The Scientific Journey to GEO-CAPE:

A Road from Termites to Soybeans to Societal Benefits

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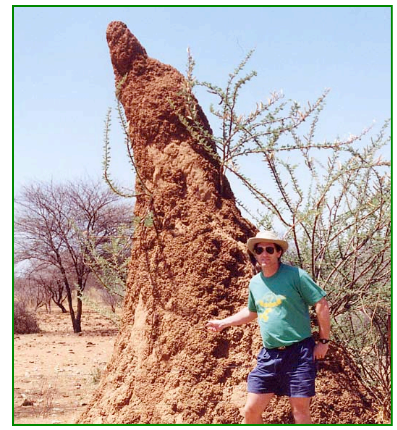
Purpose of this Presentation

- Review the State of Trace Gas Measurement Capability
  - Global Distributions
  - Seasonality
  - Trends
  - Interannual Variability
  - Insight into Global Sources
- Drivers for GEO-CAPE
  - Where did the Recommendations Come From?
  - What are the Science Challenges for GEO-CAPE?

Historical Context of the Evolution of Tropospheric Composition Measurements from Space

- **NASA's EOS Program Developed in the mid-1980s**
- **NRC "Plan for Action" for Tropospheric Chemistry in 1984**
- **Plans for a U.S. Research Program in 1986**
    - **- Determine global distributions of key trace species**
    - **- Focus on seasonal variability and long-range transport**
    - **- Quantify long-term trends of trace species**



All to be accomplished using ground-based monitors!

U.S. Research Plan Also Called for:

- Develop and deploy satellite-borne CO instrument **MOPITT on Terra**

-Explore prospects for satellite-based measurements of other tropospheric species **TES on Aura**

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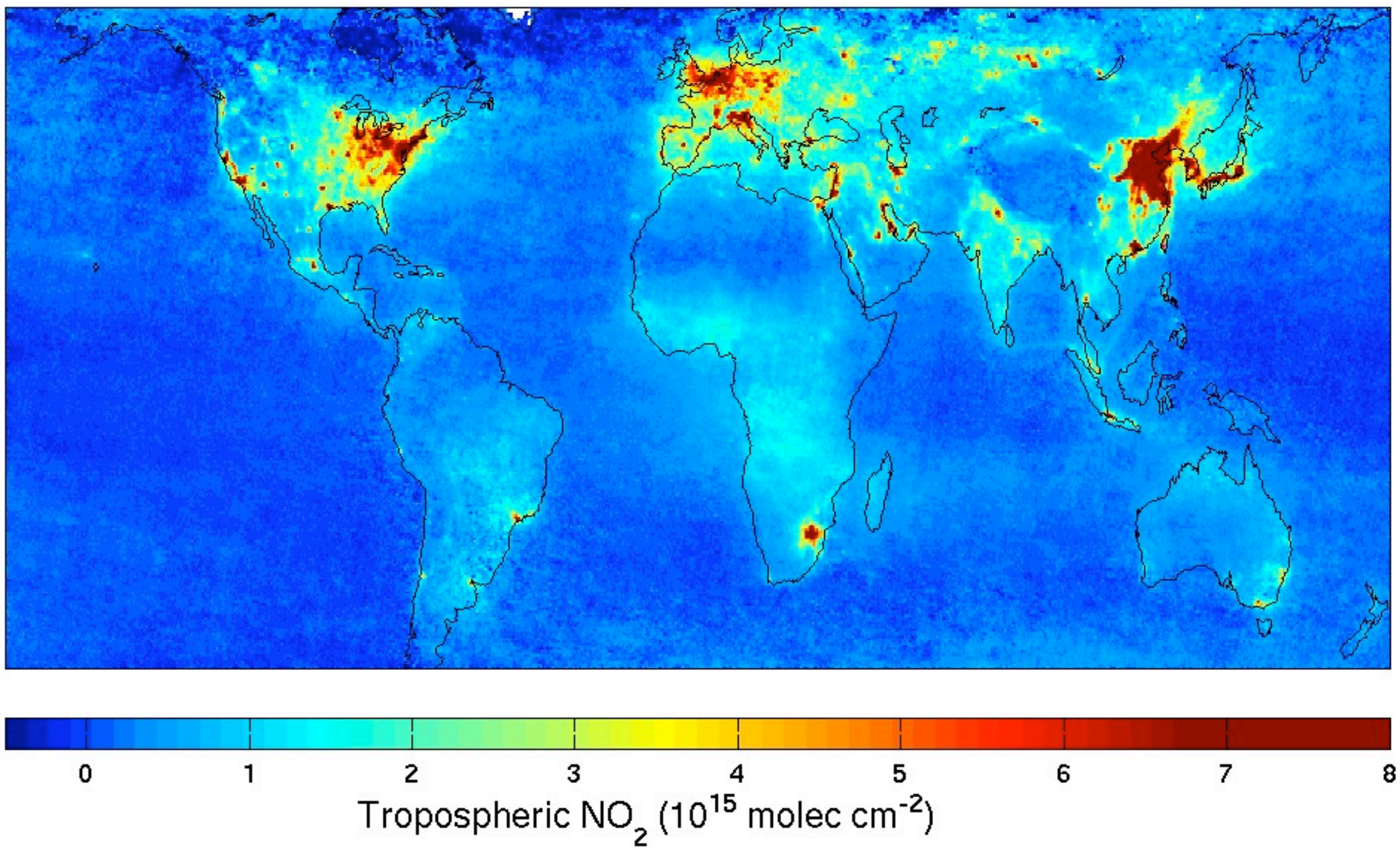
Global Distribution of Nitrogen Dioxide: Precursors to Ozone Formation



Tropospheric NO_2 columns retrieved from the SCIAMACHY satellite instrument for 2004 –2005 (after Martin et al., 2002)

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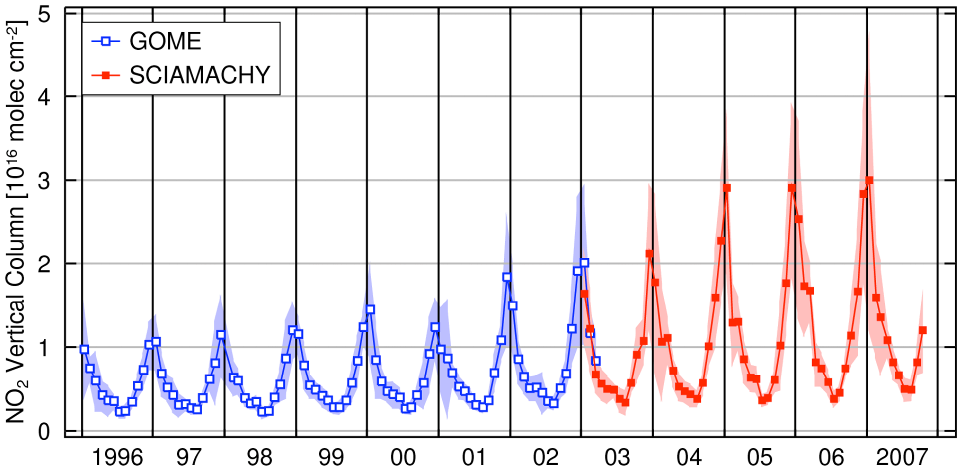
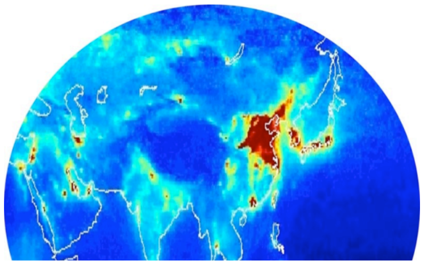
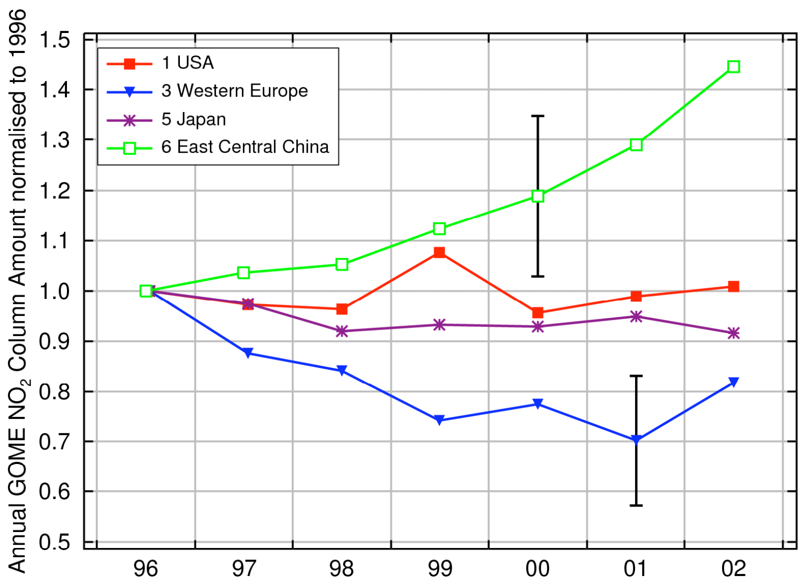
Length of Record Provides Insight to Trends: Verification of Pollution Controls





- **Decade of NO_2 measurements from GOME/SCIAMACHY clearly depict large increase in emissions from China**

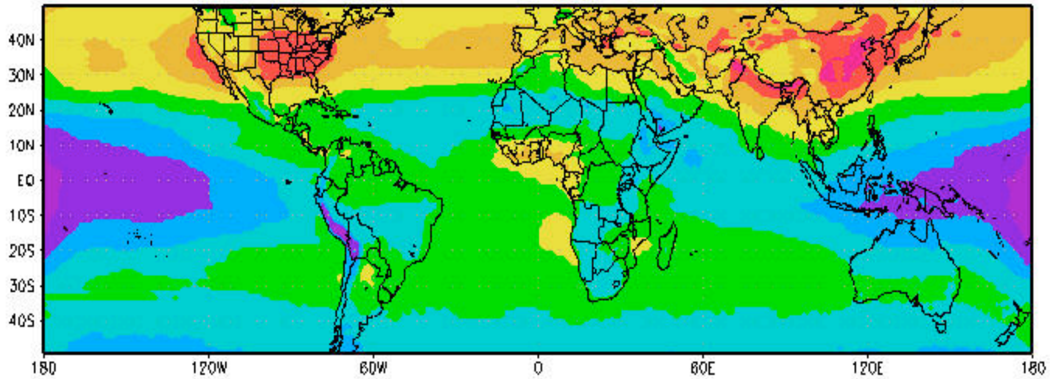
- **Seasonal cycle consistent driven by photolysis rates which are driven by magnitude of photon flux**



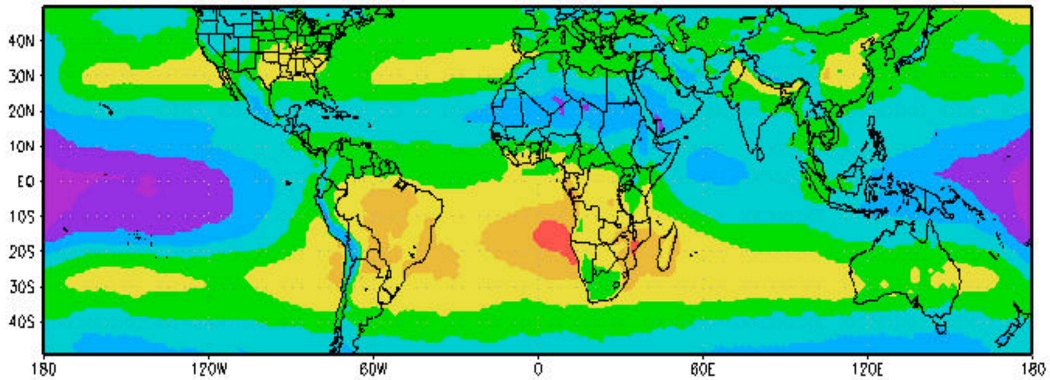
- **Trends in U.S., Japan, and western Europe consistent with enactment of pollution controls**

Figures courtesy of Andreas Richter and John Burrows

Global Seasonality of Trace Gas Composition Has Been Established with Satellites



• Summer smog dominant feature during NH summer



• African and South American biomass and savanna burning generate massive pollution plume during austral spring (Sep-Nov)

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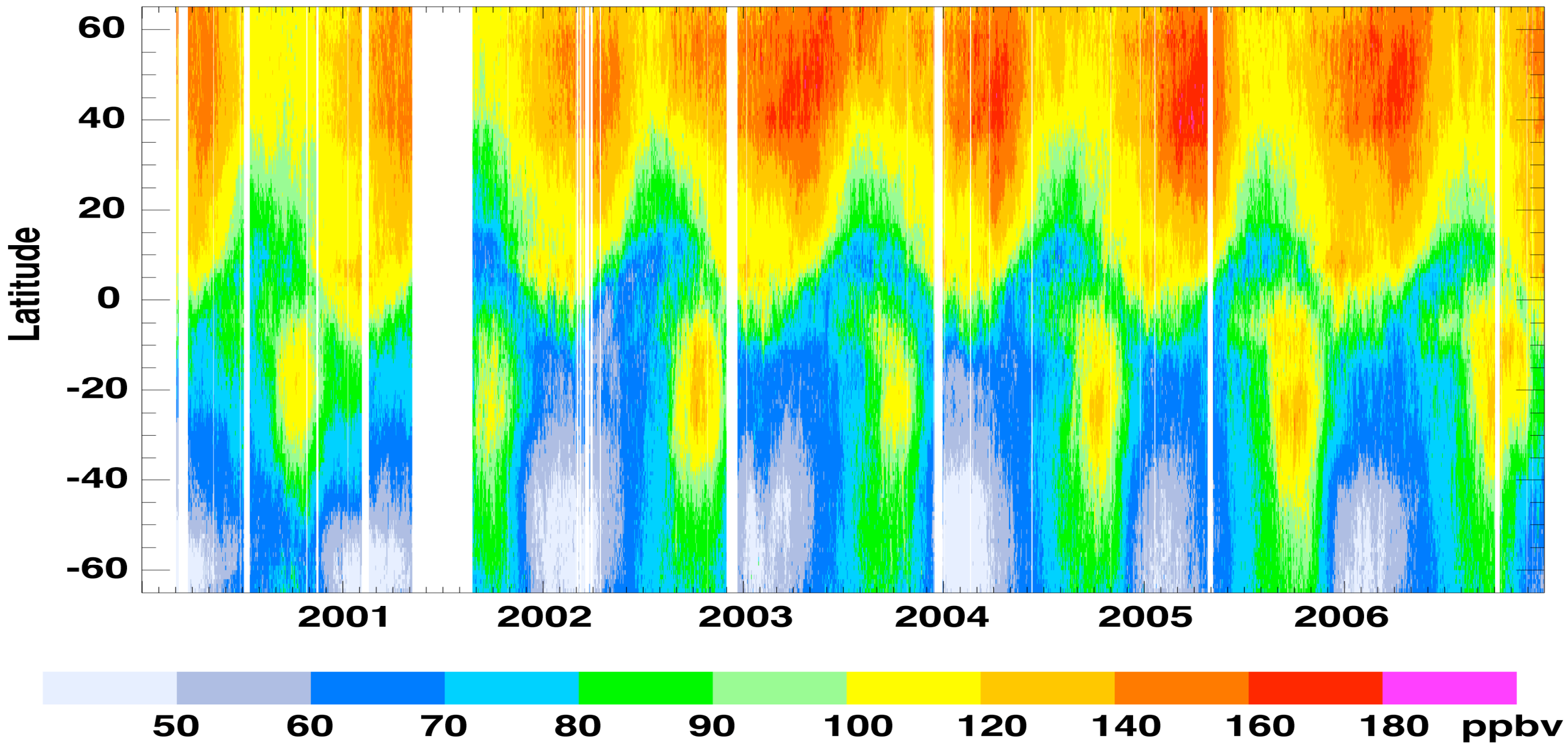
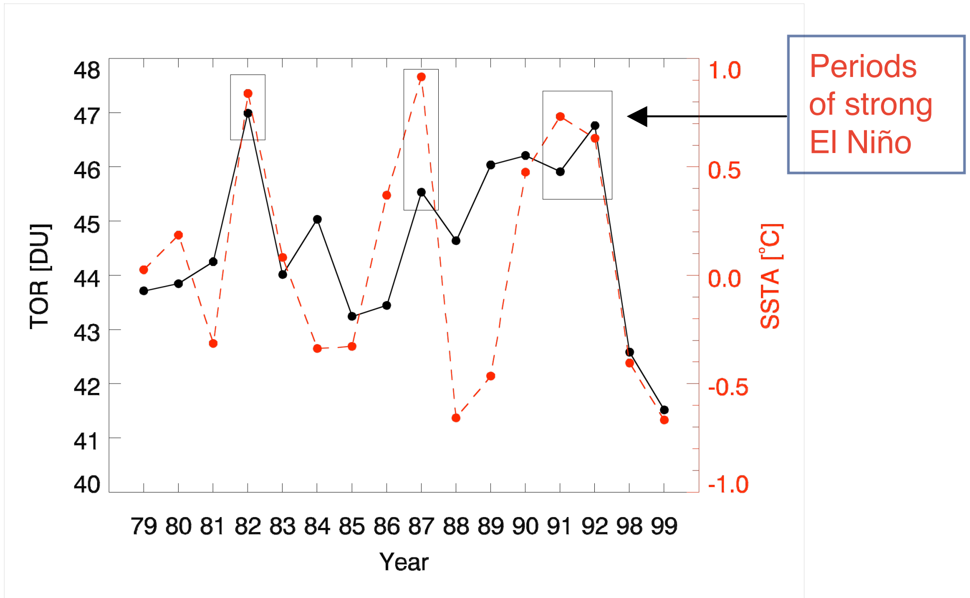
Length of Record Now Provides Insight into Global Scale Interannual Variability

