Two Decades of Tropospheric Ozone Observations from Satellite Measurements, the Use of these Data in Models, and Some Insight into Future Capabilities

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Presented at:
10th CACGP Scientific Conference
7th IGAC Scientific Conference
Heraklion, Crete, Greece
September 20, 2002

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

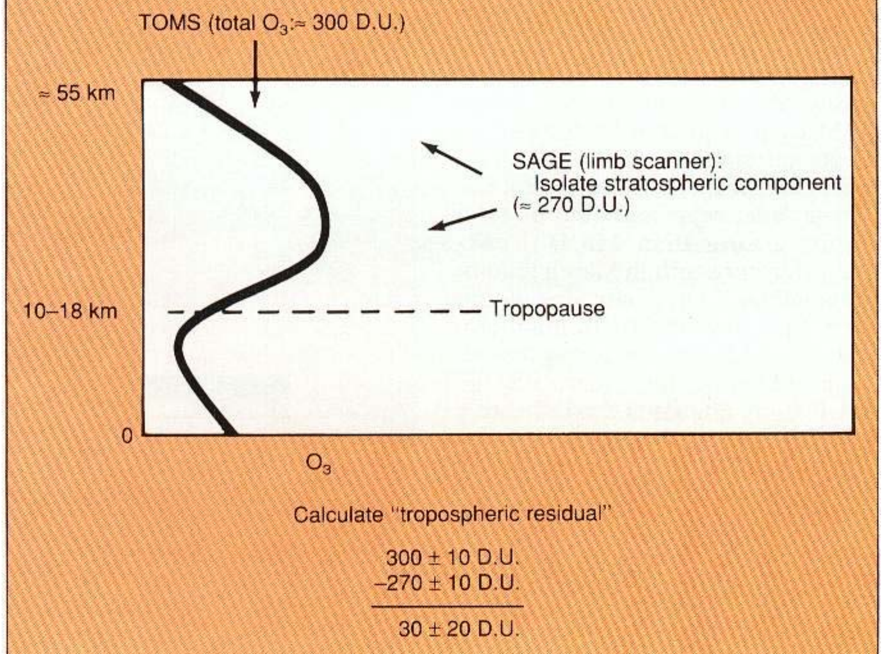
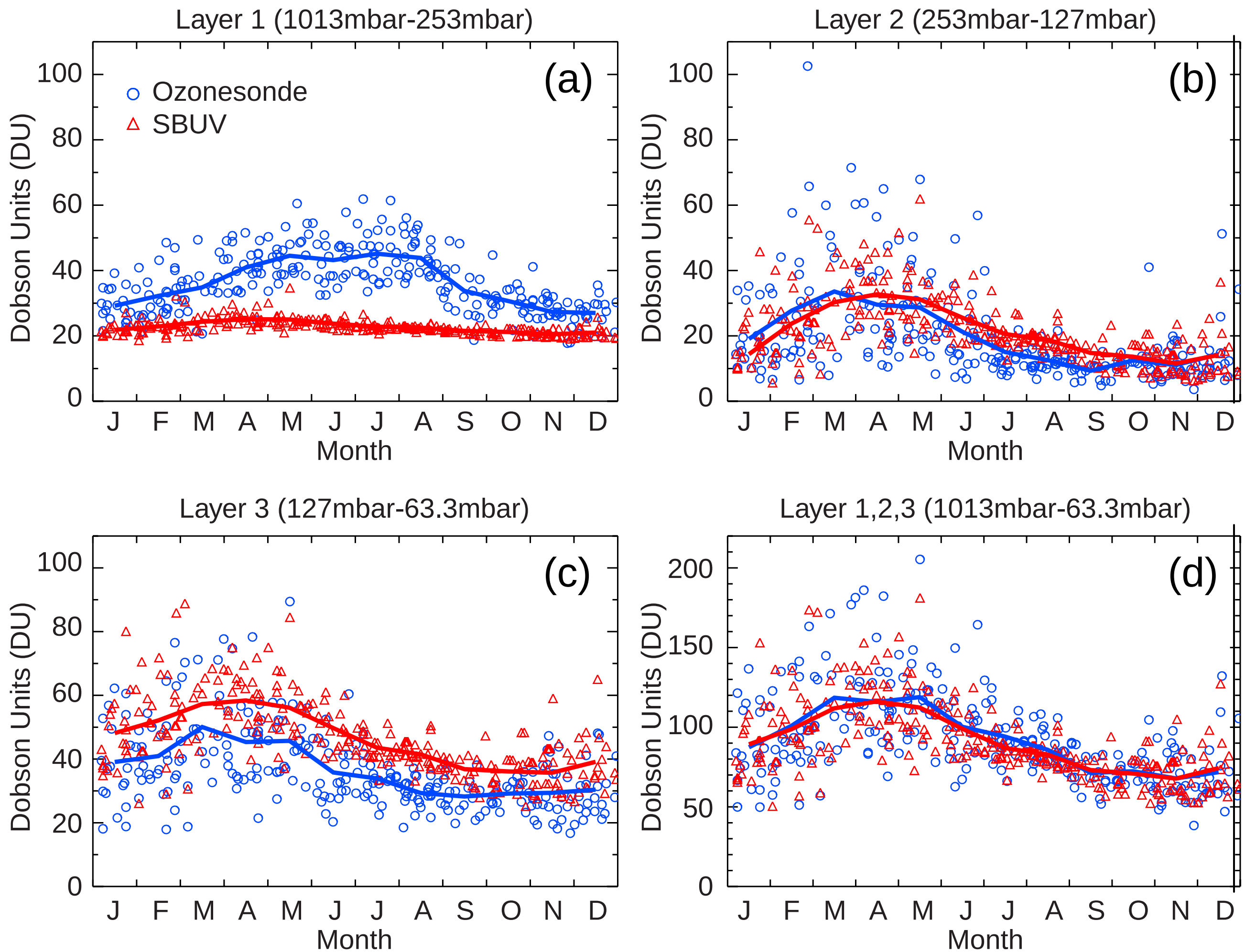
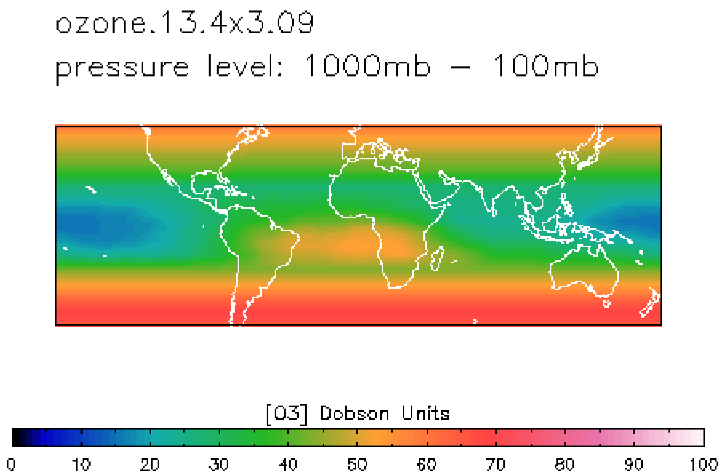


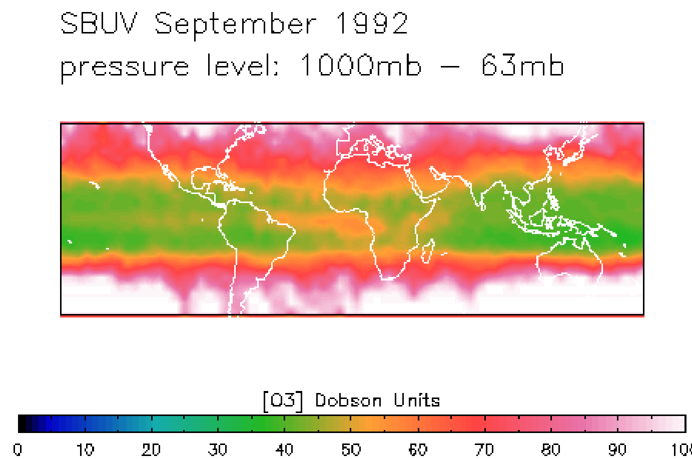
FIGURE 3
Schematic diagram showing how the tropospheric residual is calculated from coincident TOMS and SAGE measurements

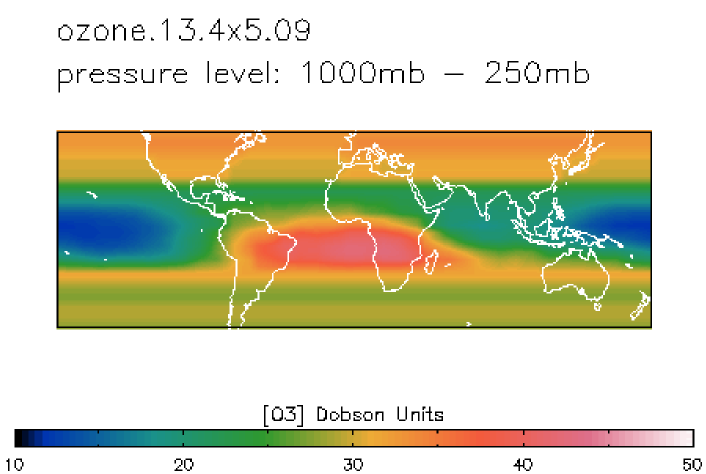
Climatological Comparison of Ozonesonde Data with SBUV Measurements at Wallops Island

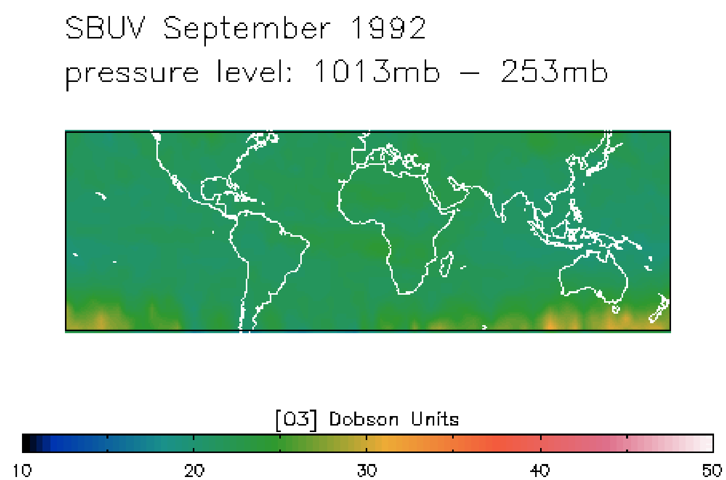


Information Contained in SBUV Measurements

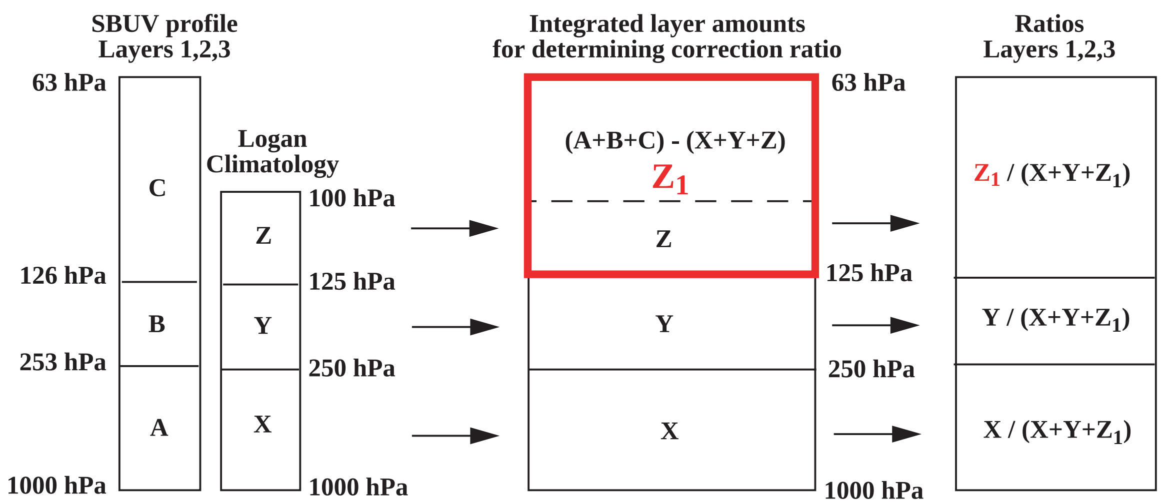








Schematic Diagram of Empirical Correction



Input SBUV Measurement:

