The Relationship between Air Pollution and El Niño: Global and Regional Perspectives Derived from Two Decades of Satellite Measurements

Jack Fishman

Atmospheric Sciences
NASA Langley Research Center
Hampton, Virginia USA 23681

Collaborators: John K. Creilson, Amy E. Wozniak
R. Bradley Pierce, Doreen O. Neil

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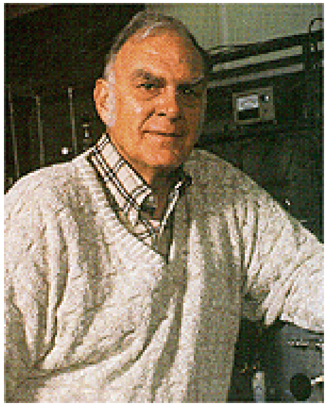
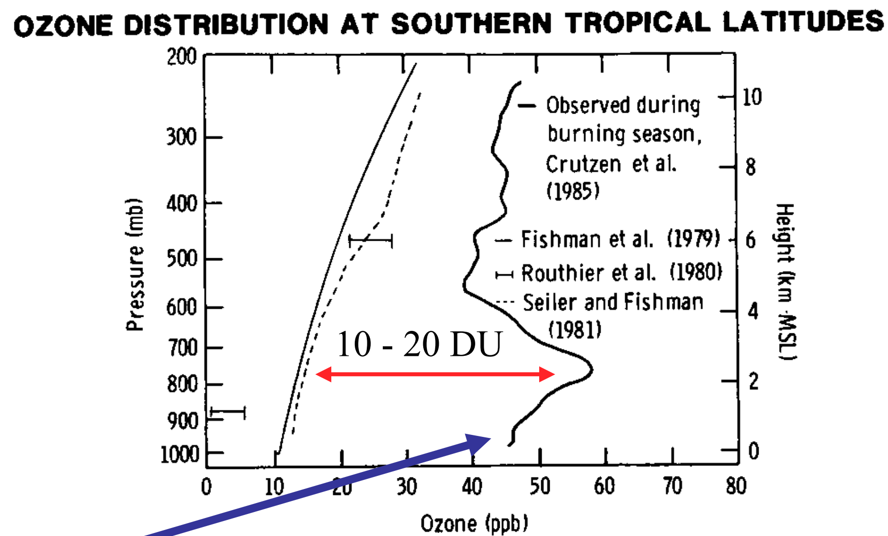
The Origin of Using Satellite Data to Study Tropospheric Ozone Can be Linked to Nobel-Prize Winning Research

from Nobel Prize press release:

The Royal Swedish Academy of Sciences has decided to award the 1995 Nobel Prize in Chemistry to **Paul Crutzen, Mario Molina** and **F. Sherwood Rowland** for their work in atmospheric chemistry, particularly concerning **the formation** and decomposition **of ozone**.



In his search for understanding the sources of ozone in the troposphere, Crutzen made the first measurements of tropospheric ozone where tropical biomass burning was occurring and found considerably higher concentrations than what had been published previously



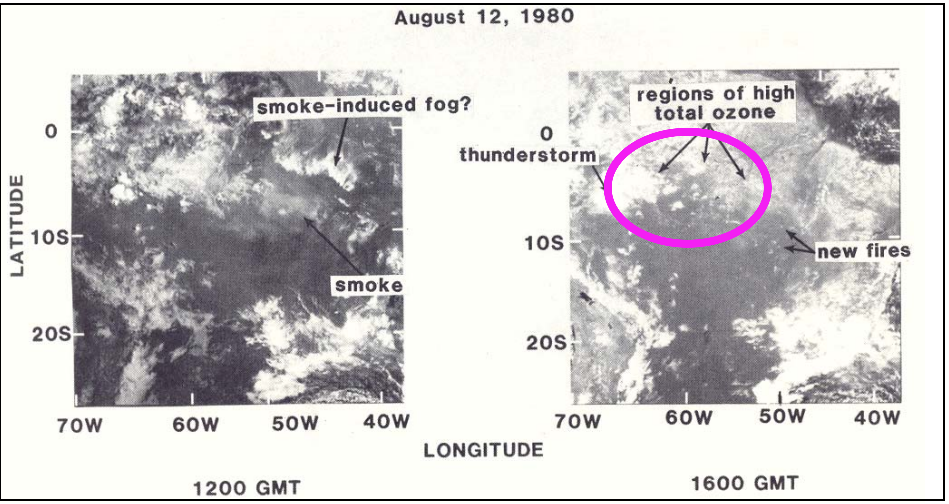
(from Fishman, Minnis & Reichle, *JGR* , **91**, 1986)

- **Can the 10-20 Dobson Unit Enhancement Be Identified from TOMS Total Ozone Measurements?**

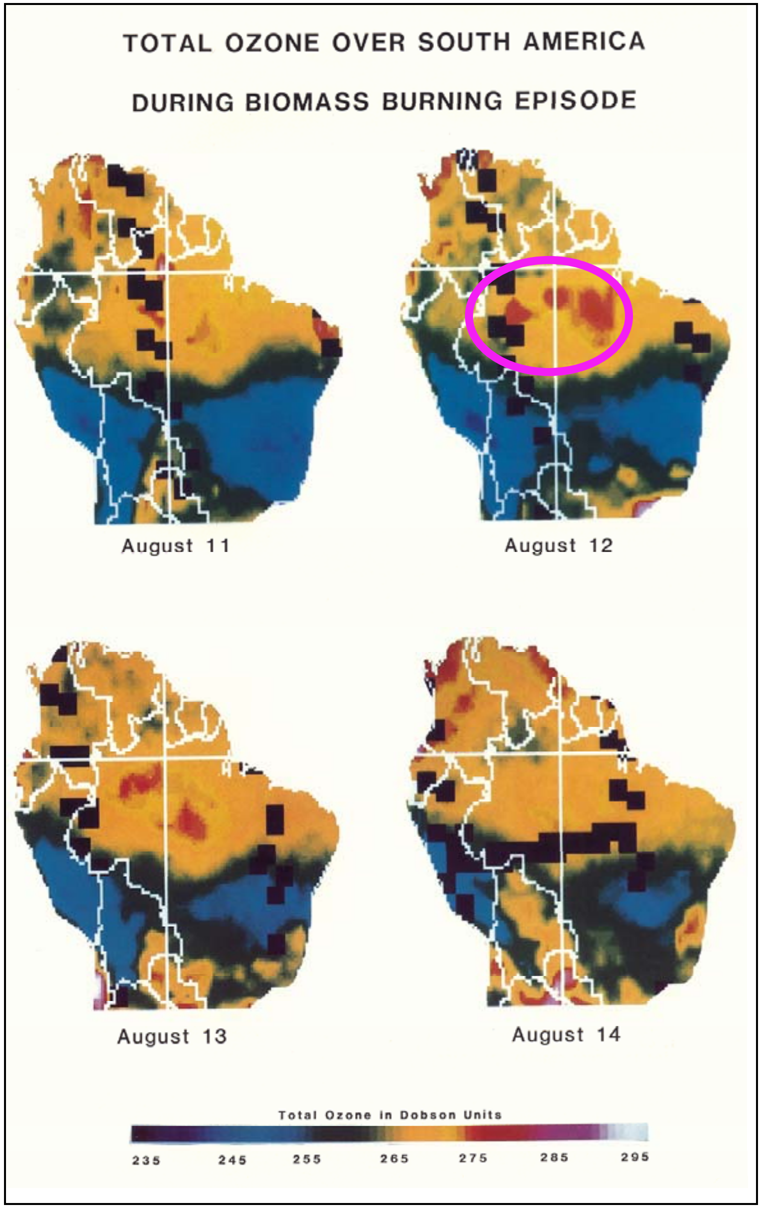
- Such Enhancements are Better Observed at Low Latitudes Due to Less Stratospheric Variability

- TOMS Precision is 1% (~ 3 DU)

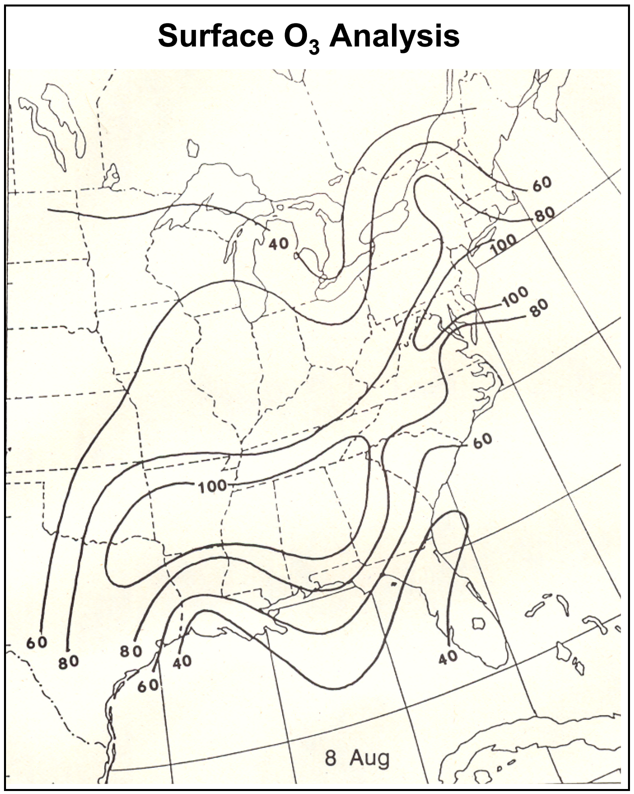
Enhanced Total Ozone Observed in Conjunction with Biomass Burning in 1980 Episode



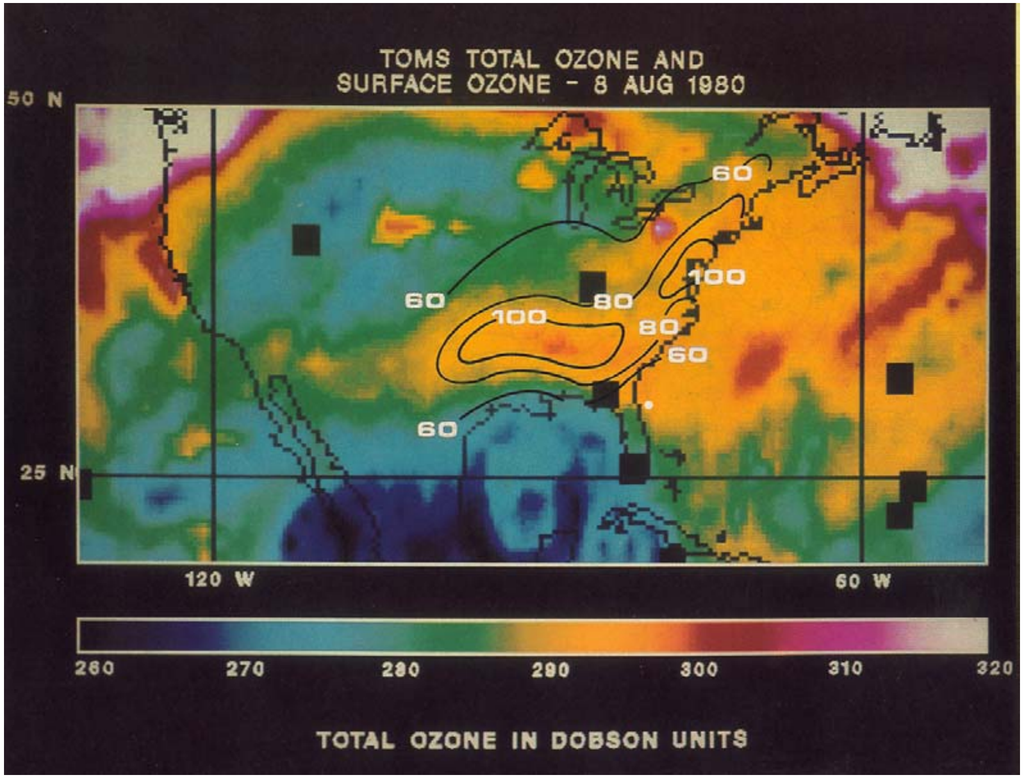
(from Fishman, Minnis & Reichle, *JGR* , **91**, 1986)



High Surface Ozone Concentrations During Pollution Episode Also Observed in TOMS Total Ozone

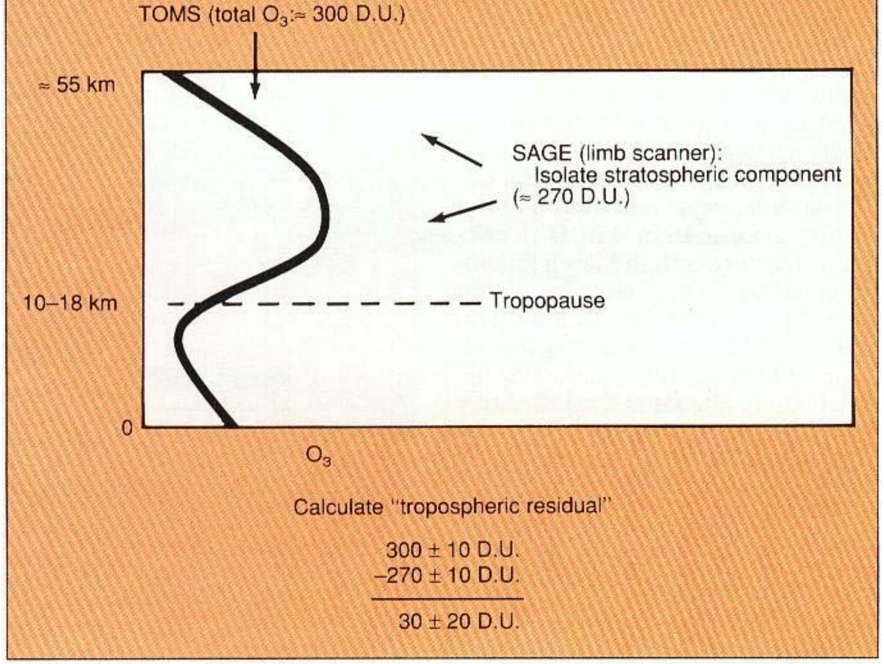


(from Fishman et al., *J. Clim. Appl. Met.*, **26**, 1987)



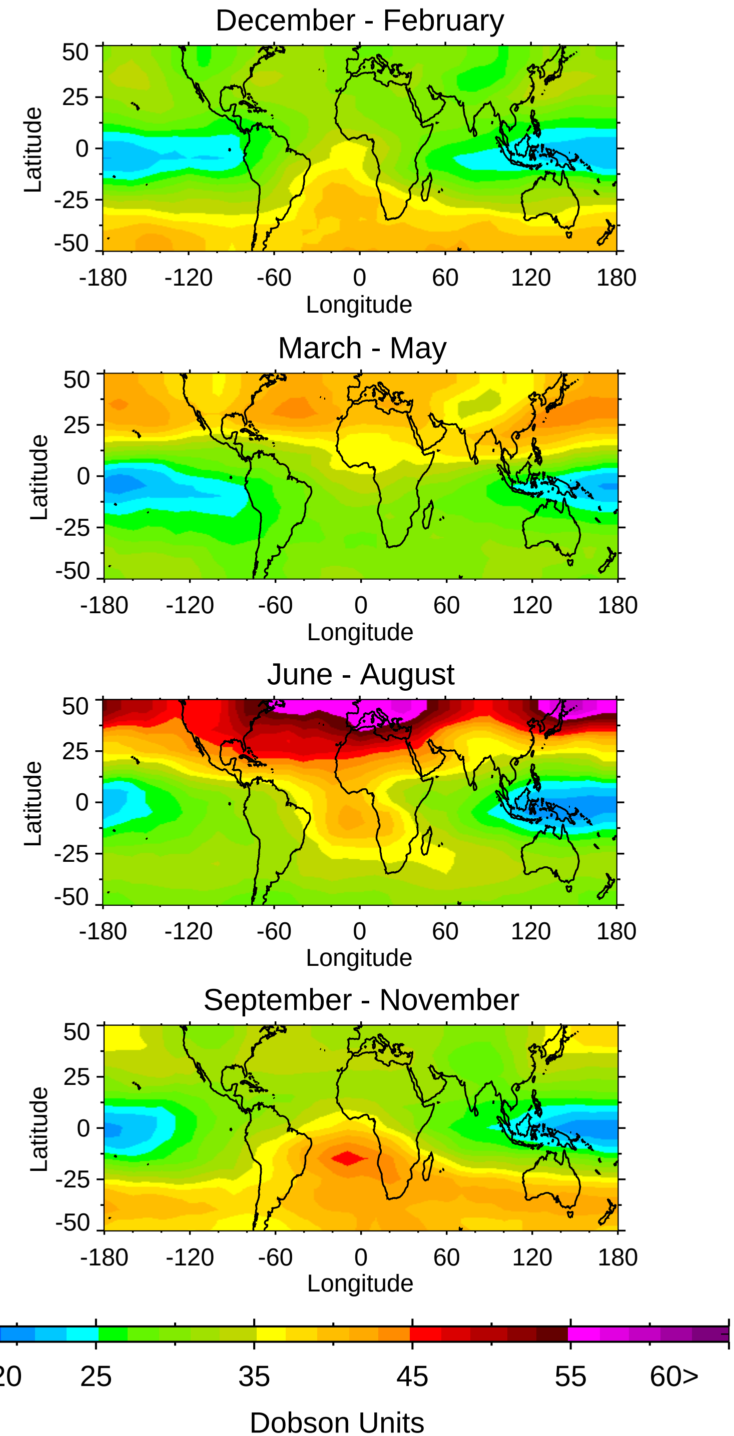
Separate Stratosphere from Troposphere to Compute Tropospheric Ozone Residual (TOR)

FIGURE 3
Schematic diagram showing how the tropospheric residual is calculated from coincident TOMS and SAGE measurements