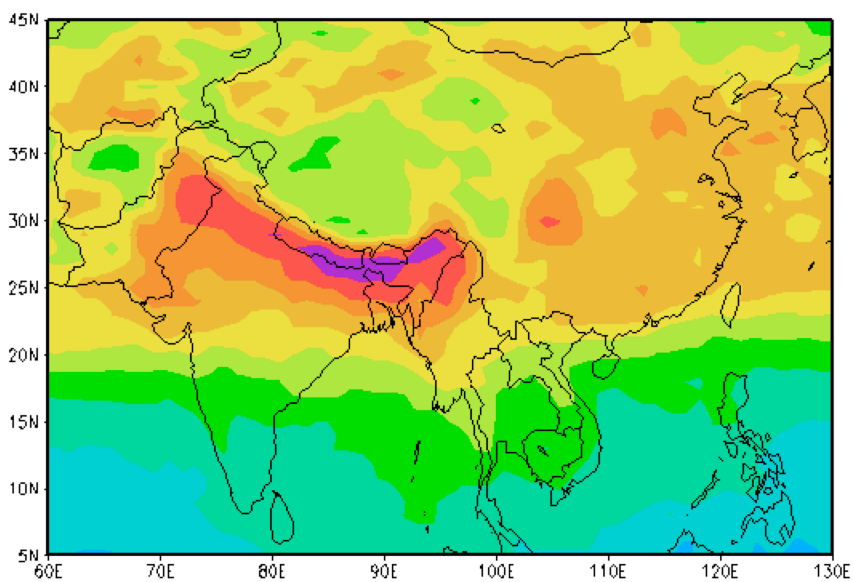


Zonal plot showing the CO 700 hPa mixing ratio at different latitudes over recent years (courtesy of David Edwards)

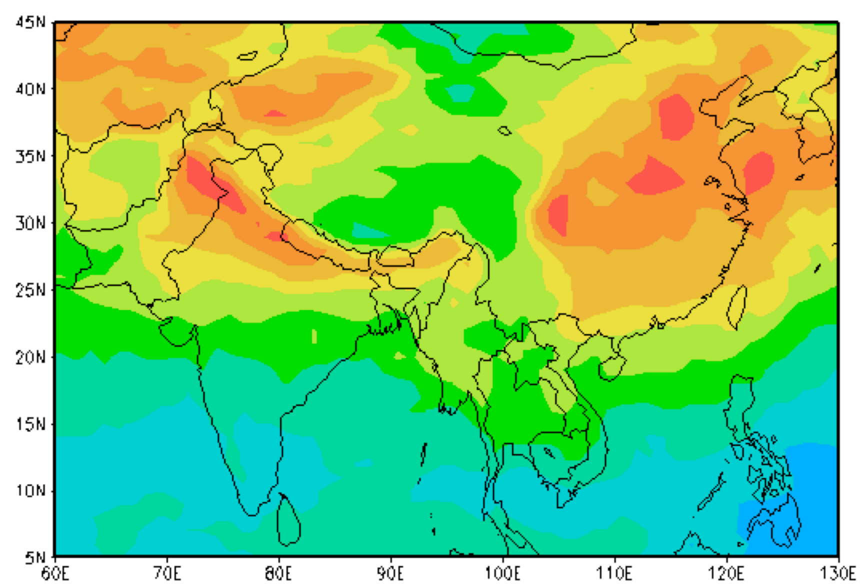
Regional Interannual Variability Determined from Satellite Data

Interannual variability of TOR over Northern India Strongly Correlated with ENSO and strength of monsoonal flow



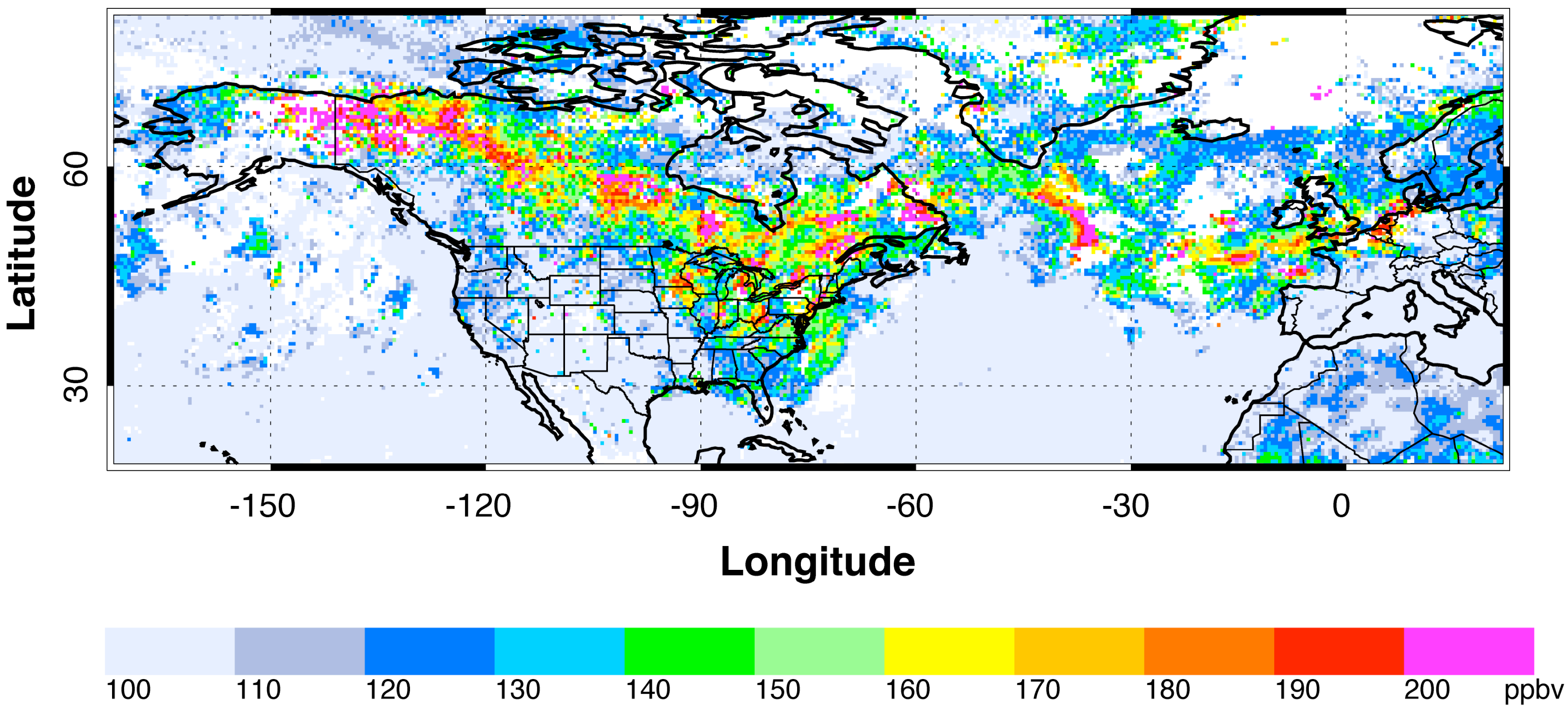


June 1982 - Strong El Niño Year



June 1999 - Strong La Niña Year

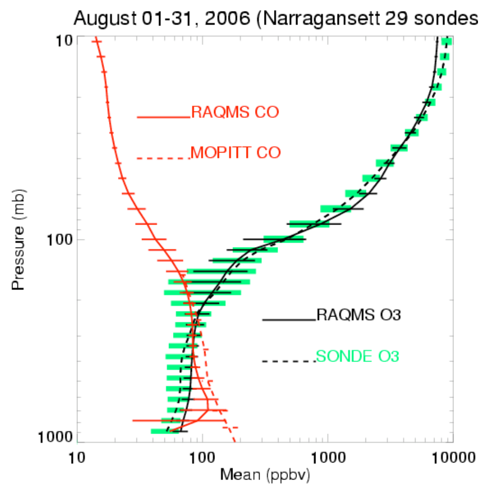
Satellite Provide Unique Perspective for Mapping the Extent of Large Pollution Events

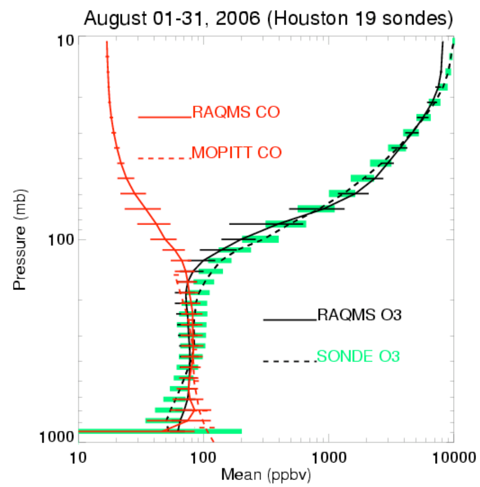


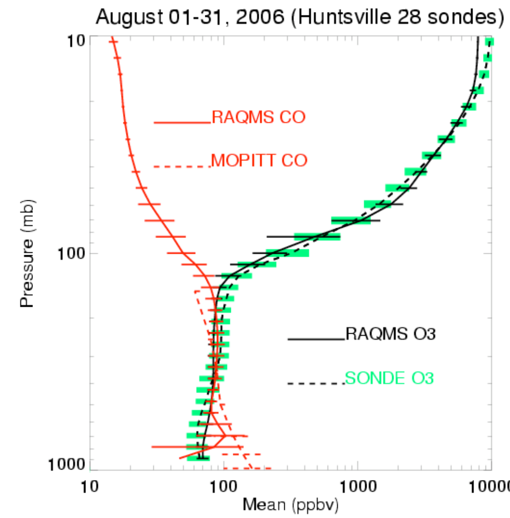
MOPITT 700 hPa CO mixing ratio for July, 15-23, 2004. Intense wildfires in Alaska produced plumes of pollution that can be traced across North America and the Atlantic Ocean.

Assimilation Models Provide Consistent Picture of Species

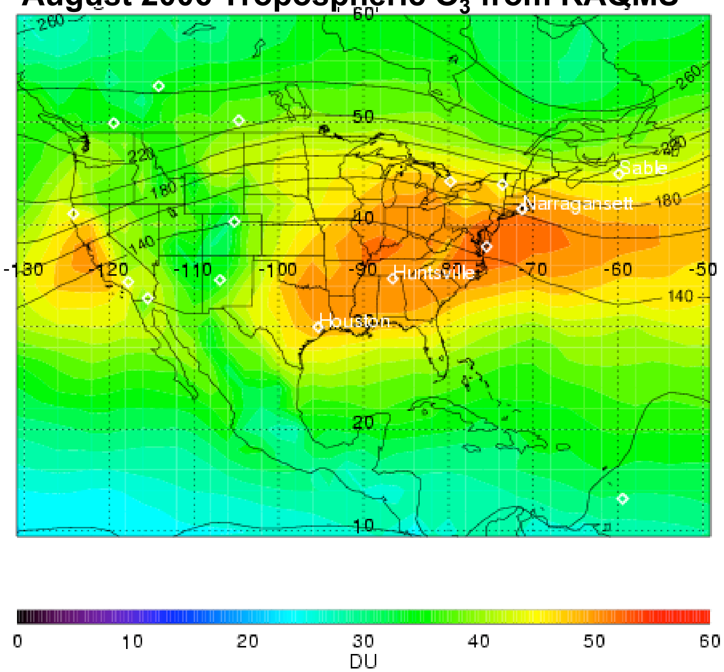
Monthly Averages Used for Validataion of Assimilated Fields



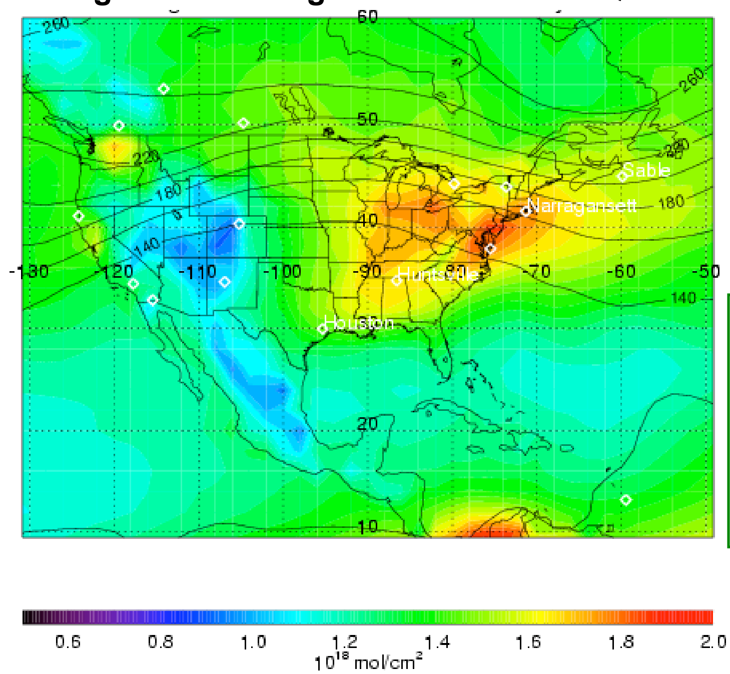




August 2006 Tropospheric O_3 from RAQMS



August 2006 Integrated CO from RAQMS



High levels of CO indicate high pollution levels over eastern U.S.

High levels of O_3 off California coast combined with low CO levels suggest O_3 of stratospheric origin

After Priece et al. (2006)

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What are the Drivers Leading to the Developing GEO-CAPE from the Atmospheric Composition Perspective?

- July 2003: Earth Summit

"Improved coordination of strategies and systems for observations of the Earth and identification of measures to minimize data gaps, with a view to moving toward a comprehensive, coordinated, and sustained Earth observation system or systems"

IGOS already established to provide guidance for measurement strategy

- September 2004: IGACO Report

Satellite instrumentation should be from a combination of GEO and LEO satellites to provide measurements with the temporal and spatial resolution for sufficient coverage.

- February 2006: Air Quality from Space Workshop

- January 2007: NRC Decadal Survey

• The Theme in the 21st Century is that Satellite Observations Should Provide "Societal Benefits"

Societal Benefit Theme Includes Measurements in Support of Air Quality

Impact on Biological Processes:

Impact on Human Health

~ 4000 premature deaths per year linked to elevated O_3 concentrations in U.S.

(from Bell et al. *J. Amer. Med. Assoc.*, **292**, 2004)

"The cost to society in terms of direct expenditures for health care, lost productivity, restriction of daily activity and a reduced quality of life, and suffering of acute symptoms and premature death is likely in the billions of dollars each year for ozone. ... Tropospheric ozone remains the most widespread, intractable, and potentially the most damaging to health and the environment of the air pollution problems facing the U.S. and many other parts of the world." (from R.H. Wh"Ozone Health Effects--A Public Health Perspective," in *Tropospheric Ozone: Human Health and Agricultural Impacts*, D.J. McKee, ed., Lewis Publ., 1994)

Forest Damage in the United States from Ozone Pollution

- **Tree Ring Analysis Indicates Substantial Decrease in Growth Rate During Past 20-25 Years**
- **Most Severe Decline Involves Red Spruce: Primary damage at High Elevations in eastern U.S. from New York/New England to S. Appalachian Mountains**
- **Laboratory Studies Indicate 20-40% Growth Decline at 80-150 ppbv (variable exposure time: 4-12 hr/day; 28-90 days)** (from Pye, *J. Env. Qual.,* **17**, 1988)

Ozone Increase on U.S. and Global Crop Production

- **Annual Cost to U.S. Agriculture Exceeds $2 Billion** (Mauzerall and Wang, *Ann. Rev. Energy Environ*, **26**, 2001)
- **10 - 35% of World's Grain Production Occur in Regions Where Ozone Pollution May Reduce Crop Yields**
- **Exposure to Yield-Reducing Ozone Pollution may Triple by 2025**
- **By 2025, 30 - 75% of World's Grains may be Grown in Regions Affected by Ozone Concentrations Reducing Crop Yields** (Chameides et al., *Science*, **264**, 1994)

Future Satellite Measurements Must Be Relevant to Societal Benefits

- **Ground Rules for Satellite Development are Different**
  - Making measurements <u>only</u> for science is not acceptable
  - Planning should involve users of measurements (i.e., other agencies)
  - Satellite measurements should be a component of **integrated** systems
    - Integrated with other satellites (CEOS)
    - Integrated with other observing networks (IGACO/GEOSS)
    - Integrated with a strong modeling component (IGACO/GEOSS)

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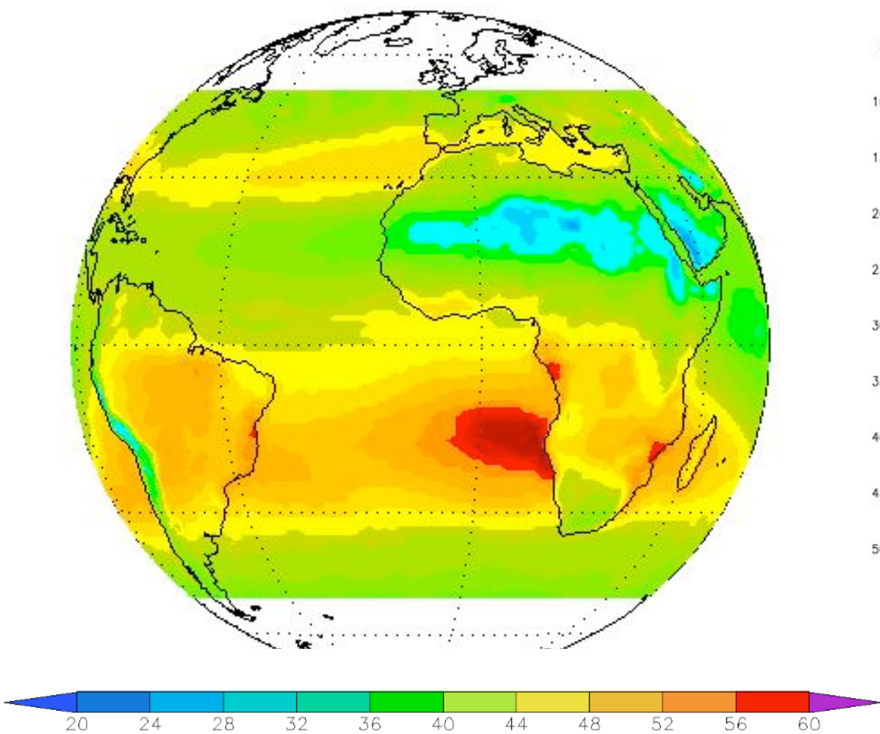
- **• The Evolution of the Outbreak of Pollution Episodes**

