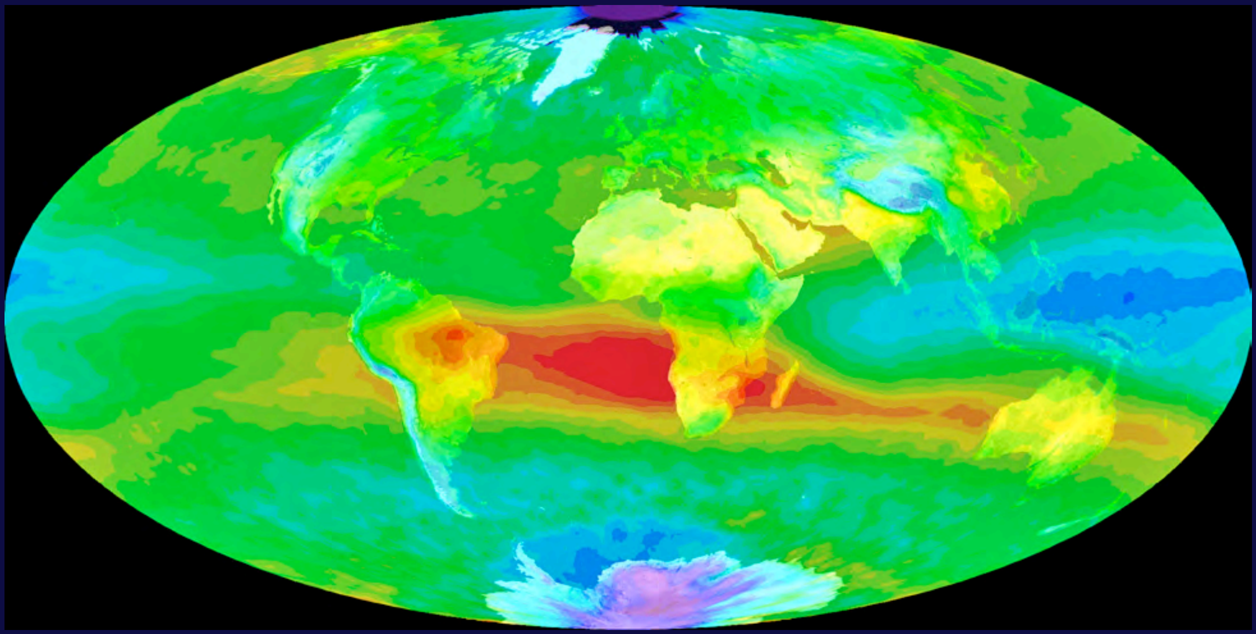
Result is insensitive to instrument drift, since it is derived from the difference between cloudy and clear data.