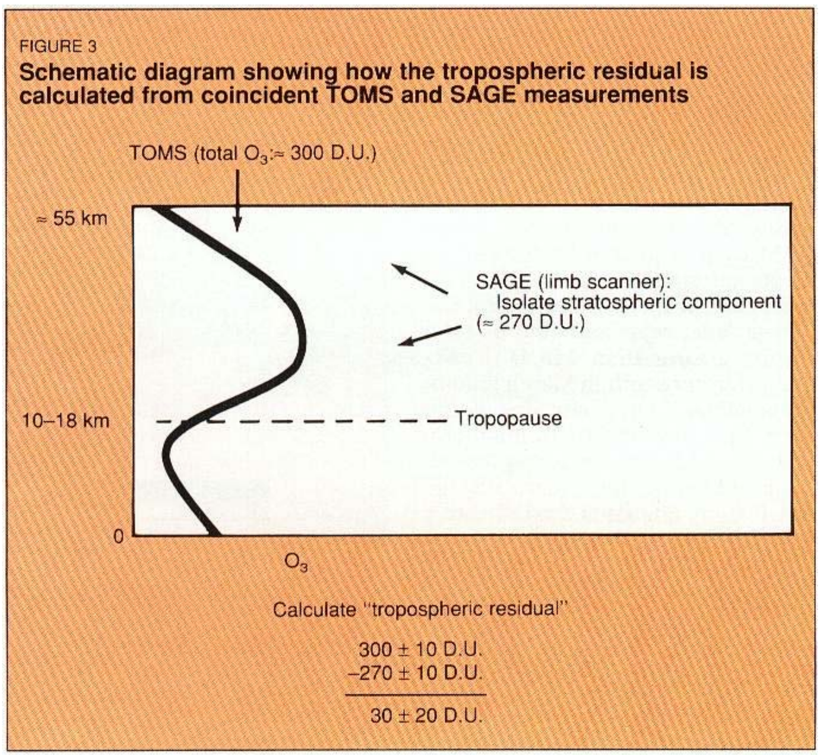


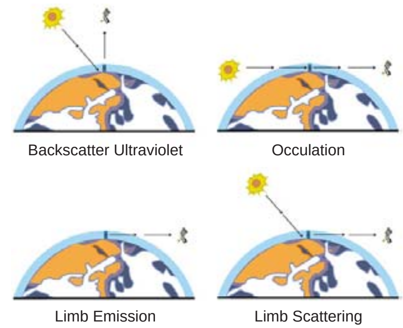
First Separation of TOMS Total Ozone to Derive Tropospheric Ozone Residual Used SAGE Measurements to Determine Stratospheric Ozone:

- Seasonal Climatologies Produced
  - Highest TOR in NH Summer
  - Tropical Enhancement in Austral Spring
- Data Too Sparse to Examine Interannual Variability



Separation of the Stratosphere from Troposphere to Isolate a Tropospheric Ozone Component Can Use Any Ozone Profiler



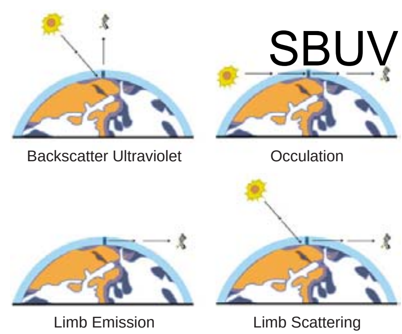


SAGE

Good vertical resolution

30 measurements/day

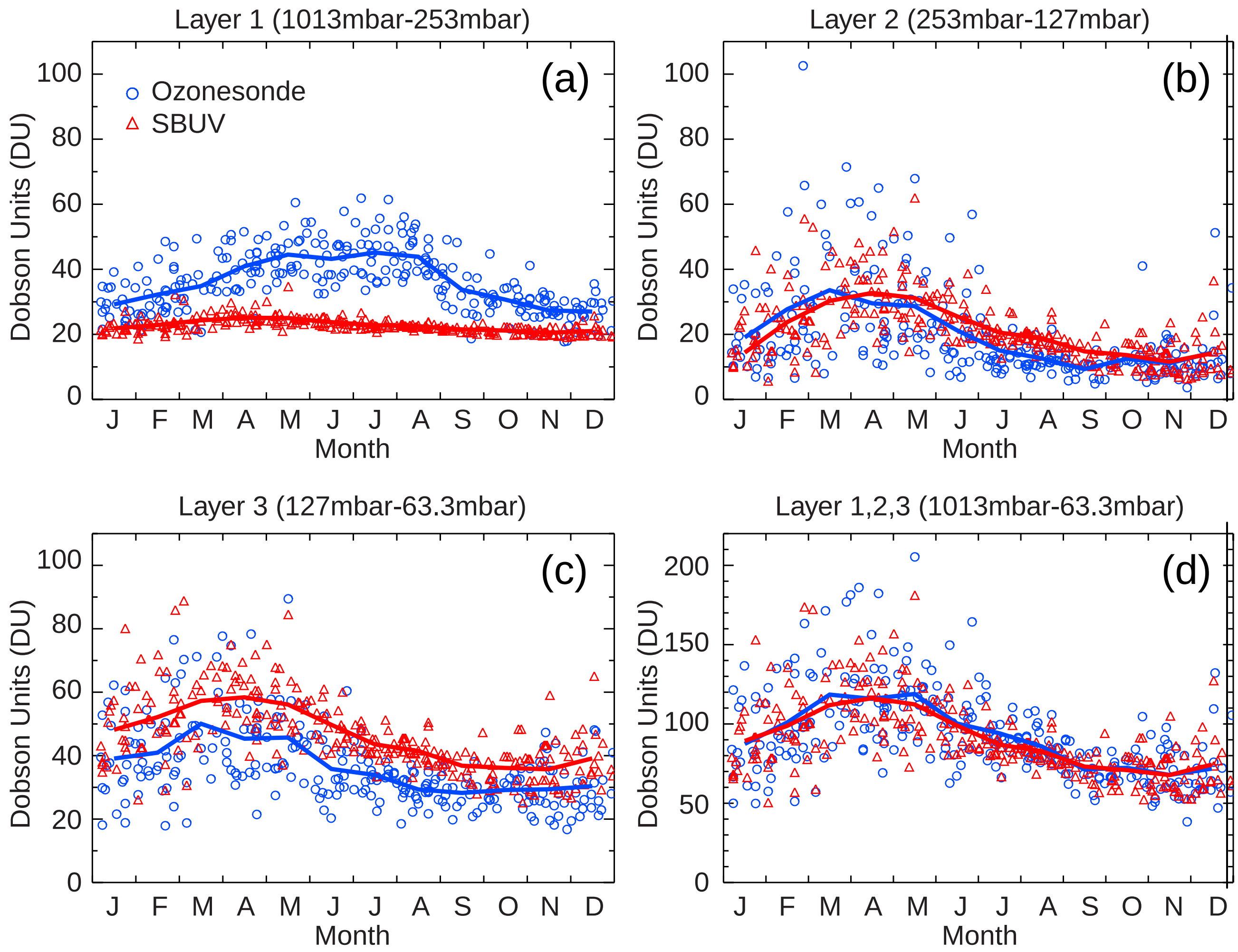
SBUV



Poor vertical resolution

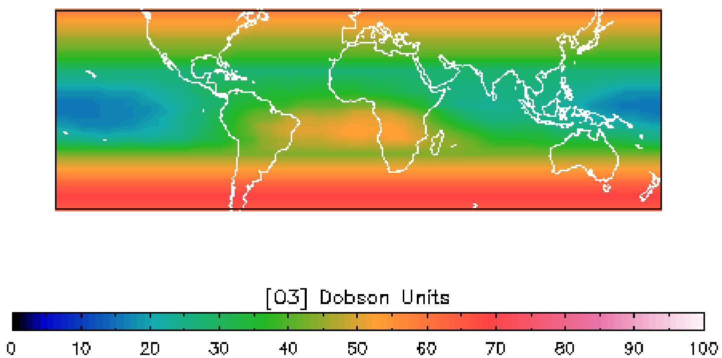
780 measurements/day

Climatological Comparison of Ozonesonde Data with SBUV Measurements at Wallops Island

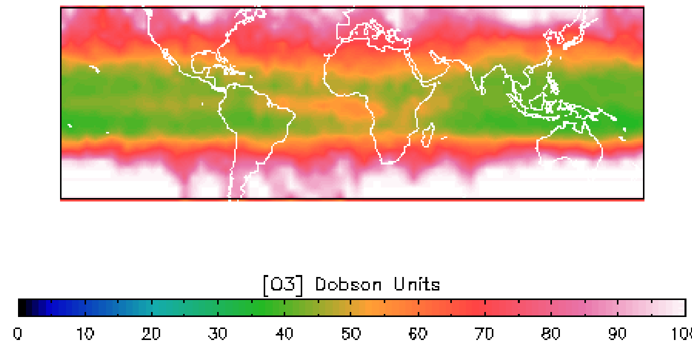


Information Contained in SBUV Measurements

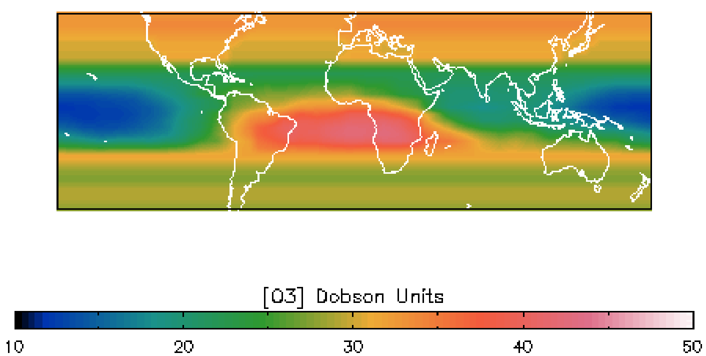
ozone.13.4x3.09
pressure level: 1000mb – 100mb



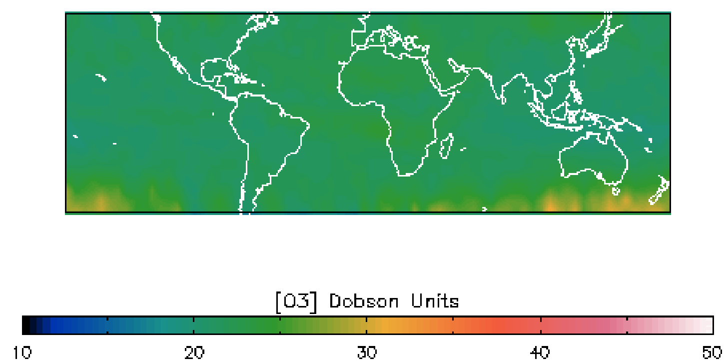
SBUV September 1992
pressure level: 1000mb – 63mb



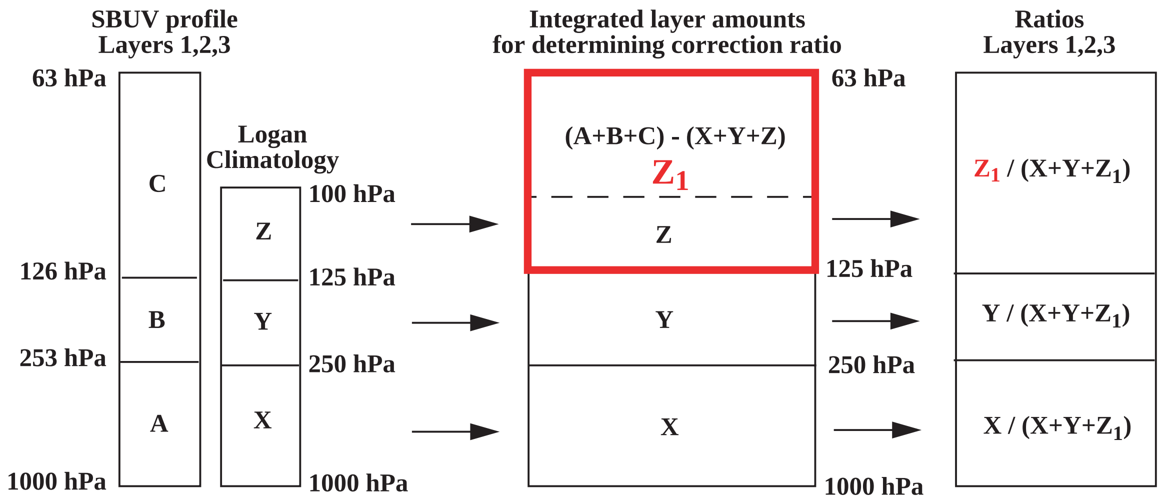
ozone.13.4x5.09
pressure level: 1000mb – 250mb



SBUV September 1992
pressure level: 1013mb – 253mb



Schematic Diagram of Empirical Correction



Input SBUV Measurement:

$(A + B + C)$

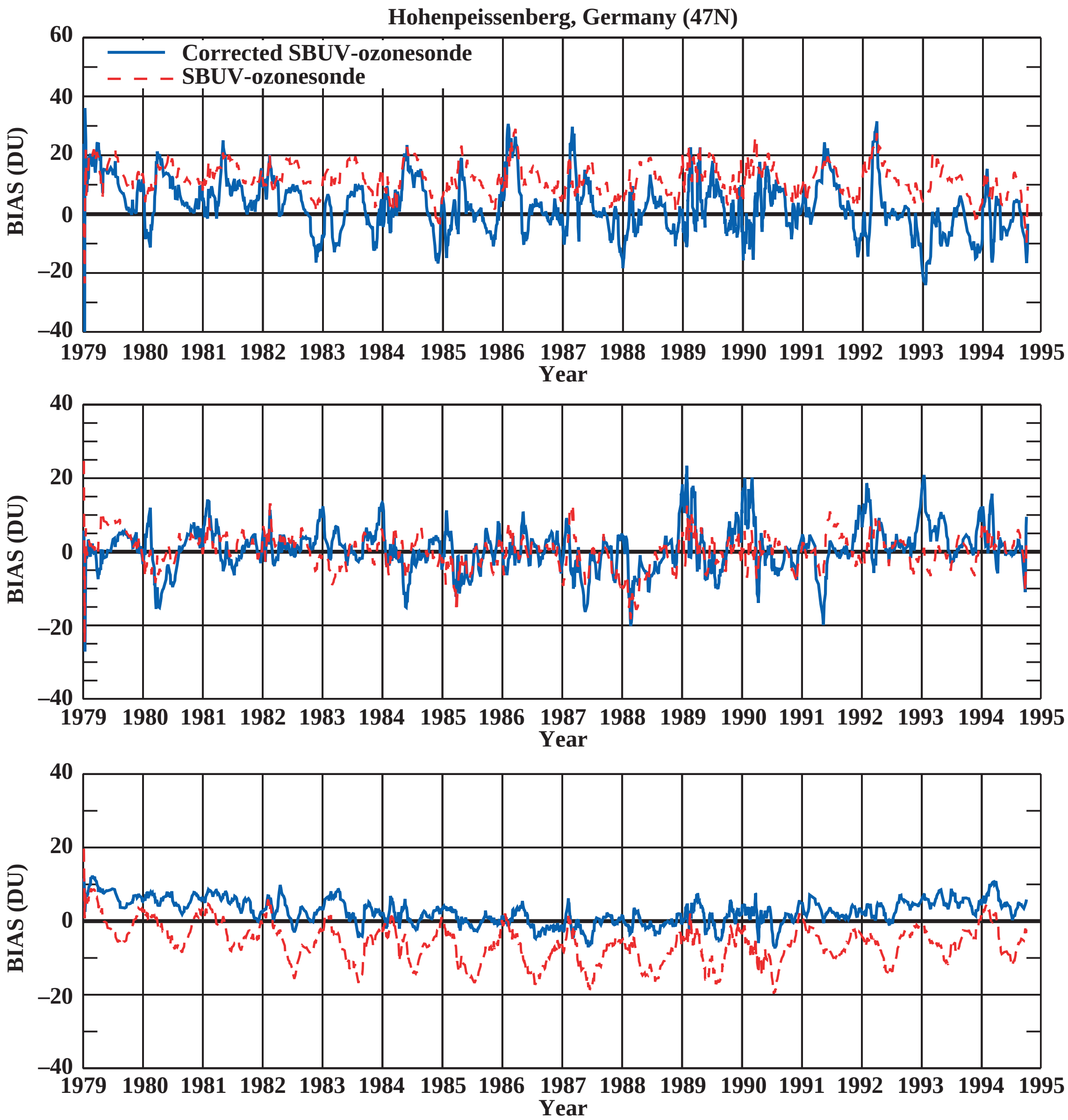
Output* for TOR Calculation

$C^* = Z_1 (A + B + C)/(X + Y + Z_1)$

$B^* = Y (A + B + C)/(X + Y + Z_1)$

$A^* = X (A + B + C)/(X + Y + Z_1)$

Comparison Using Empirical Correction with Ozonesondes



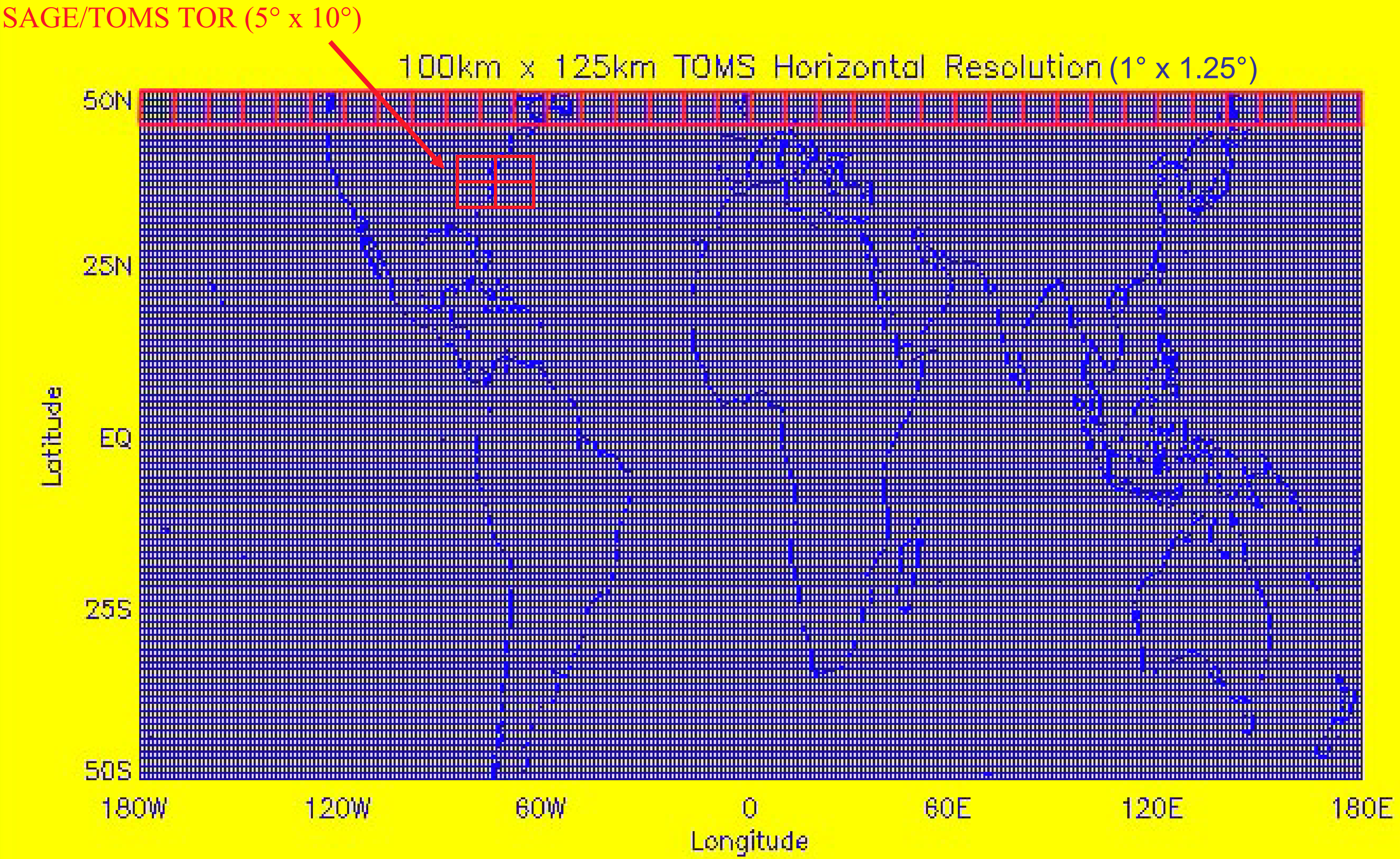
Other Data Sets Are Required To Separate Tropospheric Ozone from Total Ozone Measurements