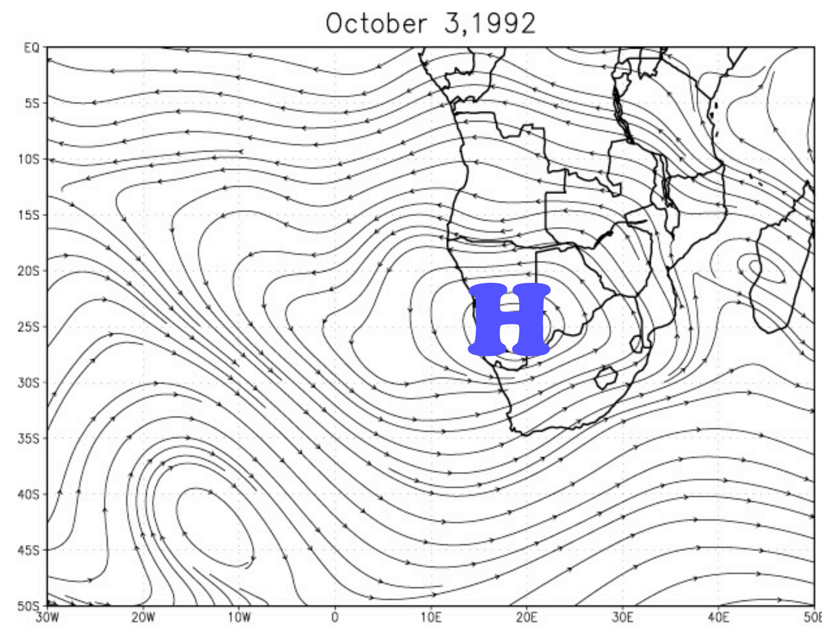
The Interaction between Meteorology and Chemistry Defines the Observations

- **Large Pollution Outbreaks Generally Associated with Stagnant Atmospheric Conditions Induced by Presence of Entrenched High Pressure System**
  - Persistent High Pressure found off West Coast of southern Africa
  - Massive High Pressure System Situated over Eastern during Extreme Episode in 1988
  - High Pressure System in Place during 2005 Case Study

Persistent Tropospheric Ozone Enhancement over South Atlantic Associated with Entrenched High Pressure in the SH Subtropics

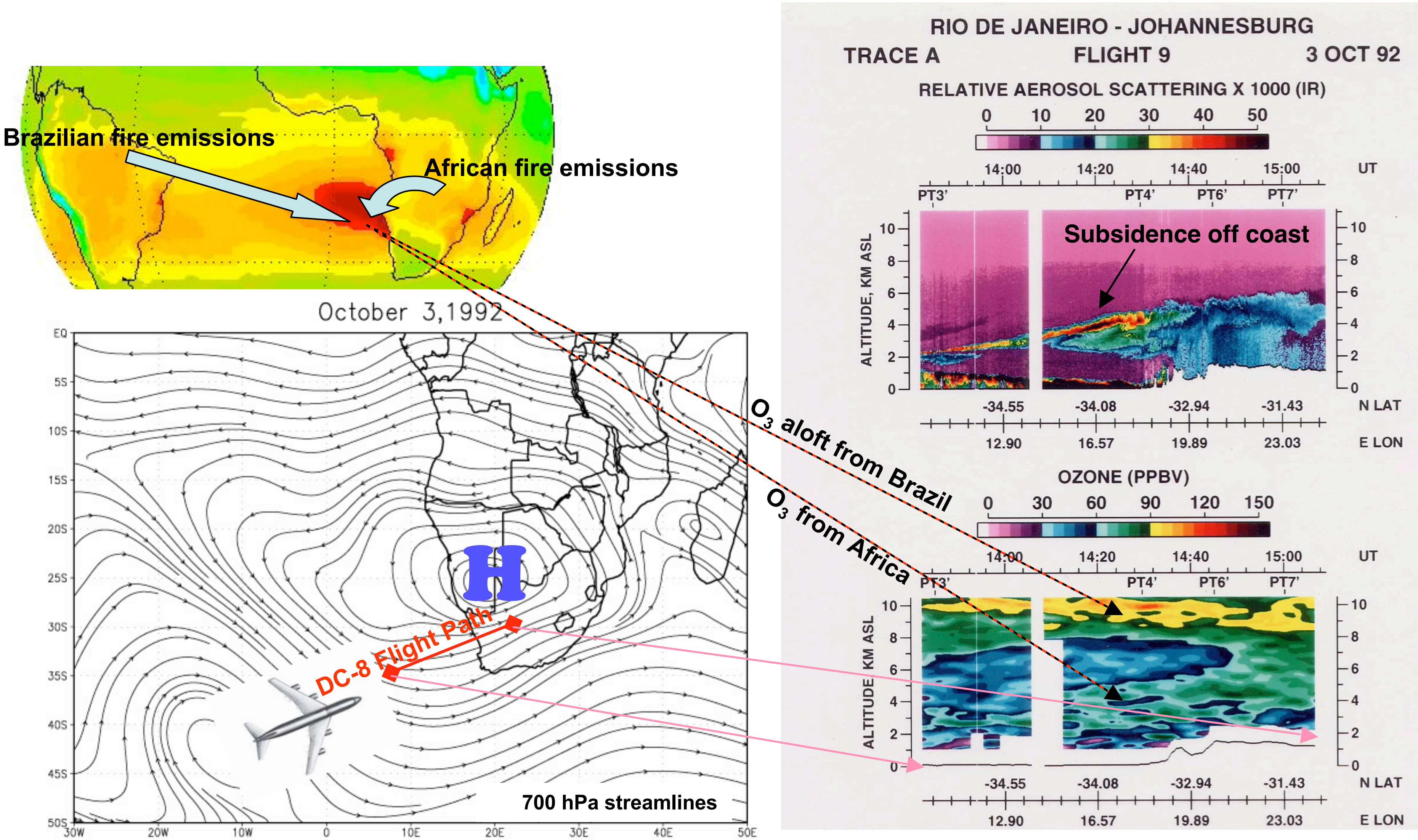
September-November TOR Climatology



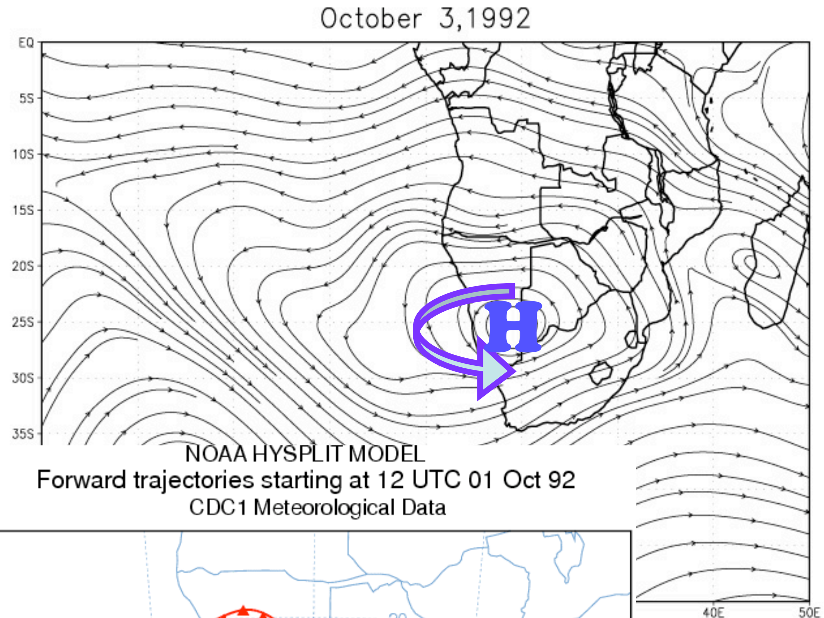


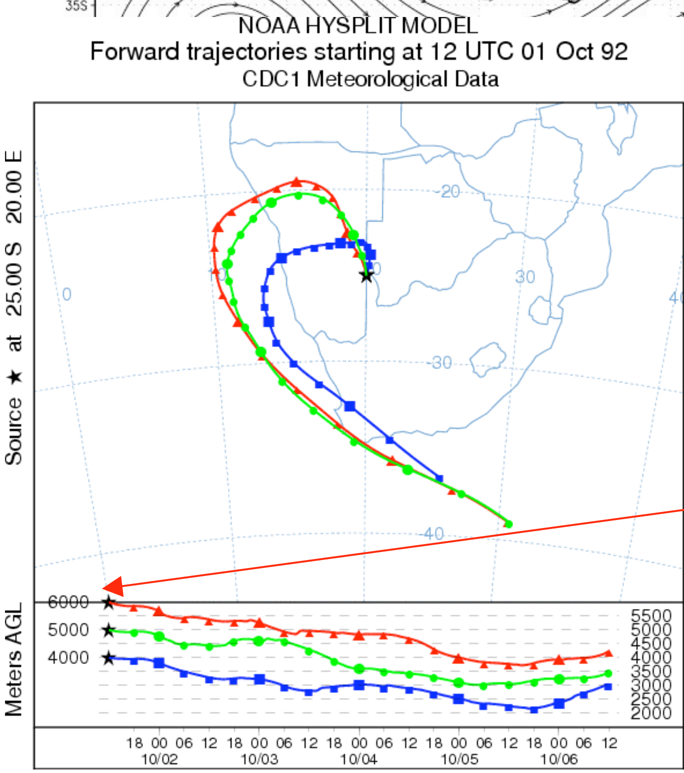
High Levels of Ozone seen by Satellite:

Combination of High Concentrations Aloft from Brazil with High Concentrations from Africa at Lower Altitudes

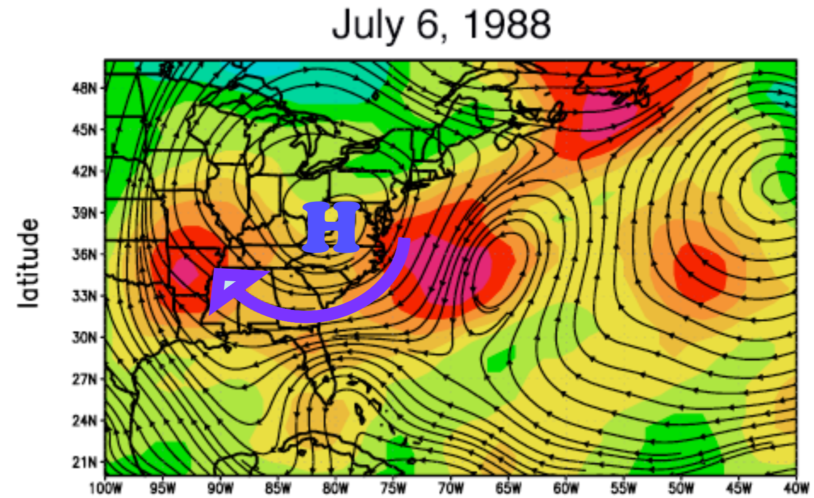


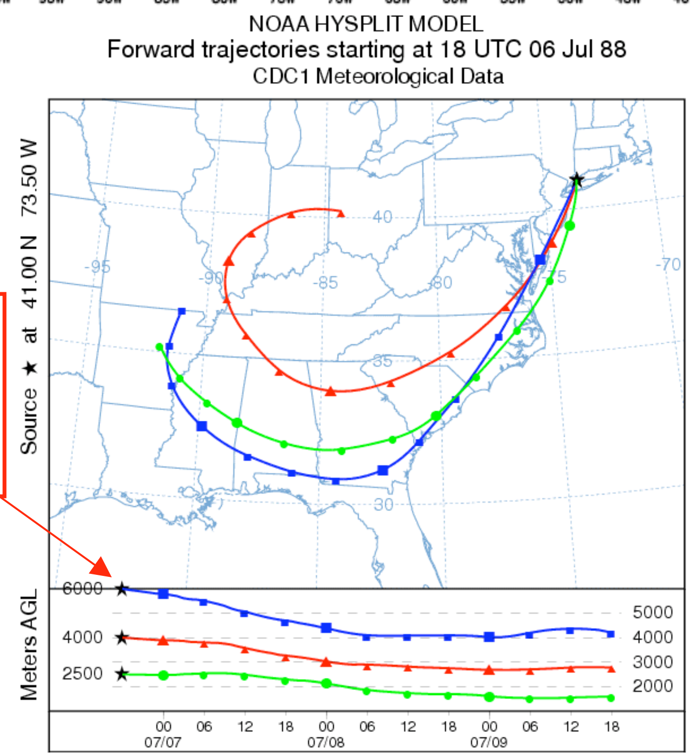
Strong Subsidence over Source Region



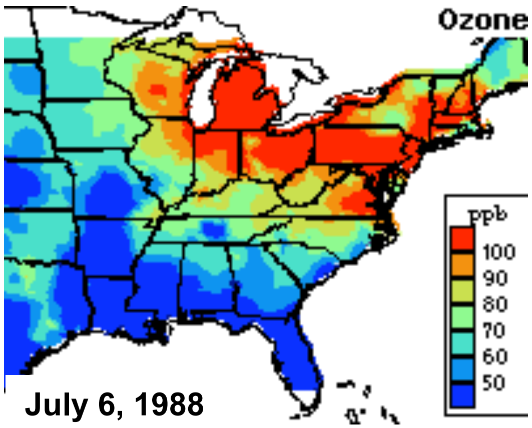


Parcels starting as high as 6000m descend significantly over several days



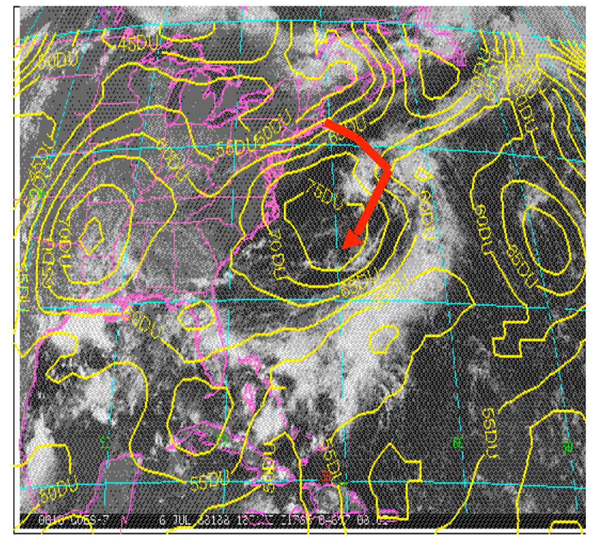


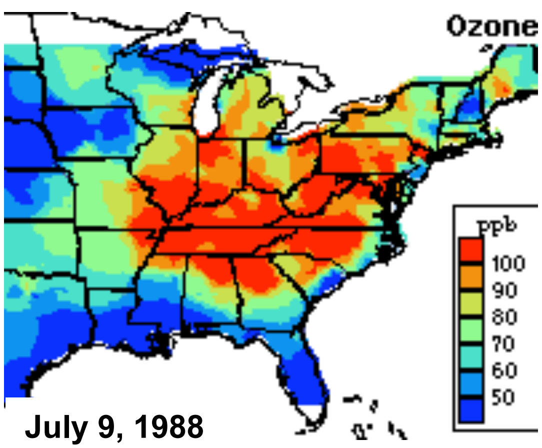
Case Study Suggests Transport from Northern U.S. Leads to Pollution Episode in Southern U.S.



