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

Presented at:
National Space Science and Technology Center
Huntsville, AL
February 10, 2003
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.

- **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

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

TOMS (total $O_3$ = 300 D.U.)
= 55 km

SAGE (limb scanner);
Isolate stratospheric component
(= 270 D.U.)

10–18 km
Tropopause

Calculate "tropospheric residual"

\[
\begin{align*}
300 \pm 10 \text{ D.U.} \\
-270 \pm 10 \text{ D.U.} \\
30 \pm 20 \text{ D.U.}
\end{align*}
\]
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

(a) Layer 1 (1013mbar-253mbar)
(b) Layer 2 (253mbar-127mbar)
(c) Layer 3 (127mbar-63.3mbar)
(d) Layer 1,2,3 (1013mbar-63.3mbar)
Information Contained in SBUV Measurements

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

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

**SBUV September 1992**
purpose level: 1000mb – 63mb

**SBUV September 1992**
purpose level: 1013mb – 253mb
Schematic Diagram of Empirical Correction

Input SBUV Measurement: 
(A + B + C)

Output* for TOR Calculation

\[ C^* = \frac{Z_1 (A + B + C)}{(X + Y + Z)} \]
\[ B^* = \frac{Y (A + B + C)}{(X + Y + Z_1)} \]
\[ A^* = \frac{X (A + B + C)}{(X + Y + Z_1)} \]
Comparison Using Empirical Correction with Ozonesondes

Hohenpeissenberg, Germany (47N)

Year

BIAS (DU)
-40 -20 0 20 40 60

Corrected SBUV-ozonesonde
SBUV-ozonesonde
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

    - ~ 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

SAGE/TOMS TOR (5° x 10°)

100km x 125km TOMS Horizontal Resolution (1° x 1.25°)
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

Column Ozone (Dobson Units)
Comparison of TOMS/SAGE TOR with TOMS/SBUV TOR

SAGE Tropospheric Ozone Residual (TOR) JJA 1979–91

SBUV Tropospheric Ozone Residual (TOR) JJA 1979–91
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 transport situation carries offshore 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. O₃
(from Schichtel and Husar, 1998)
July 1988 Monthly TOR Captures High Ozone During Major Pollution Episode

July 1988 TOR

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

July 3-15 Average Daily Max. O₃ (from Schichtel and Husar, 1998)
Lower TOR over North African Desert Regions Coincident with Higher Elevations

Implications:

- TOMS Capable of Isolating Small (Regional) Scale Features
- $\sim 3$ DU for $\int_{z=2\text{km}} dz \Rightarrow \sim 20\text{ ppb in pbl}$
- Information can be used to validate $\text{O}_3$ 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:

\[
\int_{2\ km}^{4\ km} [O_3] \, dz = \sim 3 \ \text{DU}
\]

\[
\int_{\text{Trop. (17 km)}} \ [O_3] \, dz = \sim 25 \ \text{DU}
\]
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 O₃ 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

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 1979 - Dec 1999

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>31.5</td>
<td>1992</td>
<td>33.3</td>
<td>1989</td>
<td>40.5</td>
<td>1982</td>
<td>47.2</td>
<td>1982</td>
<td>52.9</td>
<td>1982</td>
<td>52.1</td>
<td>1982</td>
</tr>
<tr>
<td>1998</td>
<td>30.0</td>
<td>1987</td>
<td>33.0</td>
<td>1982</td>
<td>38.1</td>
<td>1984</td>
<td>47.1</td>
<td>1981</td>
<td>50.0</td>
<td>1989</td>
<td>51.3</td>
<td>1992</td>
</tr>
<tr>
<td>1992</td>
<td>30.1</td>
<td>1993</td>
<td>30.7</td>
<td>1988</td>
<td>34.7</td>
<td>1980</td>
<td>44.5</td>
<td>1991</td>
<td>47.4</td>
<td>1980</td>
<td>47.5</td>
<td>1988</td>
</tr>
<tr>
<td>1991</td>
<td>29.8</td>
<td>1990</td>
<td>30.5</td>
<td>1993</td>
<td>34.7</td>
<td>1993</td>
<td>44.4</td>
<td>1979</td>
<td>47.2</td>
<td>1988</td>
<td>47.5</td>
<td>1981</td>
</tr>
<tr>
<td>1990</td>
<td>29.8</td>
<td>1985</td>
<td>30.2</td>
<td>1979</td>
<td>34.0</td>
<td>1986</td>
<td>44.4</td>
<td>1984</td>
<td>46.6</td>
<td>1981</td>
<td>47.4</td>
<td>1983</td>
</tr>
<tr>
<td>1989</td>
<td>29.7</td>
<td>1981</td>
<td>29.4</td>
<td>1986</td>
<td>34.0</td>
<td>1987</td>
<td>44.0</td>
<td>1999</td>
<td>46.2</td>
<td>1979</td>
<td>46.8</td>
<td>1986</td>
</tr>
<tr>
<td>1987</td>
<td>29.4</td>
<td>1999</td>
<td>29.0</td>
<td>1985</td>
<td>32.8</td>
<td>1990</td>
<td>43.5</td>
<td>1988</td>
<td>45.6</td>
<td>1985</td>
<td>46.6</td>
<td>1979</td>
</tr>
<tr>
<td>1984</td>
<td>27.6</td>
<td>1980</td>
<td>25.5</td>
<td>1999</td>
<td>26.7</td>
<td>1999</td>
<td>40.8</td>
<td>1998</td>
<td>42.4</td>
<td>1999</td>
<td>45.4</td>
<td>1999</td>
</tr>
</tbody>
</table>