- SAGE: Good Vertical Resolution; Poor Spatial Coverage
- HALOE: Good Vertical Resolution; Poor Spatial Coverage
- MLS: Vertical Resolution Only >68 mb; Relatively Good Spatial Coverage
- Only One Archived Layer below 100 mb
- SBUV: Poor Vertical Resolution; Good Spatial Coverage
  Archived Layers: 1000–253 mb; 253-126 mb; 126-63 mb
  Stratospheric Fields Generated from 5 Days of Data

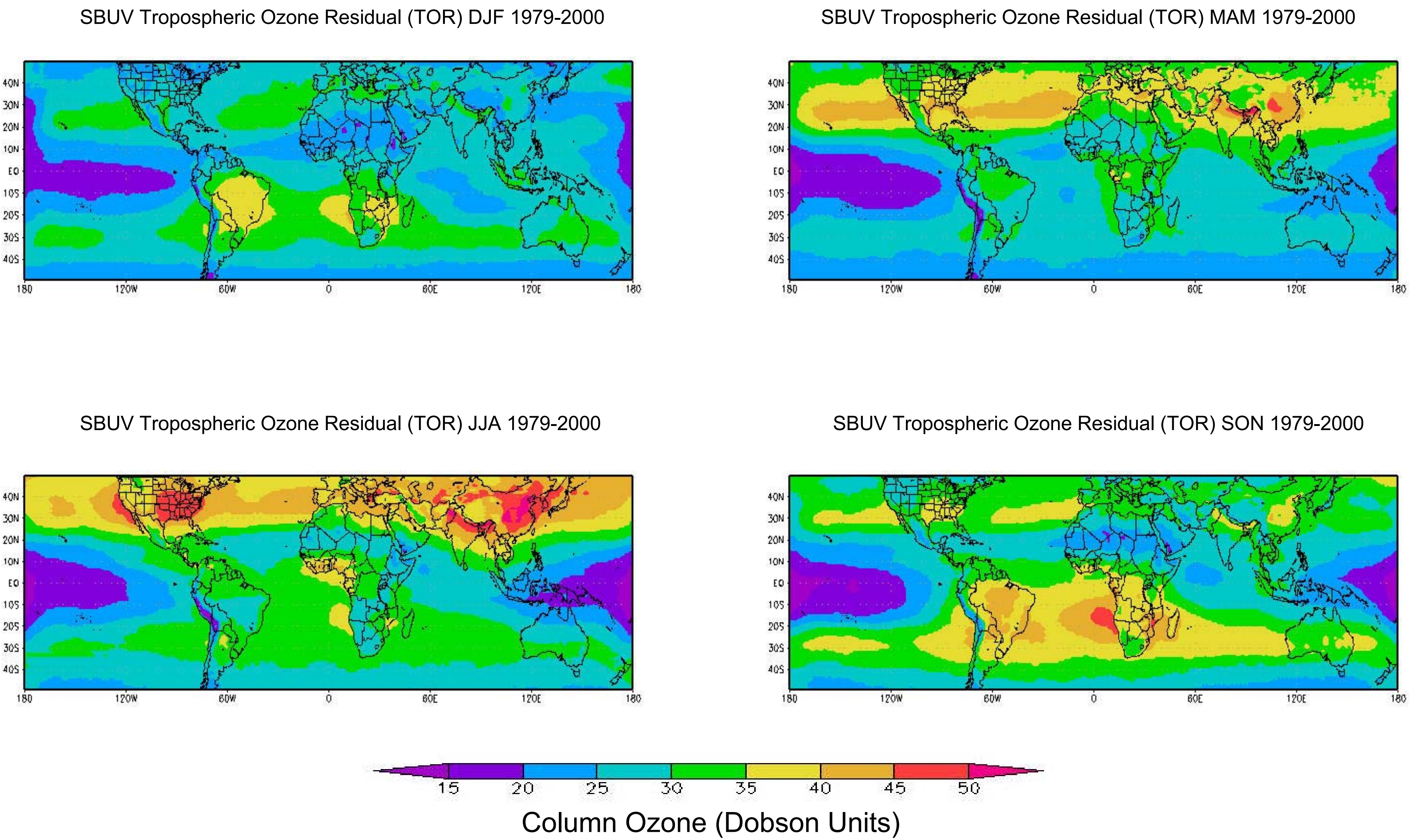
  - **SAGE/TOMS TOR:** ~ 30,000 Coincident Observations 1979-1991 [Fishman & Brackett, 1997]
    ~ **10 data points per 5° x 10° grid box** for seasonal climatology
  - **SAGE/SBUV TOR:** Use Every TOMS Observation (up to 28,800 per day)
    ~ **1500 data points per 1° x 1.25° grid box** for seasonal climatology

- Tropopause Heights: Archived Gridded Data Sets 2.5° x 2.5°

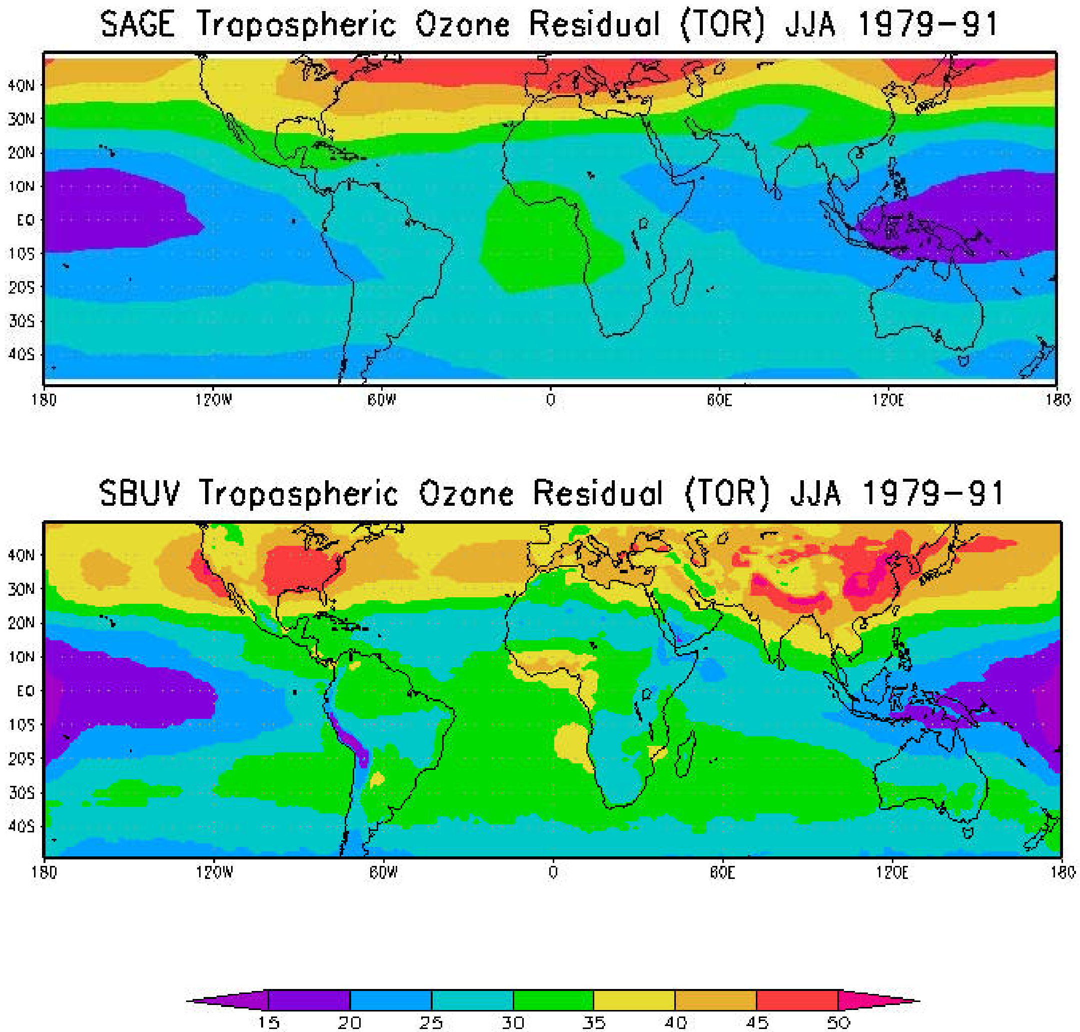
Comparison of Pixel Size for Computing TOR



Seasonal Depictions of Climatological Tropospheric Ozone Residual (TOR) 1979-2000



Comparison of TOMS/SAGE TOR with TOMS/SBUV TOR



Global TOR Averages Change with TOMS Archive

- Fishman et al. [1990]: **32.7 DU** (pseudo-Version 6/SAGE)

  Version 6 corrected for instrument drift

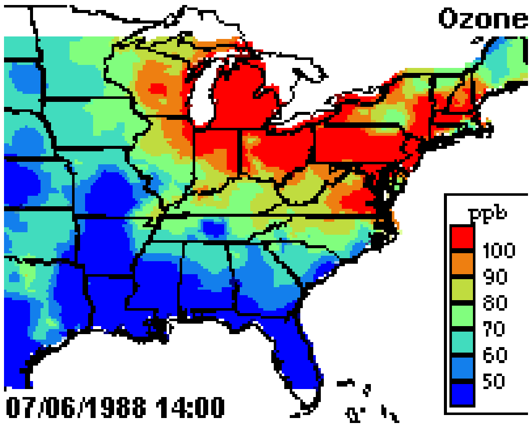
- Fishman & Brackett [1997]: **27.5 DU** (Version 7/SAGE)

  Version 7 incorporates ISCCP cloud climatology for correction

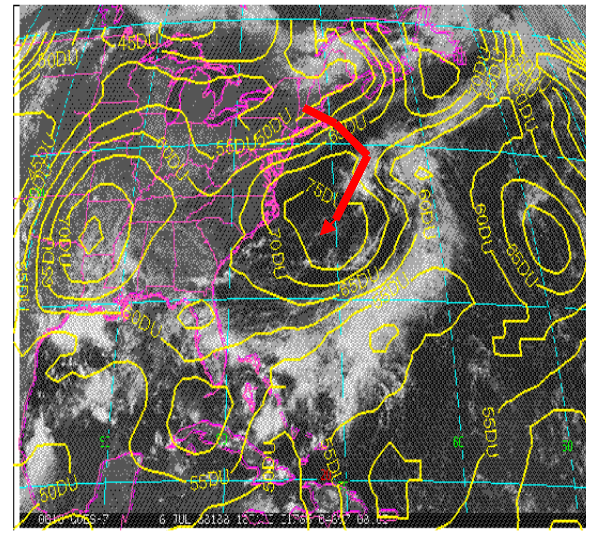
- This Study: **31.5 DU** (pseudo-Version 8/SBUV)

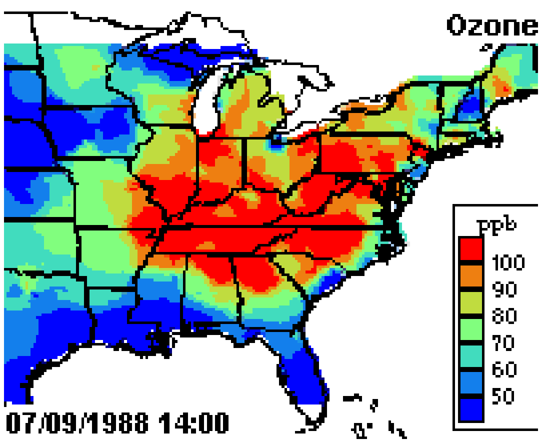
  Version 8 includes aerosol and scan-angle dependence corrections

Satellite Study Demonstrates Synoptic-Scale Pollution Transport

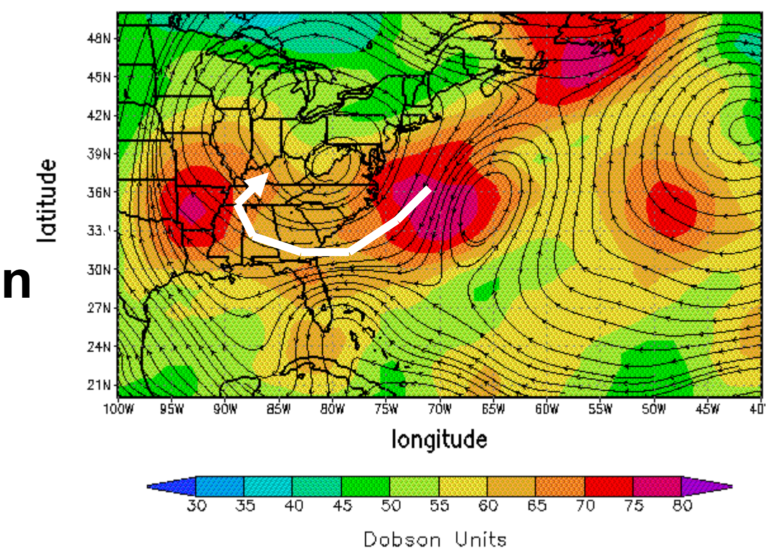


Pollution from northern states pools off North Carolina coast



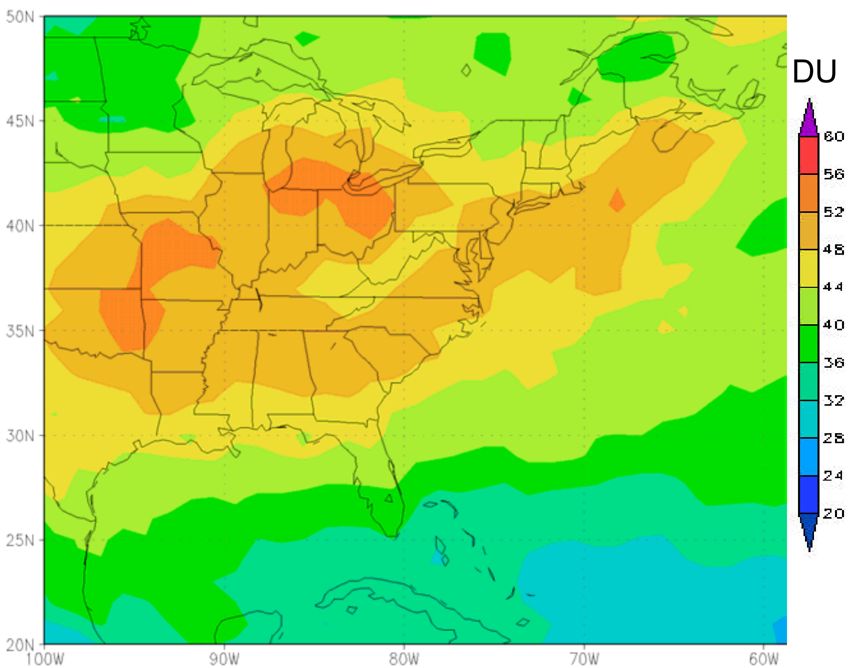


Unique trans-port situation carries off-shore pollution to southern states

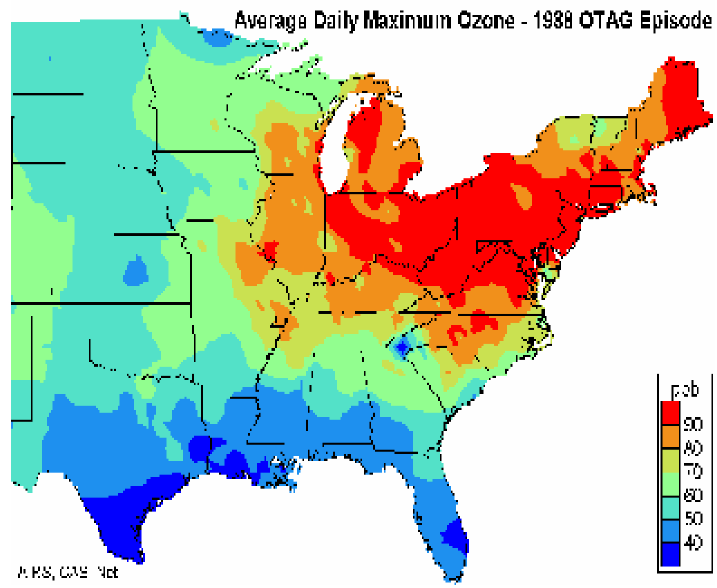


from Fishman and Balok [1999, *JGR*, 104, pp. 30,319]

July 1988 Monthly TOR Captures High Ozone During Major Pollution Episode



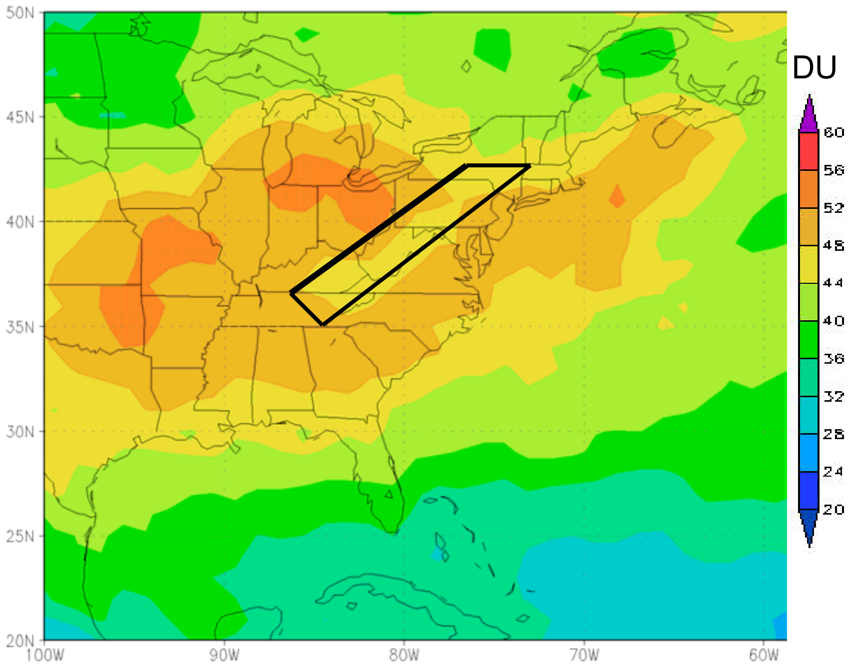
July 1988 TOR



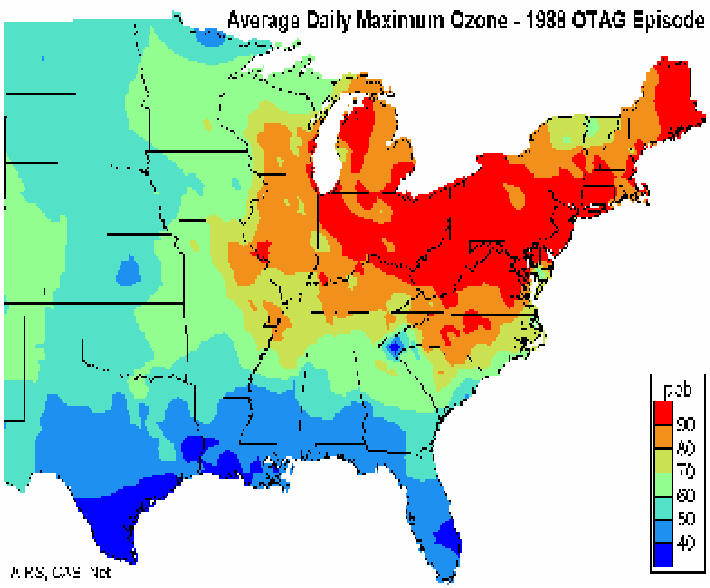
July 3-15 Average Daily Max. O_3

(from Schichtel and Husar, 1998)