$(A + B + C)$

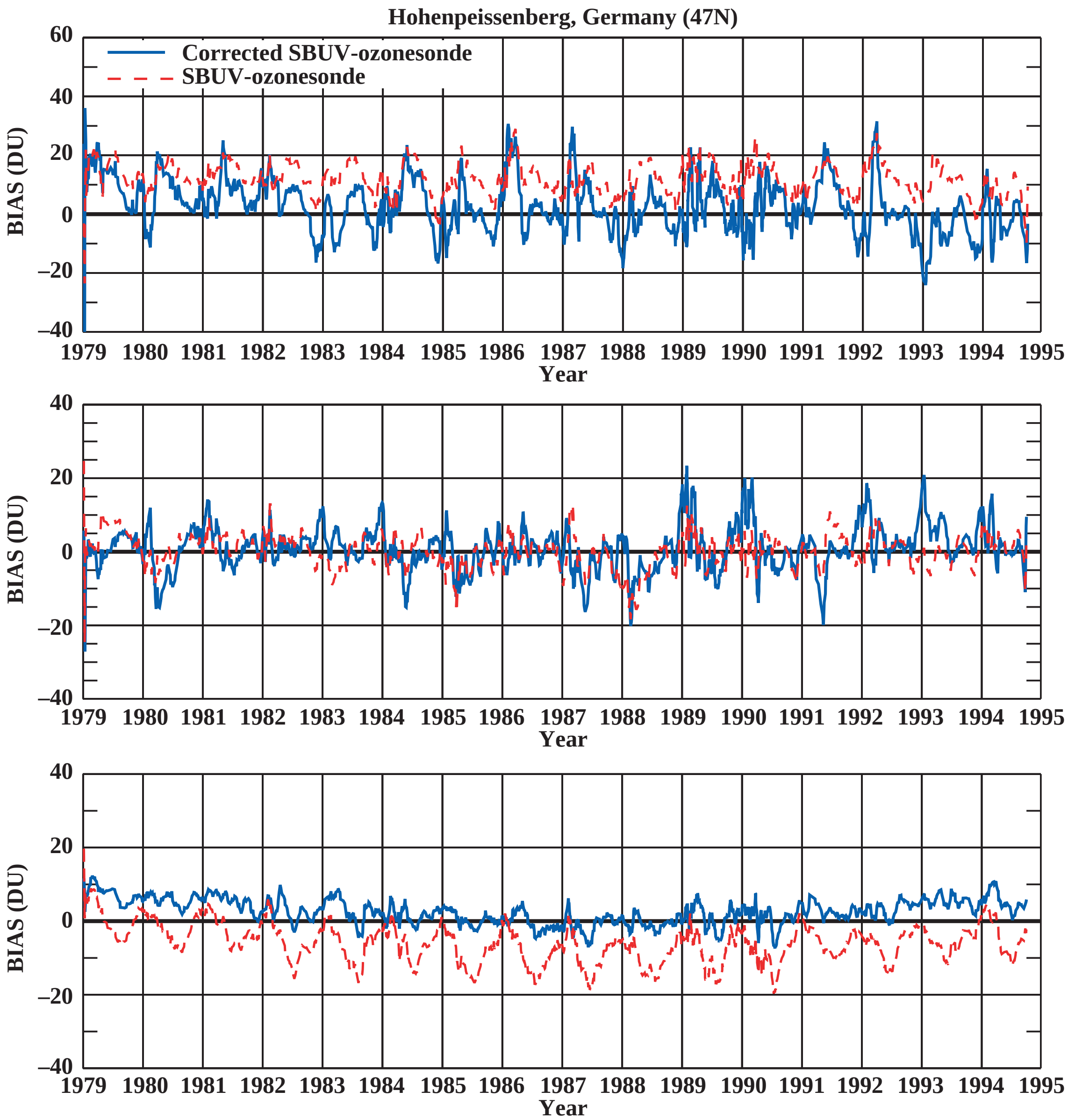
Output* for TOR Calculation

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

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

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

Comparison Using Empirical Correction with Ozonesondes



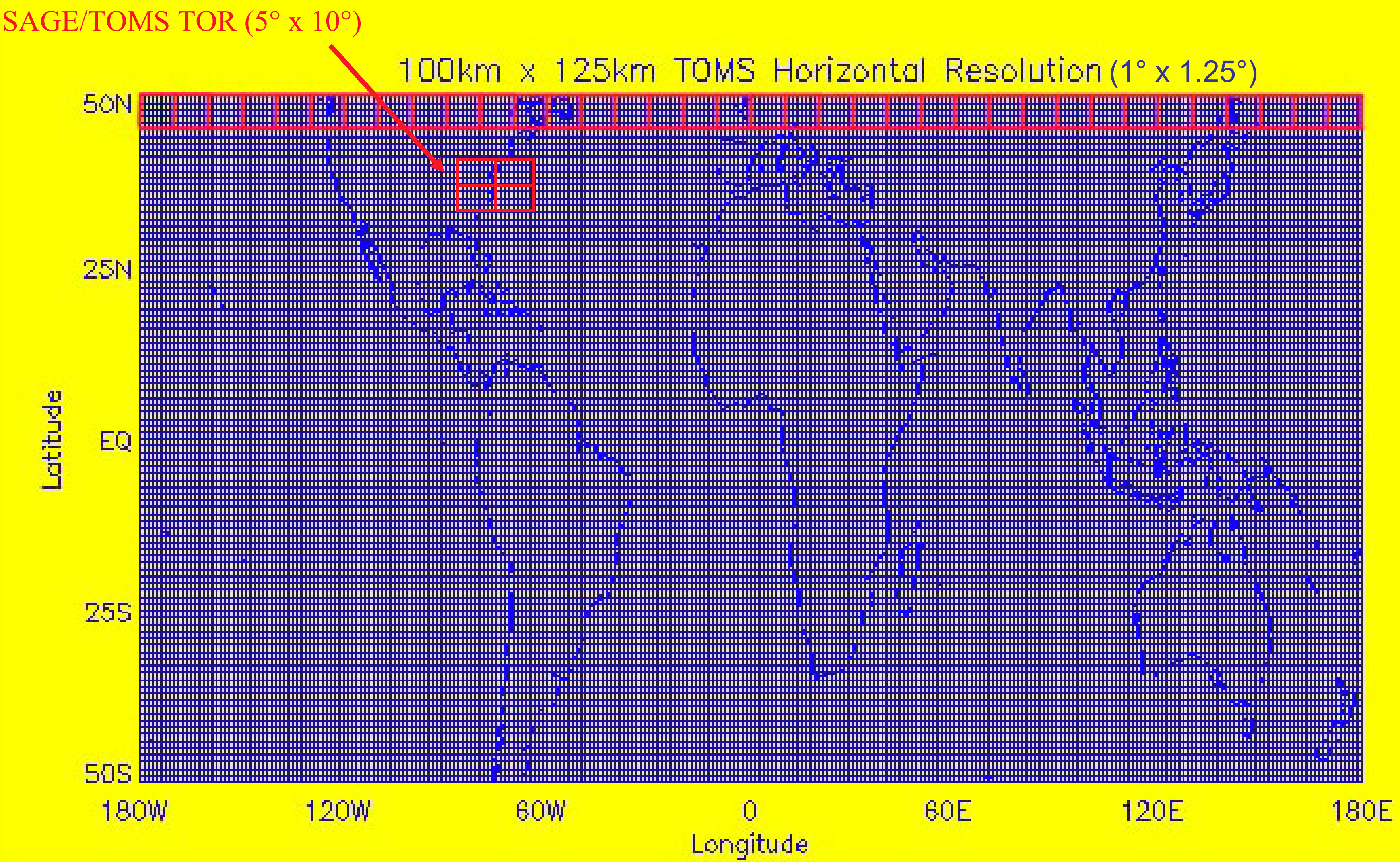
Other Data Sets Are Required To Separate Tropospheric Ozone from Total Ozone Measurements

- 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

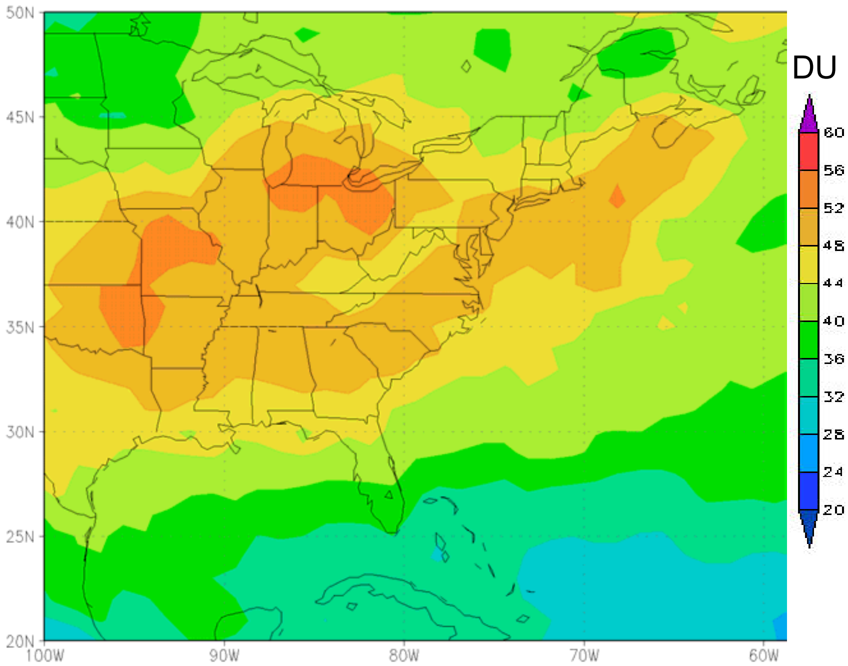
  - **SAGE/TOMS TOR:** ~ 30,000 Coincident Observations 1979-1991 [Fishman & Brackett, 1997]
    ~ **10 data points per 5° x 10° grid box** for seasonal climatology
  - **SAGE/SBUV TOR:** Use Every TOMS Observation (up to 28,800 per day)
    ~ **1500 data points per 1° x 1.25° grid box** for seasonal climatology

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

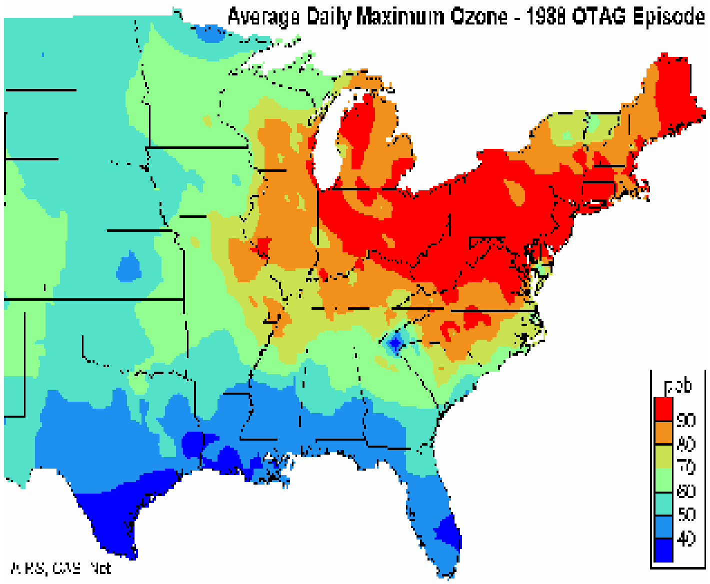
Comparison of Pixel Size for Computing TOR



July 1988 Monthly TOR Captures High Ozone During Major Pollution Episode



July 1988 TOR

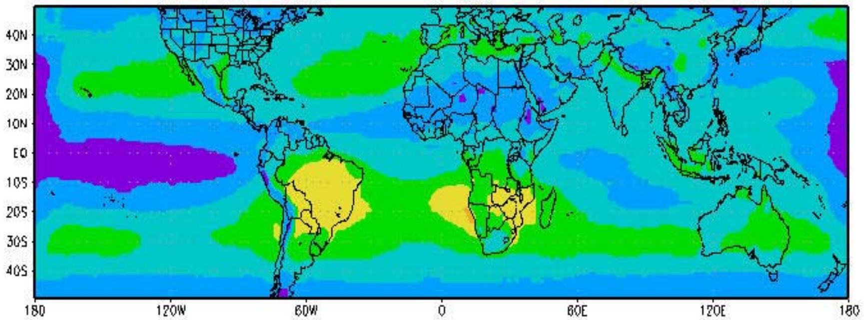


July 3-15 Average Daily Max. O_3

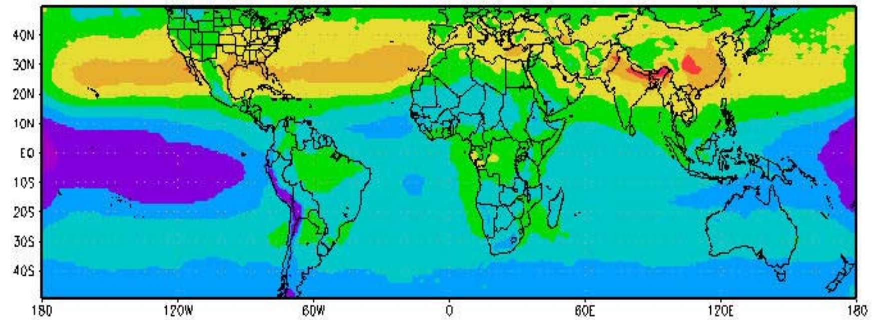
(from Schichtel and Husar, 1998)