July 6, 1988

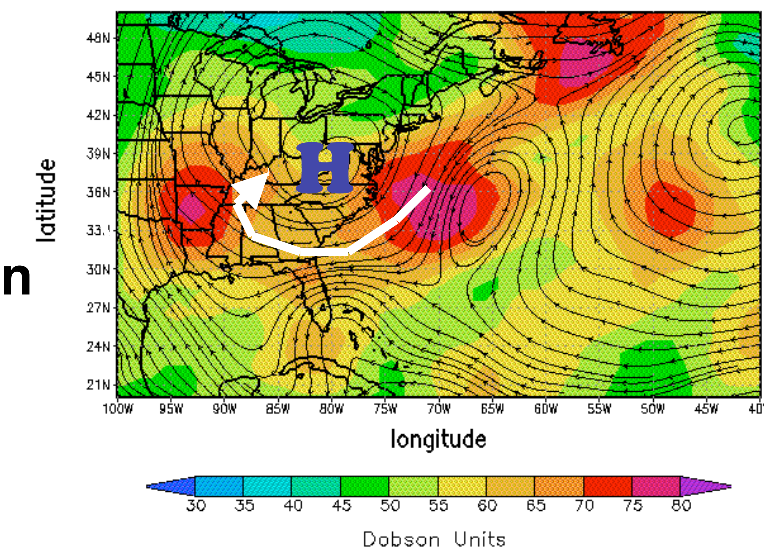
Pollution from northern states pools off North Carolina coast





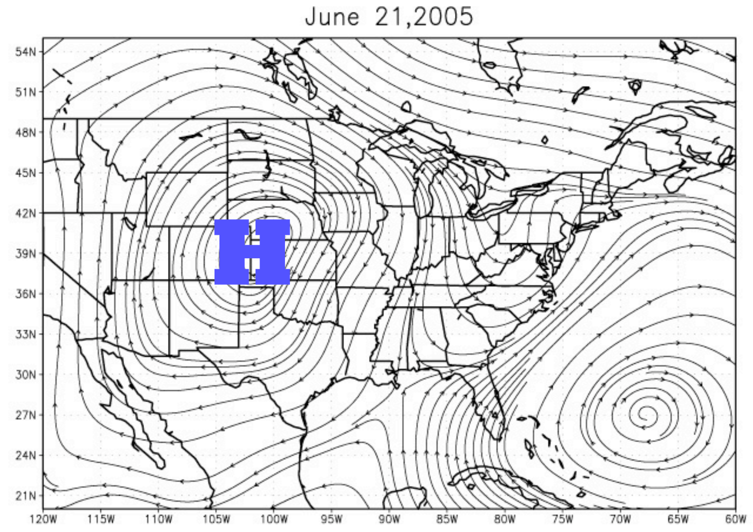
July 9, 1988

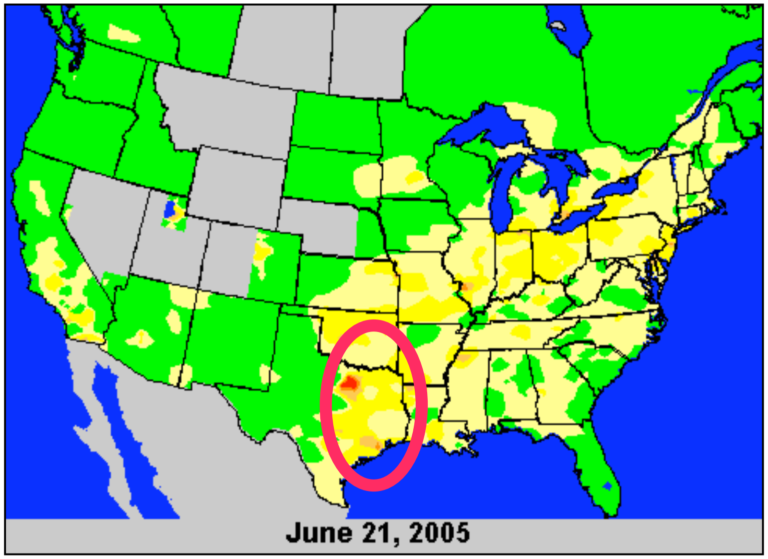
Unique transport situation carries off-shore pollution to southern states

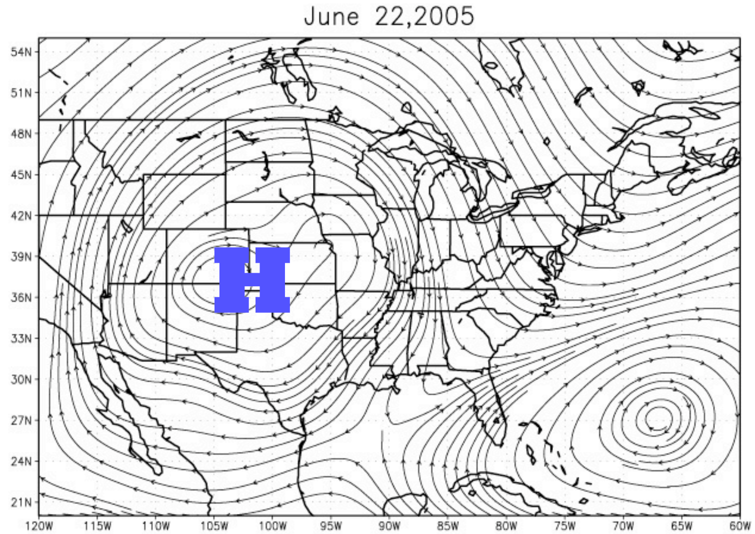


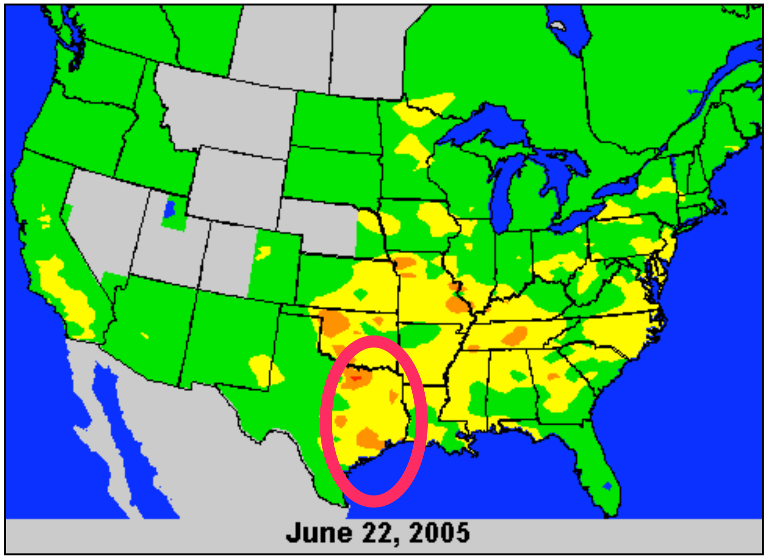
from Fishman and Balok [1999, *JGR,* 104, pp. 30,319]

Stagnant High Pressure Sets Stage for Pollution Episode over East Texas: June 21-22, 2005



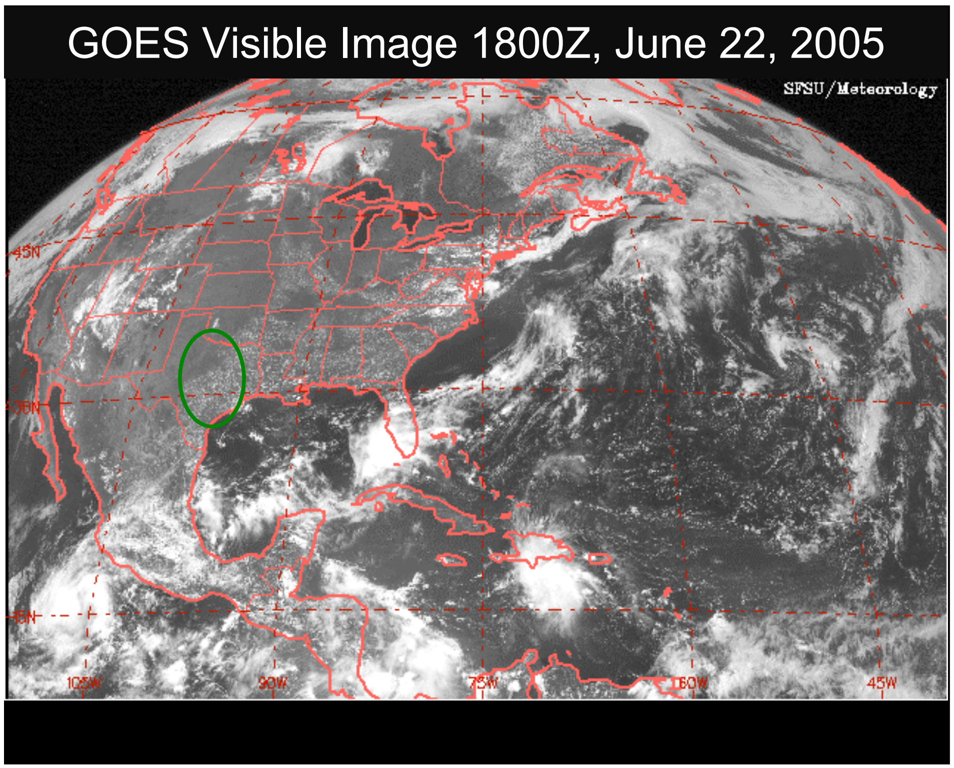




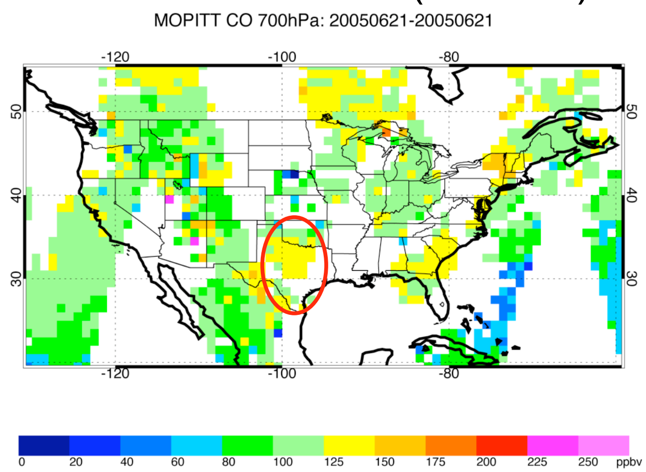


Current Capabilities Show that Measurements Provide Some Information on Distribution of Key Pollutants for Widespread Pollution Episode Formation

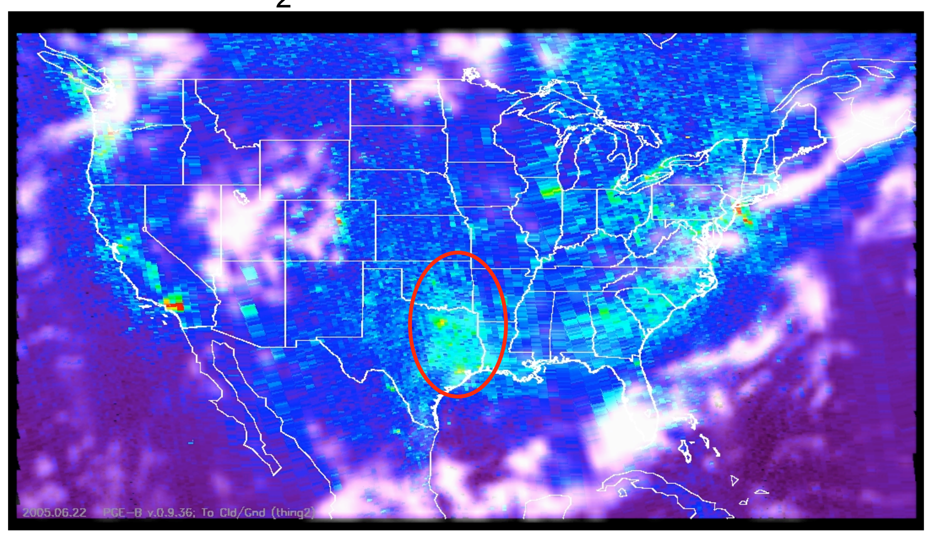
GOES Visible Image 1800Z, June 22, 2005



CO from MOPITT (June 21)



NO_2 from OMI on June 22



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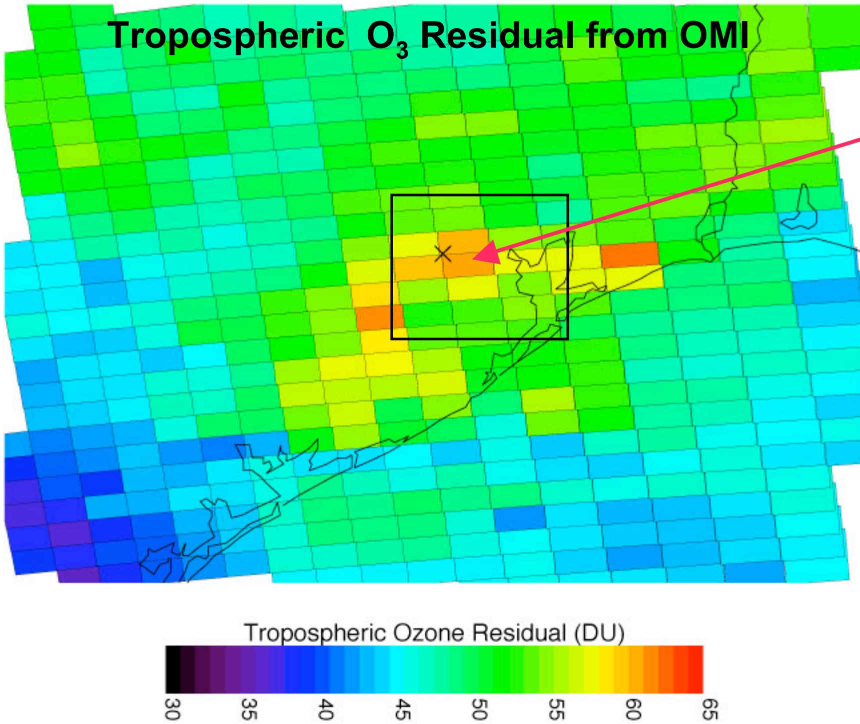
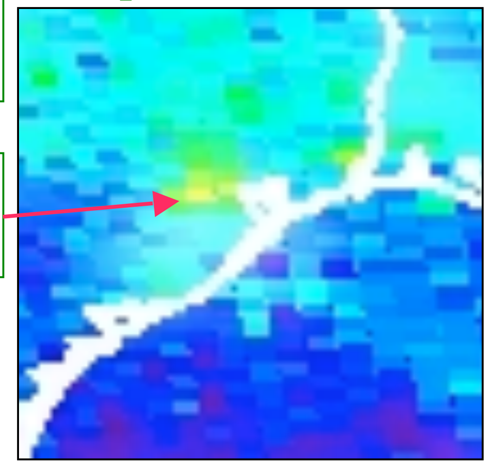
  - **Relationship between Satellite and Surface Observations**

OMI Measurements over Houston Shows Correlation between Daily Satellite and Surface Measurements

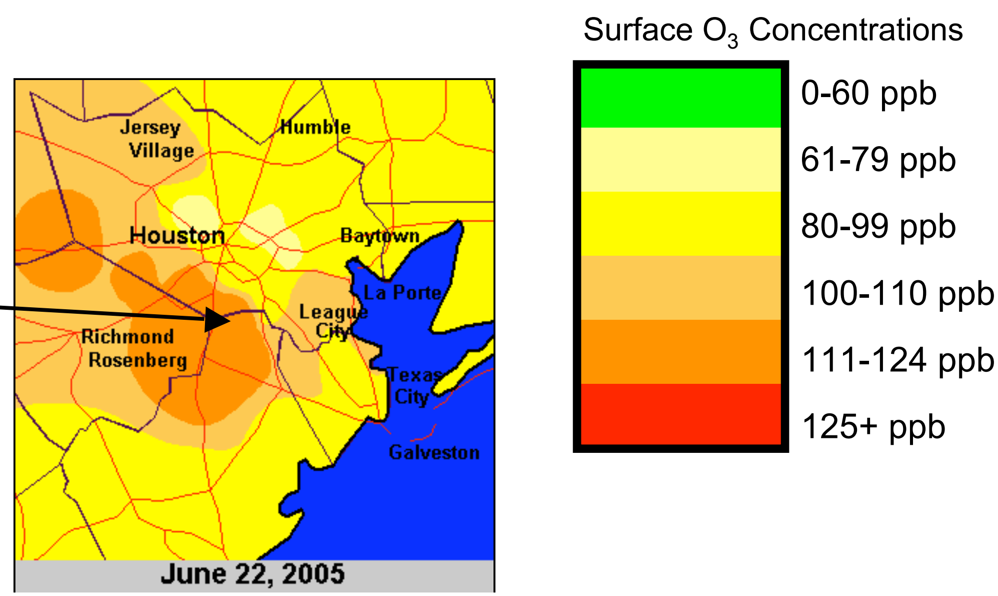


Elevated TOR from OMI

NO_2 Column from OMI

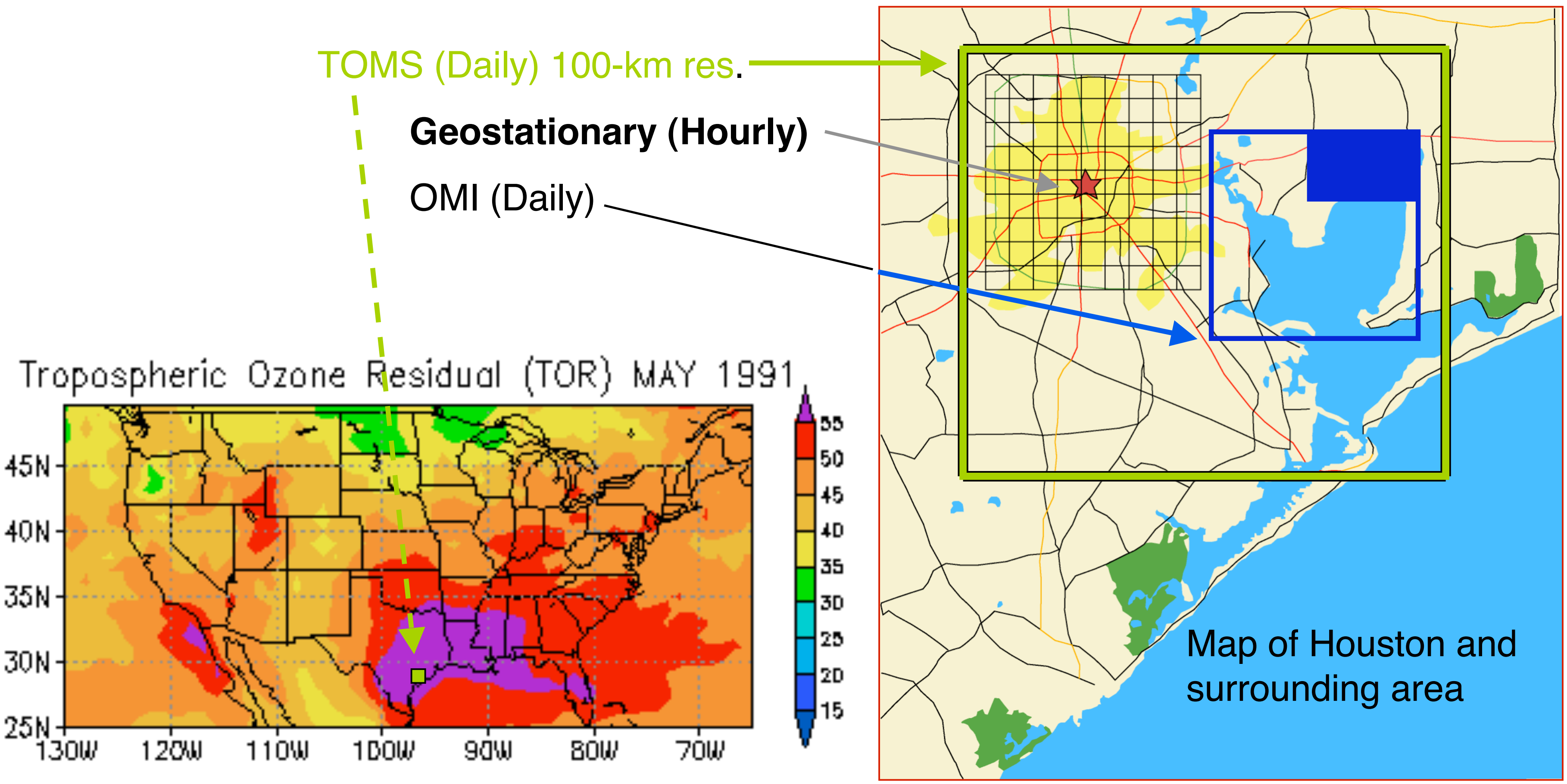


Elevated NO_2 from OMI



Elevated Surface O_3 from EPA Sites

Best Method to Observe Pollution is from Geostationary Orbit

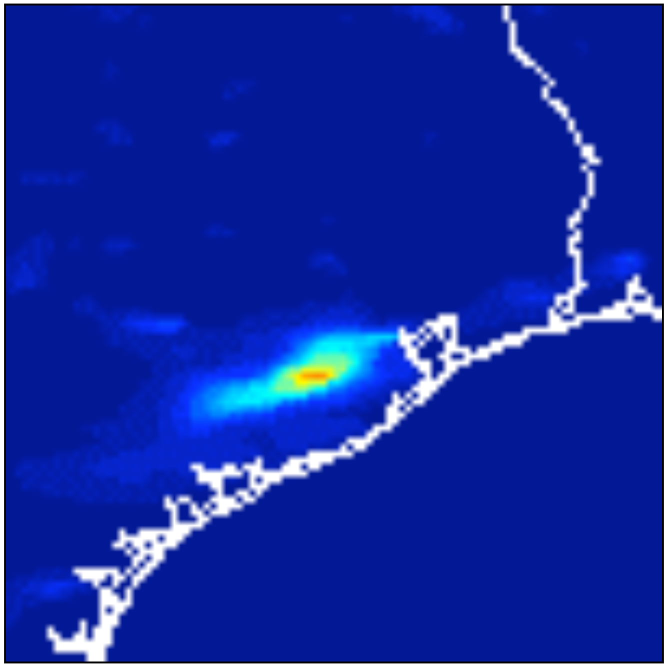


Technology Readily Available:

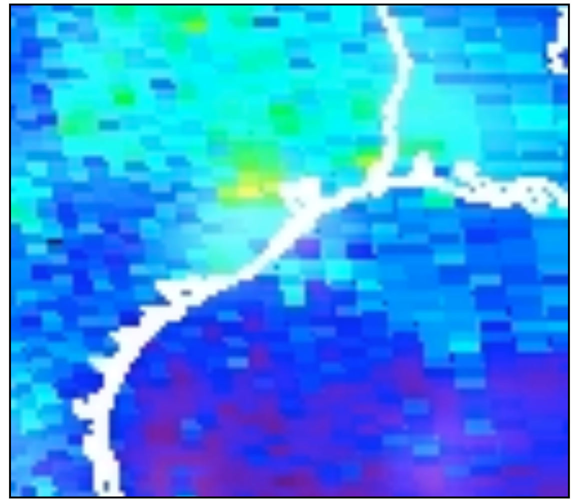
O_3, CO, NO_2, SO_2, CH_2O and aerosols

CMAQ Simulation and NO_2 from OMI in Good Agreement

June 22, 2005, 1900 Z



12-km resolution from CMAQ



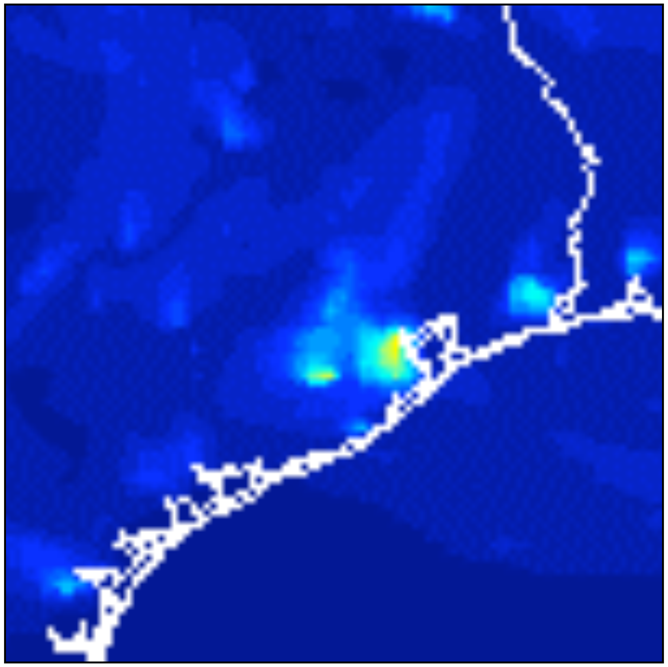
OMI NO_2

Geostationary Measurements Capture the Evolution of the NO_2 Distribution

CMAQ Model Results Courtesy of Daewon Byun

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 1200 Z

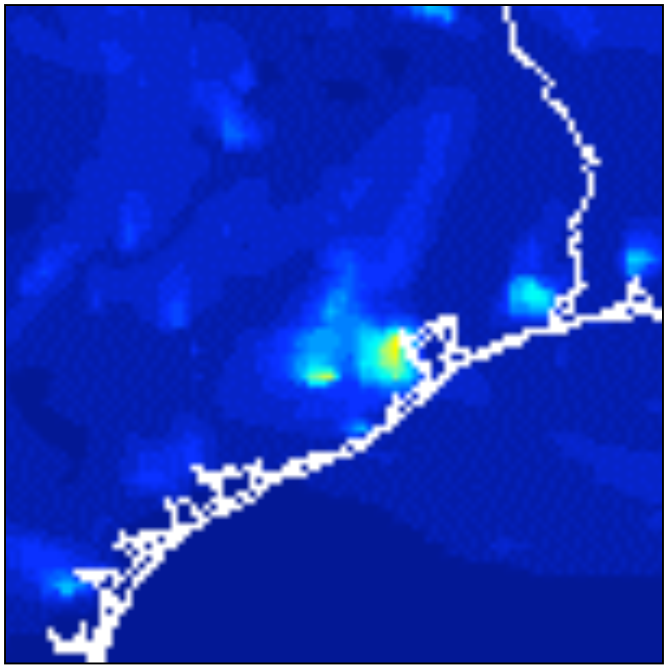


12-km resolution from CMAQ

This image is what would be seen by GeoTRACE ~1 hour after sunrise over Houston

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 1200 Z



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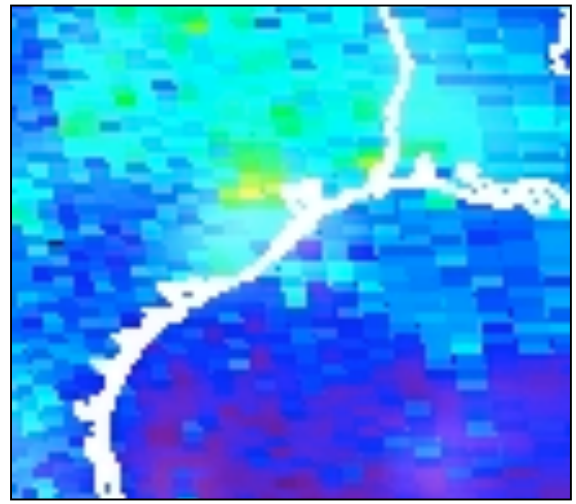
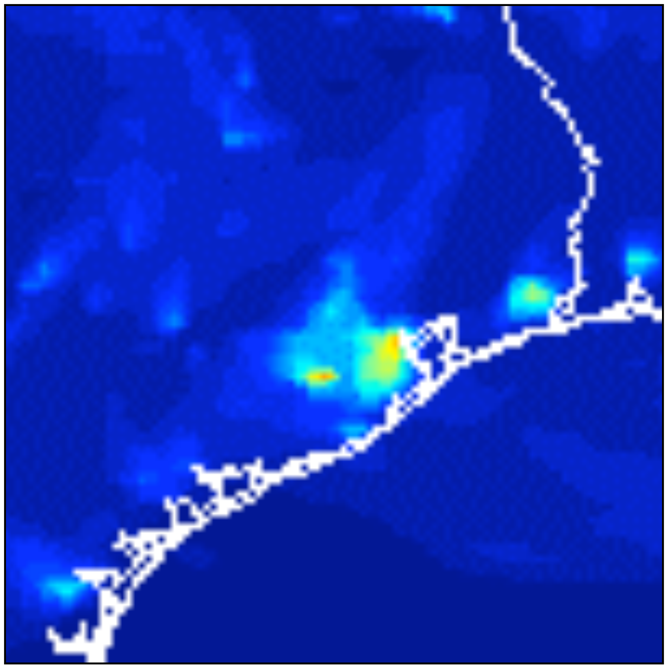


OMI NO_2

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 1300 Z



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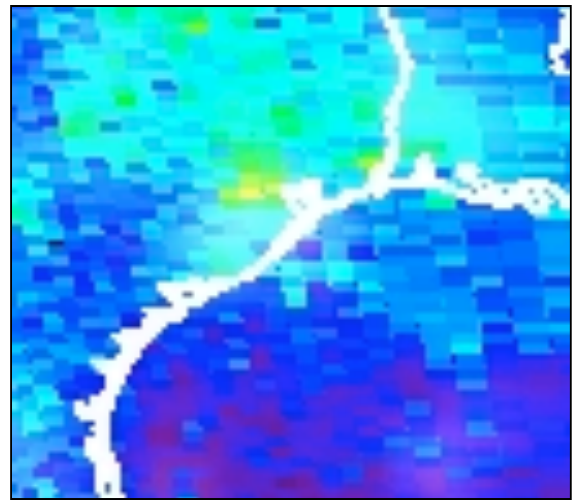
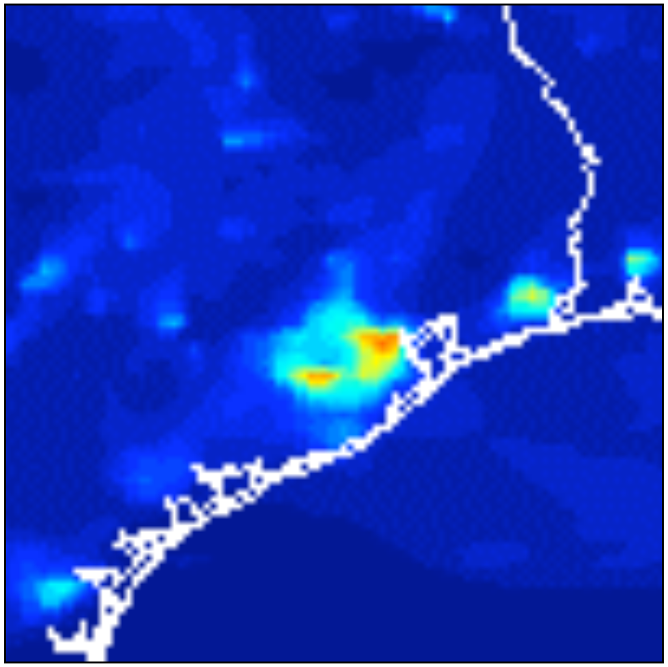