July 1988 Monthly TOR Captures High Ozone During Major Pollution Episode



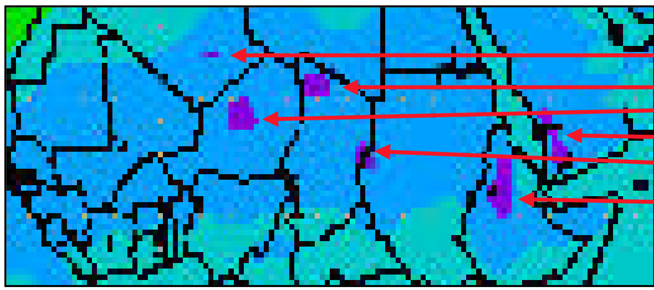
July 1988 TOR

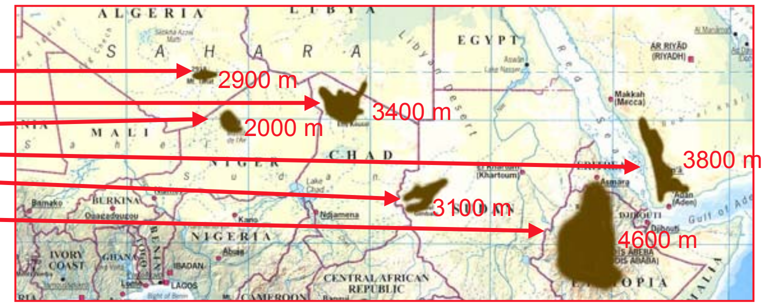


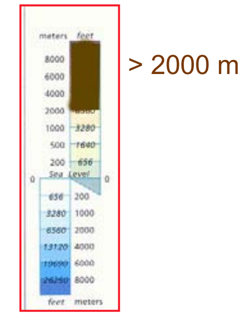
July 3-15 Average Daily Max. O_3
(from Schichtel and Husar, 1998)

- Lower TOR within box due to terrain artifact
- Use terrain information for global validation

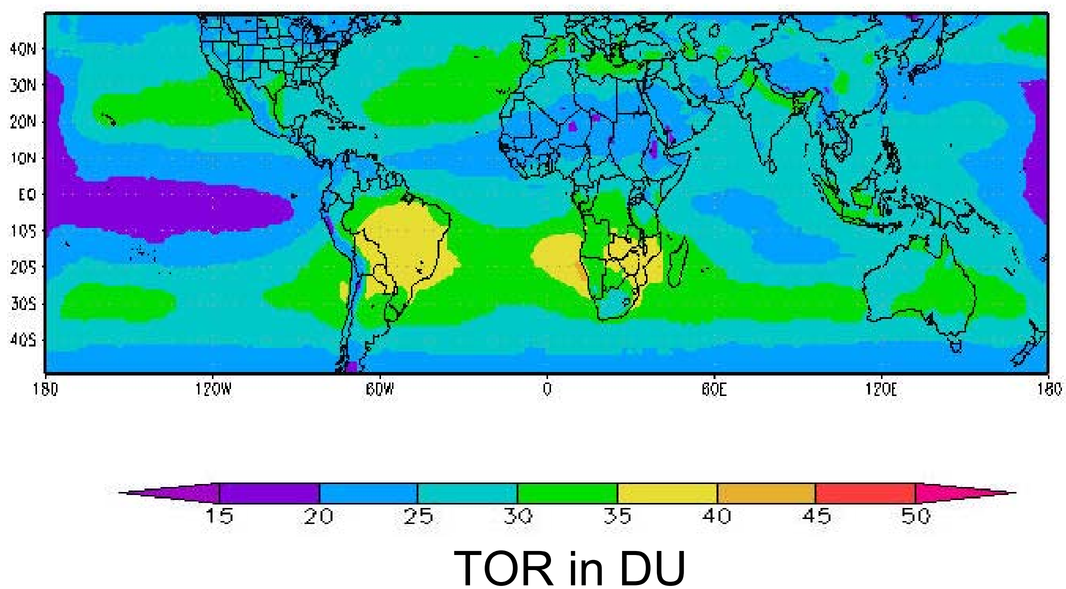
Lower TOR over North African Desert Regions Coincident with Higher Elevations







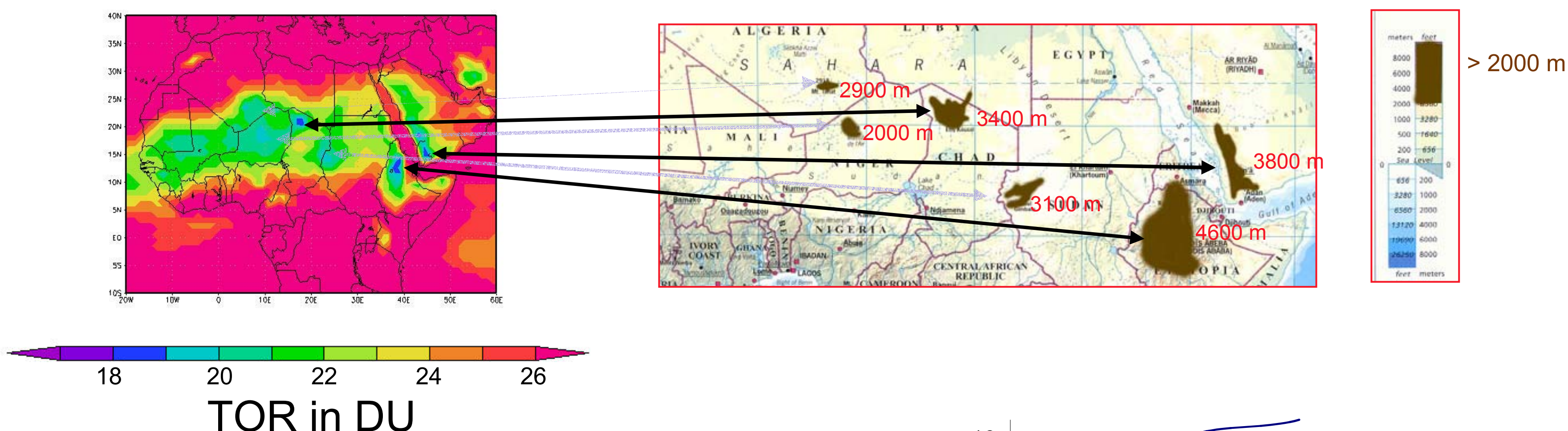
December-February TOR



<u>Implications</u>:

- TOMS Capable of Isolating Small (Regional) Scale Features
- ~3 DU for $\int^{2km} dz \Rightarrow$ ~20 ppb in pbl
- Information can be used to validate O_3 backscatter sensitivity in boundary layer over cloudless unpolluted area

Higher Elevation Differences (3-4 km) Coincident with Greater O_3 Deficits (5-7 DU)

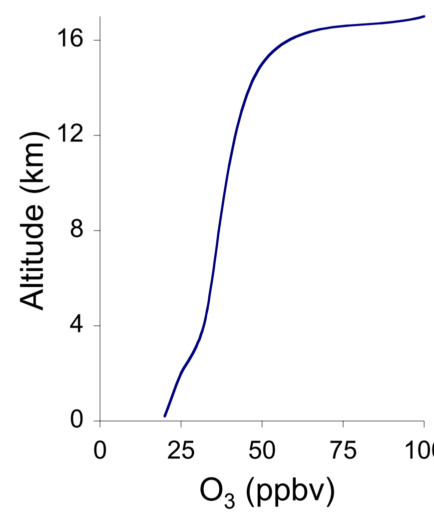


- Inferred Ozone Profile over North Africa Desert Region:

$$\int^{\mathbf{2}\ \mathrm{km}} [O_3]\, dz = \sim 3\ \mathrm{DU}$$

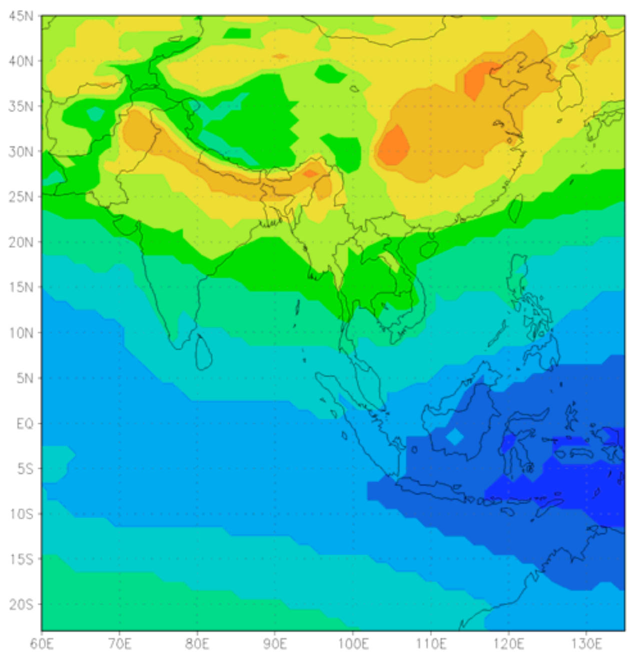
$$\int^{\mathbf{4}\ \mathrm{km}} [O_3]\, dz = \sim 6\ \mathrm{DU}$$

$$\int^{\mathrm{Trop.}\ (\sim 17\ \mathrm{km})} [O_3]\, dz = \sim 25\ \mathrm{DU}$$