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

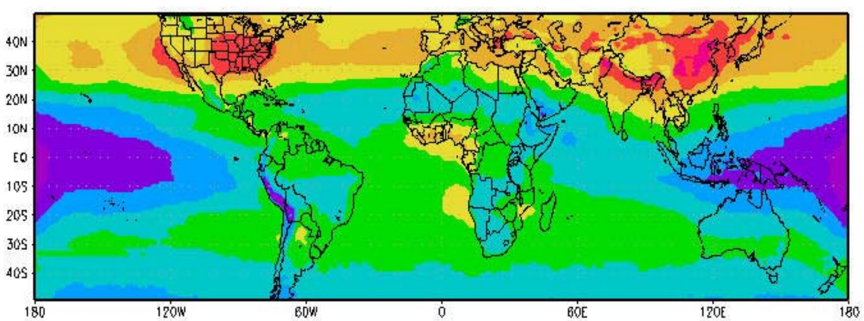
SBUV Tropospheric Ozone Residual (TOR) DJF 1979-2000



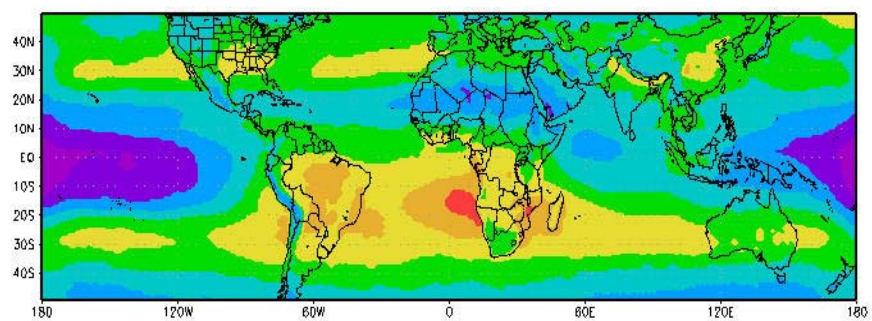
SBUV Tropospheric Ozone Residual (TOR) MAM 1979-2000

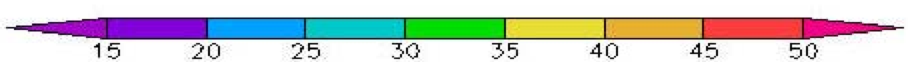


SBUV Tropospheric Ozone Residual (TOR) JJA 1979-2000

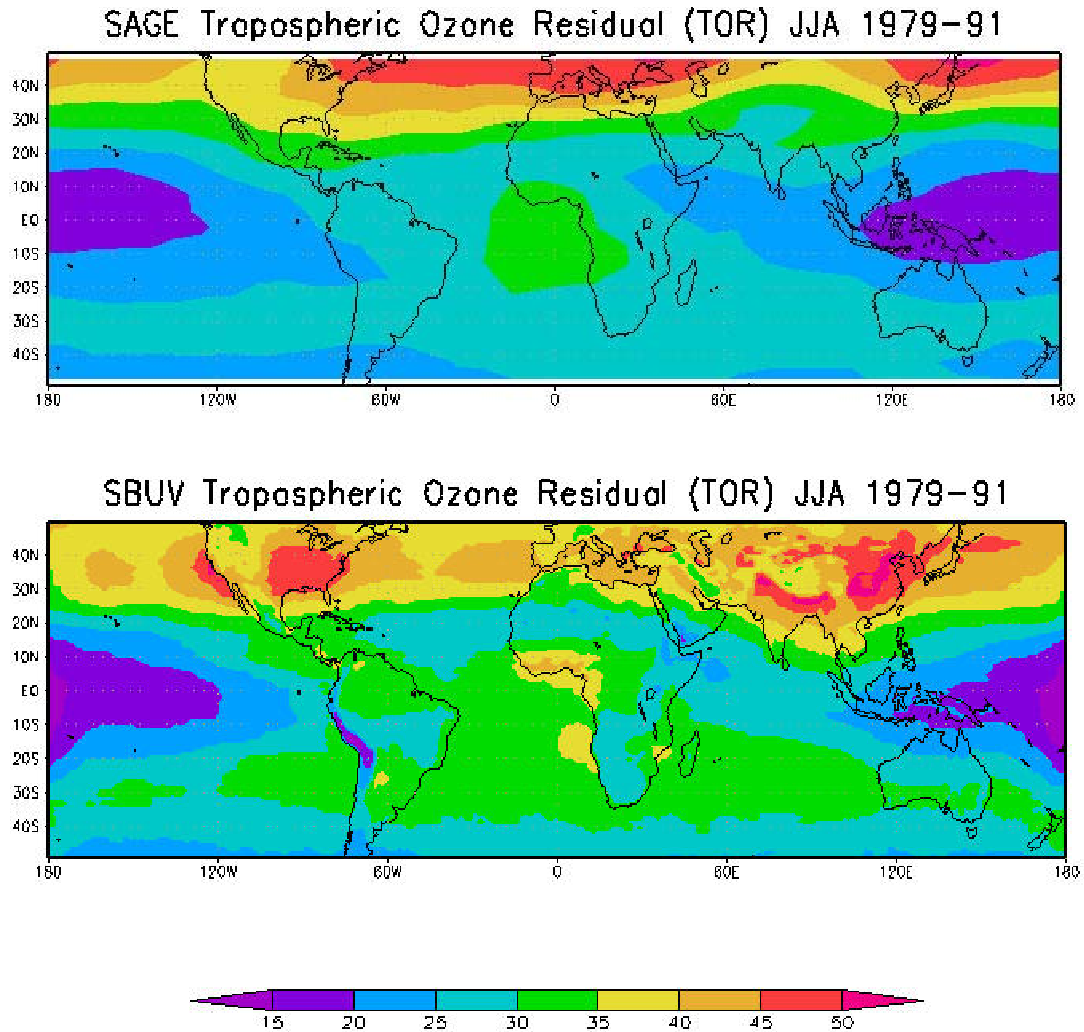


SBUV Tropospheric Ozone Residual (TOR) SON 1979-2000





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)

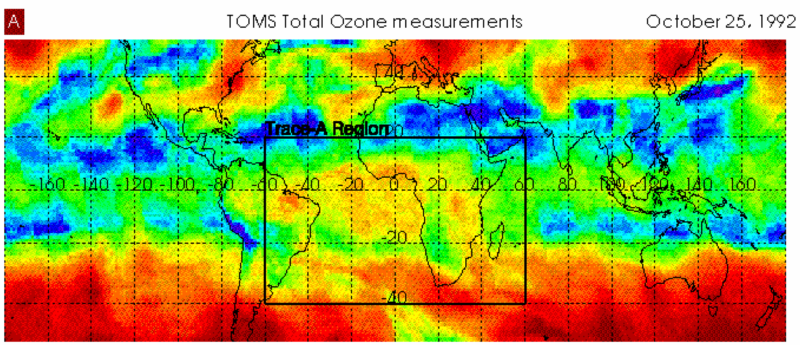
  Version 7 incorporates ISCCP cloud climatology for correction

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

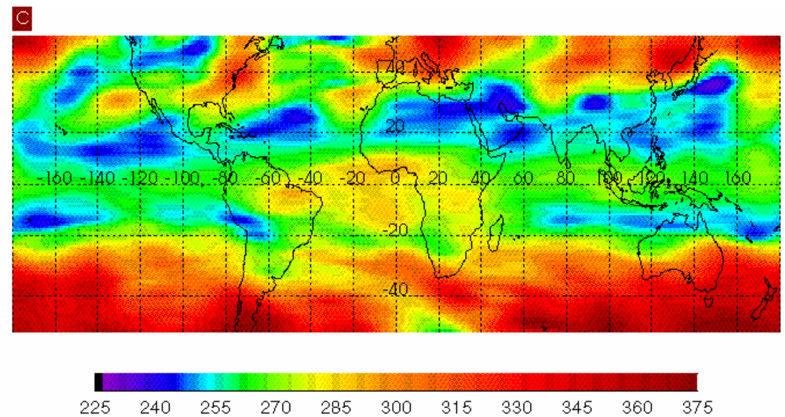
  Version 8 includes aerosol and scan-angle dependence corrections

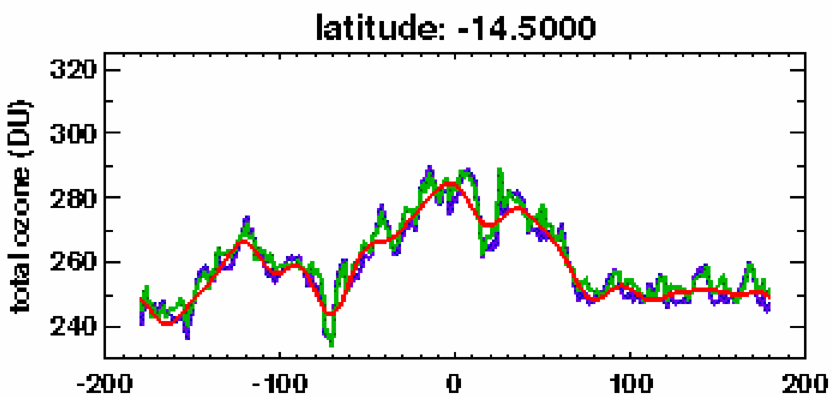
Fourier Filter Applied to TOMS Archive to Remove Scan-Angle Dependence