Trop O_3 column from OMI-MLS

June-Aug '08



Sept-Nov '07

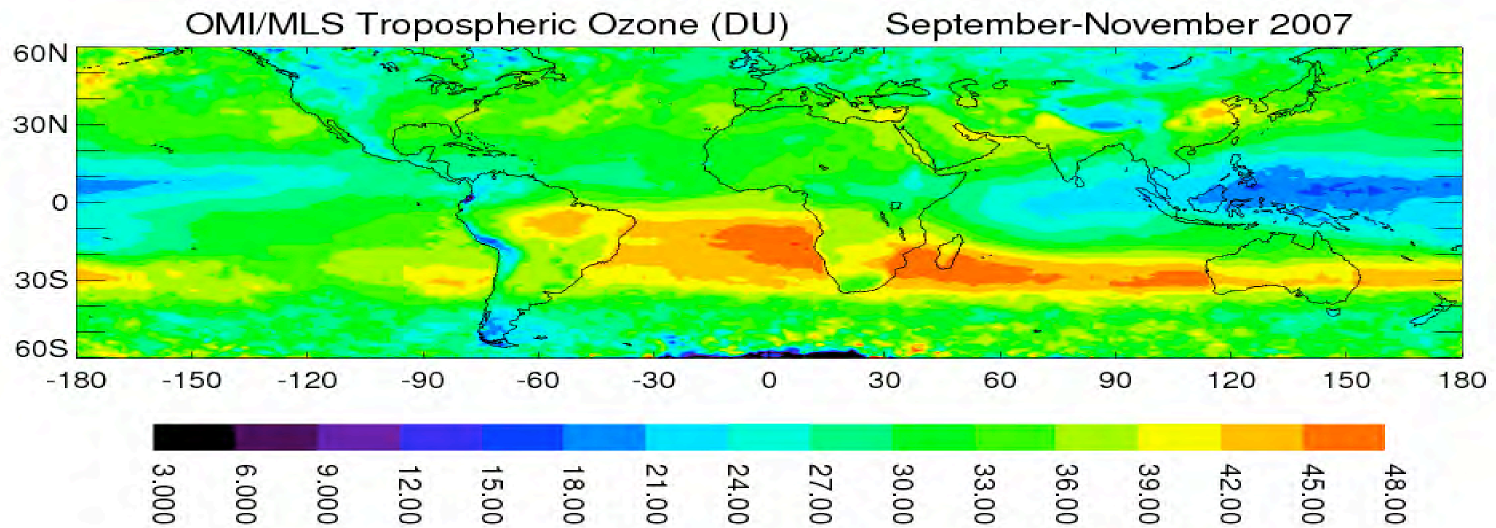


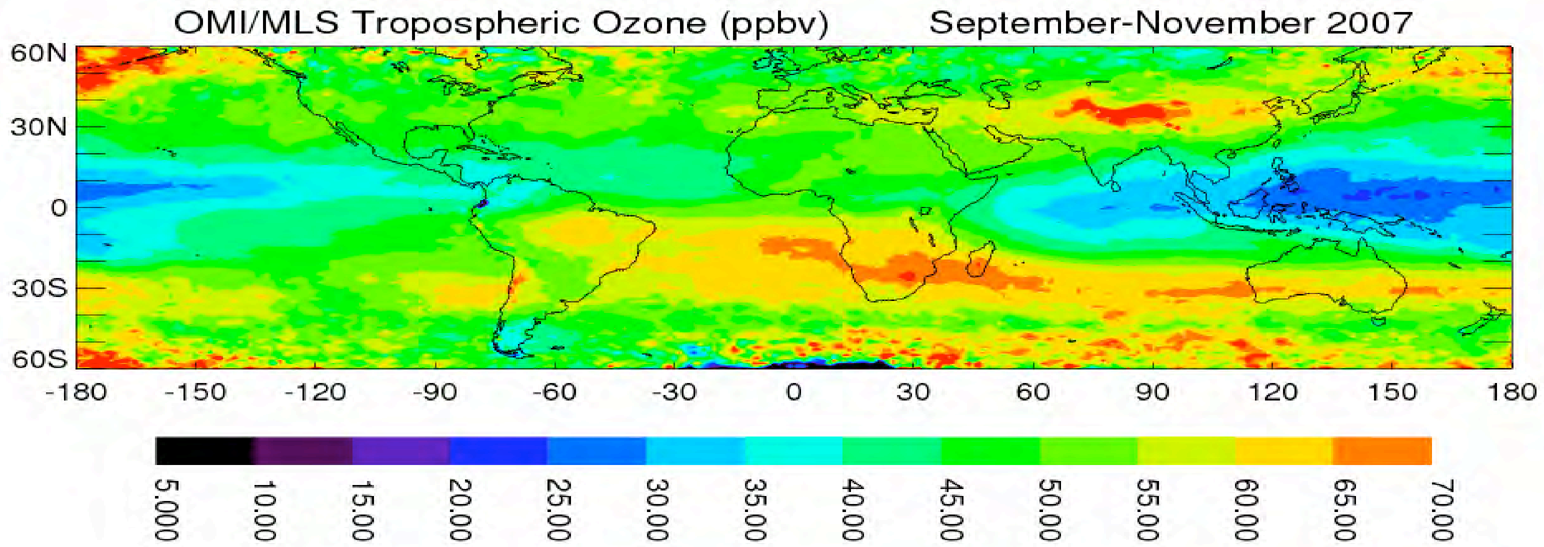
Images courtesy of Mark Schoeberl

Problems with Trop O_3 Column Concept

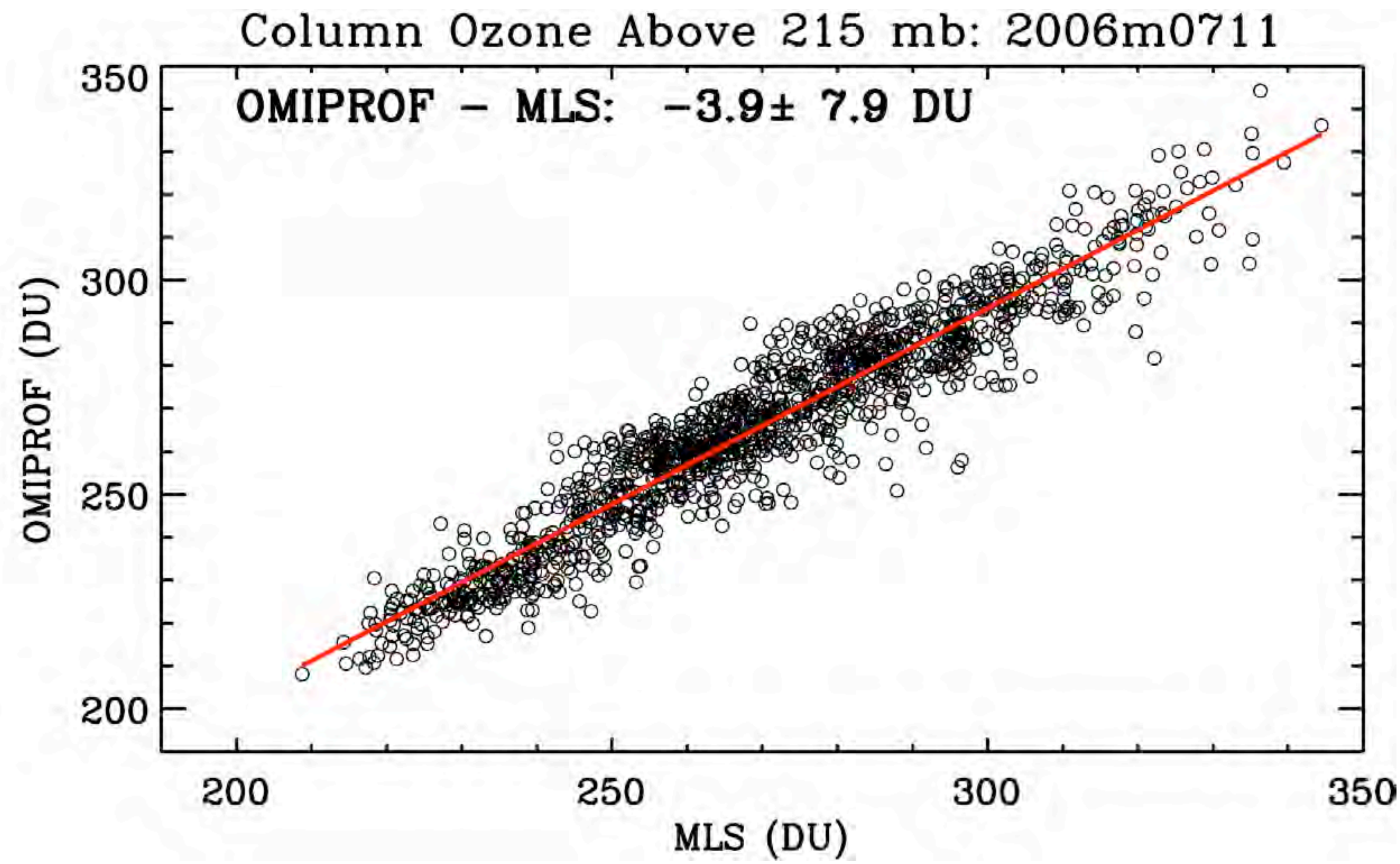
- Lower boundary of OMI-derived total O_3 column is not the surface, but the effective pressure (see slide #17). O_3 column below this altitude is estimated from climatology.
- O_3 Tropopause is often poorly known.
- Better concept: column-averaged MR
  - CMR= $(\Omega_1-\Omega_2)/(p_1-p_2)*1.27$, where Ω_i is the column above p_i, and p_i's are chosen suitably.