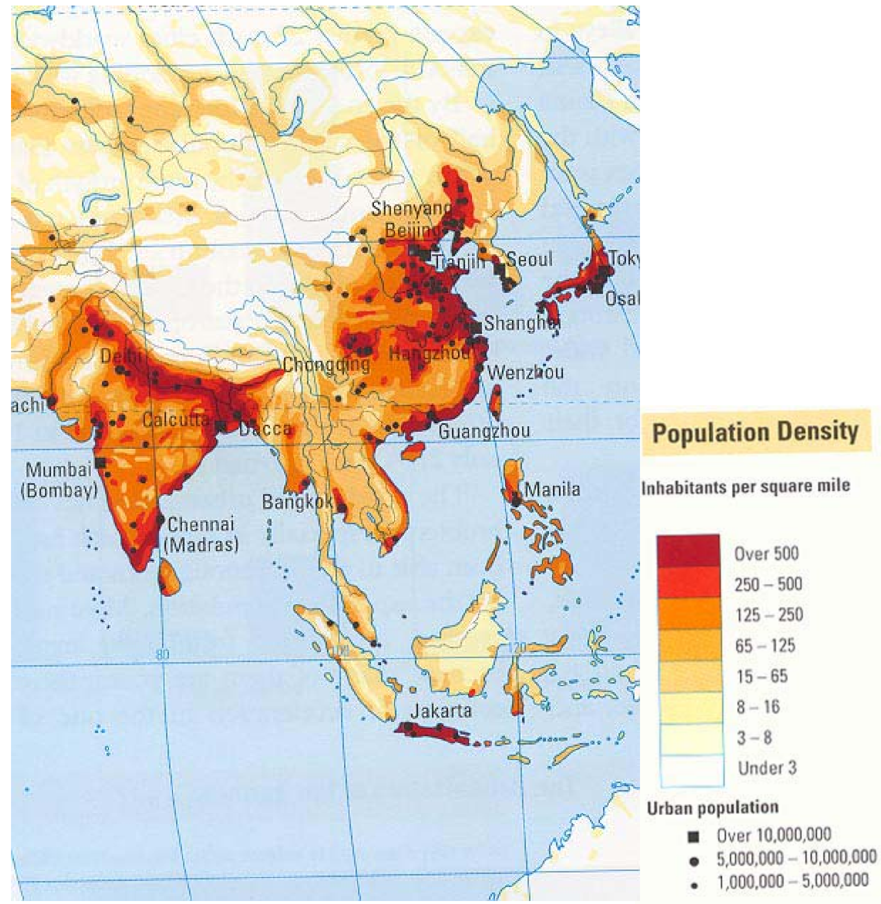


Population and Ozone Pollution Strongly Correlated in India and China

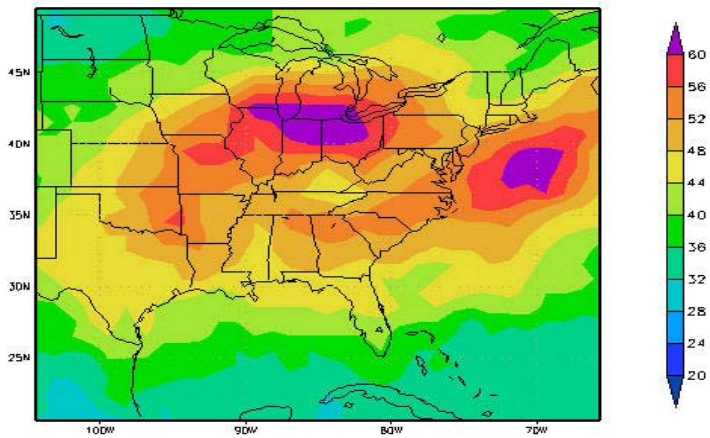
Summer Climatological Distribution

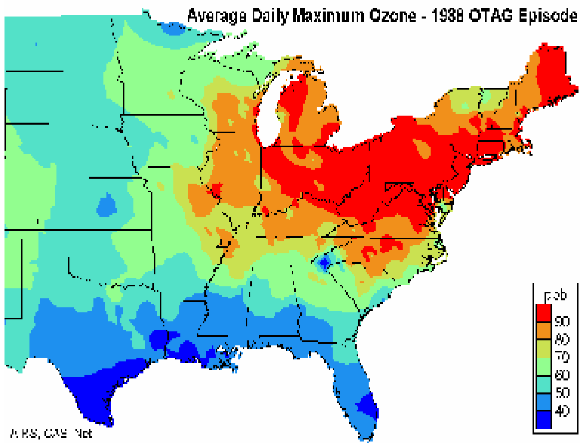


TOR in Dobson Units

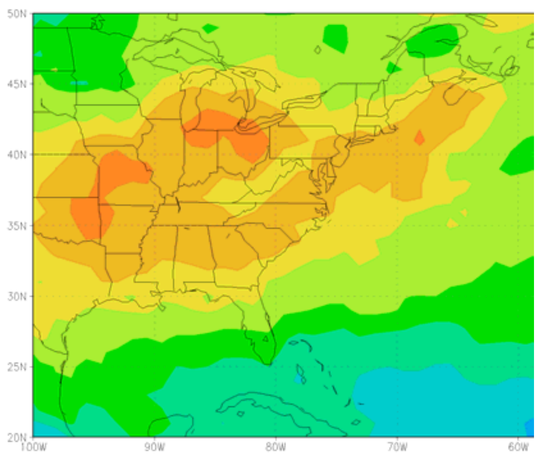


Comparison of Indian and U.S. Air Pollution Episodes

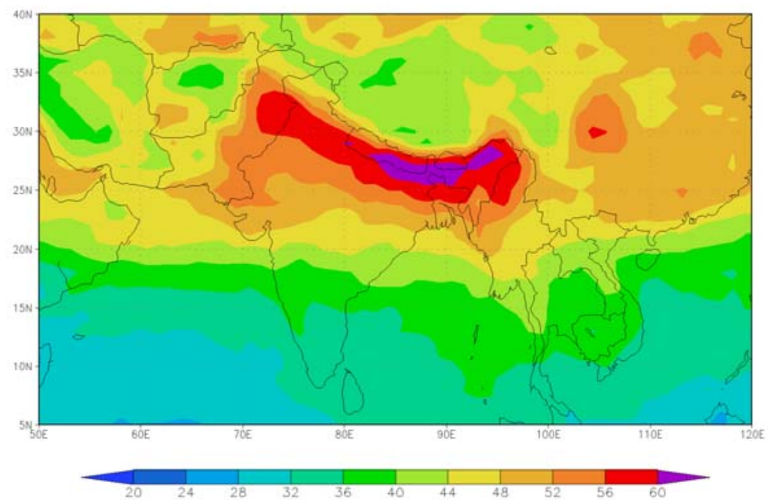




TOR and Surface O_3 Depiction During July 3-15 Pollution Episode

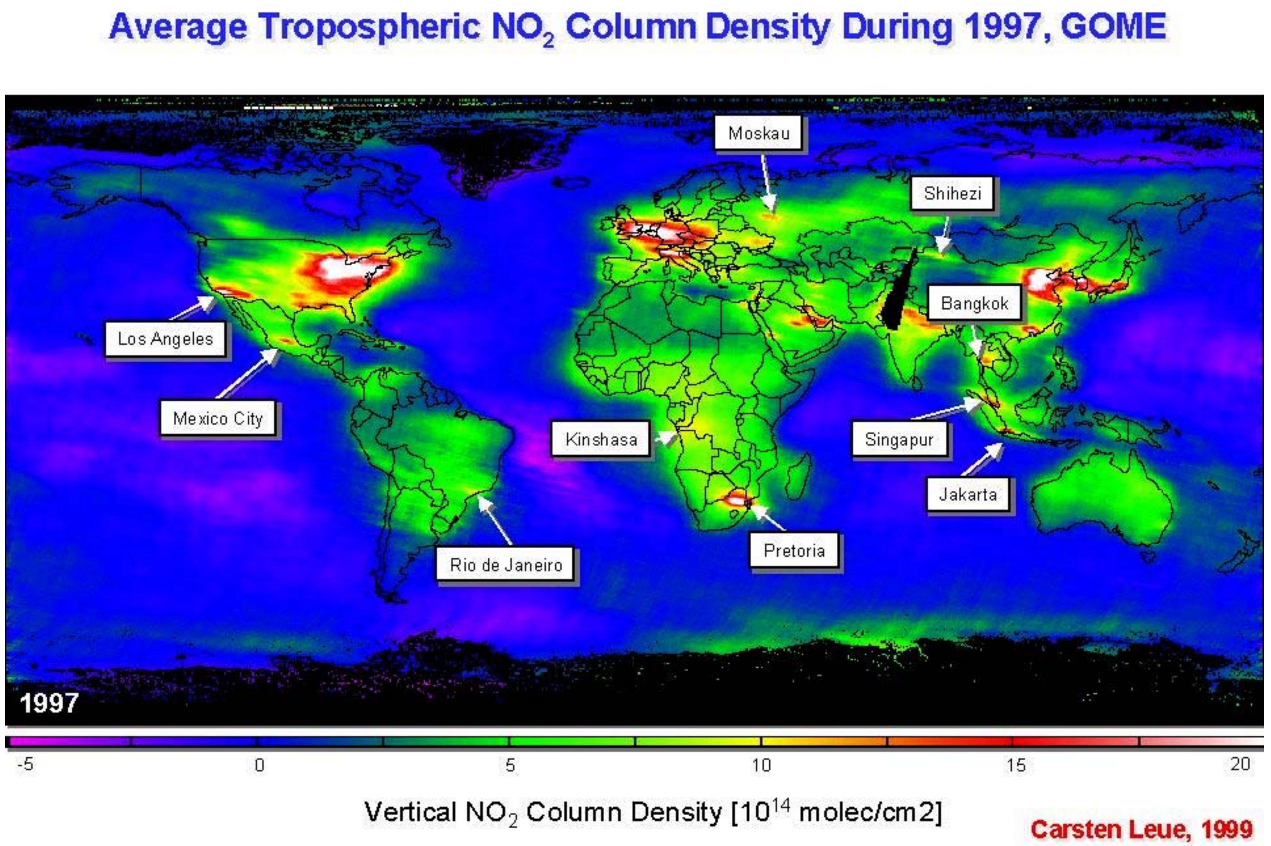


July 1988



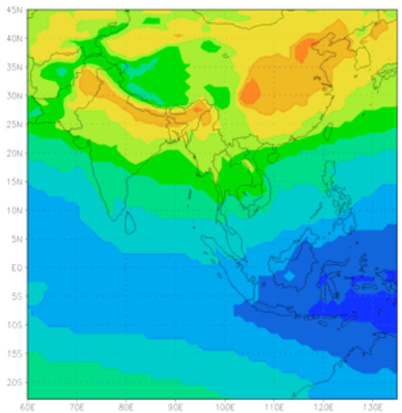
June 1982

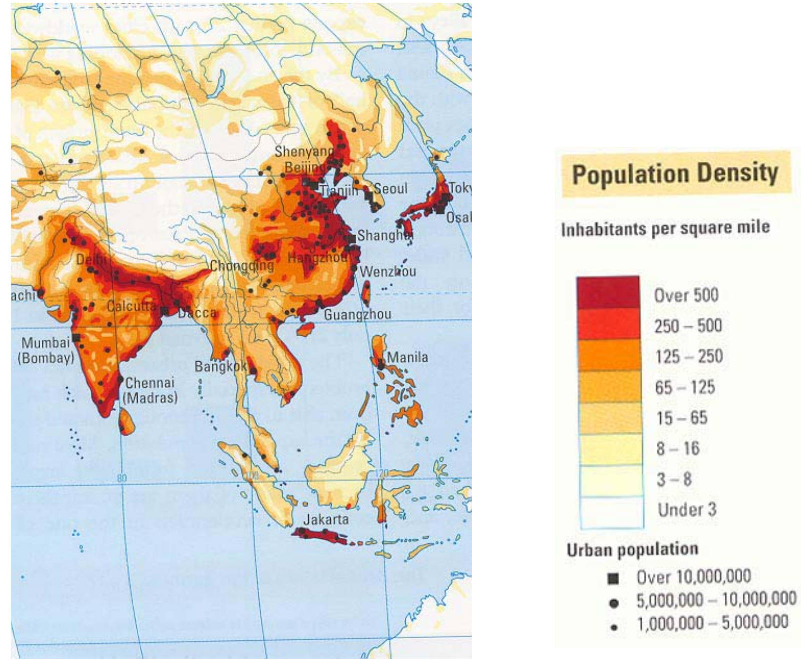
GOME NO_2 Measurements Also See Enhancements over India and China



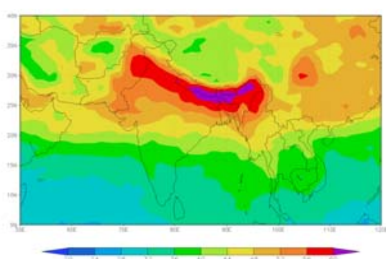
Ozone Enhancement over India

Summer Climatological Distribution

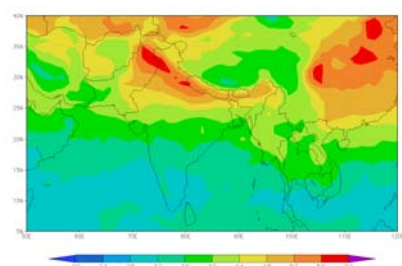




TOR in Dobson Units



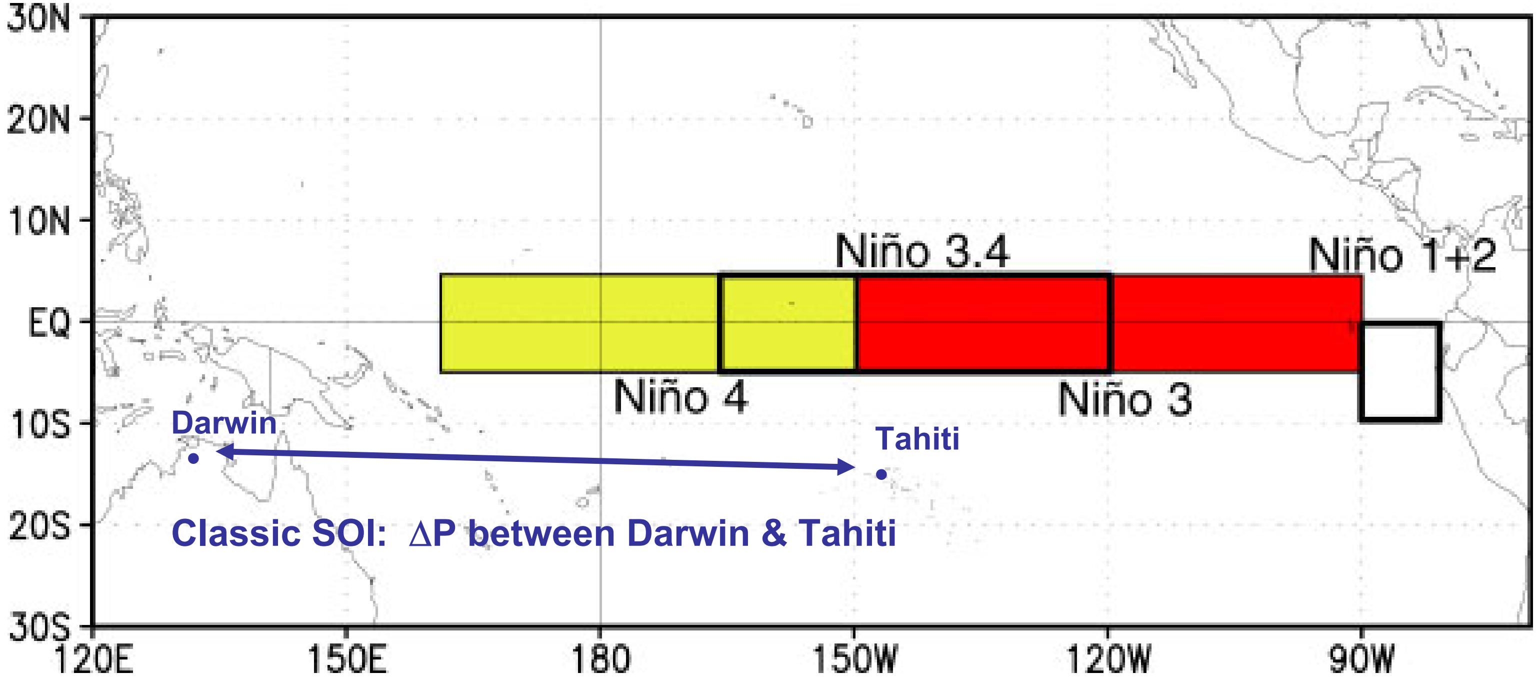
June 1982



June 1999

How does the Amount of Ozone over India Compare with the Amount Observed over the Eastern United States?

Definitions of ENSO Indicators



Other definitions include Sea Surface Temperature Anomalies (SSTA) in various regions of the Pacific:

Niño 1+2: Off coast of Ecuador; Niño 3: Eastern Pacific; Niño 4: Western Pacific; Niño 3.4: Central Pacific

Monthly TOR Values Over Northern India 1979-1999

Jan	29.8	Feb	29.9	Mar	34.6	Apr	44.	May	47.3	Jun	48.2	Jul	46.4	Aug	42.0	Sep	36.8	Oct	32.7	Nov	30.5	Dec	27.9
1991	31.5	1992	33.3	1989	40.5	1982	47.2	1982	52.9	1982	52.1	1982	48.3	1992	43.7	1990	40.1	1999	35.0	1981	33.2	1997	30.0
1984	31.2	1987	33.0	1982	38.1	1984	47.1	1981	50.0	1989	51.3	1992	47.8	1990	43.5	1988	37.9	1998	34.4	1988	32.1	1985	29.5
1998	30.9	1984	32.6	1990	37.9	1991	45.9	1990	49.8	1992	51.2	1987	47.6	1987	43.4	1992	37.6	1985	33.2	1997	31.8	1999	28.8
1990	30.7	1979	31.8	1987	36.7	1979	45.7	1989	49.5	1990	49.9	1990	47.6	1991	43.1	1991	37.3	1986	33.1	1992	31.7	1983	28.7
1986	30.7	1983	31.0	1984	35.5	1981	44.8	1992	49.2	1991	49.3	1991	47.5	1982	42.9	1989	37.1	1980	33.0	1991	31.5	1989	28.4
1987	30.7	1988	31.0	1981	34.9	1989	44.7	1983	48.1	1987	48.5	1989	46.9	1989	42.4	1986	37.0	1990	32.9	1999	31.3	1988	28.4
1979	30.3	1986	30.8	1998	34.8	1992	44.6	1986	47.5	1984	48.5	1984	46.6	1988	42.4	1998	36.8	1983	32.9	1979	31.2	1981	28.3
1988	30.1	1993	30.7	1988	34.7	1980	44.5	1991	47.4	1980	47.5	1988	46.6	1983	42.3	1985	36.7	1989	32.9	1987	30.7	1990	28.3
1999	29.8	1990	30.5	1993	34.7	1993	44.4	1979	47.2	1988	47.5	1981	46.6	1984	42.2	1987	36.7	1991	32.7	1982	30.1	1992	27.8
1981	29.8	1985	30.2	1979	34.0	1986	44.4	1984	46.6	1981	47.4	1983	46.0	1979	42.0	1983	36.6	1979	32.7	1983	30.0	1979	27.7
1983	29.7	1981	29.4	1986	34.0	1987	44.0	1999	46.2	1979	46.8	1986	46.0	1981	41.4	1997	36.4	1988	32.6	1985	29.8	1980	27.7
1993	29.7	1998	29.1	1980	33.9	1998	43.6	1980	46.1	1983	46.8	1980	45.7	1985	41.1	1980	36.3	1997	32.5	1989	29.6	1982	27.3
1985	29.4	1999	29.0	1985	32.8	1990	43.5	1988	45.6	1985	46.6	1979	45.1	1980	40.8	1981	36.0	1981	32.4	1990	29.2	1987	27.1
1982	29.1	1982	28.6	1983	32.6	1983	41.6	1985	44.4	1986	46.4	1985	44.9	1986	40.6	1984	36.0	1982	32.1	1980	28.8	1991	26.7
1989	29.1	1989	25.8	1992	32.3	1988	41.1	1987	44.2	1998	46.0	1998	44.8	1998	40.5	1999	35.8	1992	32.0	1986	28.6	1986	26.1
1992	27.6	1980	25.5	1999	26.7	1999	40.8	1998	42.4	1999	45.4	1999	44.0	1999	40.4	1982	35.5	1984	31.8	1984	28.6	1984	25.8
1980	25.7	1991	25.1			1985	40.5									1979	35.2	1987	30.6				

Monthly Averages for Each Year are Rank-Ordered:

1982 Highlighted in Red

1999 Highlighted in Blue

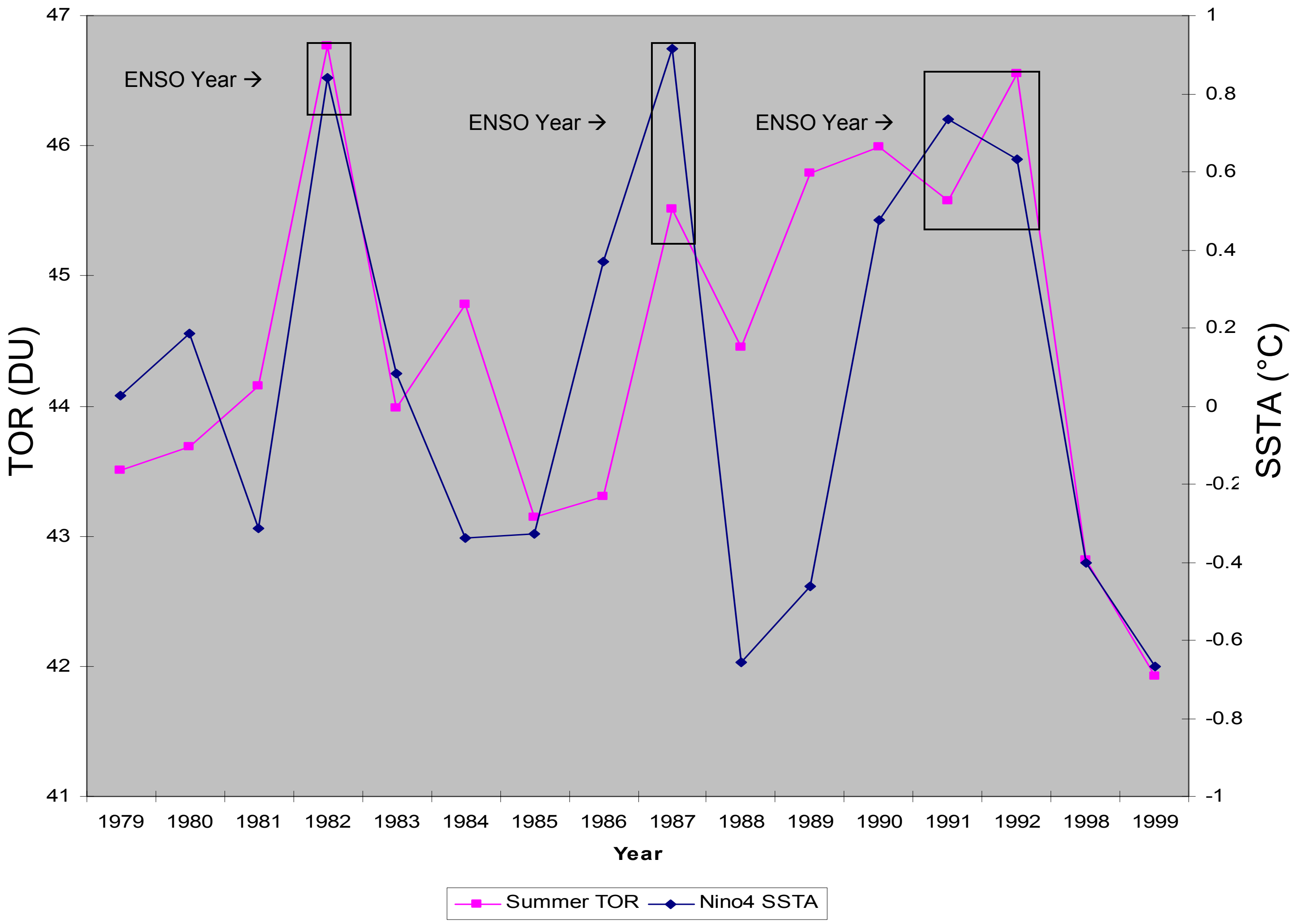
Correlation Coefficients Between Northern India Monthly TOR Values and Monthly/Seasonal ENSO Indicators (1979-1999)

Month	Mean TOR	Range		SOI		ENSO SST Region			
		High	Low	Mon	Seas	1&2	3	3.4	4
January	29.8	31.5 (1991)	25.7 (1980)	.04	-.01	.07	-.04	-.06	-.01
February	29.9	33.3 (1992)	25.1 (1991)	-.33	**-.45**	.11	.27	.33	.21
March	34.6	40.5 (1989)	26.7 (1999)	.02	.02	-.15	-.14	-.06	.15
April	44.0	47.2 (1982)	40.5 (1985)	-.21	-.23	-.05	.13	.19	.31
May	47.3	52.9 (1982)	42.4 (1998)	.21	.23	-.17	.11	.15	.31
June	48.2	52.1 (1982)	45.4 (1999)	**-.45**	**-.56**	-.09	.28	.41	**.44**
July	46.4	48.3 (1982)	44.0 (1999)	**-.53**	**-.60**	.09	**.43**	**.62**	**.70**
August	42.0	43.7 (1992)	40.4 (1999)	**-.44**	**-.53**	.15	**.46**	**.54**	**.61**
September	36.8	40.1 (1990)	35.2 (1979)	.09	.16	-.26	-.25	-.22	.06
October	32.7	35.0 (1999)	30.6 (1987)	**.55**	**.45**	-.36	-.42	**-.46**	**-.52**
November	30.5	33.2 (1981)	28.6 (1984)	.27	.08	.11	.04	.00	-.12
December	27.9	30.0 (1997)	25.8 (1984)	**.43**	.21	.14	.02	-.07	-.13

Note: Monthly Average for each year comprised of >7500 TOR measurements (252 points x ~30 days)