Unfiltered V.7Total Ozone from TOMS Archive

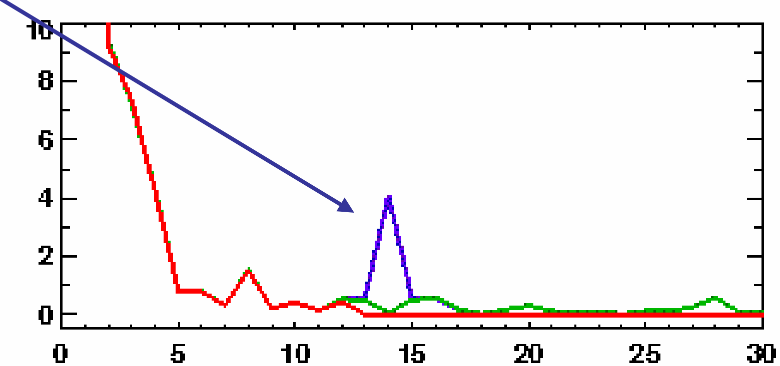


TOMS Total Ozone After Fourier Filter





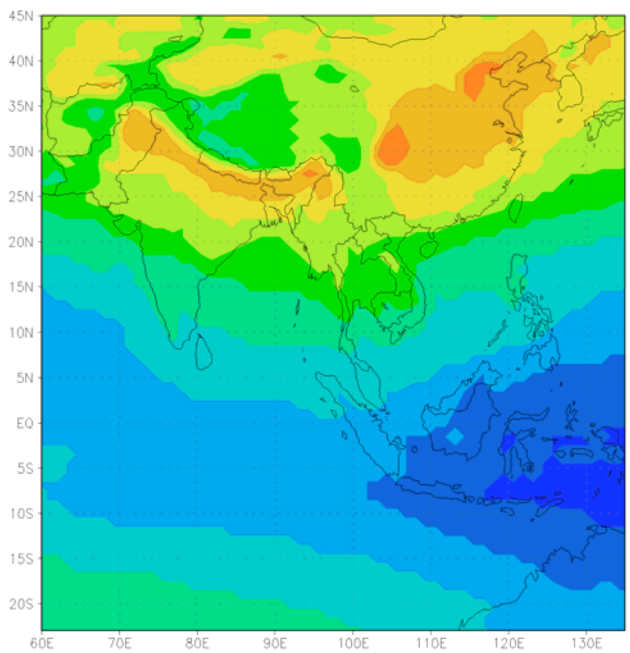
Total Ozone along Latitude Line



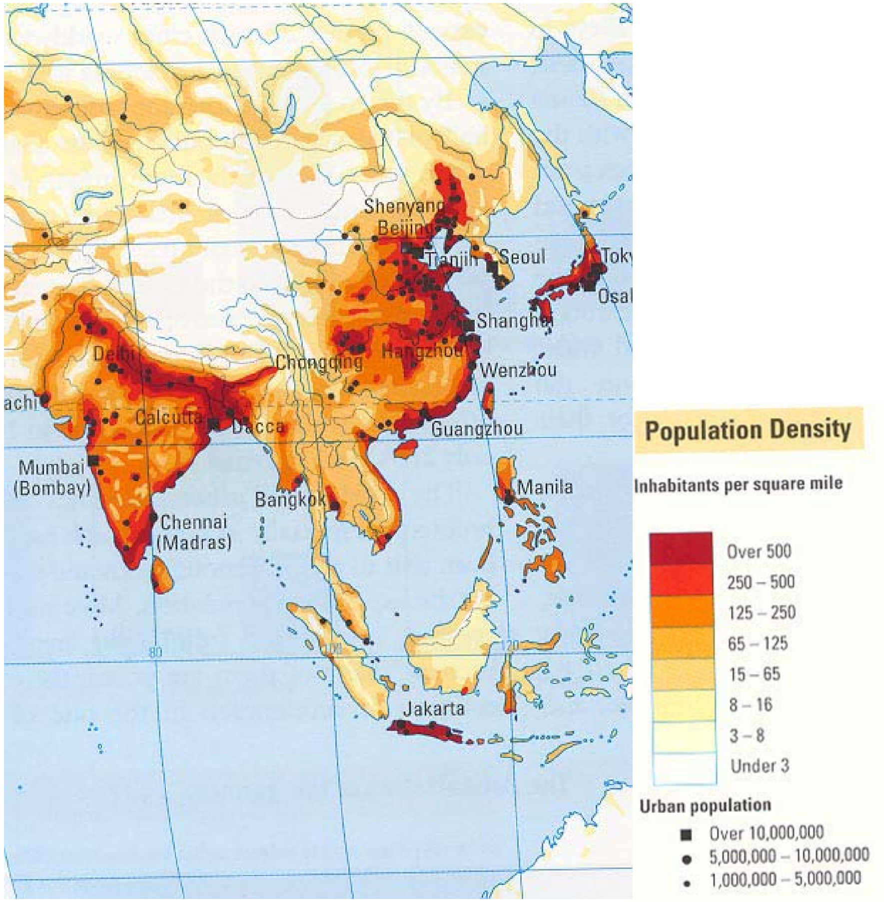
Spectral Contribution to Total Ozone at 14.5°S

Population and Ozone Pollution Strongly Correlated in India and China

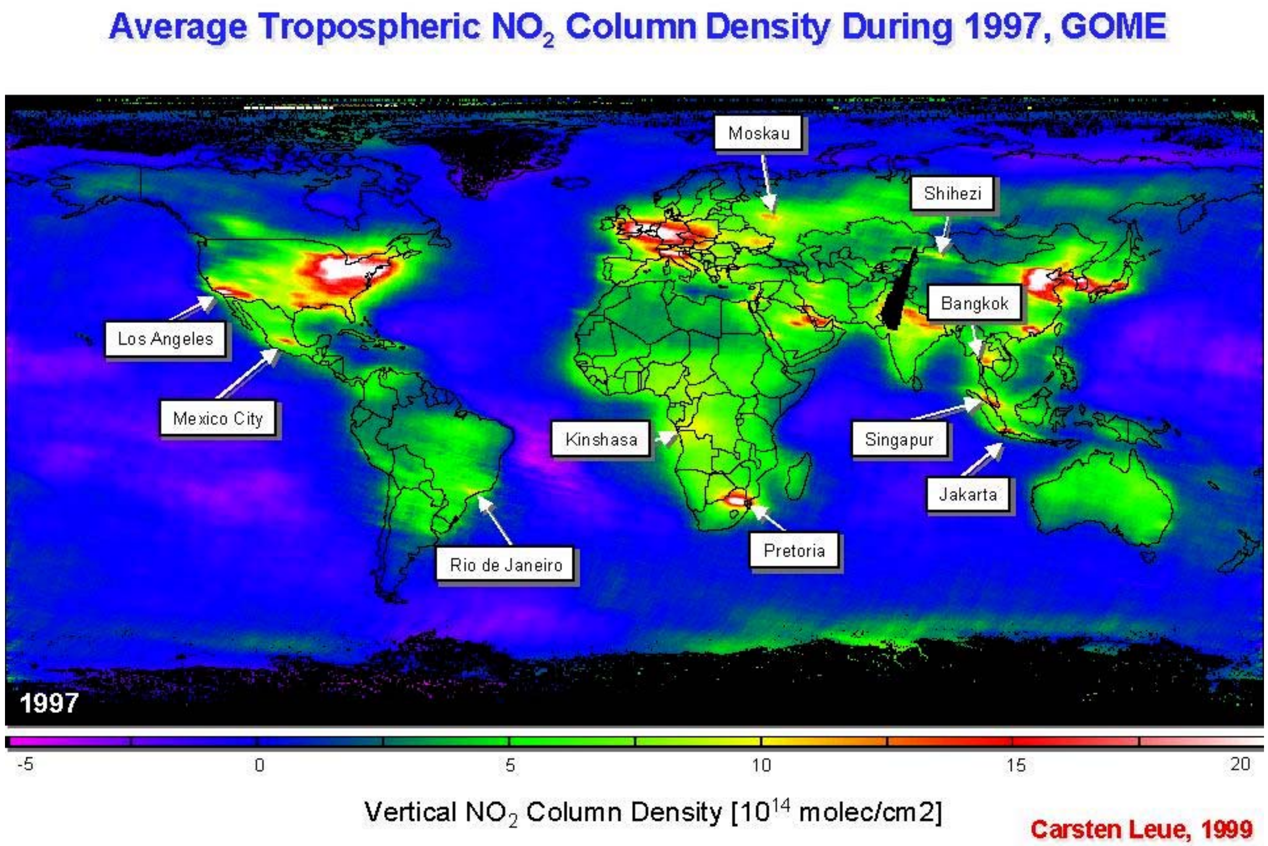
Summer Climatological Distribution



TOR in Dobson Units



GOME NO_2 Measurements Also See Enhancements over India and China



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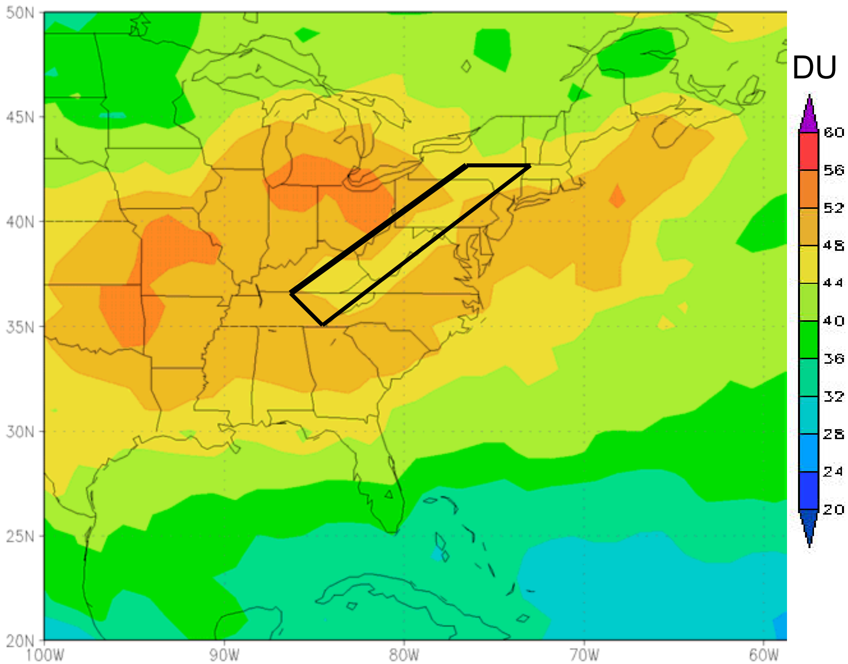
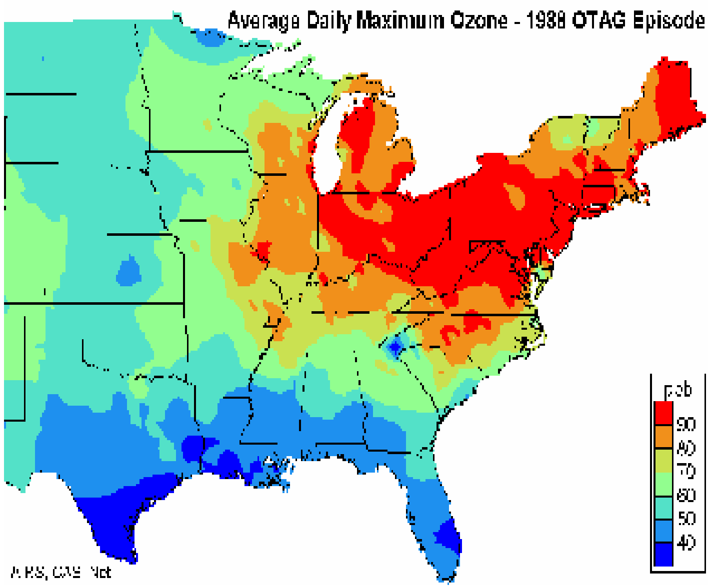


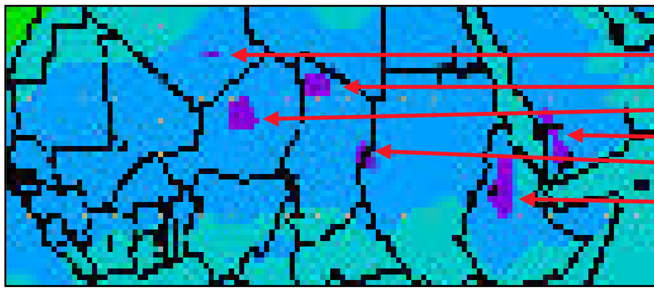
July 1988 TOR

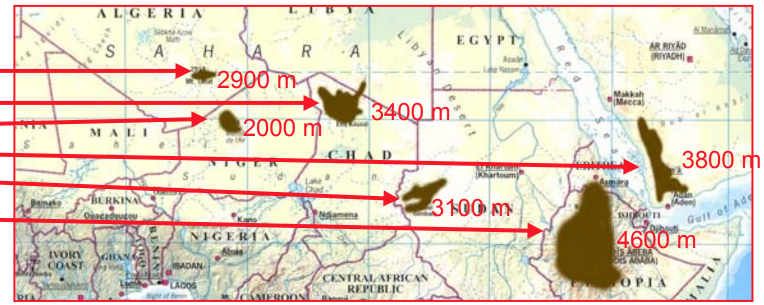


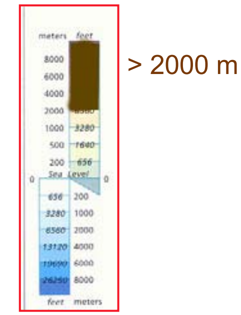
July 3-15 Average Daily Max. O_3
(from Schichtel and Husar, 1998)

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

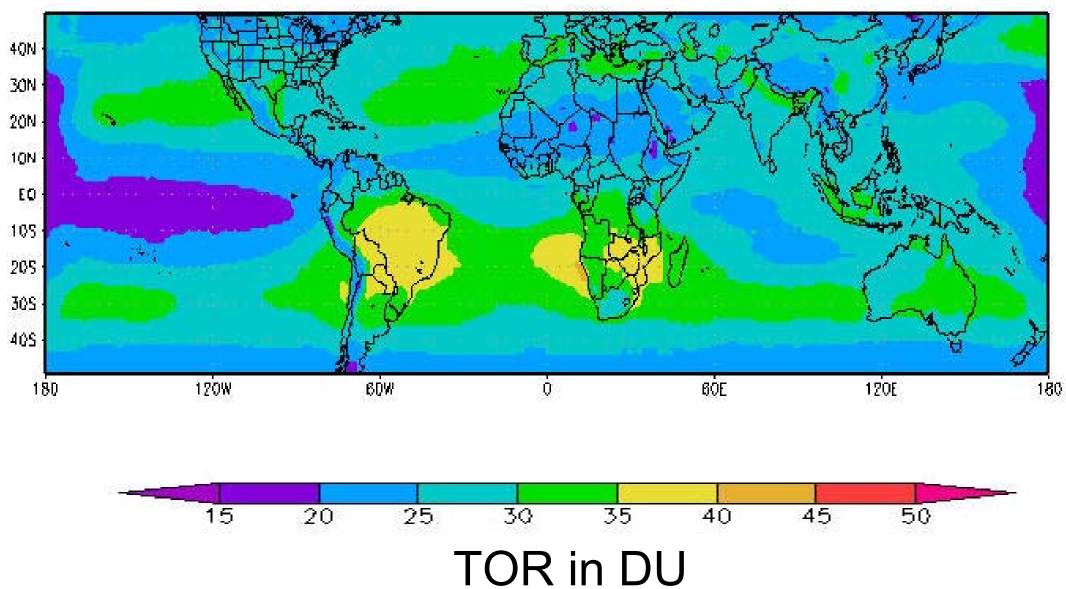
Lower TOR over North African Desert Regions Coincident with Higher Elevations