Trop Column O_3 vs CMR

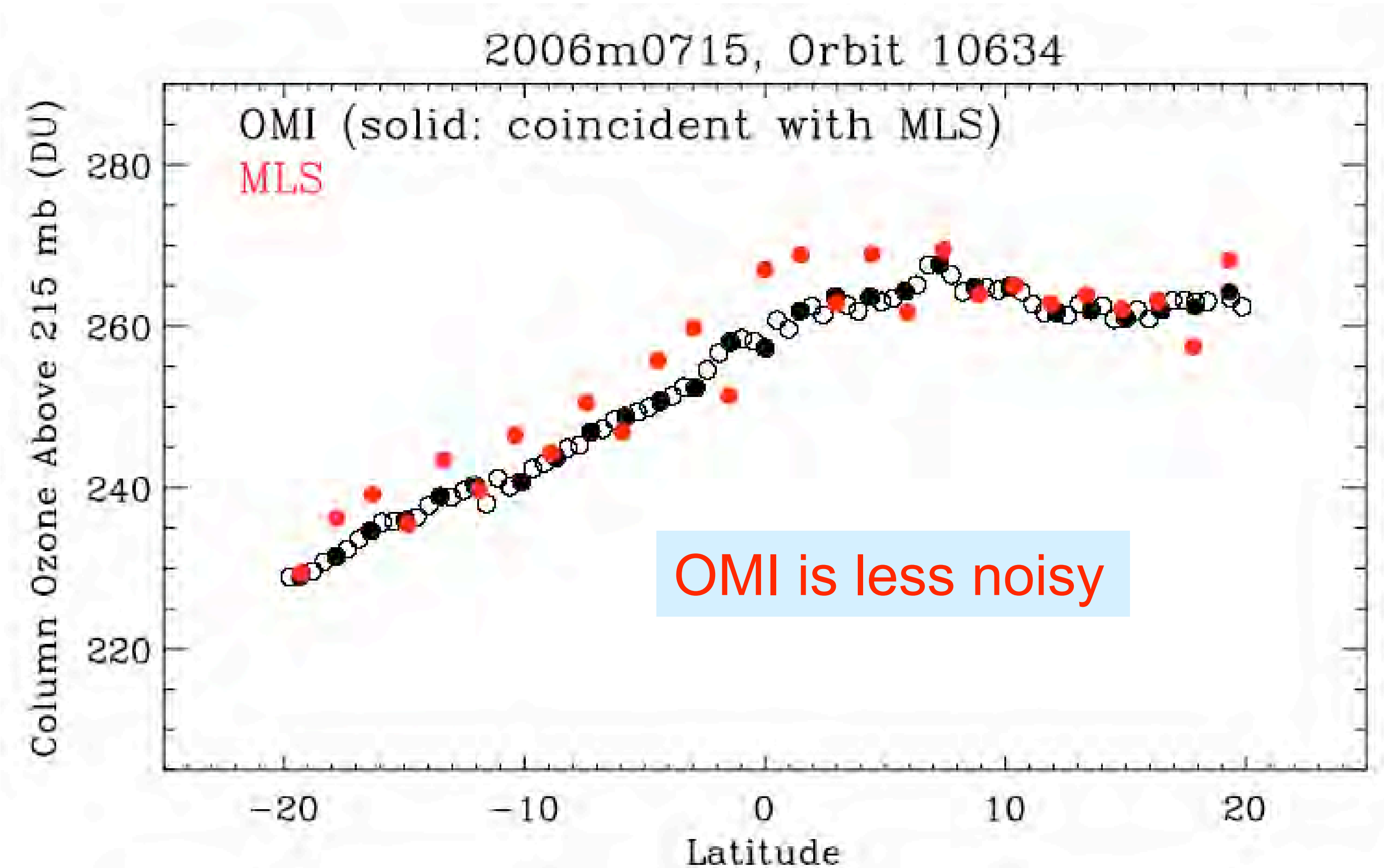




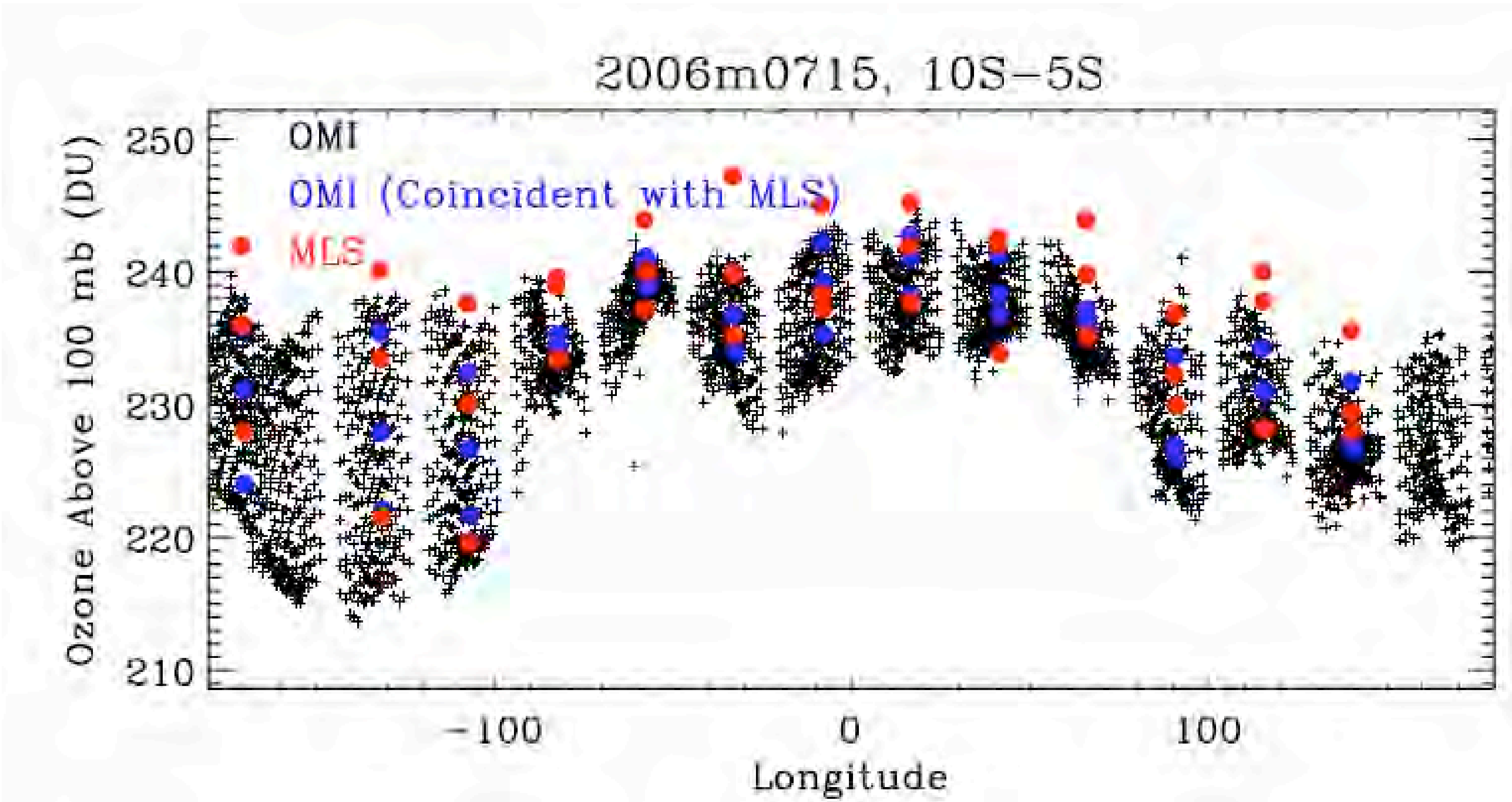
Direct Retrieval of O_3 column above 215 hPa from OMI vs MLS-derived column



Direct Retrieval vs MLS- Single Orbit Comparison



Direct retrieval captures the variability of strat O_3 column seen by MLS in the tropics