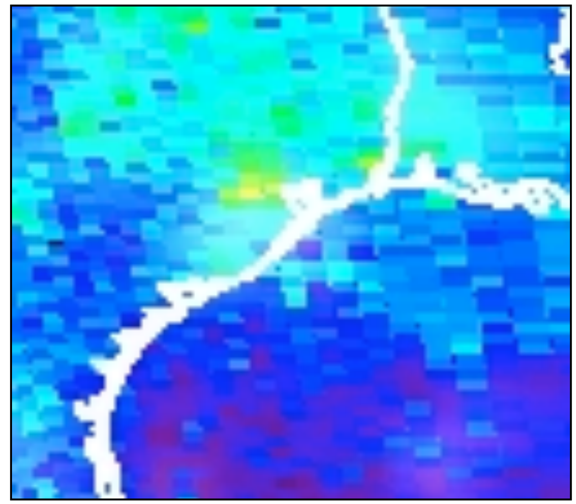
OMI NO_2

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 1400 Z



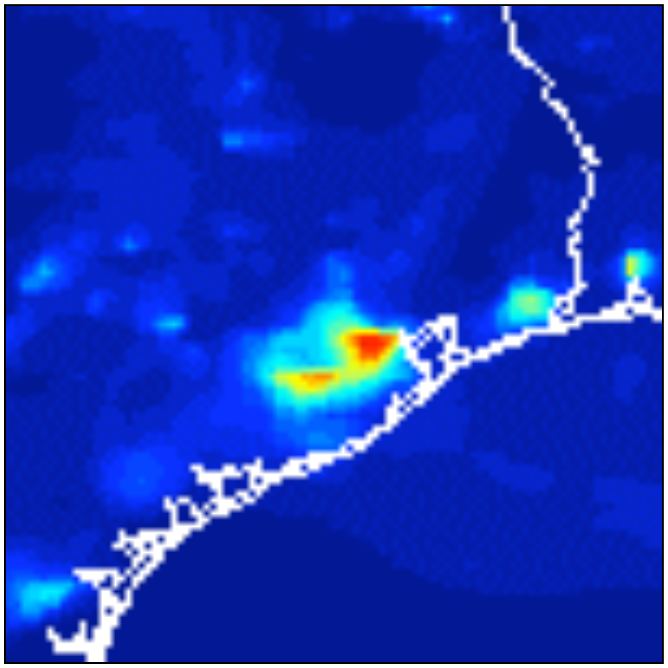
12-km resolution from CMAQ



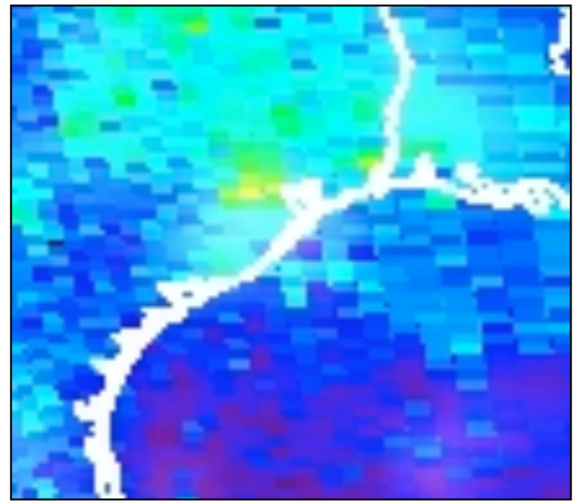
OMI NO_2

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 1500 Z



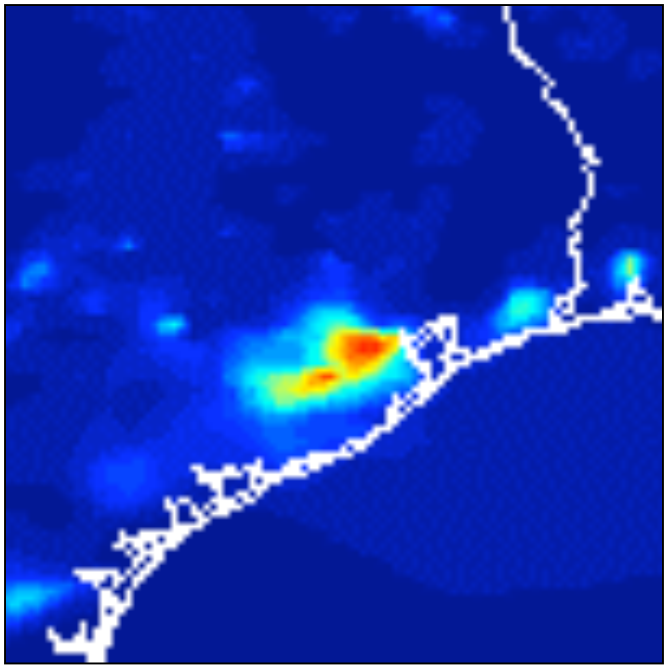
12-km resolution from CMAQ



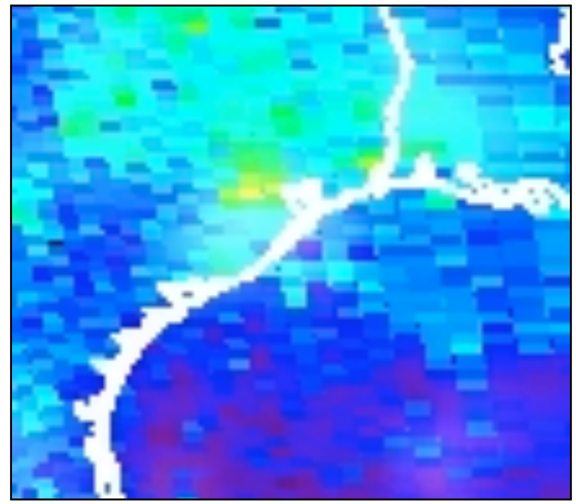
OMI NO_2

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 1600 Z



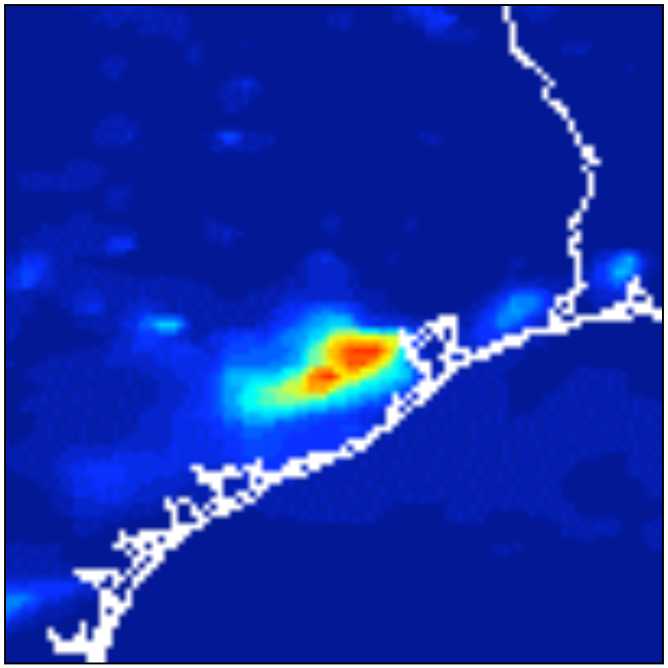
12-km resolution from CMAQ



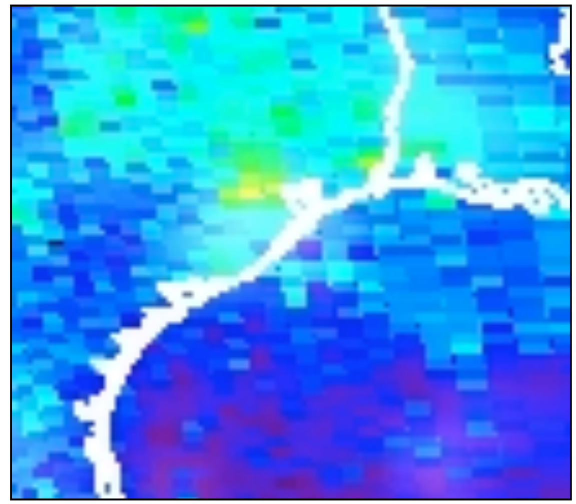
OMI NO_2

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 1700 Z



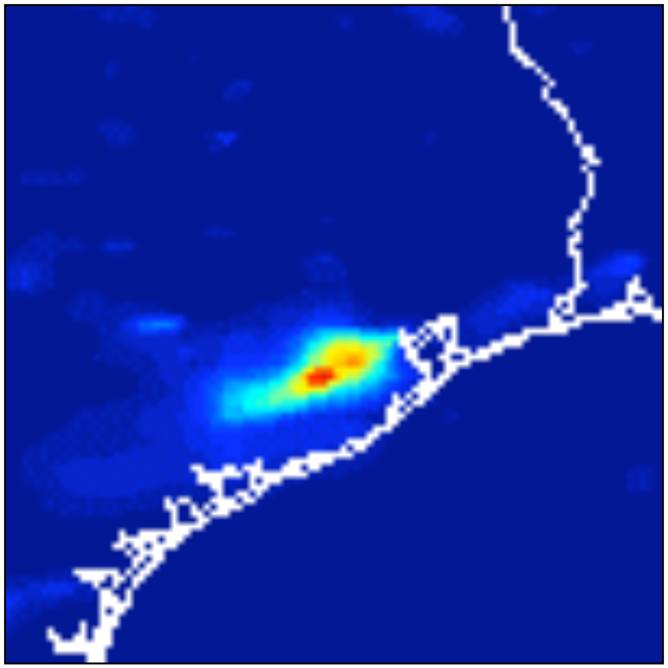
12-km resolution from CMAQ



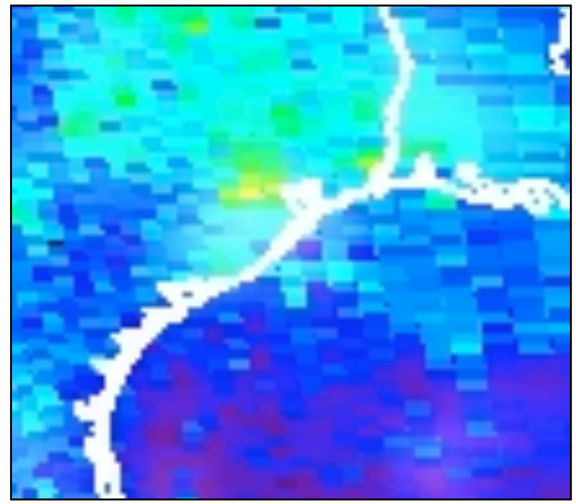
OMI NO_2

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 1800 Z



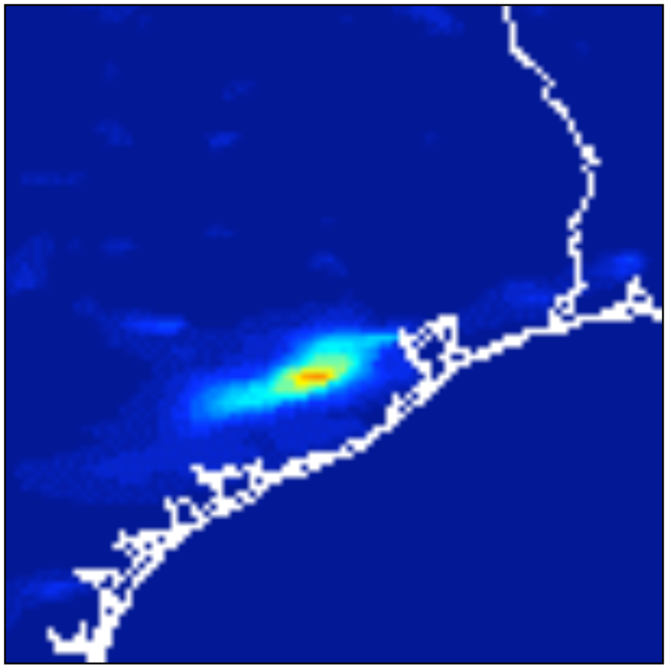
12-km resolution from CMAQ



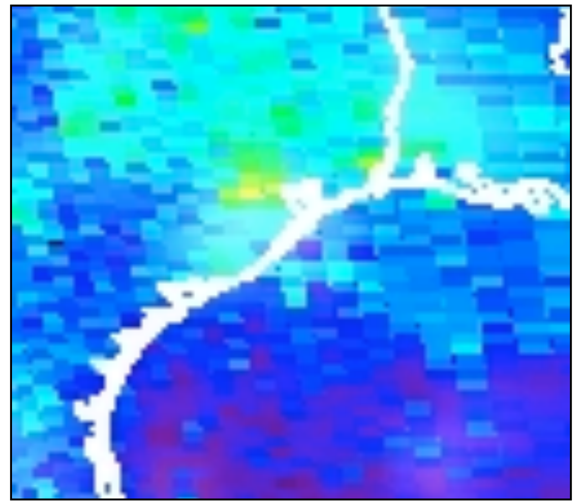
OMI NO_2

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 1900 Z



12-km resolution from CMAQ

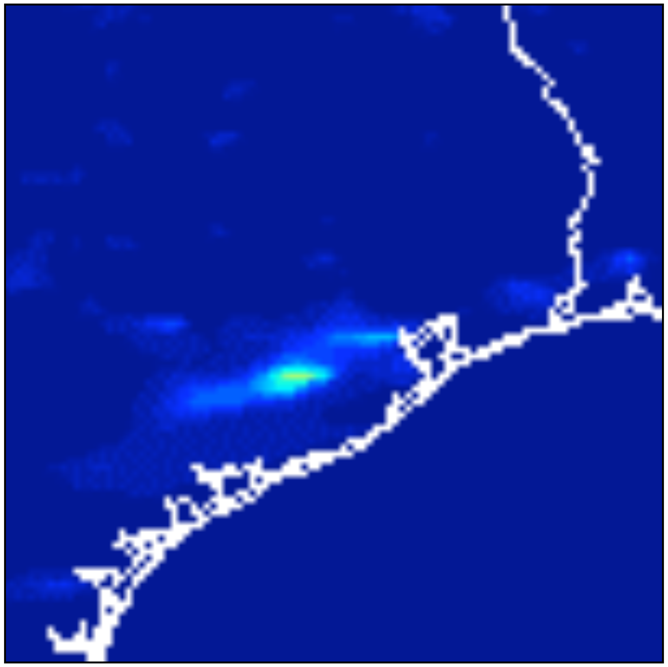


OMI NO_2

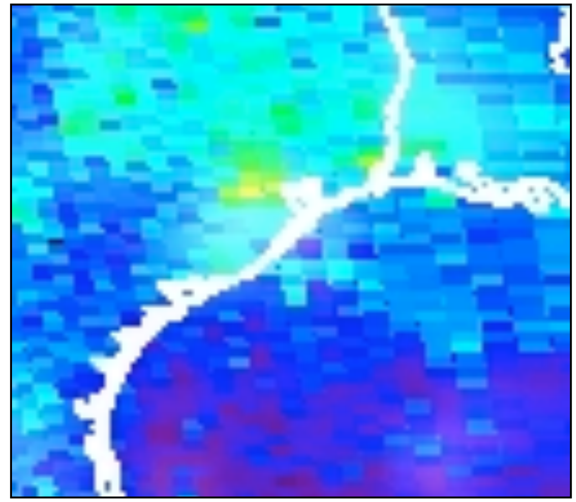
Distribution Coincident with time of OMI Overpass

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 2000 Z



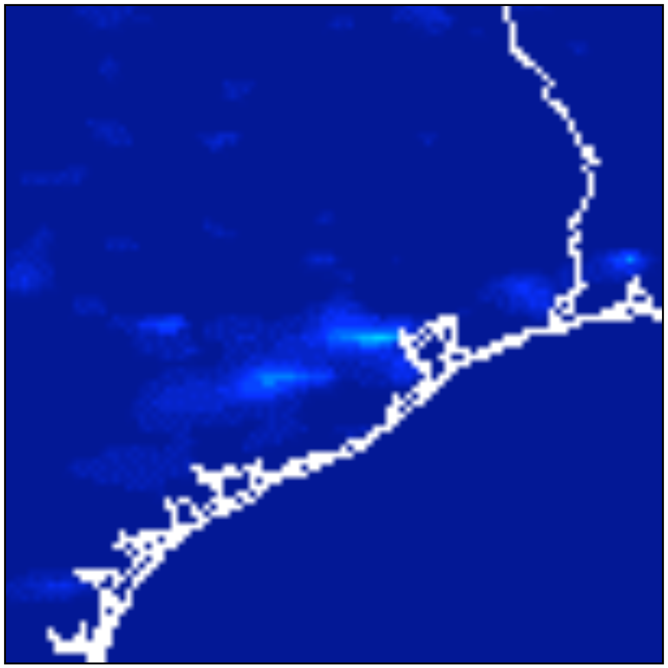
12-km resolution from CMAQ



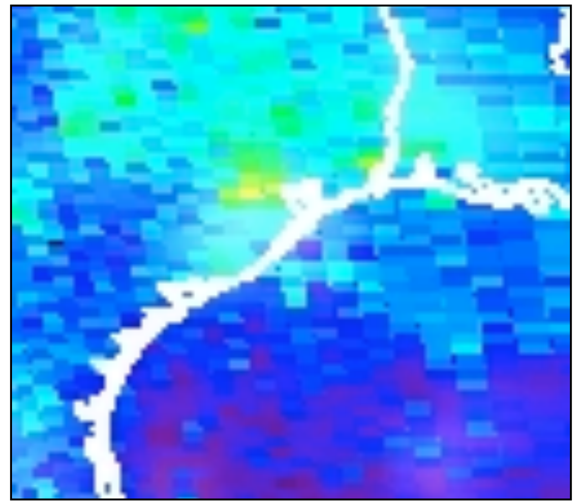
OMI NO_2

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 2100 Z



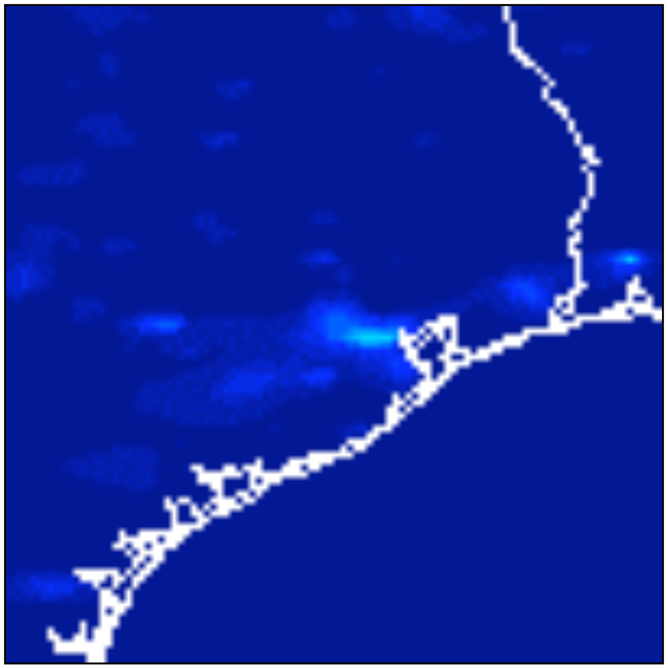
12-km resolution from CMAQ



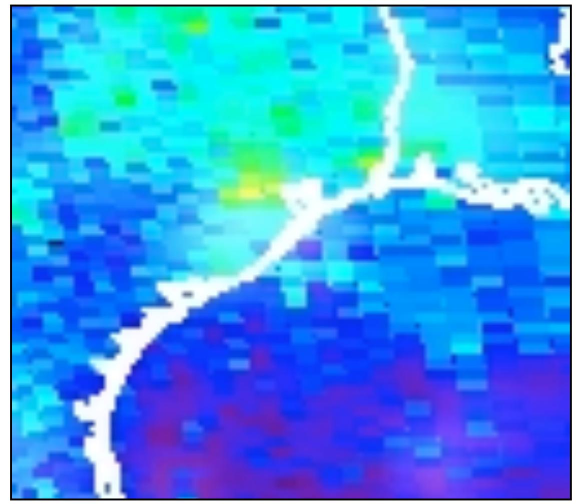
OMI NO_2

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 2200 Z



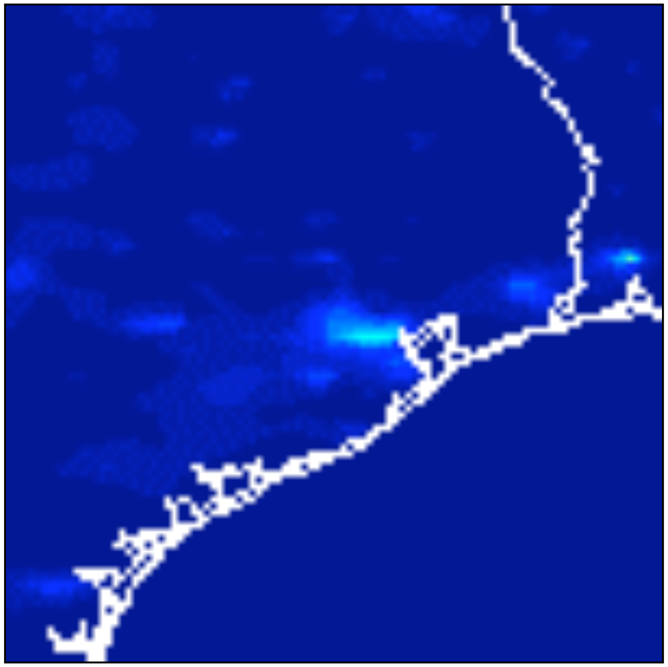
12-km resolution from CMAQ



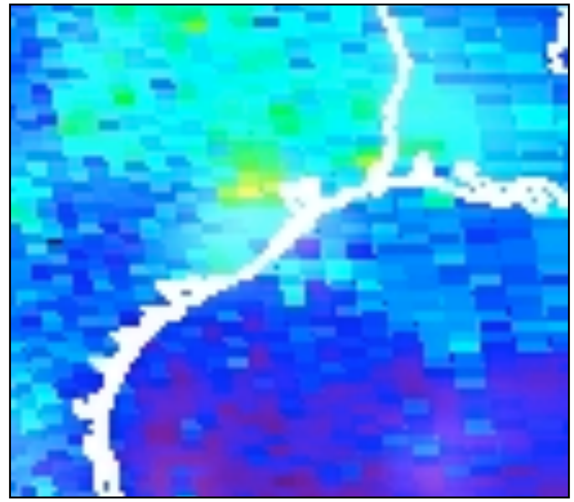
OMI NO_2

CMAQ Simulation and NO_2 from OMI

June 22, 2005, 2300 Z

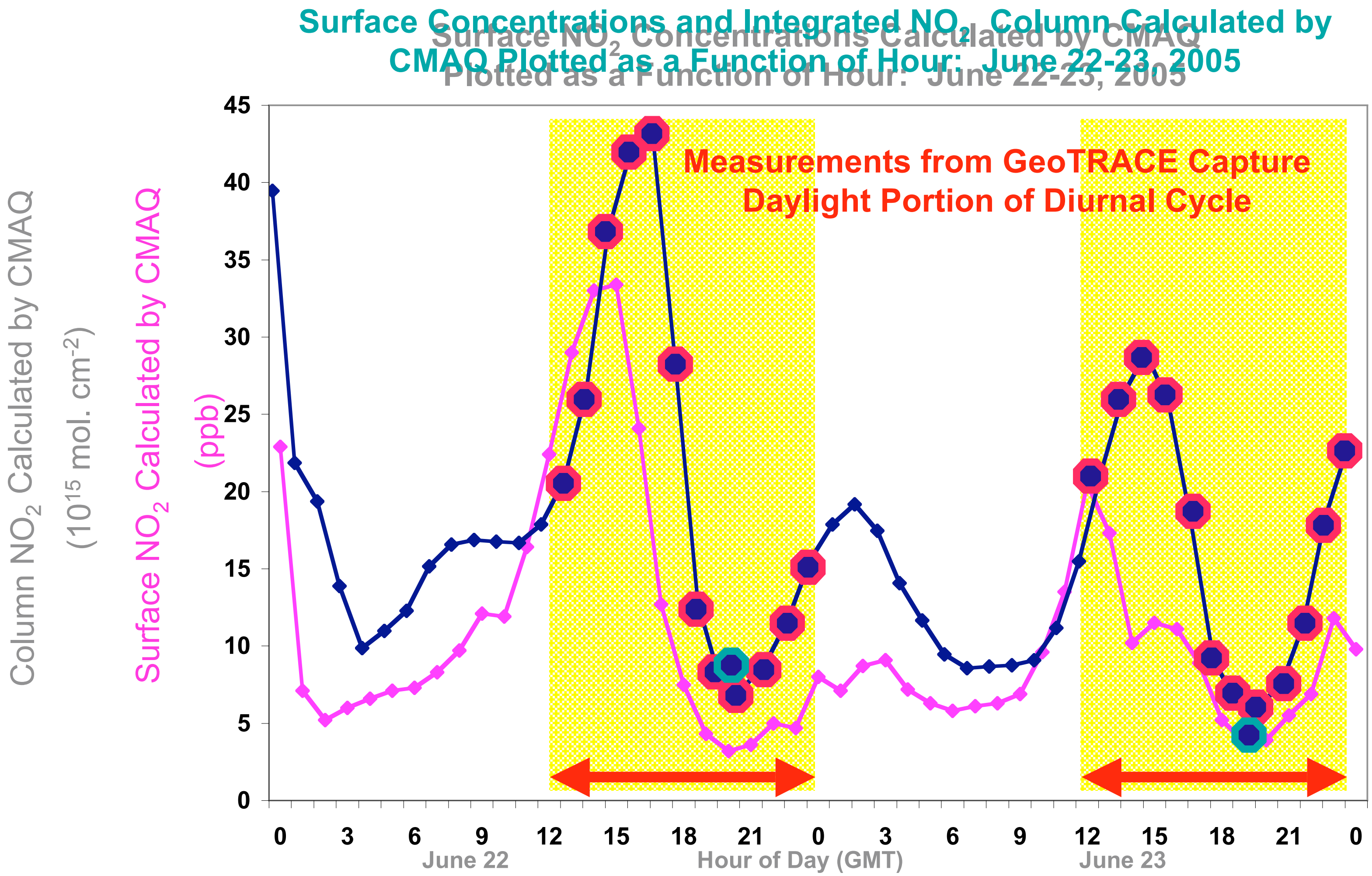


12-km resolution from CMAQ



OMI NO_2

Integrated Column NO_2 Accurately Captures Diurnal Behavior



Observations from GEO: NO_2 Measurements Every 30-60 Minutes Throughout Sunlit Hours

Societal Benefit Theme Includes Measurements in Support of Air Quality

Cost Impact on Human Health

~ 4000 premature deaths per year linked to elevated O_3 concentrations in U.S.