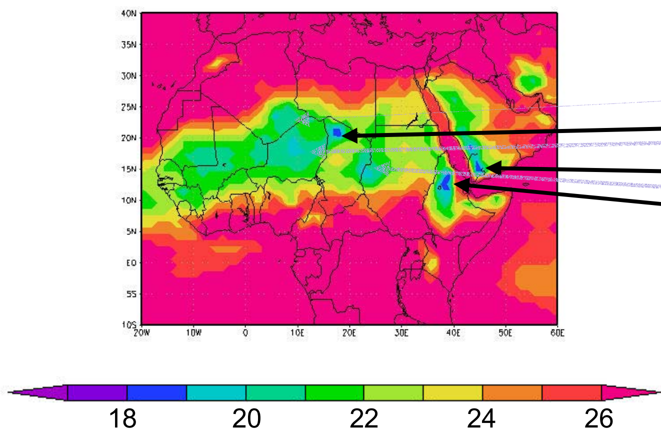
December-February TOR



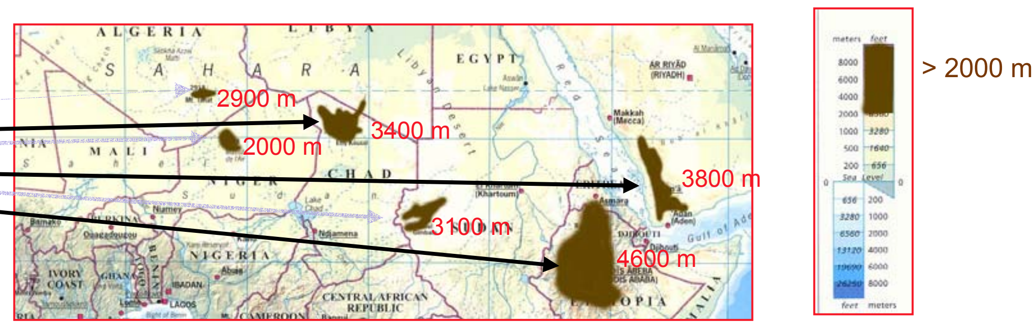
<u>Implications</u>:

- 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)



TOR in DU

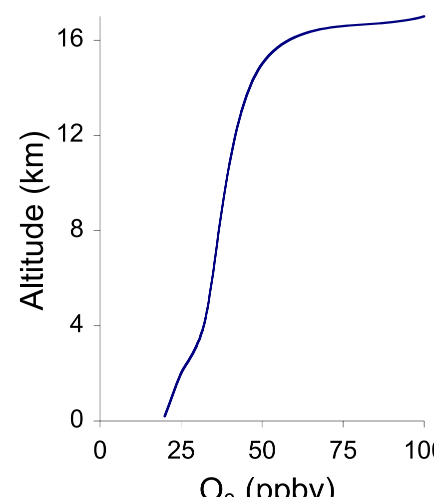


• Inferred Ozone Profile over North Africa Desert Region:

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

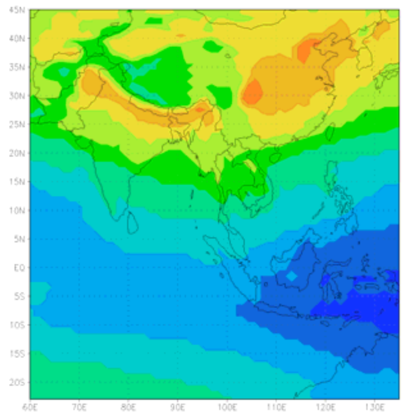
$$\int^{4\ \mathrm{km}} [O_3]\, dz = \sim 6\ \mathrm{DU}$$

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

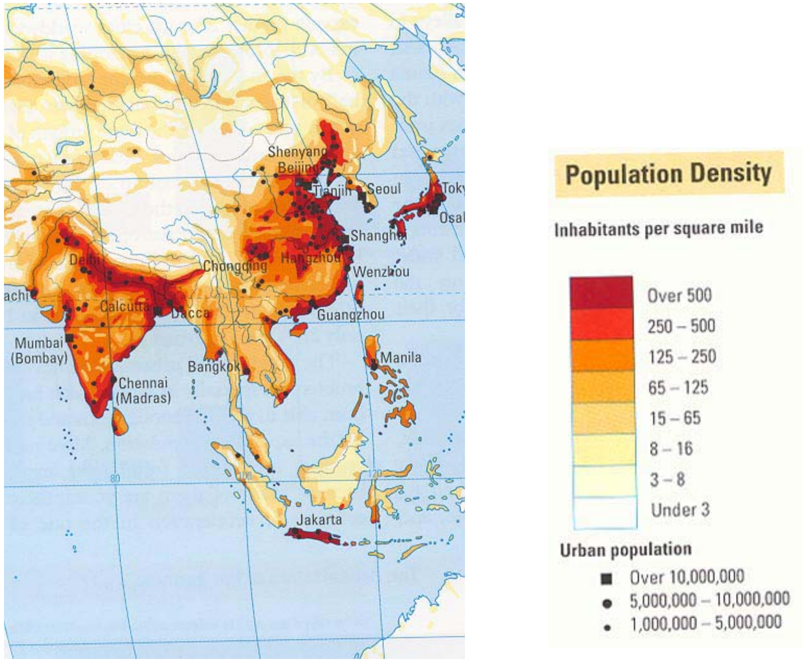


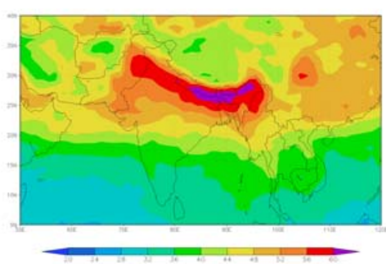
Ozone Enhancement over India

Summer Climatological Distribution

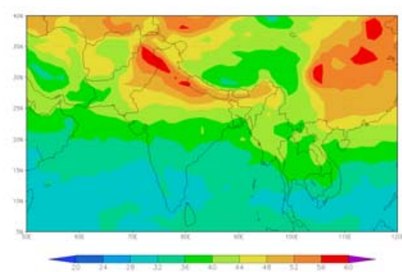


TOR in Dobson Units





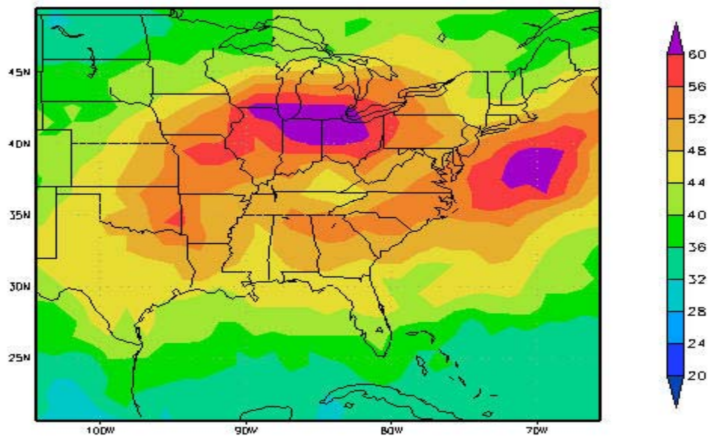
June 1982

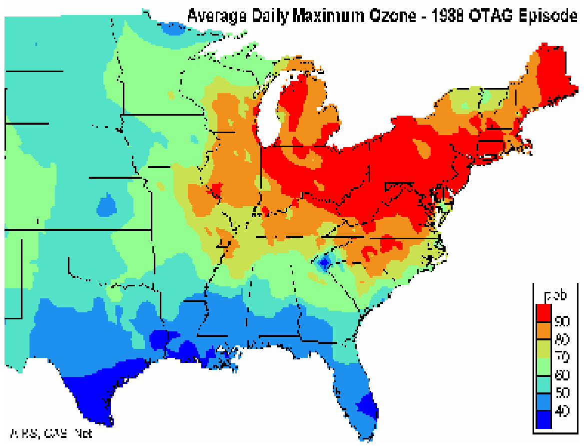


June 1999

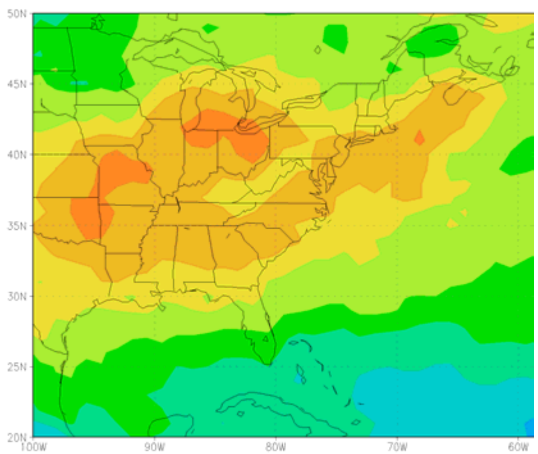
How does the Amount of Ozone over India Compare with the Amount Observed over the Eastern United States?

Comparison of Indian and U.S. Air Pollution Episodes

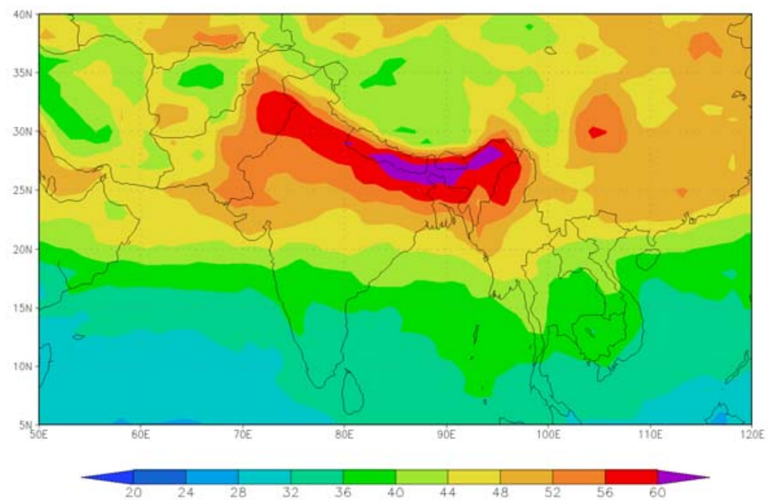




TOR and Surface O_3 Depiction During July 3-15 Pollution Episode



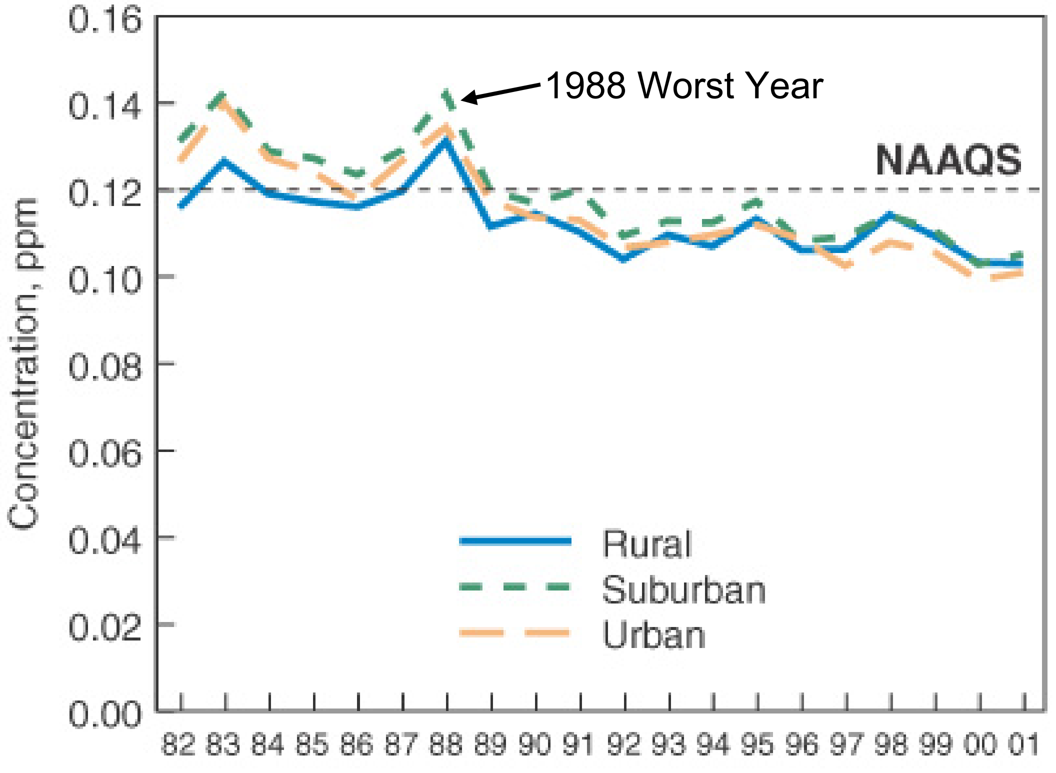
July 1988



June 1982

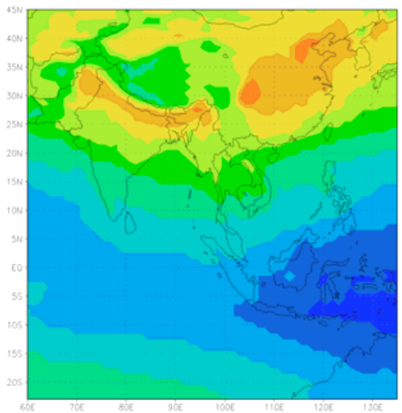
Trend in 1-hour Ozone Levels, 1982–2001, by Location of Site