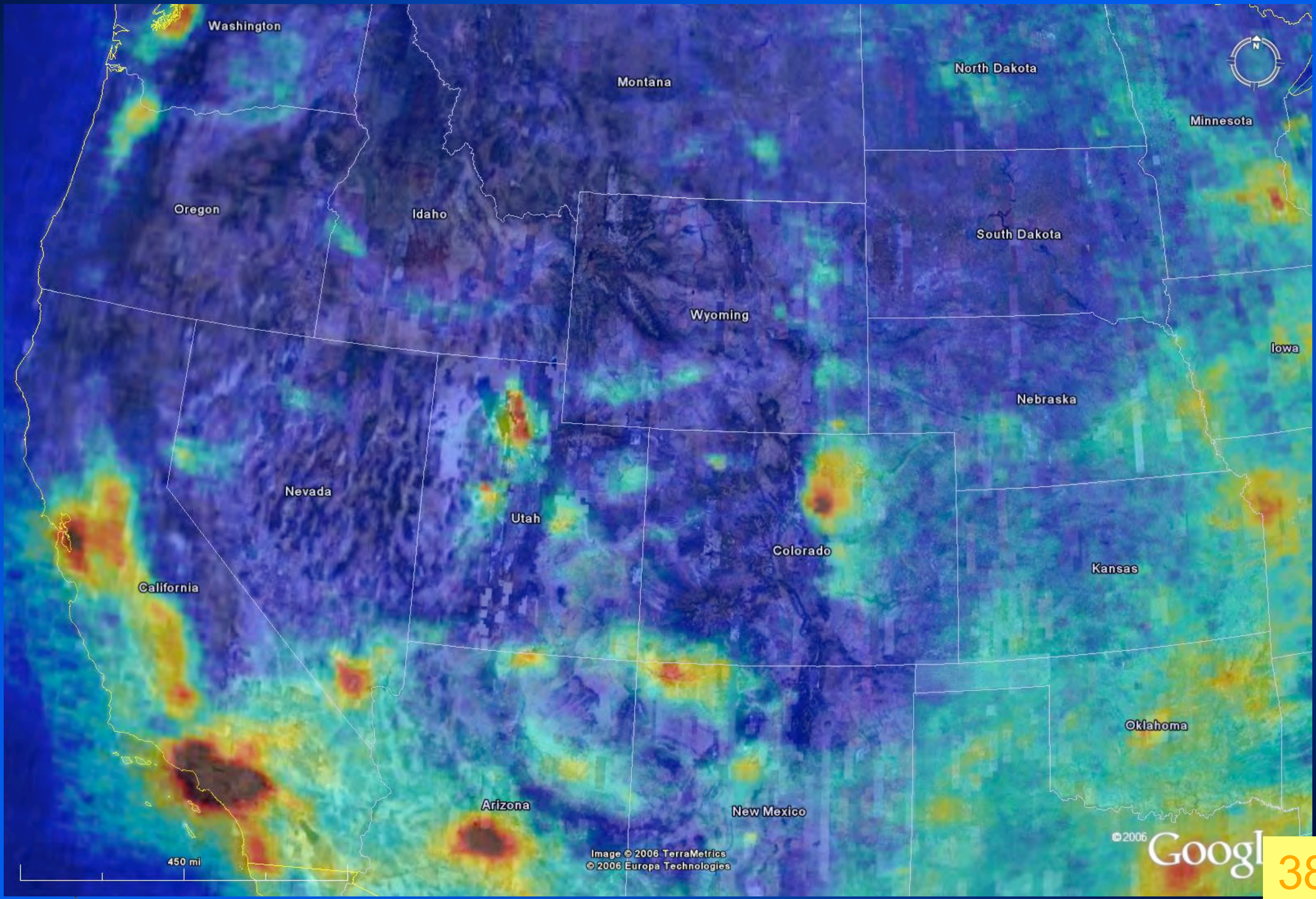
AQ related products from OMI

- NO_2
- Aerosols
- SO_2
- Formaldehyde (HCHO)
- BrO
- Glyoxol (CHOCHO)

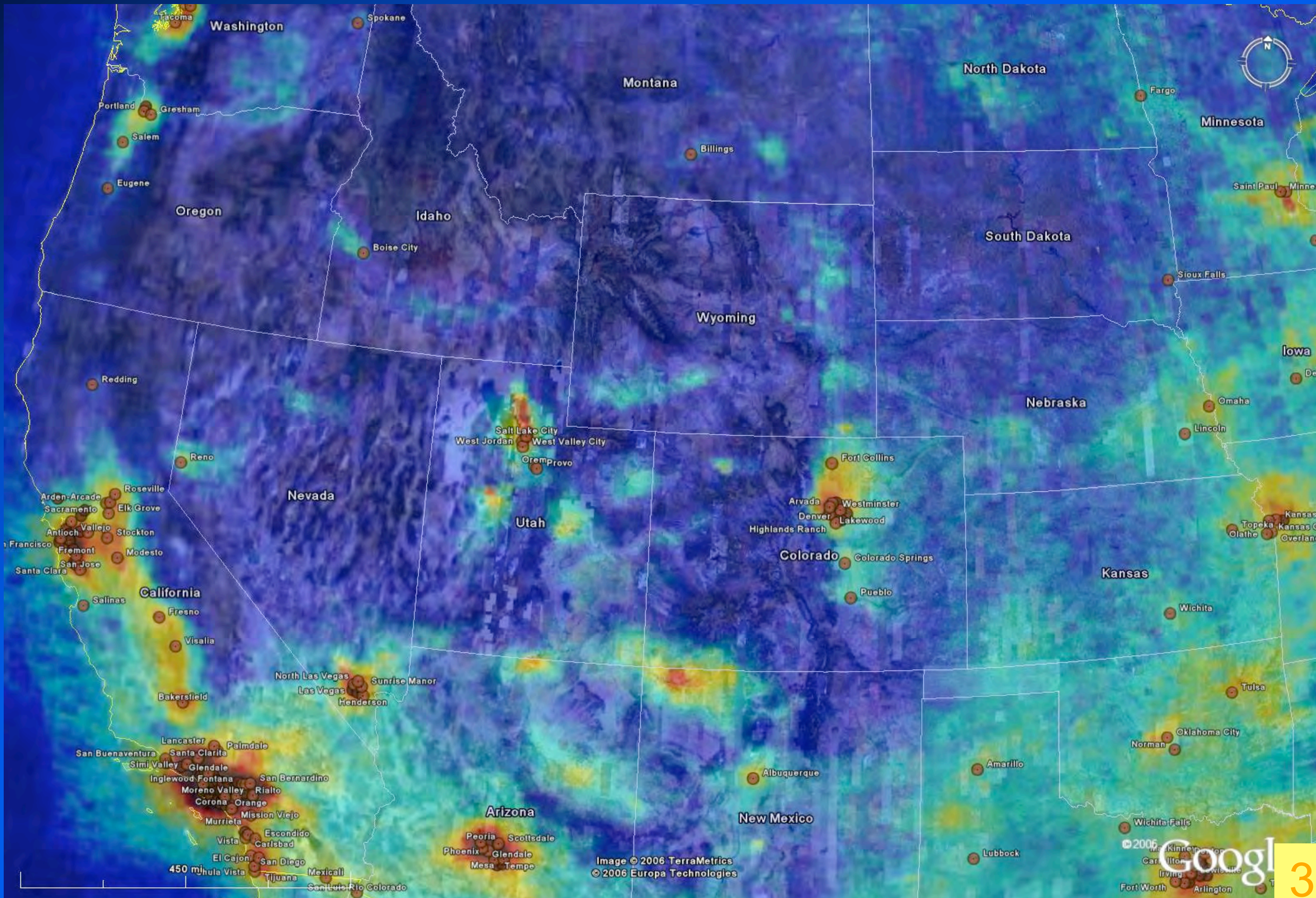
OMI AQ Products- Sources of Error

- Sub-pixel clouds
  - Cloud effect is enhanced since clouds are much brighter than the boundary layer. Most serious for aerosols, moderately serious for NO_2, less serious for O_3 and SO_2.
- Surface BRDF
  - Currently assumed to be Lambertian
- Vertical profile
  - Based on models
- Aerosols
  - Absorbing aerosols reduce the sensitivity