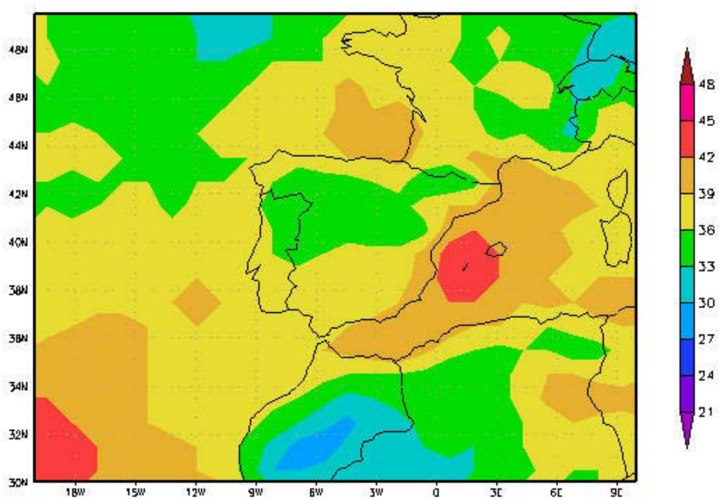
- Shaded Values Statistically Significant (>.9 confidence level)
- Most Significant Relationship between Summer TOR and Seasonal ENSO Indicators

Summer India TOR and SSTA-Niño 4 from 1979-1999

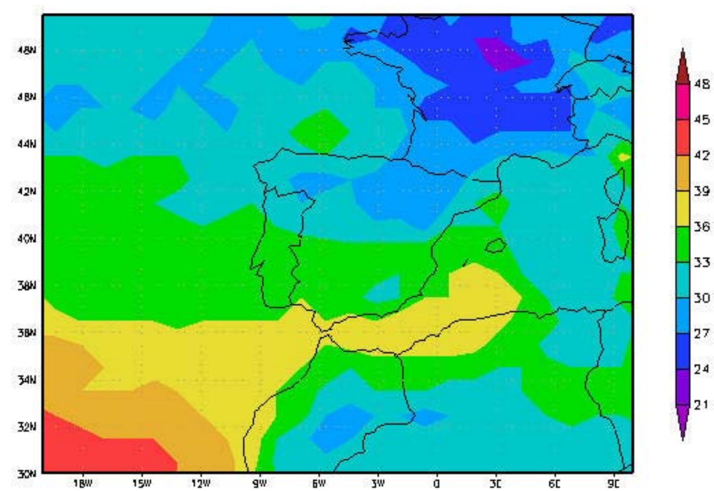


Springtime TOR Variability Over Atlantic Mid-Latitudes Linked to Differences in Prevailing Transport Patterns

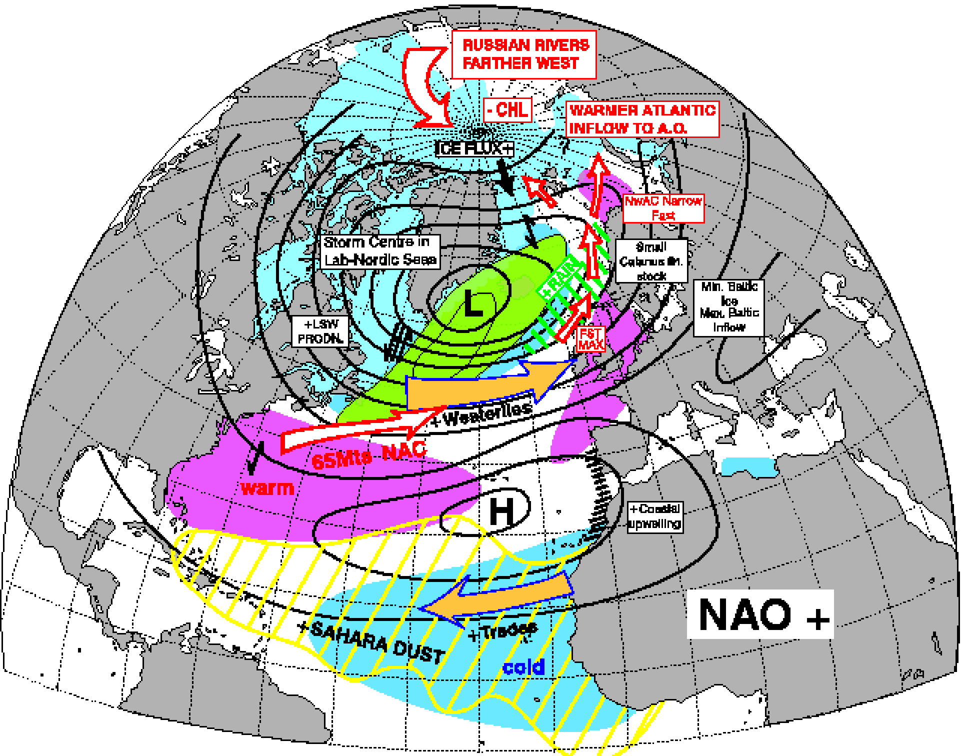
Spring 1992

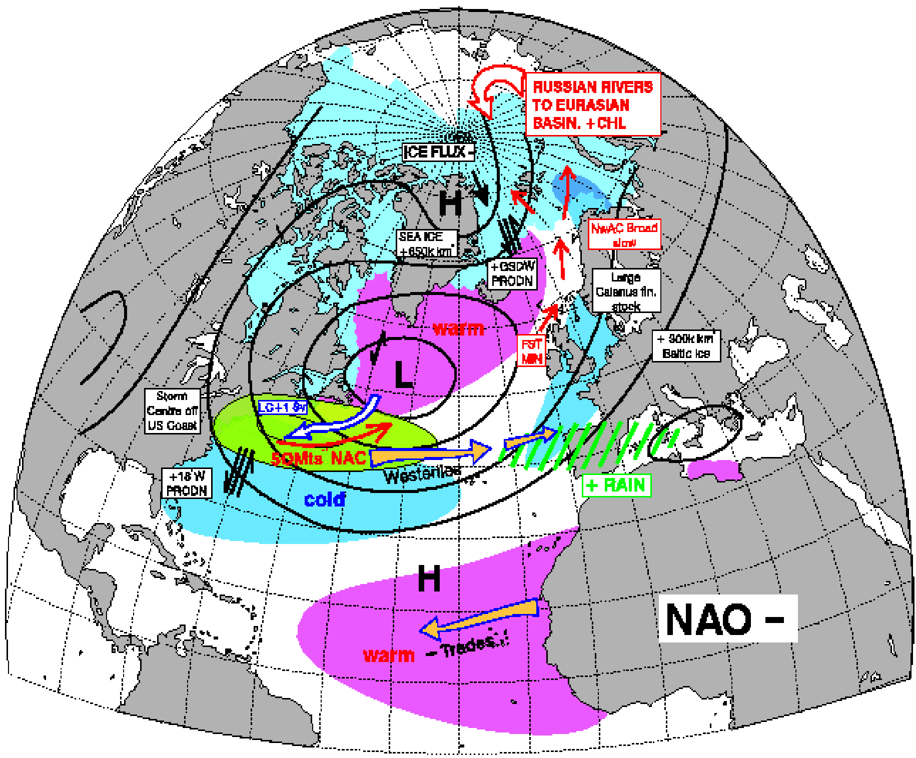


Spring 1980

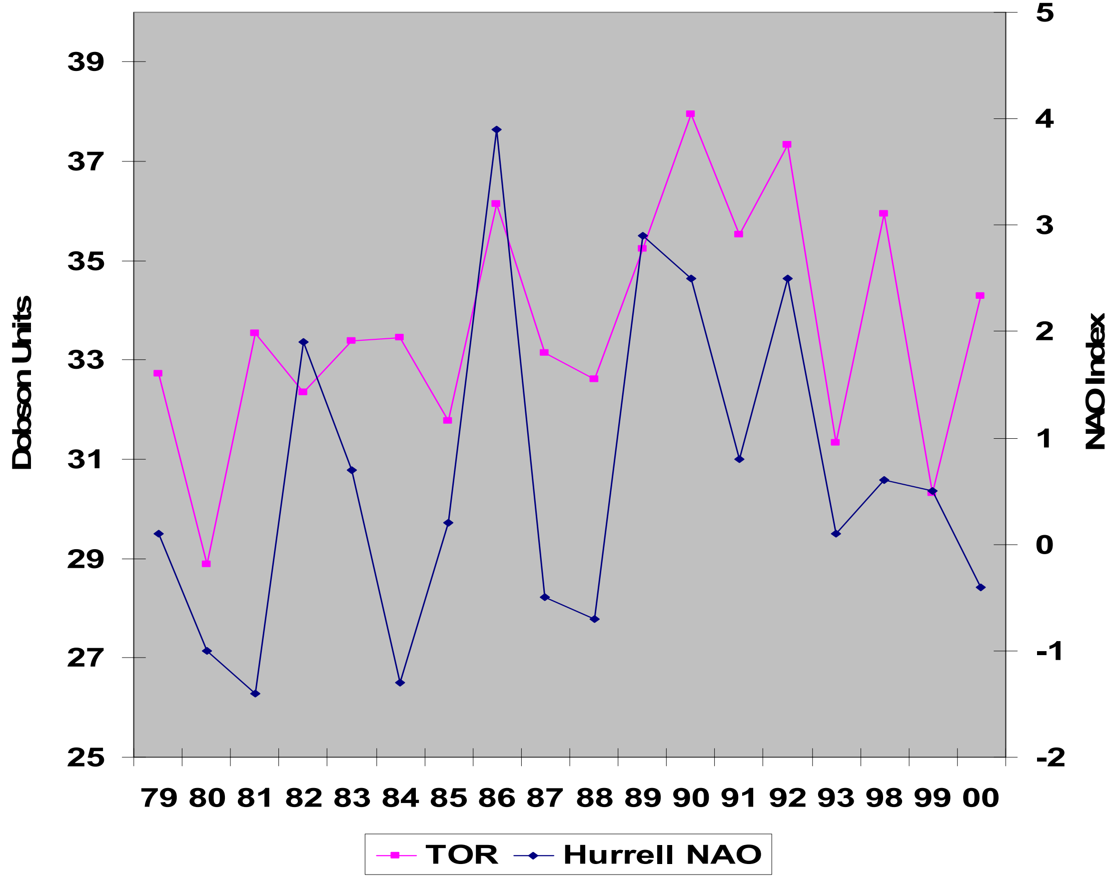


North Atlantic Oscillation Determines Intensity of Transport Across Atlantic





Strong Correlation between TOR and NAO Index

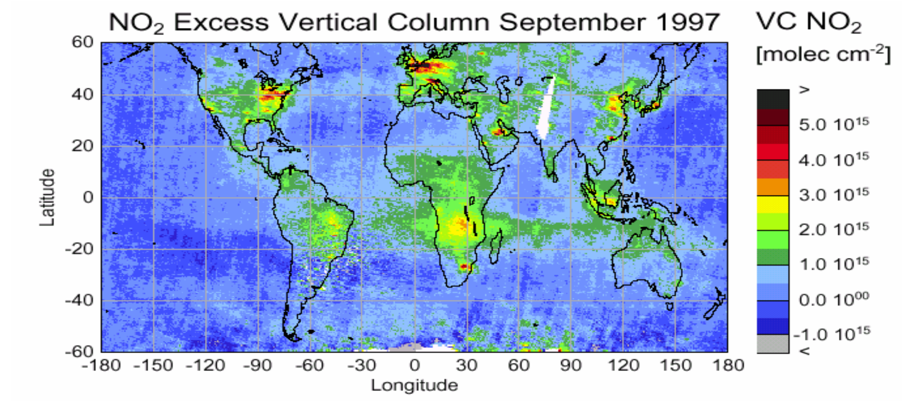


What Improvements Will Take Place in the Near Future and What are the Long-Term Plans for Using Trace Gas Measurements from Space?

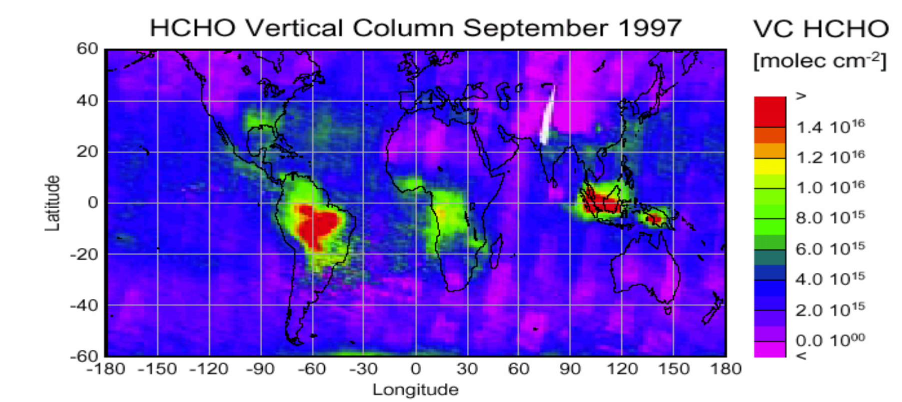
Tropospheric Trace Gases Observable by Satellite

Nitrogen Dioxide:

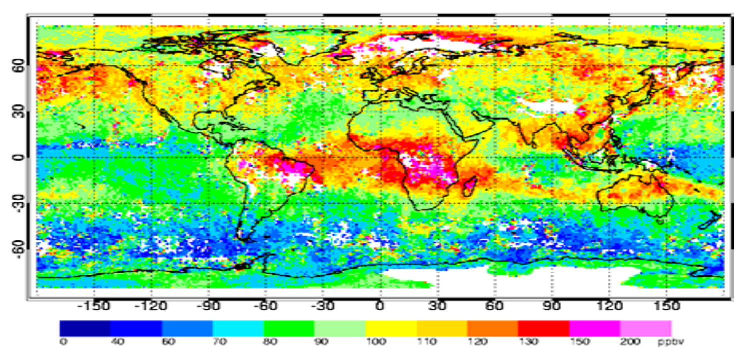
(requires separation from stratosphere)



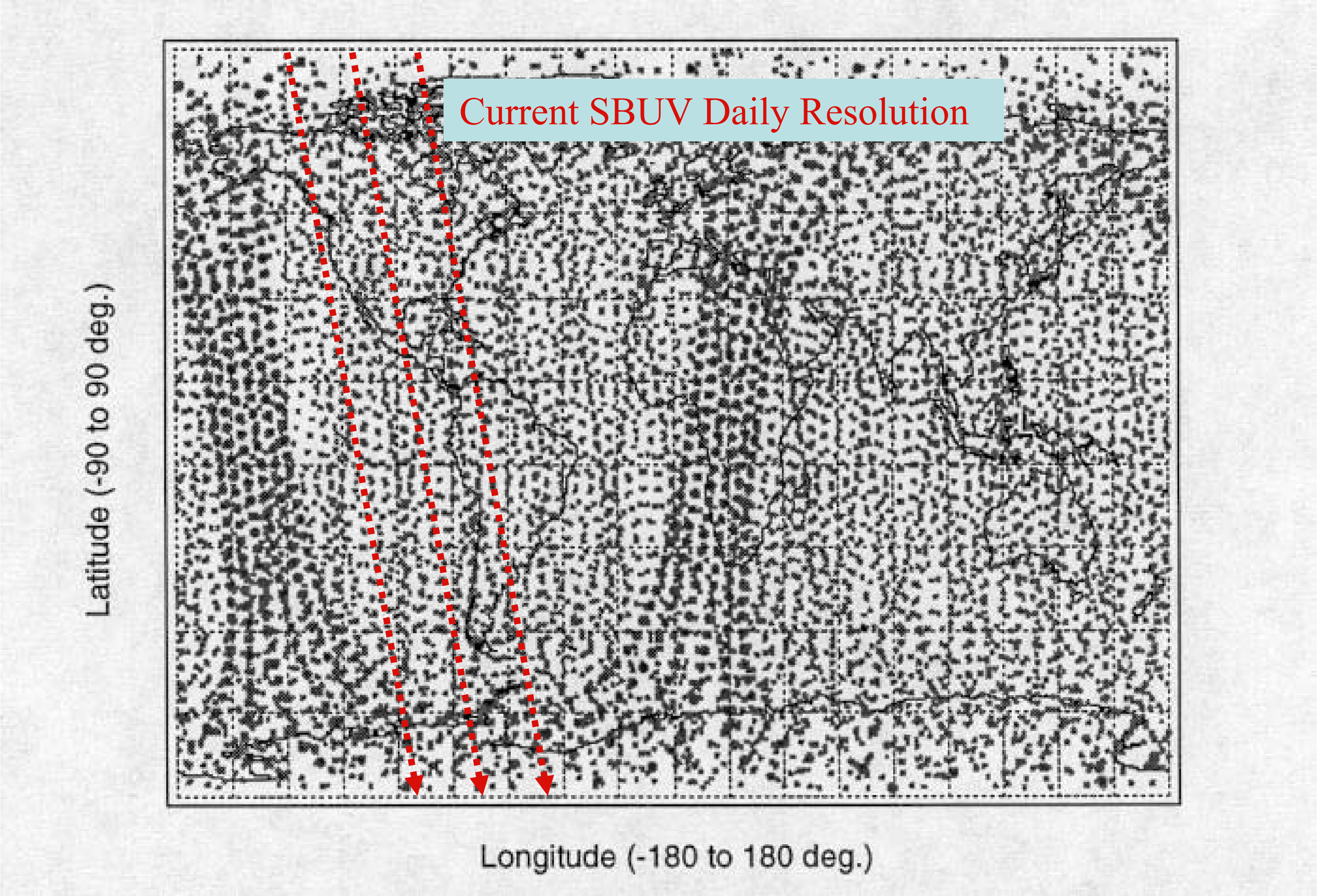
Formaldehyde



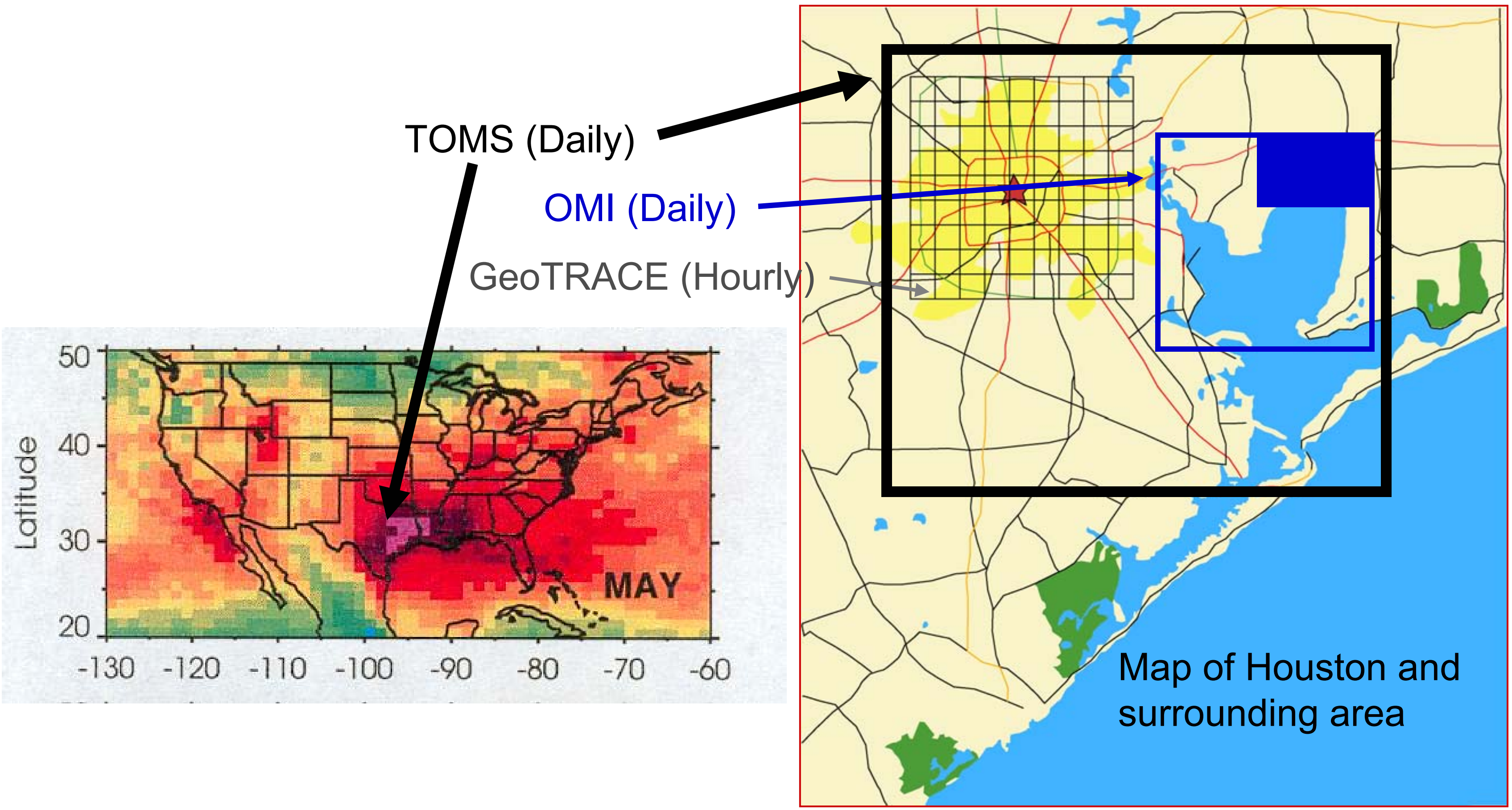
Carbon Monoxide



HIRDLS Daily Profile Coverage Will Provide Sufficient Information to Derive 3-Dimensional Stratospheric Ozone Distribution Down to 1 km Below Tropopause