Based on Annual 2nd Highest Daily Maximum

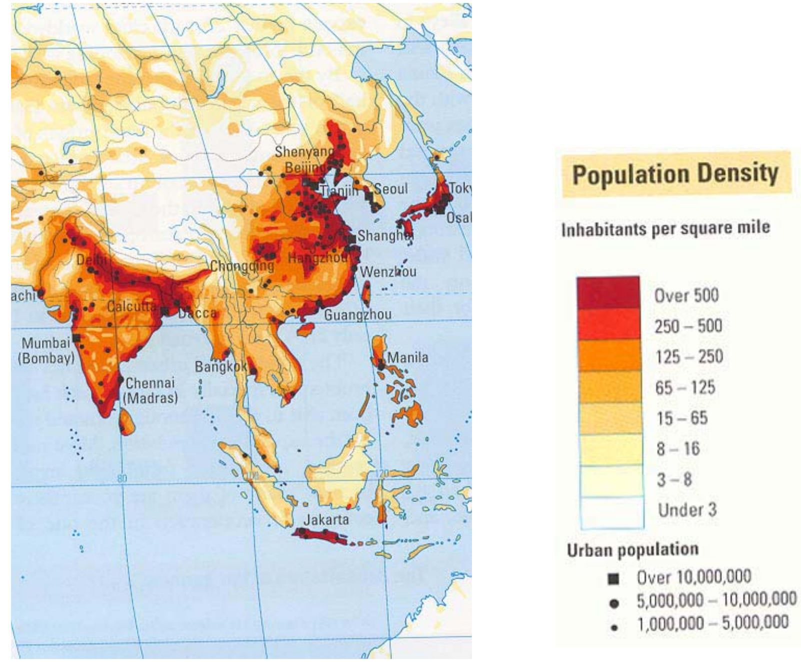


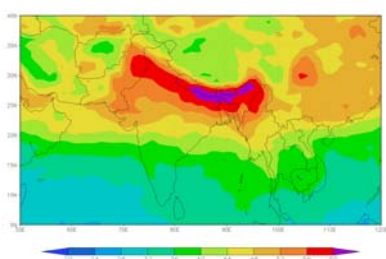
Examine Interannual Variability of Ozone Enhancement over India

Summary Climatological Distribution

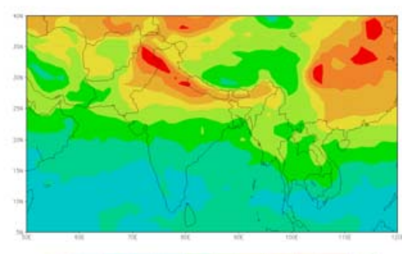


TOR in Dobson Units





June 1982



June 1999

1982: El Niño Year <u>and</u> El Chichon Eruption on 6 April

Did aerosol loading affect TOMS total ozone retrieval?

Monthly TOR Values Over Northern India 1979-1999

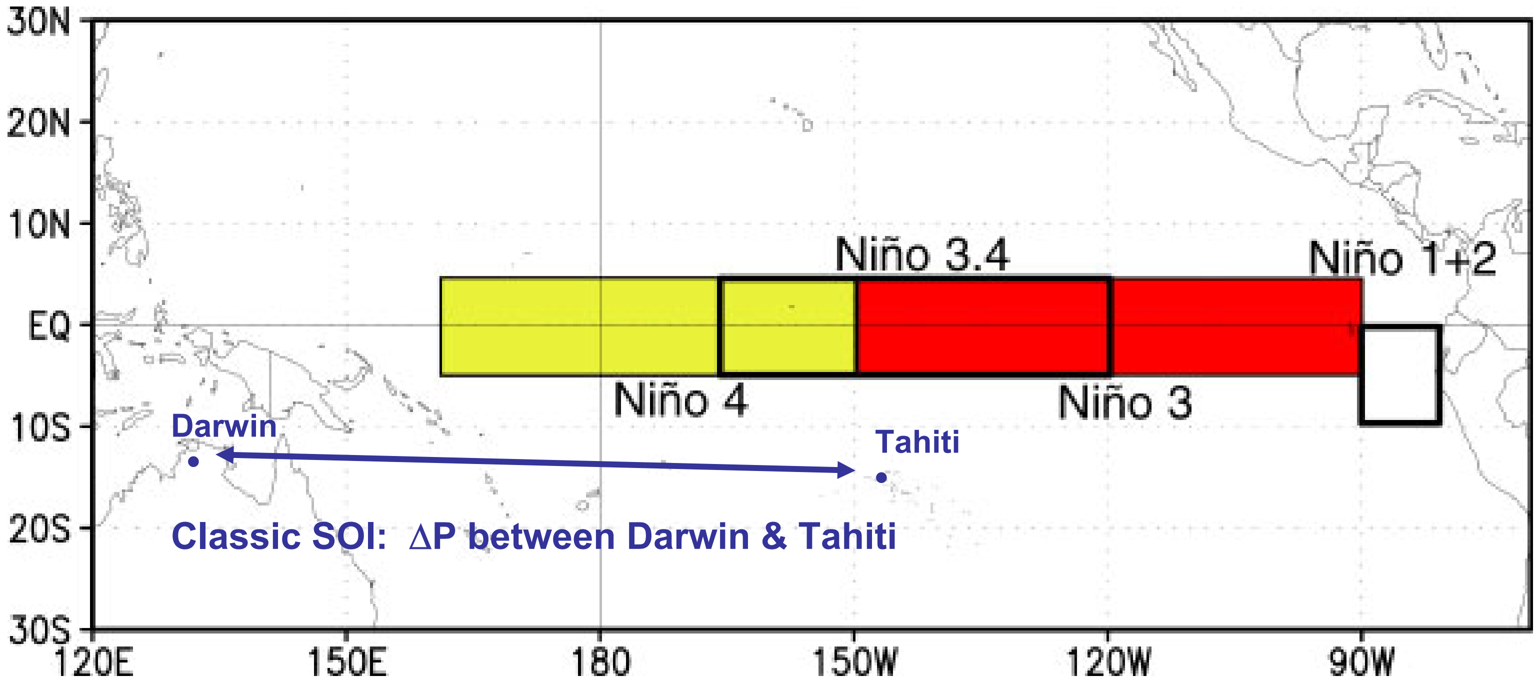
Jan	29.8	Feb	29.9	Mar	34.6	Apr	44.	May	47.3	Jun	48.2	Jul	46.4	Aug	42.0	Sep	36.8	Oct	32.7	Nov	30.5	Dec	27.9
1991	31.5	1992	33.3	1989	40.5	1982	47.2	1982	52.9	1982	52.1	1982	48.3	1992	43.7	1990	40.1	1999	35.0	1981	33.2	1997	30.0
1984	31.2	1987	33.0	1982	38.1	1984	47.1	1981	50.0	1989	51.3	1992	47.8	1990	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

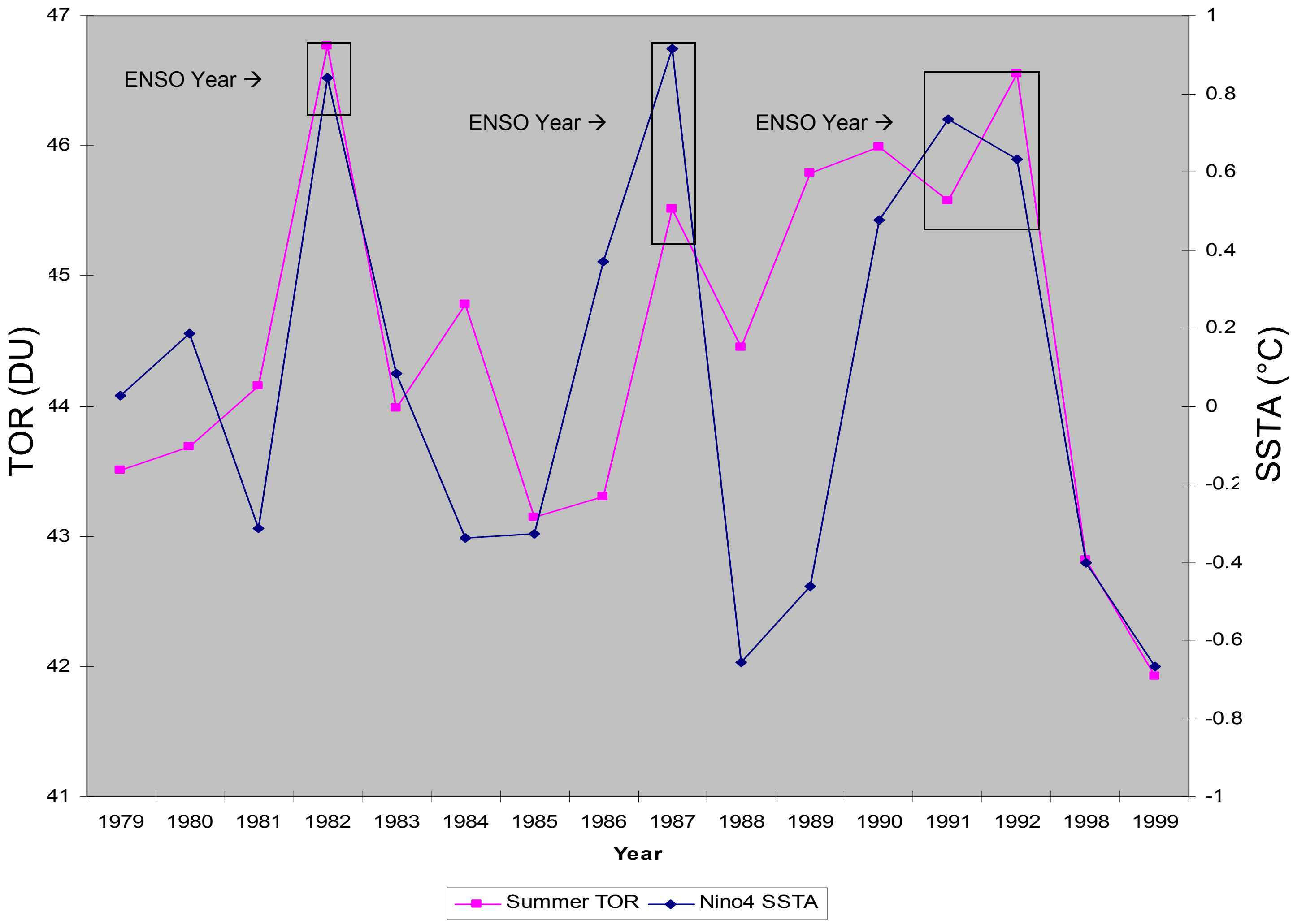
Definitions of ENSO Indicators



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

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



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

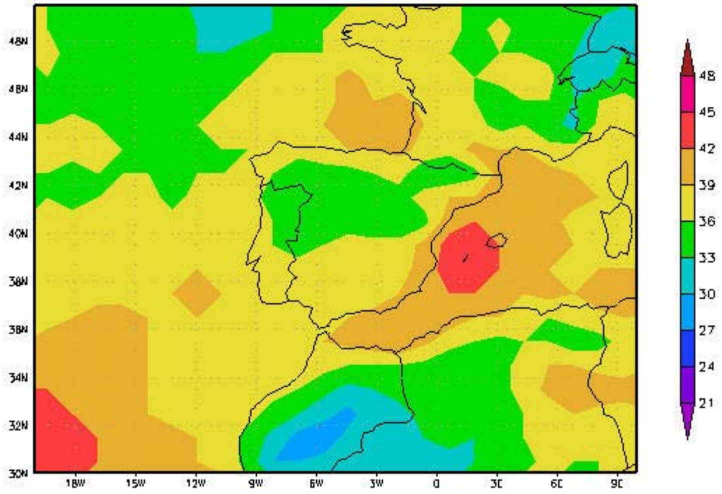
Month	Mean TOR	Range		SOI		ENSO SST Region			
		High	Low	Mon	Seas	1&2	3	3.4	4
January	29.8	31.5 (1991)	25.7 (1980)	.04	-.01	.07	-.04	-.06	-.01
February	29.9	33.3 (1992)	25.1 (1991)	-.33	**-.45**	.11	.27	.33	.21
March	34.6	40.5 (1989)	26.7 (1999)	.02	.02	-.15	-.14	-.06	.15
April	44.0	47.2 (1982)	40.5 (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)