"The cost to society in terms of direct expenditures for health care, lost productivity, restriction of daily activity and a reduced quality of life, and suffering of acute symptoms and premature death is likely in the billions of dollars each year for ozone.

Forest Damage in the United States from Ozone Pollution

- **Tree Ring Analysis Indicates Substantial Decrease in Growth Rate During Past 20-25 Years**
- **Most Severe Decline Involves Red Spruce: Primary damage at High Elevations in eastern U.S. from New York/New England to S. Appalachian Mountains**

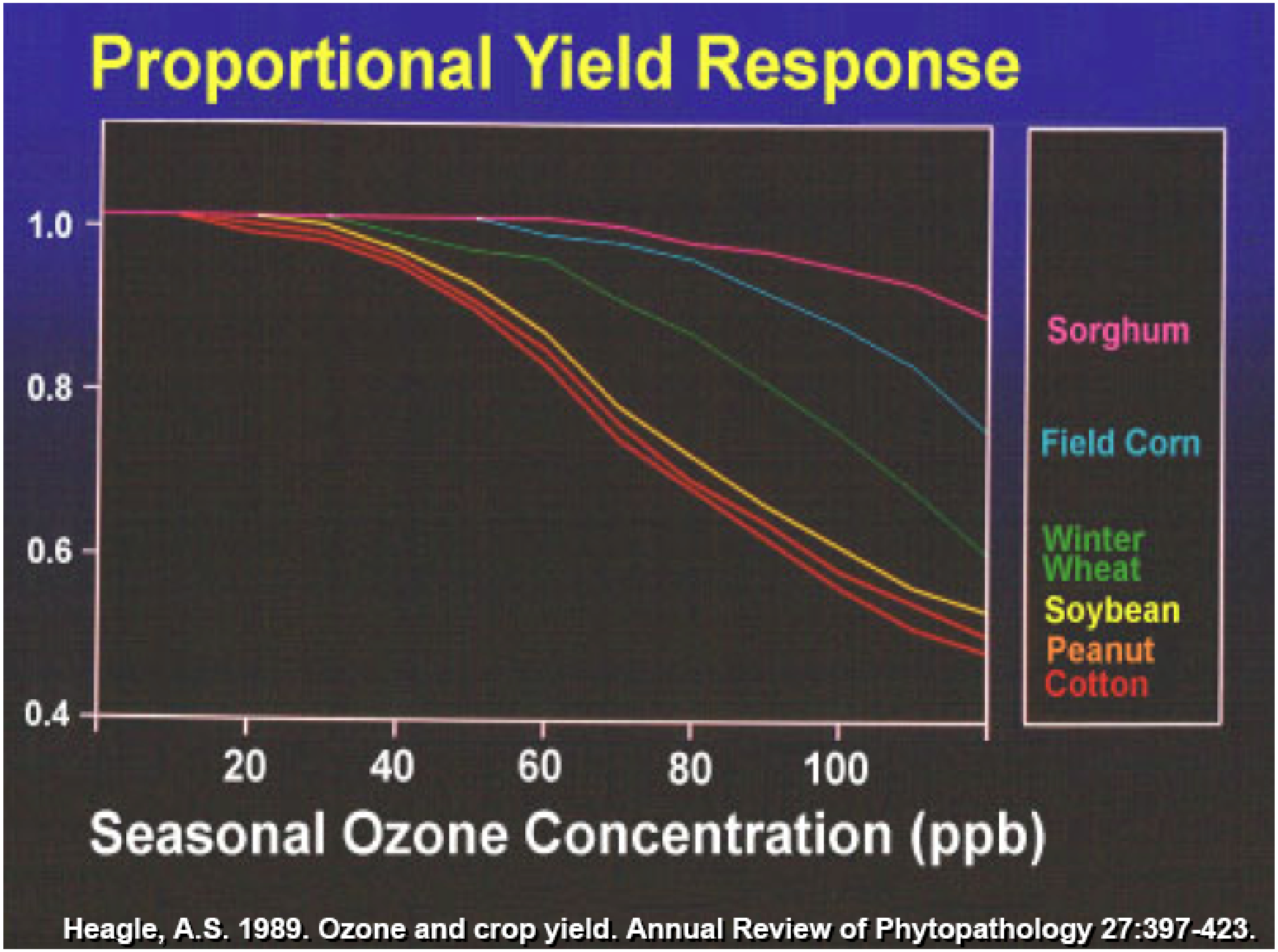
Ozone Increase on U.S. and Global Crop Production

- **Annual Cost to U.S. Agriculture Exceeds $2 Billion** (Mauzerall and Wang, *Ann. Rev. Energy Environ*, **26**, 2001)

- Detrimental Effects Come Primarily from Exposure to High Concentrations during Episodic Events

- Understanding how these events develop should be the driving question that can uniquely be answered by GEO-CAPE because of its higher temporal and spatial resolution

Damage to Crops Occurs above Threshold Concentration



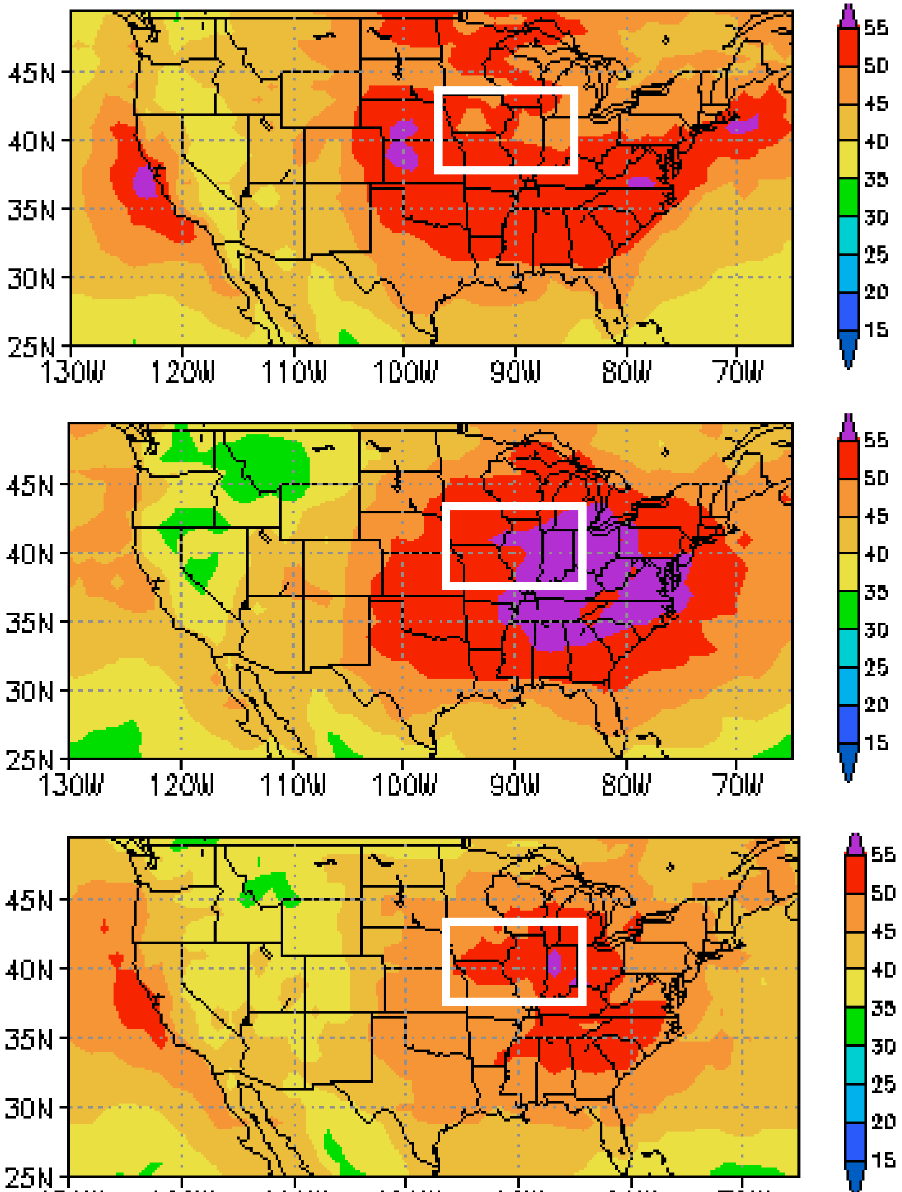
Ozone Damage to U.S. Crop Production

Annual Cost to U.S. Agriculture Exceeds $2 Billion

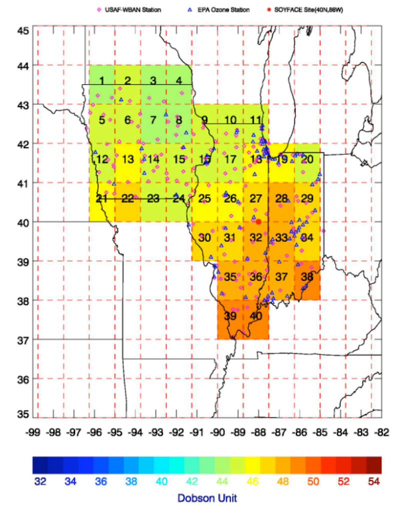
- Satellite Information can be used to Characterize Where Crop Injury Occurs
- Current Temporal Resolution Should be Adequate to Assess Seasonal Effects
- Development of Statistical Model to Assess Impact of Ozone on Soybean Yield Developed
    - Scales of observation (monthly) achievable from current capability
    - Challenge is understanding Interaction between chemistry and meteorology

Interannual Variability of Ozone over Midwest Should Impact Crop Yield

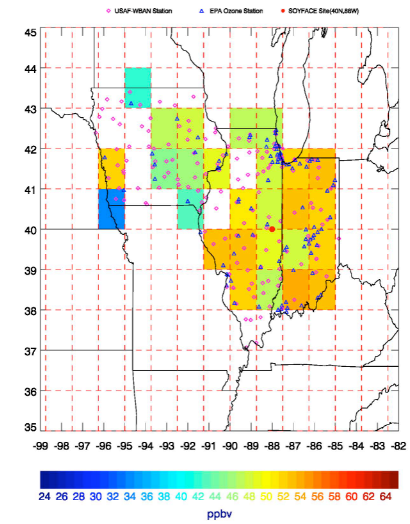
July TOR for Three Consecutive Years



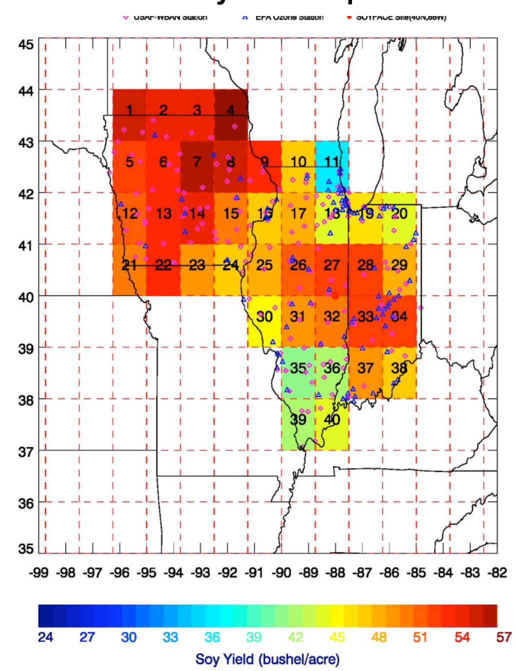
Jun-Aug 2005 TOR



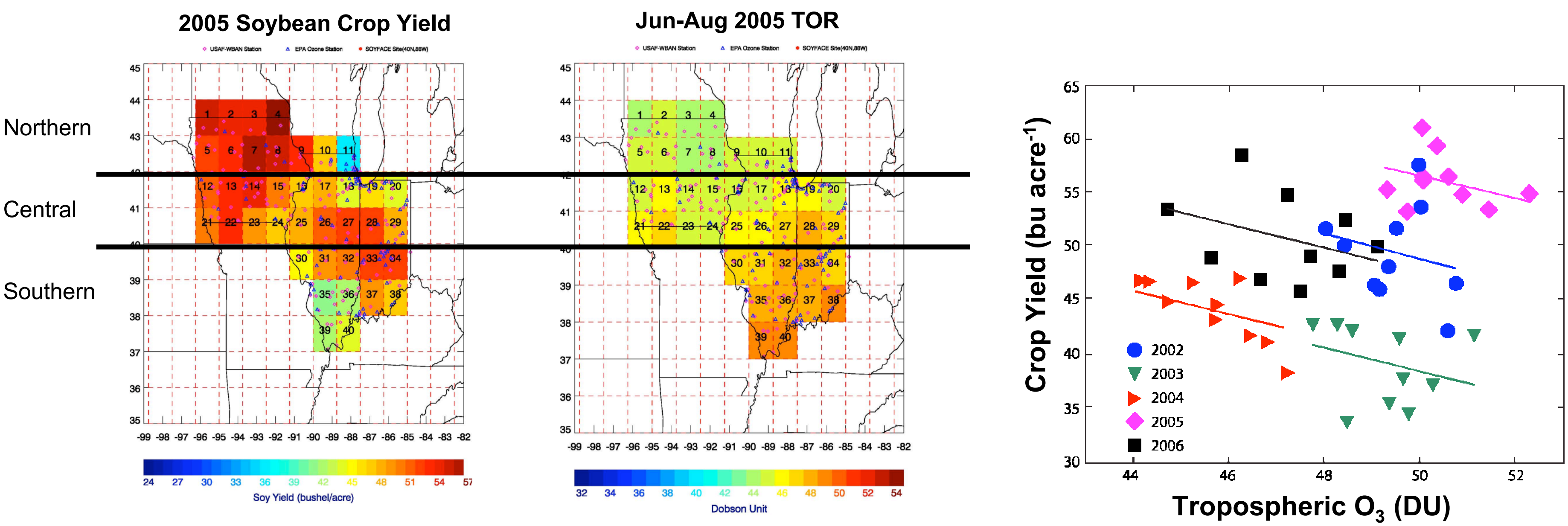
Jun-Aug Surface O_3



2005 Soybean Crop Yield



Use of Satellite Data to Quantify Impact of Ozone on Crop Yield



• Monthly-averaged data only during cloud-free days (~70% of data)

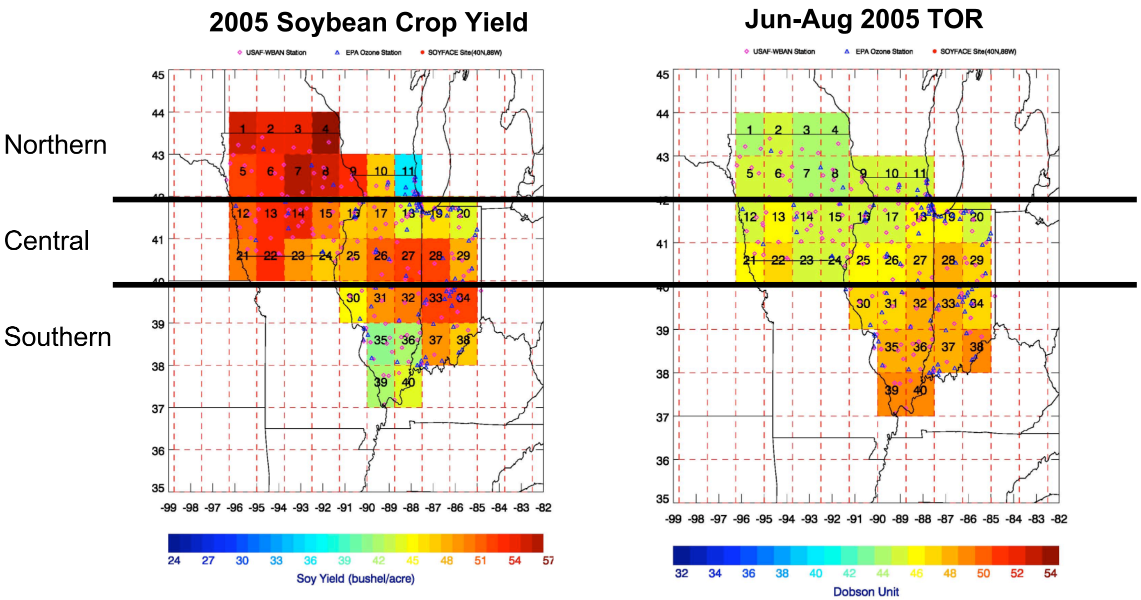
• Outcome (crop yield) is an integral of the entire growing season