OMI NO_2 Western US

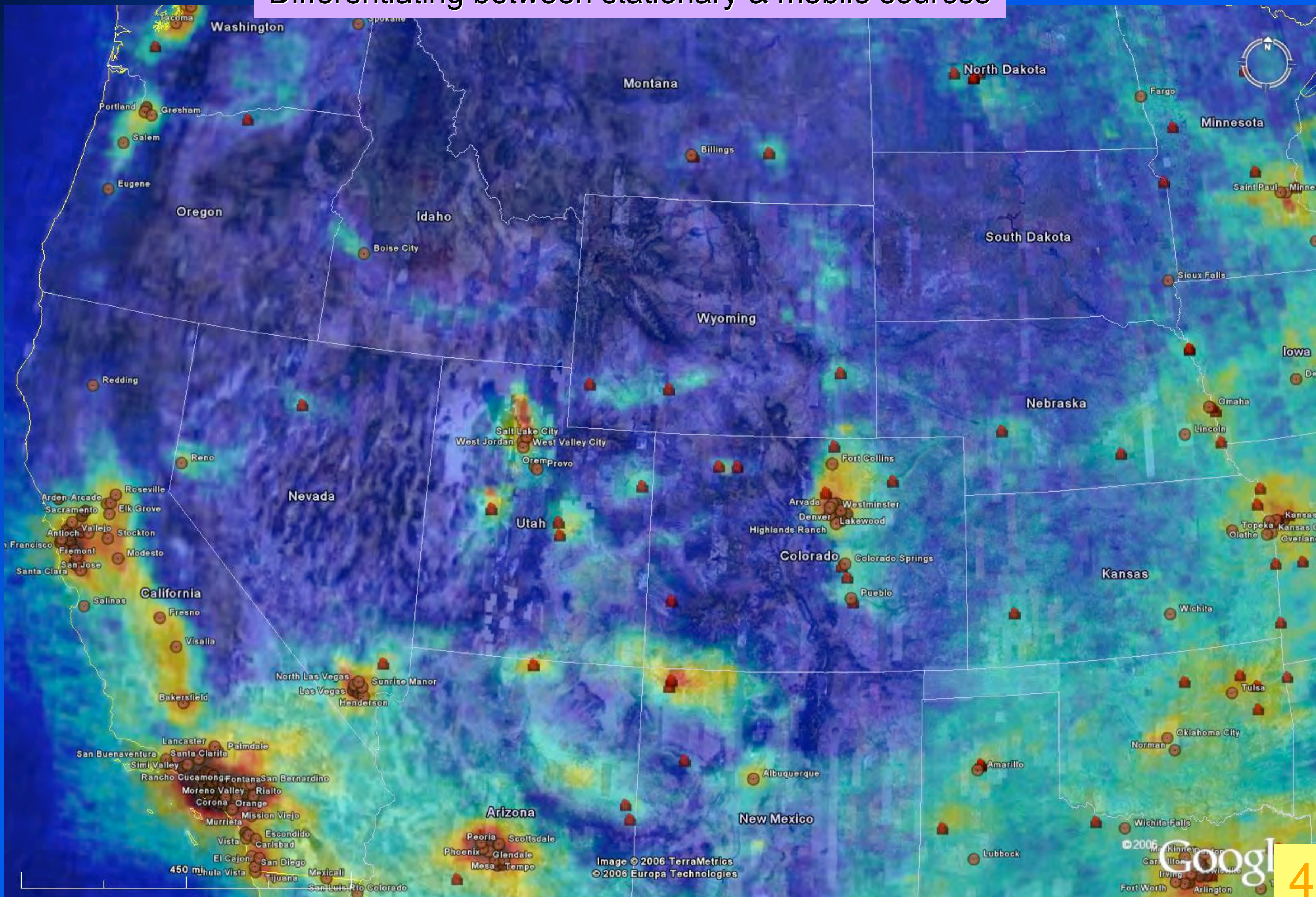


OMI NO_2 Western US + Cities

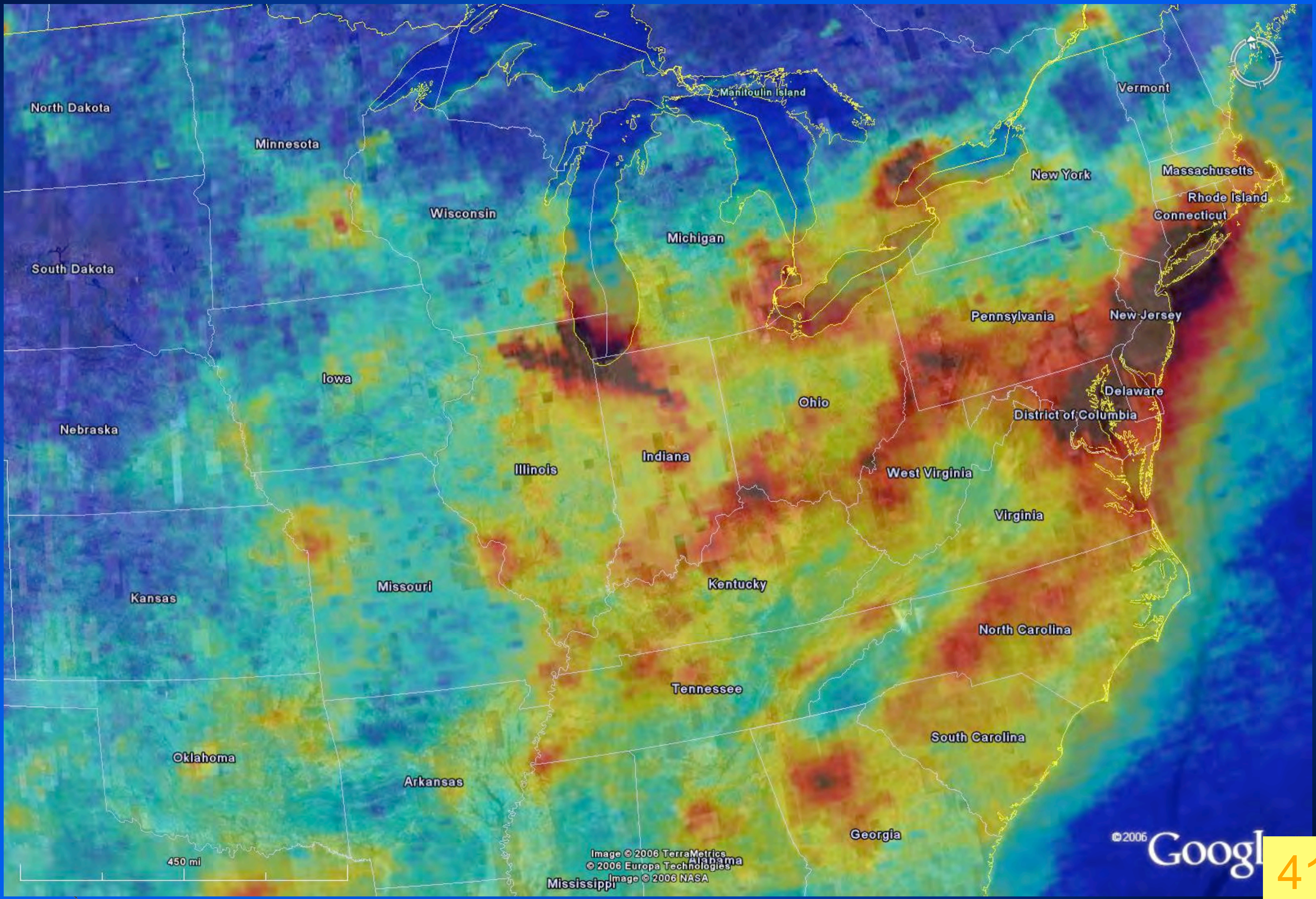


OMI NO_2 Western US + Cities + Power Plants

Differentiating between stationary & mobile sources



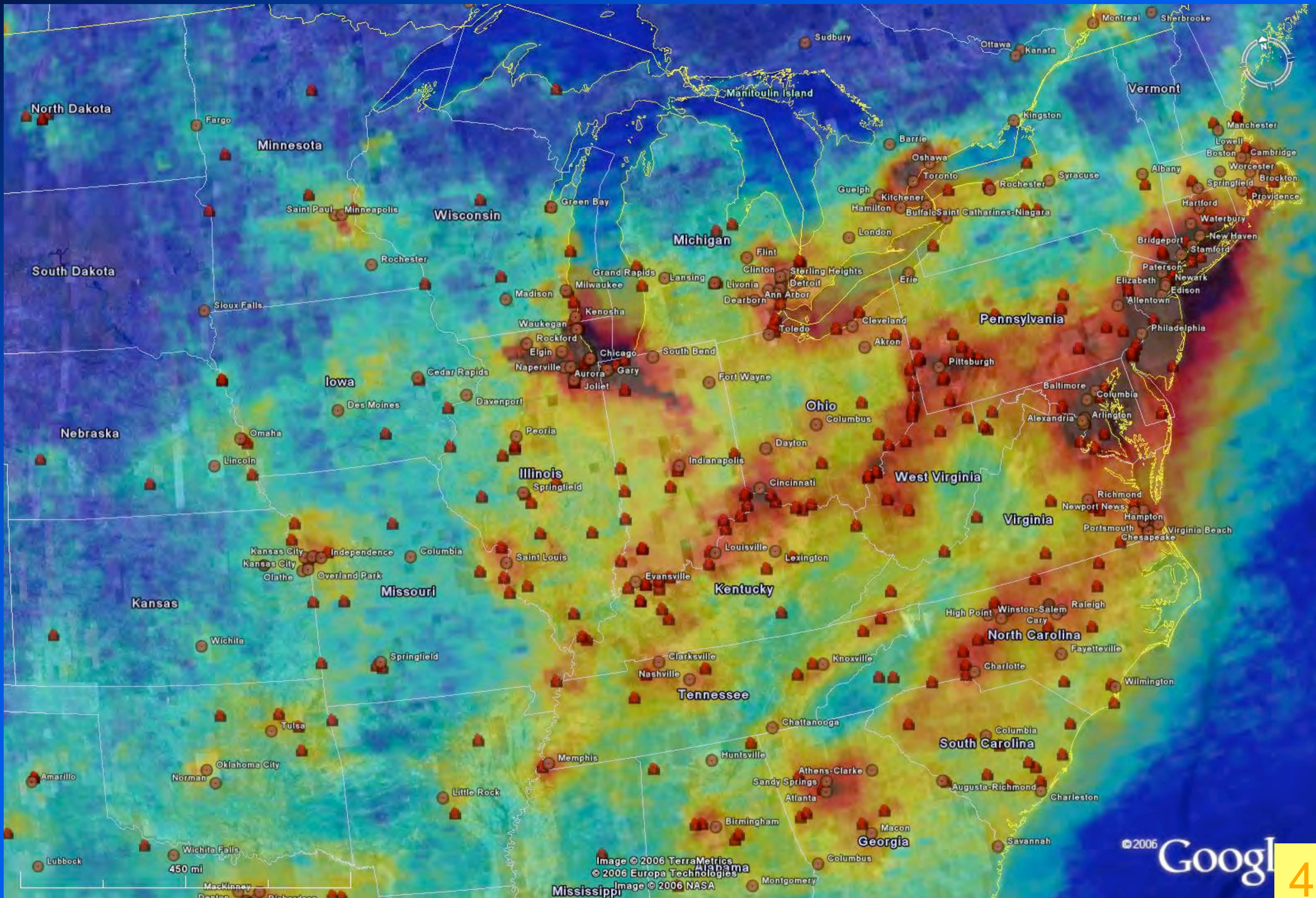
OMI NO_2 Eastern US



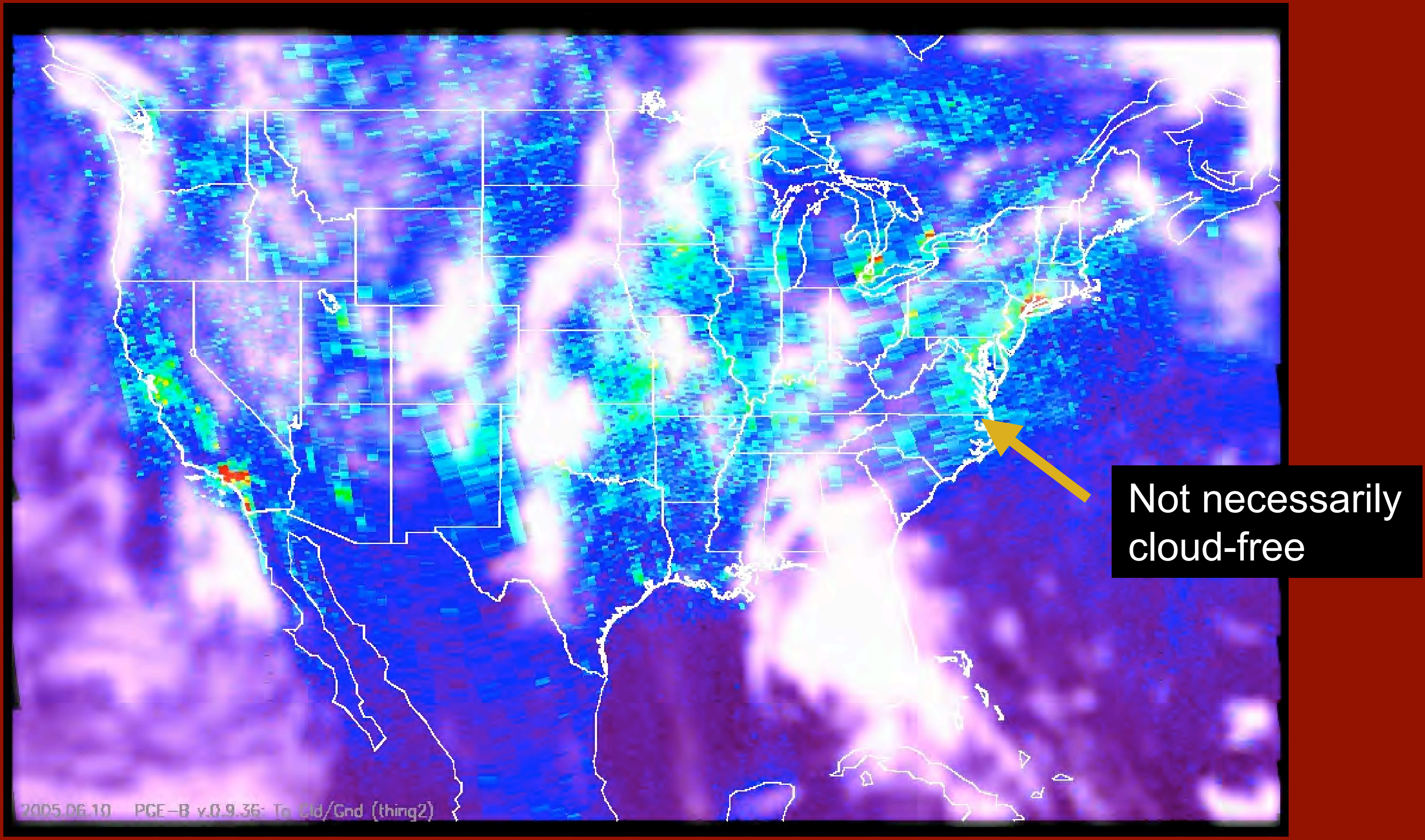
OMI NO_2 Eastern US + Cities + Power Plants

OMI NO_2 Eastern US + Cities + Power Plants

OMI



Cloud interference on a single day

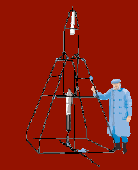


Tropospheric NO_2 from OMI for June 6, 2005

Issues with Assimilation of Atm Composition Data to Study AQ

- Lifetime is short so system resets itself in hours and days, i.e., there is less dependence on initial conditions that make met data assimilation a fundamental necessity.
- Sparse or non-existent vertical profile information (getting better for aerosols).
- No information below clouds. Convective clouds change composition discontinuously.
- A very ill-posed mathematical problem, particularly for aerosols.
- Short lifetime and point emission sources require high temporal and spatial resolution data that are not currently available.

Issues for the Audience



- Given the issues that I have identified in this talk, is assimilation of OMI data worthwhile?
- What is the best way to assimilate data that provide column amounts in relatively thick layers?
- Can an assimilation system be designed to use cloudy data to improve assimilation rather than discarding cloudy pixels?
- How does one account for clouds and aerosols in a pure radiance assimilation?
- Is a hybrid assimilation approach- half way between product and radiance assimilation- more useful?