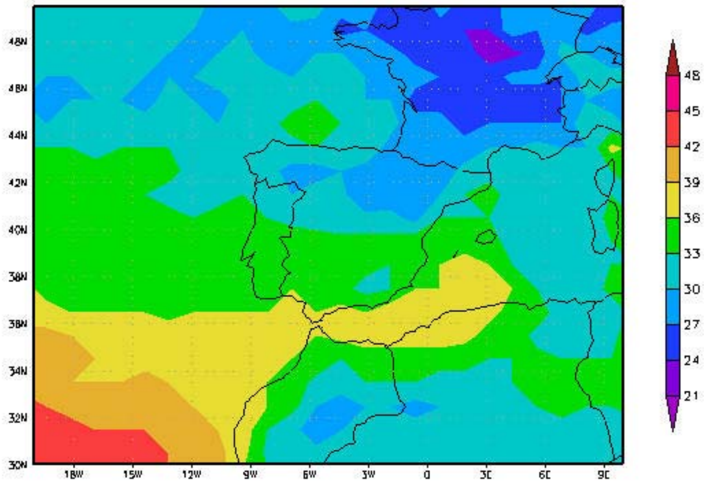
- Shaded Values Statistically Significant (>.9 confidence level)
- Most Significant Relationship between Summer TOR and Seasonal ENSO Indicators

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

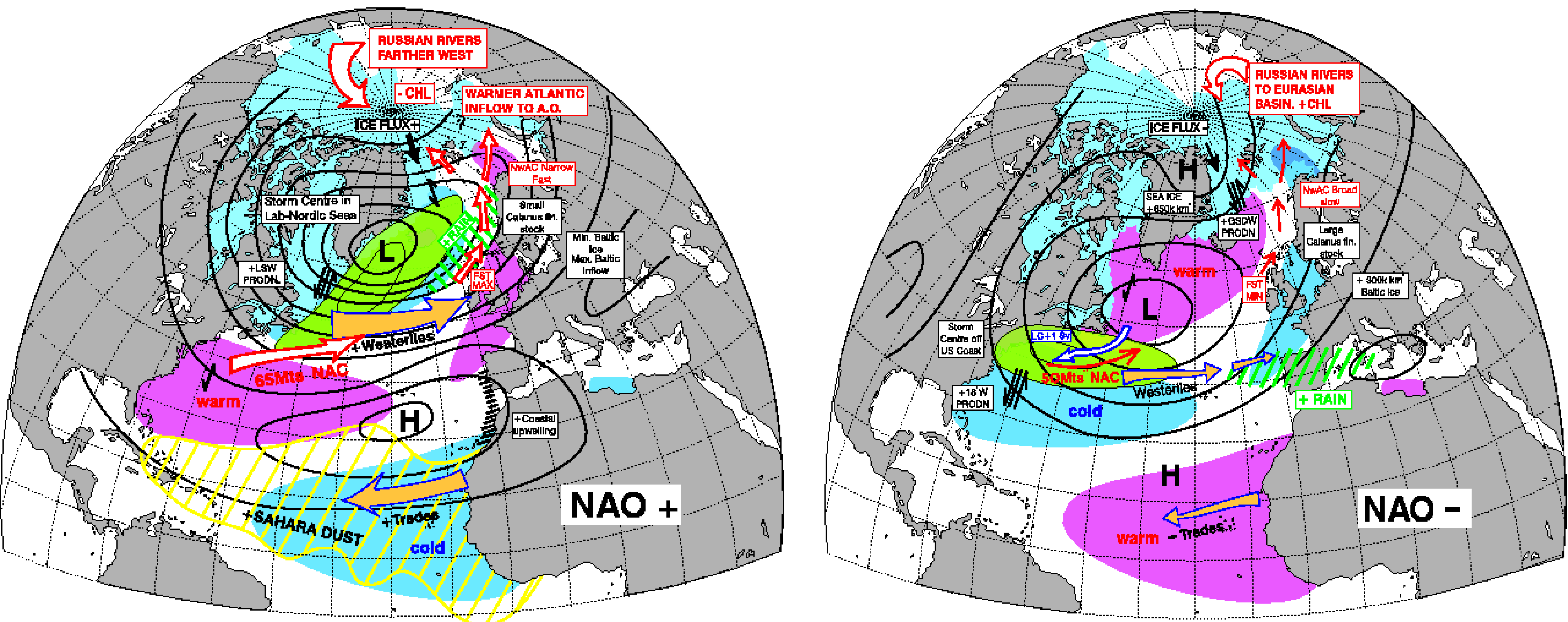
Spring 1992



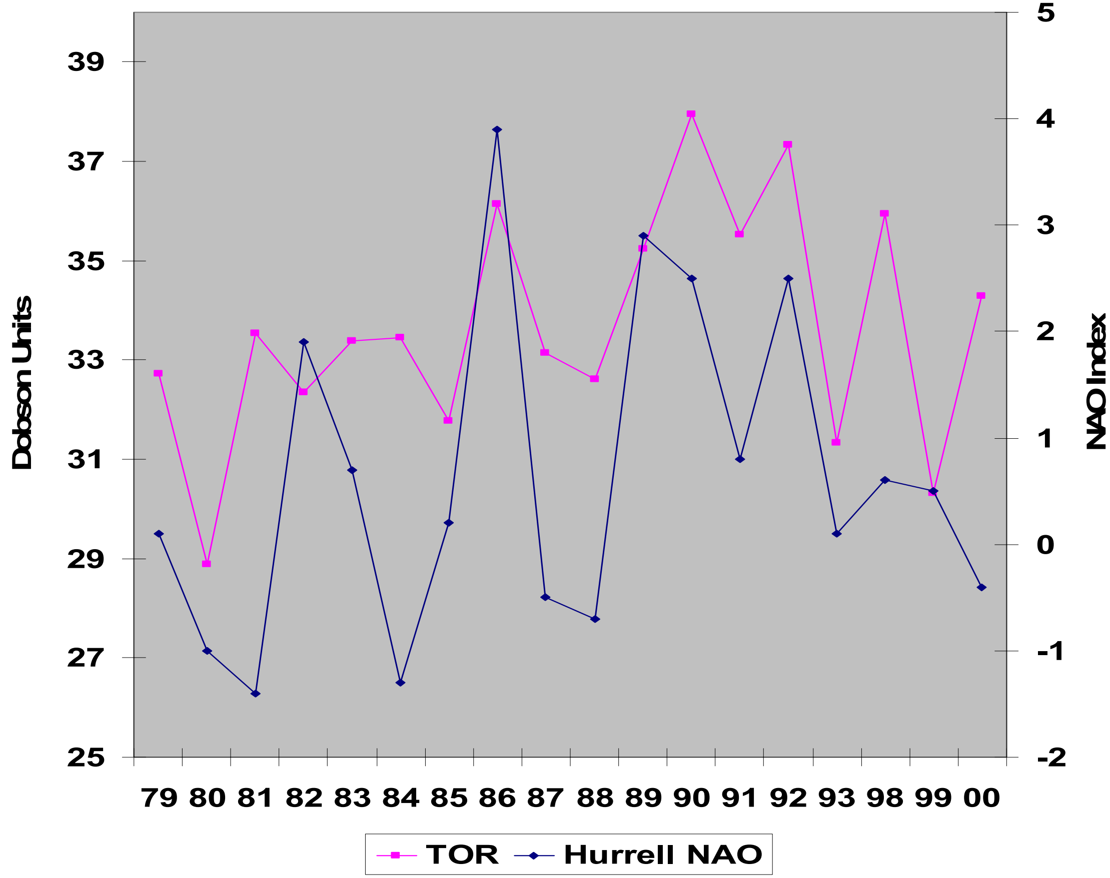
Spring 1980



North Atlantic Oscillation Determines Intensity of Transport Across Atlantic



Strong Correlation between TOR and NAO Index



Summary of 20 Years of SBUV/TOMS TOR Measurements

Data located at:

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

- Strong Correlations Apparent:
  - Pollution and Population Distributions
  - N.E. India and ENSO
  - Atlantic and NAO
- High Resolution Data Delineate Elevated Terrain
  - Possible Use for Validation
- Can ENSO or Other Indicators be Used as Predictors?

Part II:

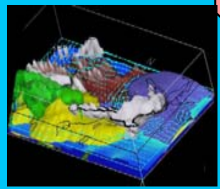
The Use Satellite Data to Improve Atmospheric Chemistry Models

Road Map to Use Satellite Measurements In Conjunction with Global and Regional Models to Develop Air Quality Forecast Capability

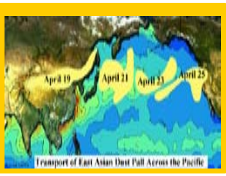
Earth System Modeling Framework Forecasts by 2012:
Robust emissions control planning and management. Routine warnings of elevated pollution episodes. Accurate 3-day air quality forecasts.

- Simultaneous, high time & space resolved multi-pollutant (O3, CO, NOx, SO2, HCHO, aerosol) data enables sound decision making

Outcomes: Accurate (regional, multi-day) pollution forecasts. NAAQS planning and mitigation based on validated models.



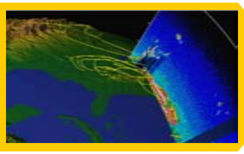
- Couple chemistry & aerosol models
- Assimilate satellite data for trace constituents



Outcomes: Reassess ozone and precursor transport across state boundaries. Implement air quality strategies & related development policy based on detailed data and models.

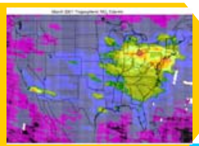
Impacts: Reduce asthma & lung related diseases. Improve visibility. Improve crop health & yields.

- Monitor long range transport of mineral and pollution aerosol (CALIPSO)



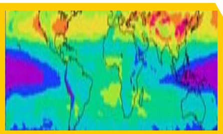
Outcomes: Determine source and destination of long range dust and pollutants. Route airplanes. More accurate forecasts of haze & pollution episodes. Warn hospitals & farmers.

- Ozone, SO_2 & NO_2 profiles & regional transport (Build on TOMS & GOME)
- Continental inflow/outflow



Outcomes: Quantify contributions of physical & chemical processes to pollutant concentrations. Extend ozone forecasting to regional transport for urban to rural areas.

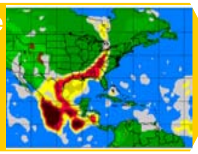
- Improve boundary conditions (ozone residual)
- Validate measurements



Outcomes: Assess effects of emissions control options. Evaluate development options and emissions strategies to set policies and construct attainable State (air quality) Implementation Plans.

Impacts: Reduce impaired lung function and use of medications. Reduce hospital admissions and lost work/school days.

- Large scale transport of aerosols (TOMS aerosol index)



Outcomes: Evaluate exceptional events for effect on NAAQS violations; provide exceptions for attainment.

Current trajectory:
Steady improvement in documenting the chemical content of the lower atmosphere,
Steady improvement in the physical accuracy of modeled processes for pollution episode warnings.

CMAQ / Forecasts:
State/regional planning.
Same-day air quality predictions.