Geostationary Observations Will Provide Hourly Observations with 5-km Resolution



The National Air Quality Goal

With Data from August 9:

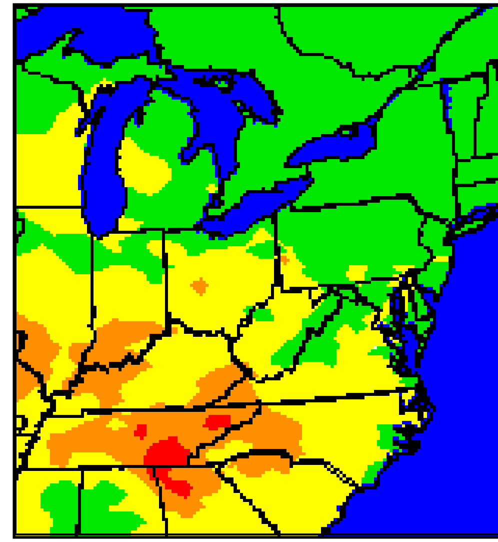
Can we predict **unhealthy O_3**

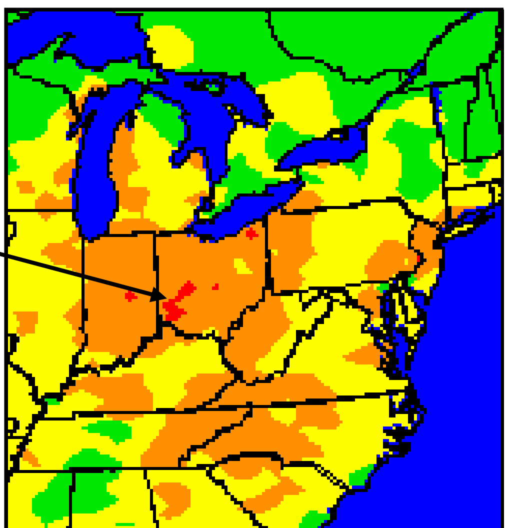
- in Cincinnati on the 10th?
- in Pittsburgh and and Buffalo on the 11th?
- in Philadelphia and New Jersey on the 12th?

Air Quality Index (AQI): Ozone

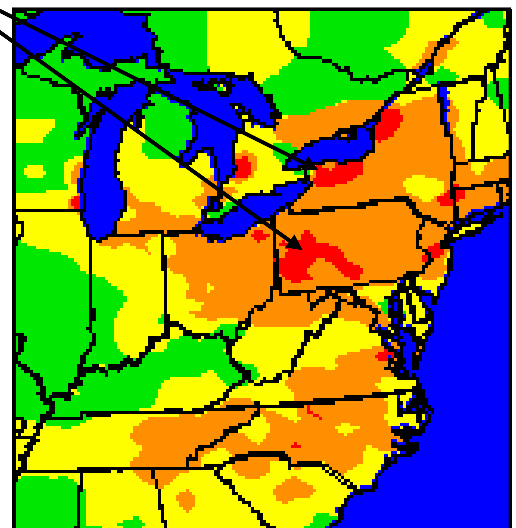
Index Values	Levels of Health Concern	Cautionary Statements
0 - 50	Good	None
51 - 100*	Moderate	Unusually sensitive people should consider limiting prolonged outdoor exertion.
101 - 150	Unhealthy for Sensitive Groups	Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion.
151 - 200	Unhealthy	Active children and adults, and people with respiratory disease such as asthma, should avoid prolongd outdoor exertion; everyone else, especially children, should limit prolonged outdoor exertion.
201 - 300	Very Unhealthy	Active children and adults, and people with respiratory disease such as asthma, should avoid all outdoor exertion; everyone else, especially children, should limit outdoor exertion.
301 - 500	Hazardous	Everyone should avoid all outdoor exertion.

August 9, 2002

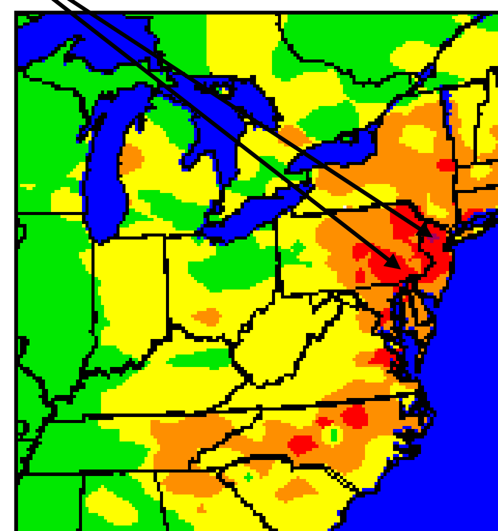




August 10



August 11

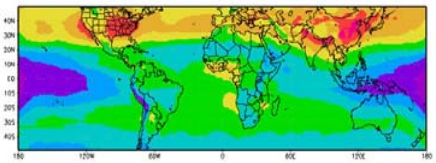


August 12

The Roadmap Has Been Laid Out

We must now pave the road and travel on it to our destination

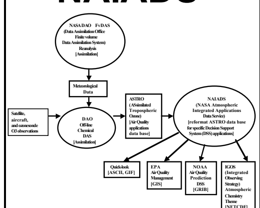
2002

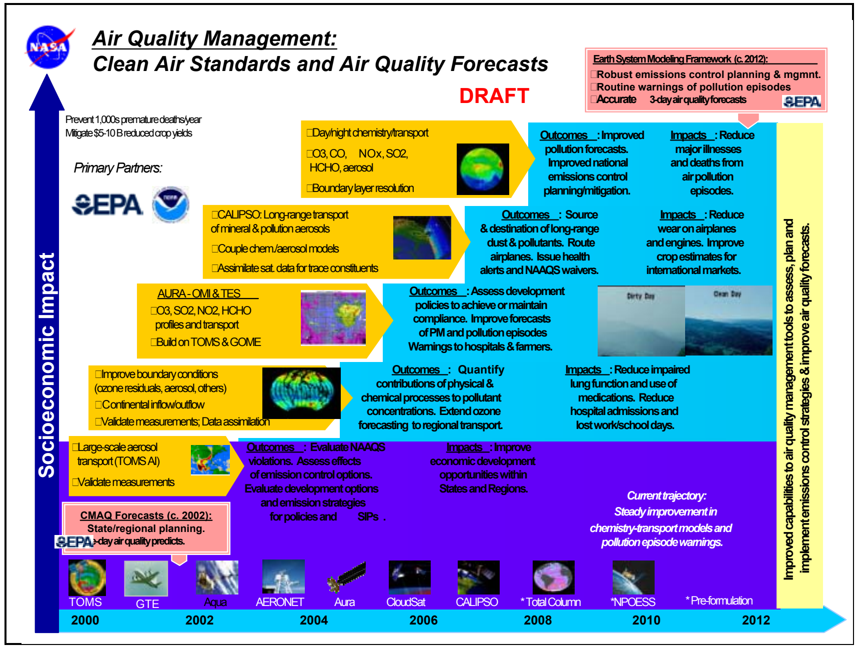


Satellite Measurements: Poor Temporal & Spatial Resolution (LEO Only)

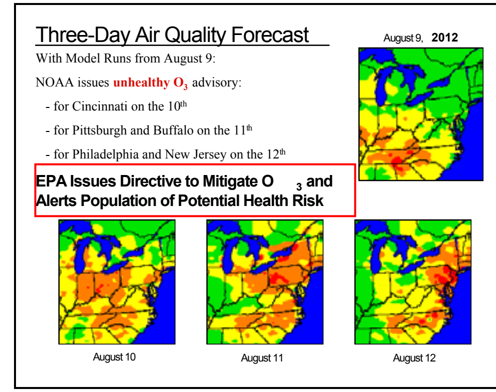
CMAQ: Runs Independent of Surrounding Conditions

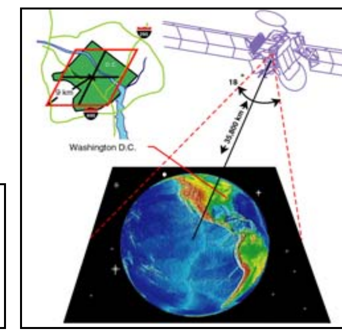
ASTRO-NAIADS





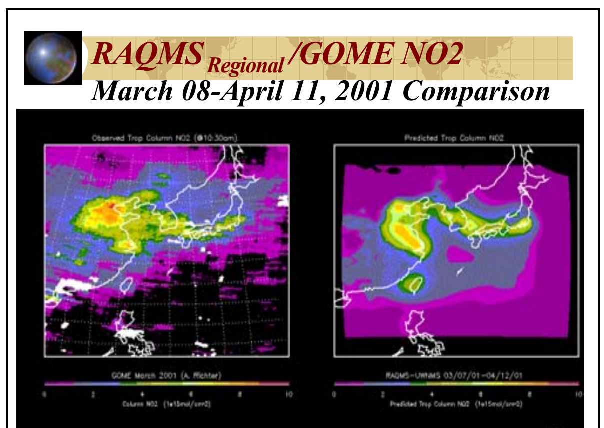
2012





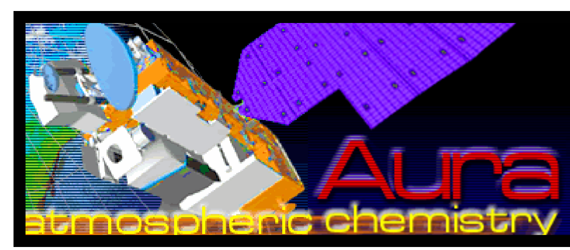
Develop Data Assimilation and Modeling Tools

Validate on Existing Data Sets



GOME V4.6 retrieval from A. Richter University of Bremen, GR

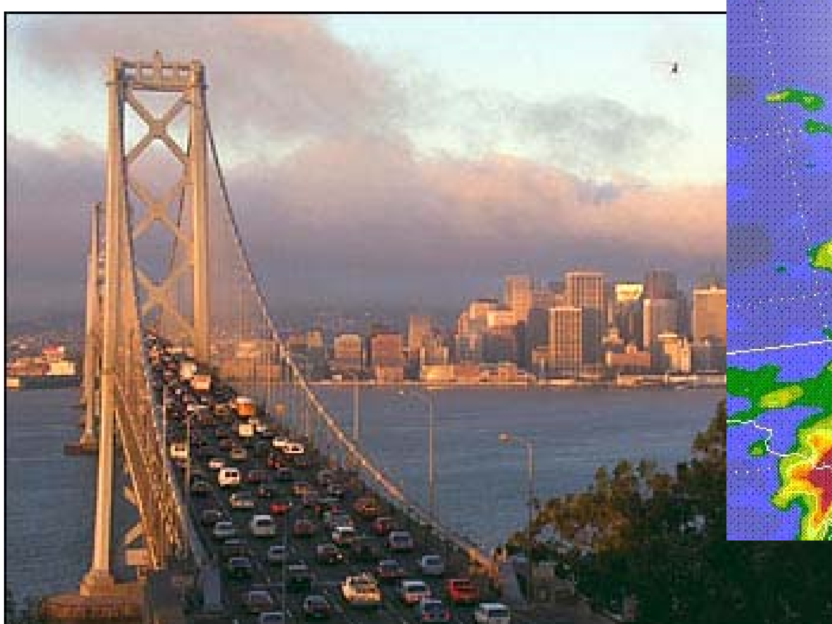
New Satellite Capabilities: LEO and GEO?



Why Geo?

- temporal resolution appropriate to the processes never before achieved
- vast contiguous area observable
- high SNR from staring
- temporal and morphological changes observable
- sunrise, sunset data provide stratospheric/tropospheric discrimination for constituents measured in uv

IDEA: NASA-EPA-NOAA partnership to improve air quality assessment, management, and prediction
by infusing (NASA) satellite measurements into (EPA, NOAA) analyses for public benefit.



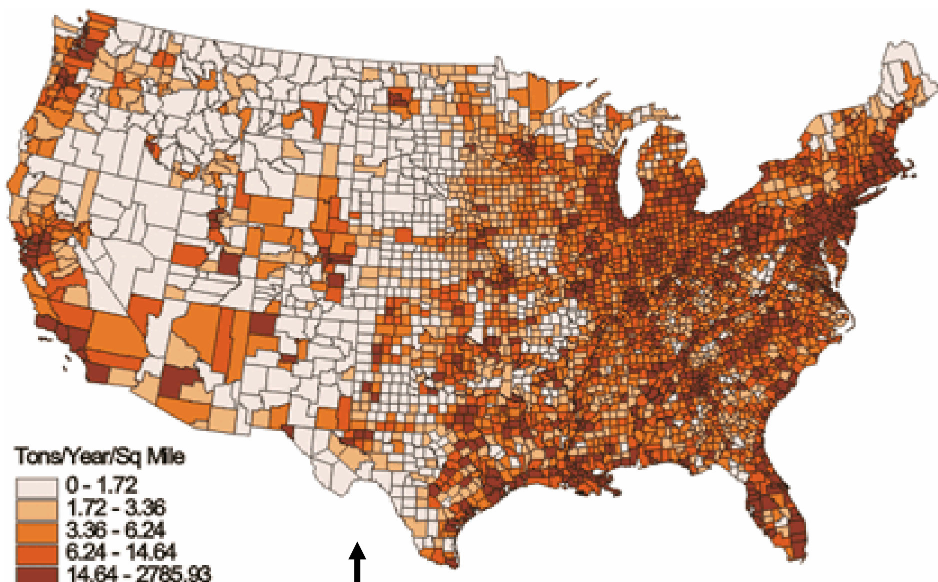
IDEA (Infusing satellite data into environmental air quality applications)

Present state:

EPA develops national emission inventories, assesses air quality, predicts future conditions based on ground network measurements and models.

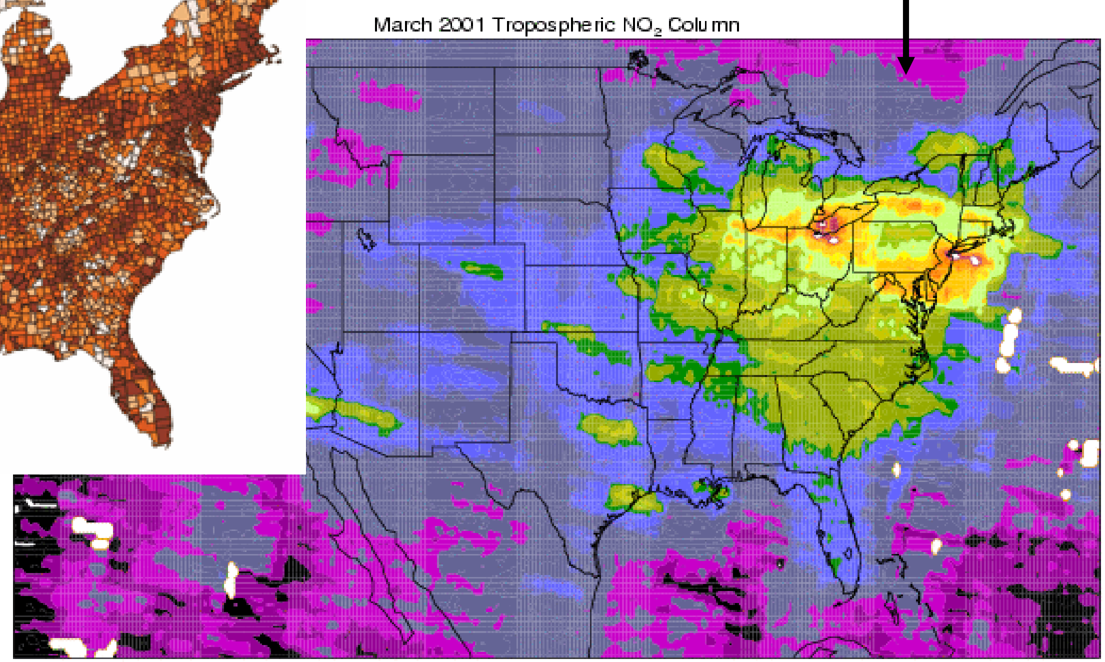
NOAA operates the national forecast system and environmental data satellites.

NASA inventories the global atmosphere from space; models chemical sources, transport, and transformation in the atmosphere.