#### 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)

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean TOR</th>
<th>Range</th>
<th>SOI</th>
<th>ENSO SST Region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>High</td>
<td>Low</td>
<td>Mon</td>
</tr>
<tr>
<td>January</td>
<td>29.8</td>
<td>31.5 (1991)</td>
<td>25.7 (1980)</td>
<td>.04</td>
</tr>
<tr>
<td>February</td>
<td>29.9</td>
<td>33.3 (1992)</td>
<td>25.1 (1991)</td>
<td>-.33</td>
</tr>
<tr>
<td>March</td>
<td>34.6</td>
<td>40.5 (1989)</td>
<td>26.7 (1999)</td>
<td>.02</td>
</tr>
<tr>
<td>April</td>
<td>44.0</td>
<td>47.2 (1982)</td>
<td>40.5 (1985)</td>
<td>-.21</td>
</tr>
<tr>
<td>May</td>
<td>47.3</td>
<td>52.9 (1982)</td>
<td>42.4 (1998)</td>
<td>.21</td>
</tr>
<tr>
<td>June</td>
<td>48.2</td>
<td>52.1 (1982)</td>
<td>45.4 (1999)</td>
<td>-.45</td>
</tr>
<tr>
<td>July</td>
<td>46.4</td>
<td>48.3 (1982)</td>
<td>44.0 (1999)</td>
<td>-.53</td>
</tr>
<tr>
<td>August</td>
<td>42.0</td>
<td>43.7 (1992)</td>
<td>40.4 (1999)</td>
<td>-.44</td>
</tr>
<tr>
<td>September</td>
<td>36.8</td>
<td>40.1 (1990)</td>
<td>35.2 (1979)</td>
<td>.09</td>
</tr>
<tr>
<td>October</td>
<td>32.7</td>
<td>35.0 (1999)</td>
<td>30.6 (1987)</td>
<td>.55</td>
</tr>
<tr>
<td>November</td>
<td>30.5</td>
<td>33.2 (1981)</td>
<td>28.6 (1984)</td>
<td>.27</td>
</tr>
<tr>
<td>December</td>
<td>27.9</td>
<td>30.0 (1997)</td>
<td>25.8 (1984)</td>
<td>.43</td>
</tr>
</tbody>
</table>

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 O₃**

- in Cincinnati on the 10ᵗʰ?
- in Pittsburgh and Buffalo on the 11ᵗʰ?
- in Philadelphia and New Jersey on the 12ᵗʰ?
We must now pave the road and travel on it to our destination.

The Roadmap Has Been Laid Out

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

CMAQ: Runs Independent of Surrounding Conditions

ASTRO-NAIADS

Develop Data Assimilation and Modeling Tools

Validate on Existing Data Sets

RAQMS Regional/GOME NO2
March 08-April 11, 2001 Comparison

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

- spatial resolution: $\sim 20 \times 20$ km$^2$
- spatial sample: 640 km swath in 90 minutes
- temporal sample: $\sim$once every 3 days (available from LEO)

- spatial resolution: $4 \times 4$ 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

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

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
“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 (O₃, CO, NO₂, SO₂, CH₂O) 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
With Model Runs from August 9:

NOAA issues unhealthy O₃ 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 O₃ and Alerts Population of Potential Health Risk
Summary

• 2-Decade Record of TOR Now Available
  

• 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