TOMS TERRA SAGE III AQUA AURA Cloud Sat CALIPSO NPOESS

2000 2002 2004 2006 2008 2010 2012

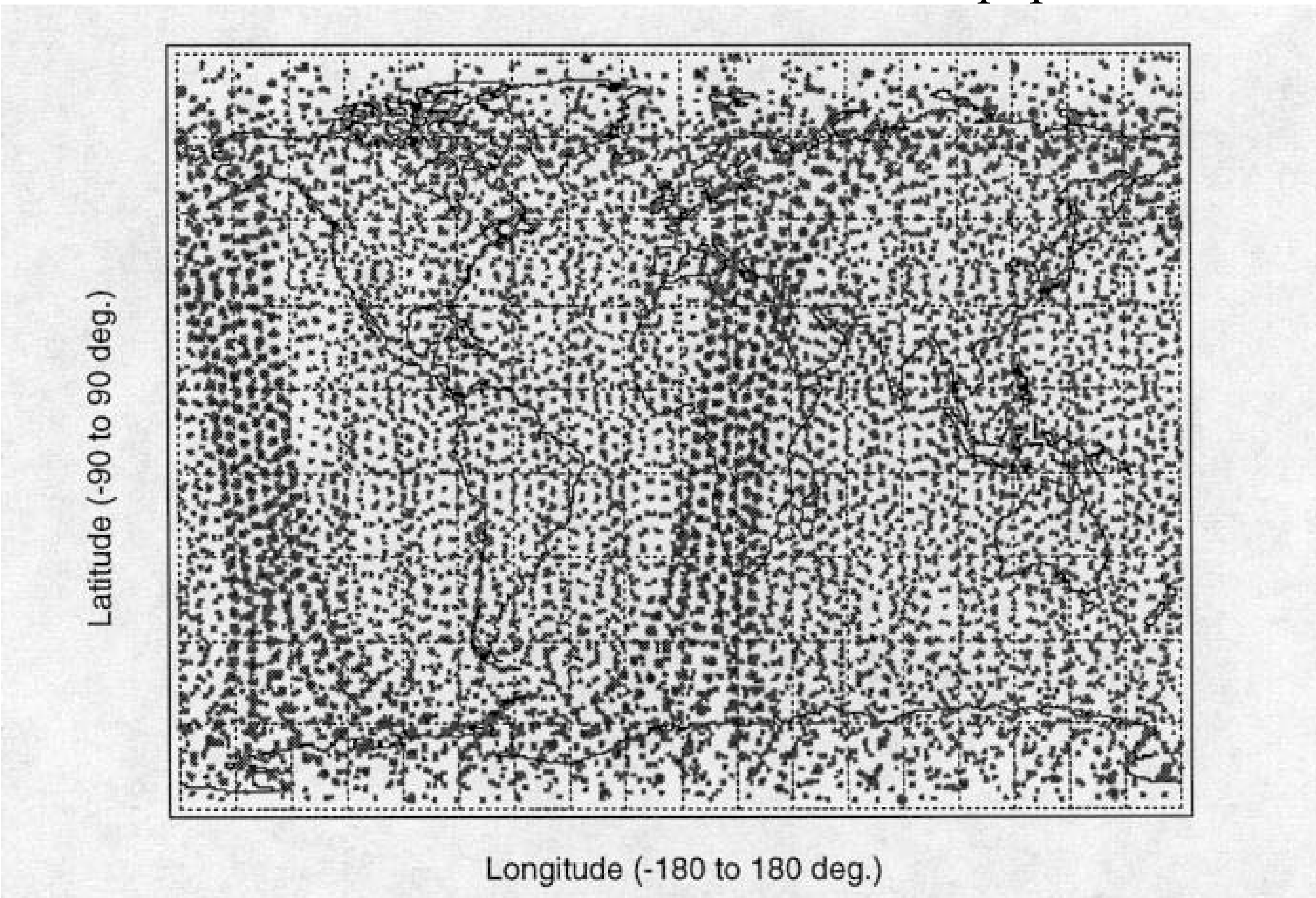
Part III:

New Satellites Will Provide Better Measurements

Methodology to Derive TOR with Instruments from Aura Satellite Using HIRDLS (High-resolution Infrared Dynamic Limb Sounder) and OMI (Ozone Monitoring Instrument)

- **Define Distribution of Ozone in the Stratosphere and Upper Troposphere from Profile Information**
  - Use HIRDLS Profiles with 4°-latitude x 5°-longitude Resolution
  - Normalize HIRDLS Stratospheric Column Ozone (SCO) to OMI SCO Derived from Convective Cloud Differential (CCD) Method
- **Subtract Stratospheric Ozone Fields from Higher Resolution OMI Total Ozone Fields to Derive TOR Distribution**

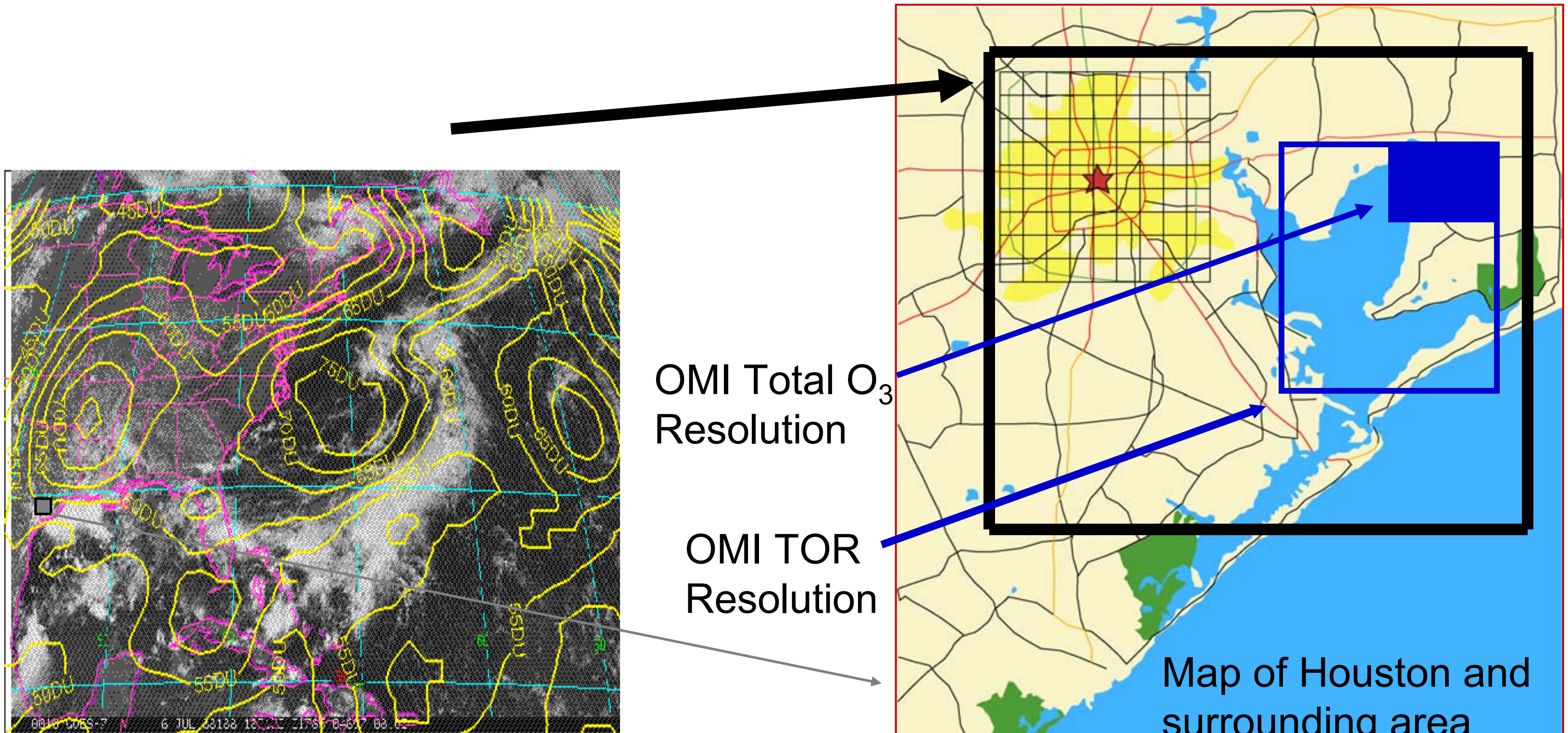
HIRDLS Daily Profile Coverage Will Provide Sufficient Information to Derive 3-Dimensional Stratospheric Ozone Distribution Down to 1 km Below Tropopause



Objective

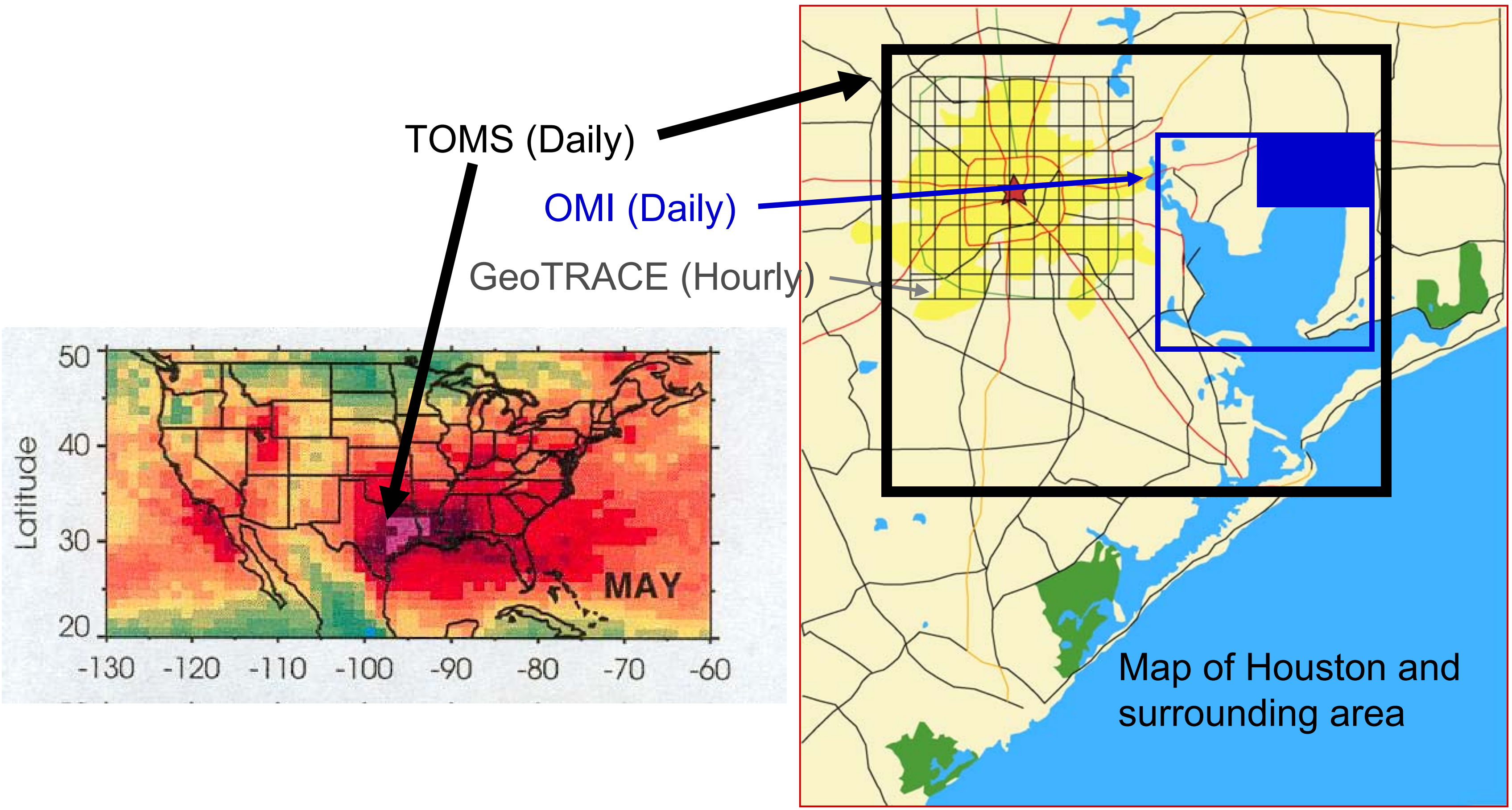
- Provide Quasi-Global Daily Maps of Tropospheric Ozone with 48 x 52-km Resolution

OMI Goal is to Produce Daily TOR Distribution with Better Resolution



From Fishman and Balok (1999)

Geostationary Observations Will Provide Hourly Observations with 5-km Resolution



Summary

- 2-Decade Record of TOR Now Available
- Strong Correlation between Population and Pollution
- Interannual Variability over Northern India Linked to ENSO
- 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