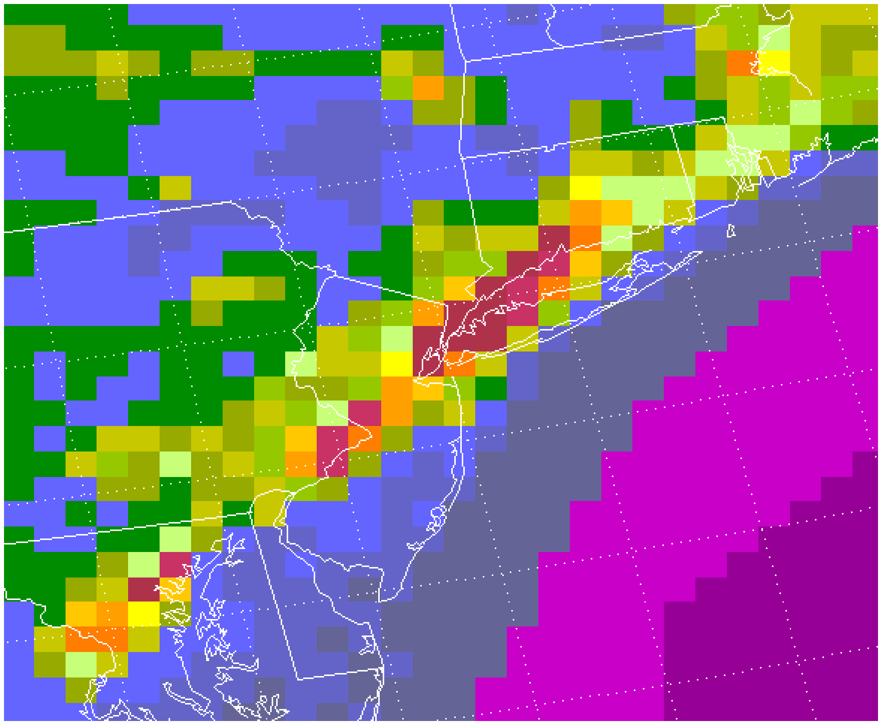


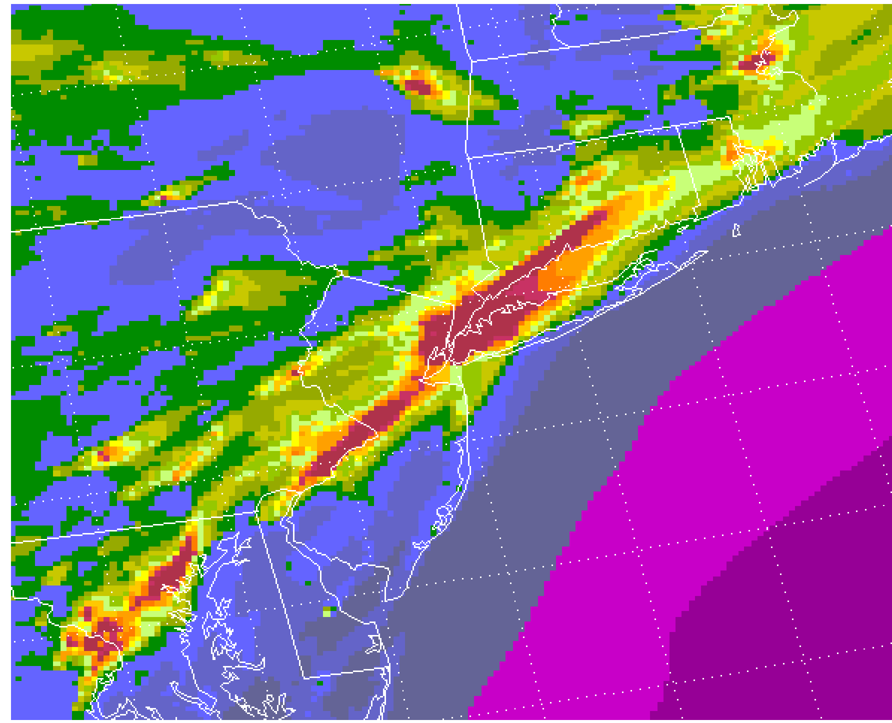
EPA emissions inventory

GOME tropospheric NO_2 column



Simulated observations over northeastern US (provided by CMAQ) demonstrate the importance of horizontal spatial resolution for air quality





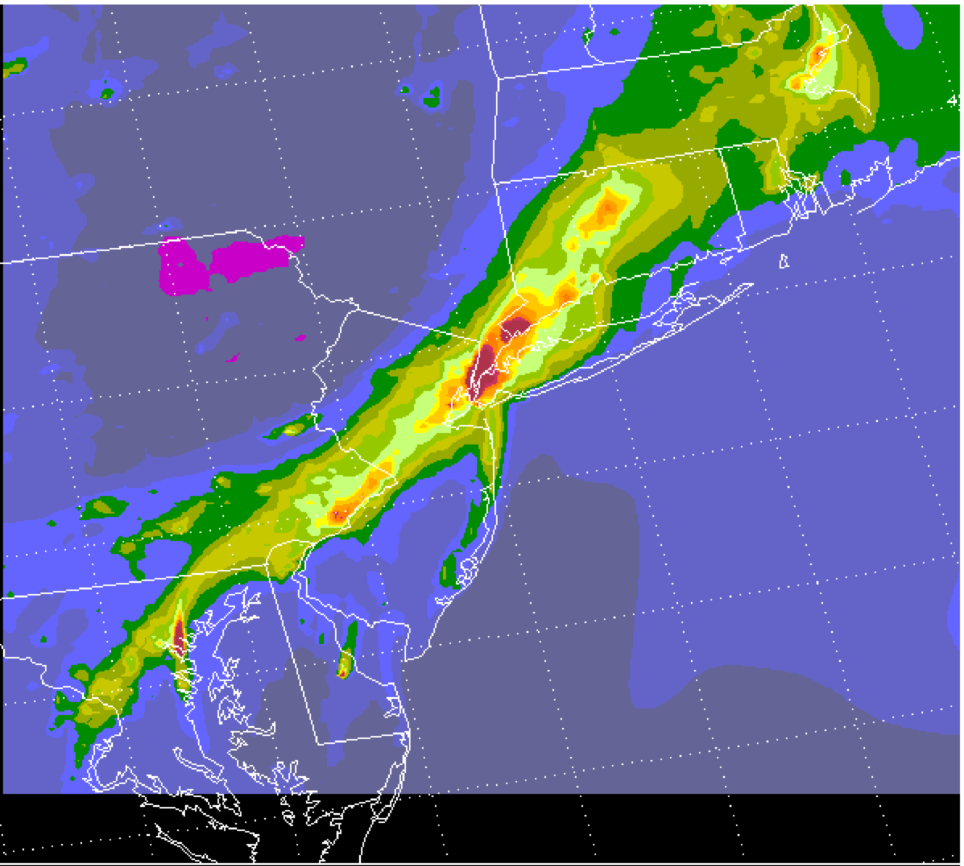
- spatial resolution: ~20 x 20 km^2
- spatial sample: 640 km swath
  in 90 minutes
- temporal sample: ~once every 3 days

(available from LEO)

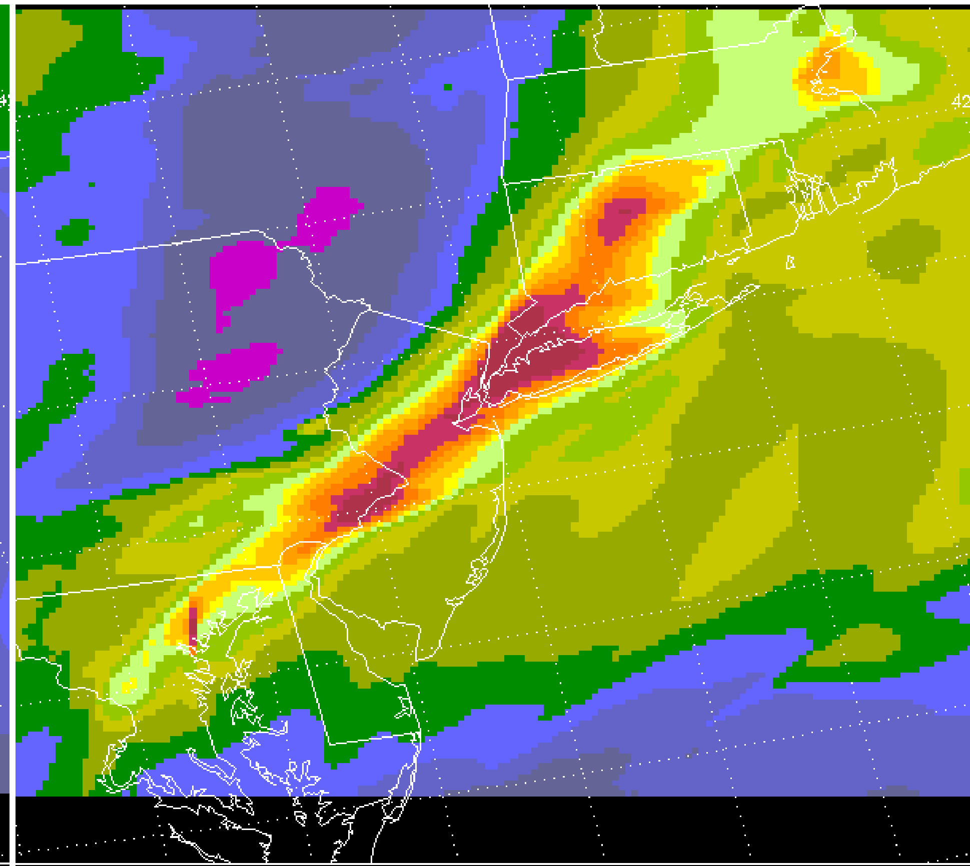
- spatial resolution: 4 x 4 km^2
- spatial sample: continental USA
  in 60 minutes
- temporal sample: once every hour
  (72 samples every three days)

(available from GEO)

Simulated observations provided by CMAQ contribute to our development of techniques to correlate surface and column measurements for use in air quality

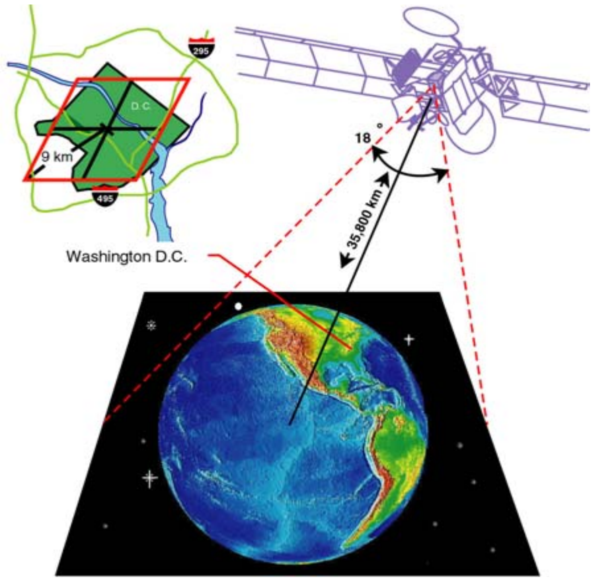


Hourly **surface CO** at
4 km horizontal resolution



Hourly **column CO** at
4 km horizontal resolution

GeoTRACE (proposed in 1999)
Geostationary Observatory for Tropospheric Air Chemistry



Geostationary orbit: 35,800 km
Nadir footprint: 7 x 7 km
Spectral range: UV/Mid-IR

Technologies

Large format FPAs (1536x1536)
Advanced detector cooling technology
Autonomous operations
Modular, advanced instrument controller
Internet node in space

PI: Dr. Jack Fishman

New Millennium Program Goals

Flight validate technologies for future science missions
Enable entirely new measurements and science
Increase science quality/quantity for future missions
Reduce cost of future Space and Earth Science missions

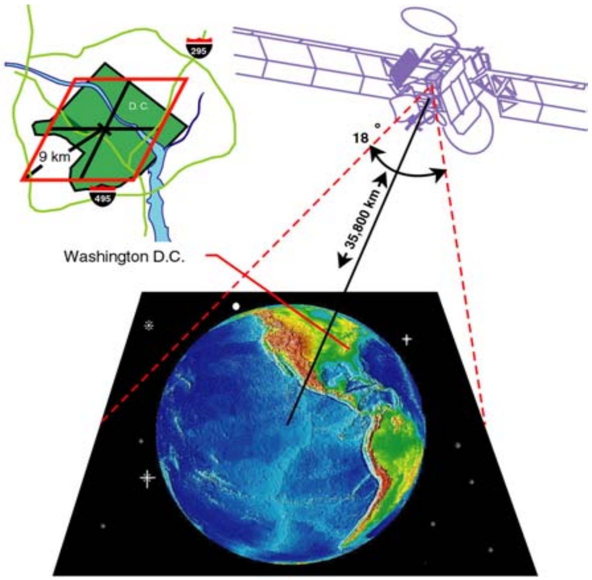
Strategic Program Objectives

Create unprecedented capability to conduct detailed tropospheric chemistry measurements and analysis by measuring a suite of key tropospheric trace gases across the Earth disk every 15 minutes
Create new mutually beneficial partnerships between commercial sector and science investigators

Measurement Characteristics

Backscattered UV spectrometry and IR correlation radiometry accurately measure spatial distributions
Large focal plane arrays capture wide temporal variability of tropospheric phenomena

"GeoTRACE-2" ESSP-3 Mission (proposed in 2001)



Geostationary orbit: 35,800 km
Nadir footprint: 5 x 5 km
Spectral range: UV/Mid-IR

Technologies Secondary in ESSP

Large format FPAs (1024x1024) still cornerstone of instruments in IR and UV/VIS

Regional field of view (5000 km x 5000 km)
Footprint at mid-latitudes 6-7 km

Lead Science Team Members: Brune (Penn State), Fishman, Neil (LaRC), Gleason (GSFC)

ESSP Goals

The Earth System Science Pathfinder (3rd solicitation) Program is a science program designed to deliver "quick" specific scientific missions; science proposal [Goddard mission lead] due May 2001; launch in 2006

Strategic Program Objectives

Create unprecedented capability to conduct detailed tropospheric chemistry measurements and analysis by measuring a suite of key tropospheric trace gases (O_3, CO, NO_2, SO_2, CH_2O) and aerosols over region of interest every 15-30 minutes

Science Objectives to focus on regional atmospheric chemistry and interaction between global and regional air quality

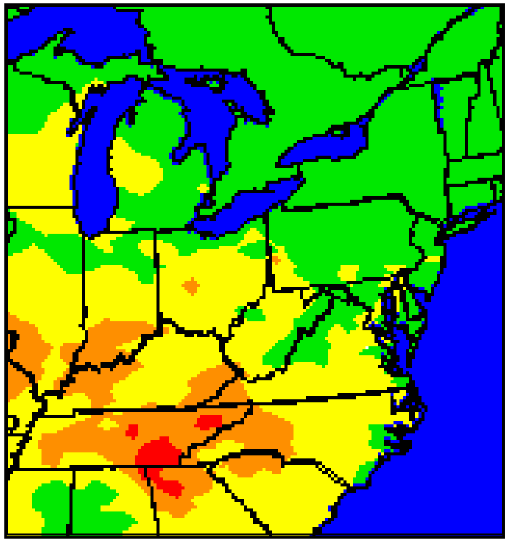
Measurement Characteristics

Backscattered UV spectrometry and IR correlation radiometry accurately measure spatial distributions

Large focal plane arrays capture wide temporal variability of tropospheric phenomena

Three-Day Air Quality Forecast

August 9, **2012**

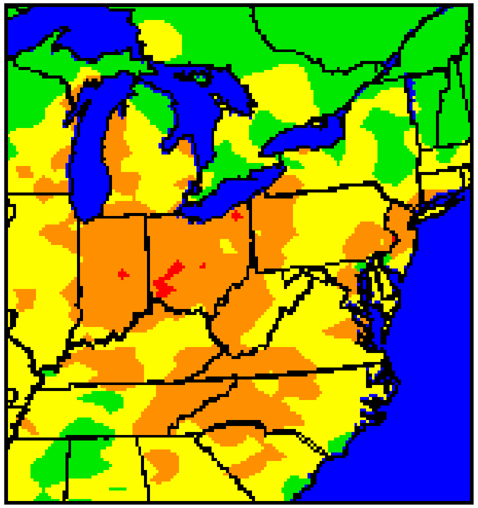


With Model Runs from August 9:

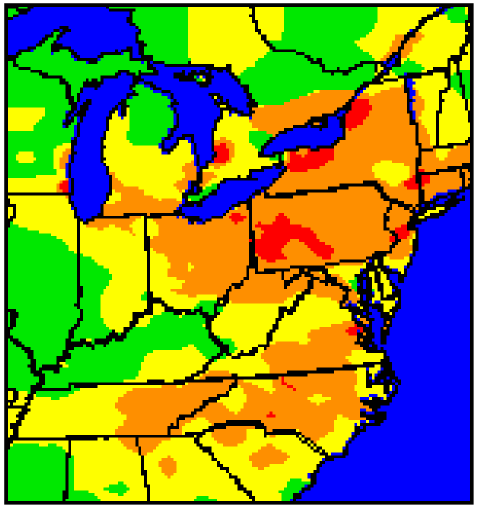
NOAA issues **unhealthy O_3** advisory:

- for Cincinnati on the 10th
- for Pittsburgh and Buffalo on the 11th
- for Philadelphia and New Jersey on the 12th

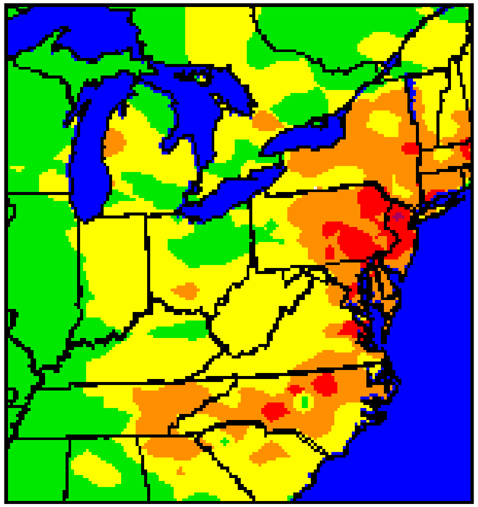
EPA Issues Directive to Mitigate O_3 and Alerts Population of Potential Health Risk



August 10



August 11



August 12

Summary

• 2-Decade Record of TOR Now Available

http://**asd-www.larc.nasa.gov/TOR/data.html**

• High Resolution Data Delineate Elevated Terrain

- Possible Use for Validation

• Strong Correlation between Population and Pollution

- Interannual Variability over Northern India Linked to ENSO

- Can ENSO or Other Indicators be Used as Predictors?

• Transport of Pollution across Atlantic Linked to NAO

• Challenge to Use Satellite Measurements with Models to Understand/Forecast Global and Regional Pollution

• New Satellites Promise Much Better Tropospheric Measurement Capability within Next Few Years

• Geostationary Measurements Ideal for Tropospheric Trace Gases