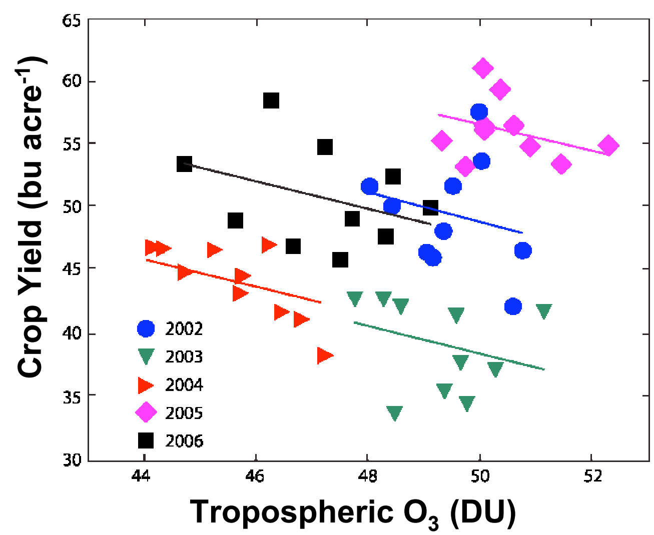
(compatibility of temporal scales)

• Must use multiple regression model to include effects of temperature and moisture

Yield (2005) = 59.65 – 1.09*(TOR – 47.22) – 1.91*(Temp – 72.39) + 4.86*(PCMI + .08)

Use of Satellite Data to Quantify Impact of Ozone on Crop Yield (2)





- **Regression valid only for Southern region**

  (correlations for other regions not statistically significant)

- Crop damage only occurs when concentrations are above threshold

- **Injury to Both Plants and Humans is Episodic**

- **Better Temporal and Atmospheric Composition Information is a Prerequisite for Understanding Processes that Evolve over Periods of Days rather than Months**

Summary

• An Air Quality Application is NOT Concerned with Determining Distributions - That has already been done

• Understanding Formation and Evolution of Episodes Most Relevant to Determining when and how Much of the Population is Exposed to Harmful Pollutant Levels

• Formation of Episodes Dependent on Prevailing Meteorology, Emissions, Chemical Transformations, and Transport

• Models to Understand these Processes Use Grid Sizes of 4 - 32 km

• Temporal Resolution Must Capture Diurnal Variability

• Atmospheric Composition Measurements Need to Compliment Models to be Useful

One Last Thought

Purpose of this Presentation

- Review the State of Trace Gas Measurement Capability

- Global Distributions

- Seasonality

- Trends

- Interannual Variability

- Insight into Global Sources

- **Drivers for GEO-CAPE**

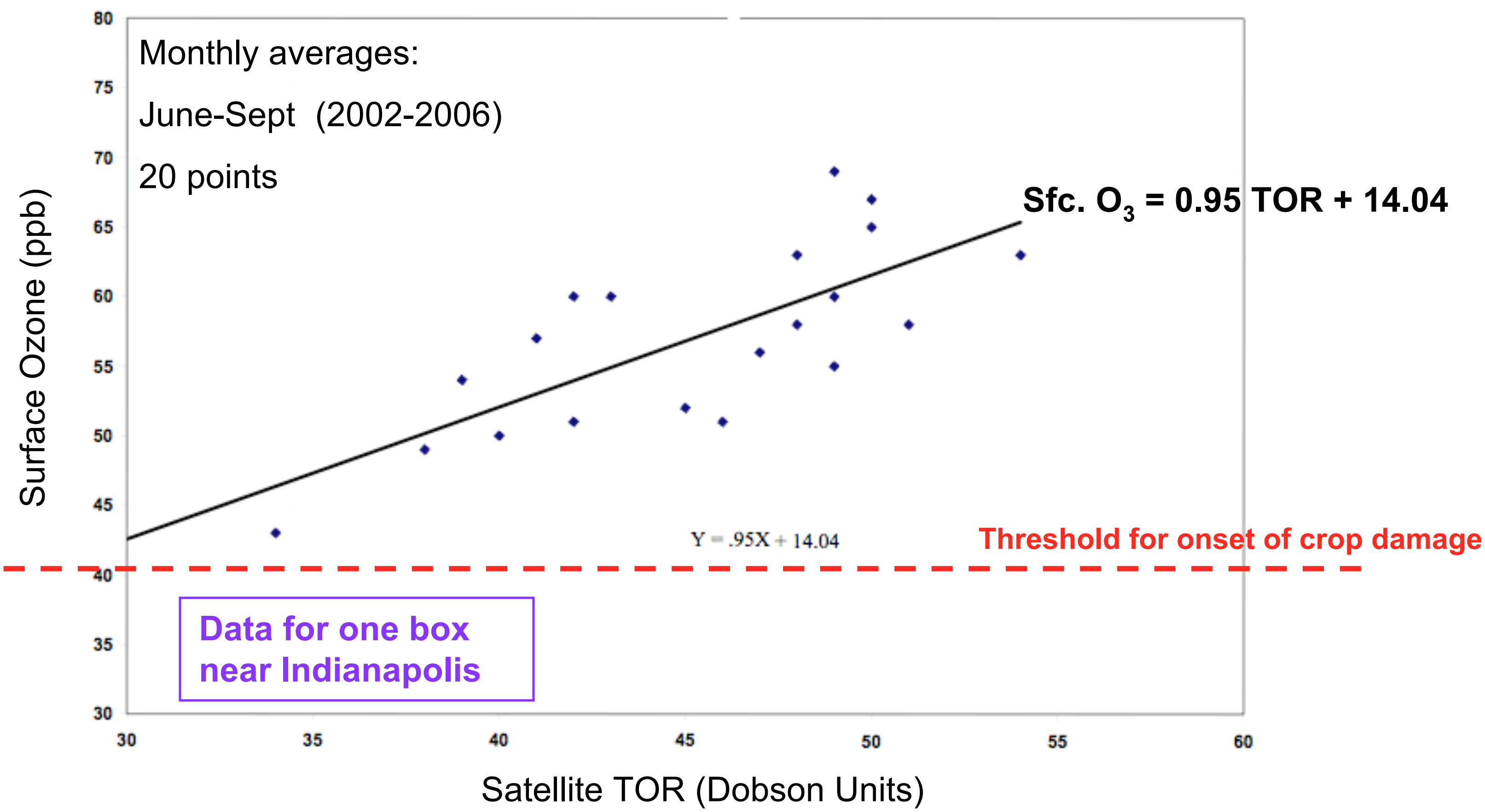
- Where did the Recommendations Come From?

-What are the Science Challenges for GEO-CAPE?

- **Relationship between Satellite and Surface Observations**

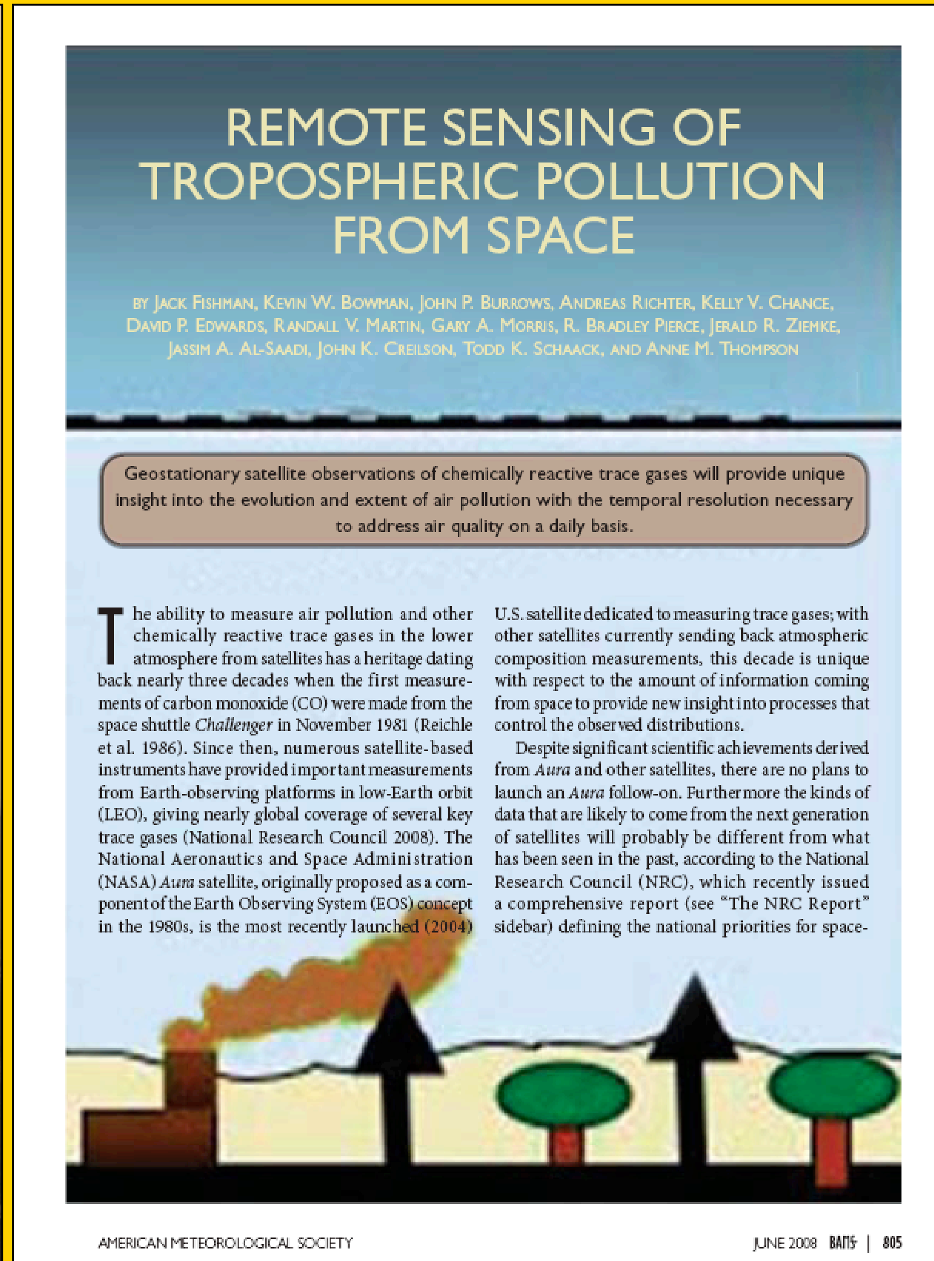
Importance of "Seeing the Boundary Layer"

- **For human health implications, concentrations are meaningful only at the surface**
- **Must understand the limitation of the measurement**
- **Must understand the relationship between the what is measured from space and how it relates to surface values**



BACK-UP SLIDES

Article on Satellites and Air Pollution Appeared in BAMS



REMOTE SENSING OF TROPOSPHERIC POLLUTION FROM SPACE

BY JACK FISHMAN, KEVIN W. BOWMAN, JOHN P. BURROWS, ANDREAS RICHTER, KELLY V. CHANCE, DAVID P. EDWARDS, RANDALL V. MARTIN, GARY A. MORRIS, R. BRADLEY PIERCE, JERALD R. ZIEMKE, JASSIM A. AL-SAADI, JOHN K. CREILSON, TODD K. SCHAACK, AND ANNE M. THOMPSON

Geostationary satellite observations of chemically reactive trace gases will provide unique insight into the evolution and extent of air pollution with the temporal resolution necessary to address air quality on a daily basis.

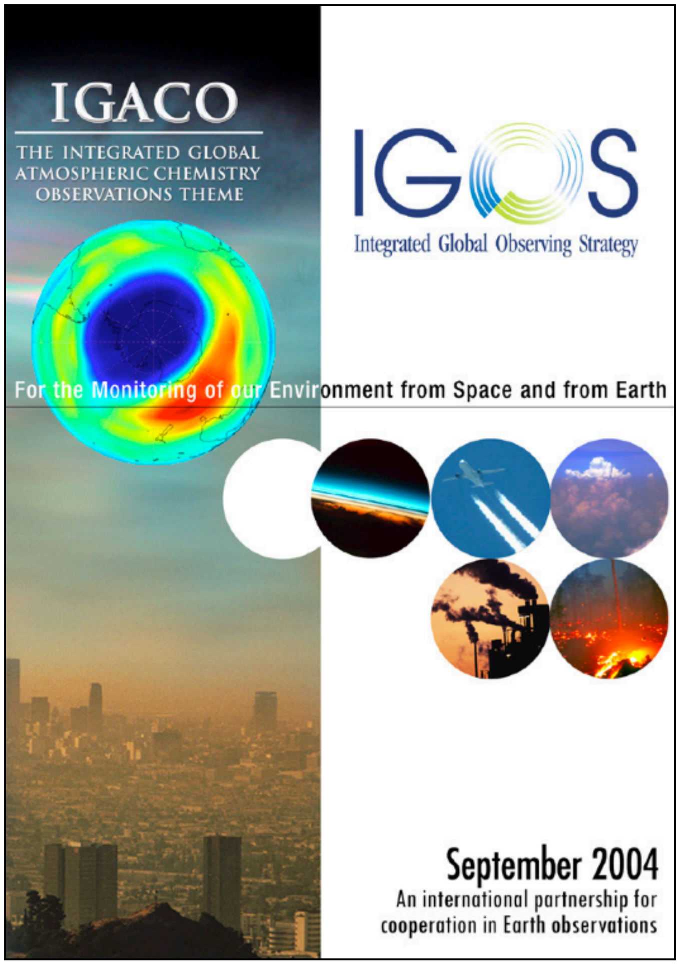
The ability to measure air pollution and other chemically reactive trace gases in the lower atmosphere from satellites has a heritage dating back nearly three decades when the first measurements of carbon monoxide (CO) were made from the space shuttle *Challenger* in November 1981 (Reichle et al. 1986). Since then, numerous satellite-based instruments have provided important measurements from Earth-observing platforms in low-Earth orbit (LEO), giving nearly global coverage of several key trace gases (National Research Council 2008). The National Aeronautics and Space Administration (NASA) *Aura* satellite, originally proposed as a component of the Earth Observing System (EOS) concept in the 1980s, is the most recently launched (2004) U.S. satellite dedicated to measuring trace gases; with other satellites currently sending back atmospheric composition measurements, this decade is unique with respect to the amount of information coming from space to provide new insight into processes that control the observed distributions.

Despite significant scientific achievements derived from *Aura* and other satellites, there are no plans to launch an *Aura* follow-on. Furthermore the kinds of data that are likely to come from the next generation of satellites will probably be different from what has been seen in the past, according to the National Research Council (NRC), which recently issued a comprehensive report (see "The NRC Report" sidebar) defining the national priorities for space-

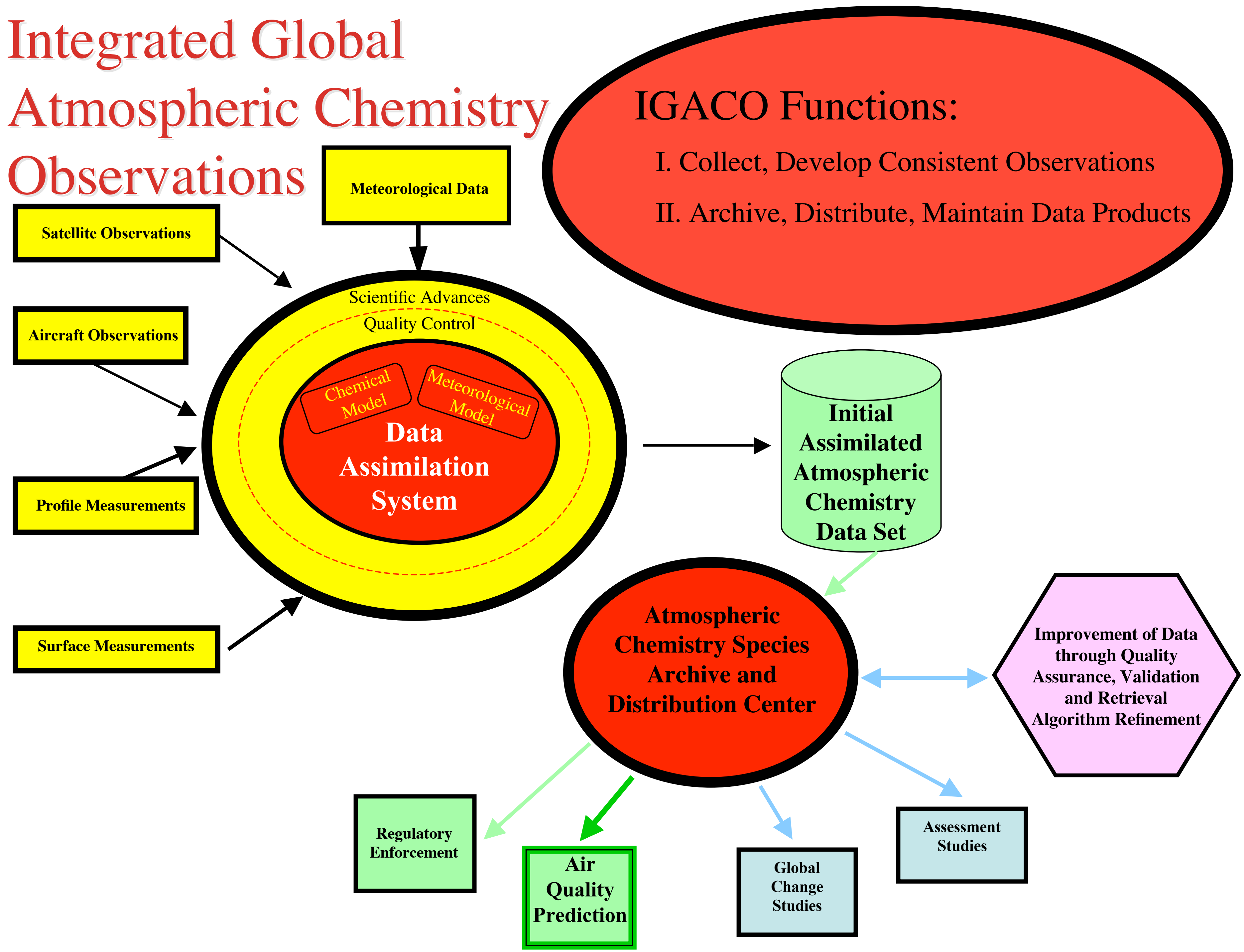
Available at: http://ams.allenpress.com/archive/1520-0477/89/6/pdf/i1520-0477-89-6-805.pdf

NAS Recommendation of GEO-CAPE Influenced by Previous Science Consensus:

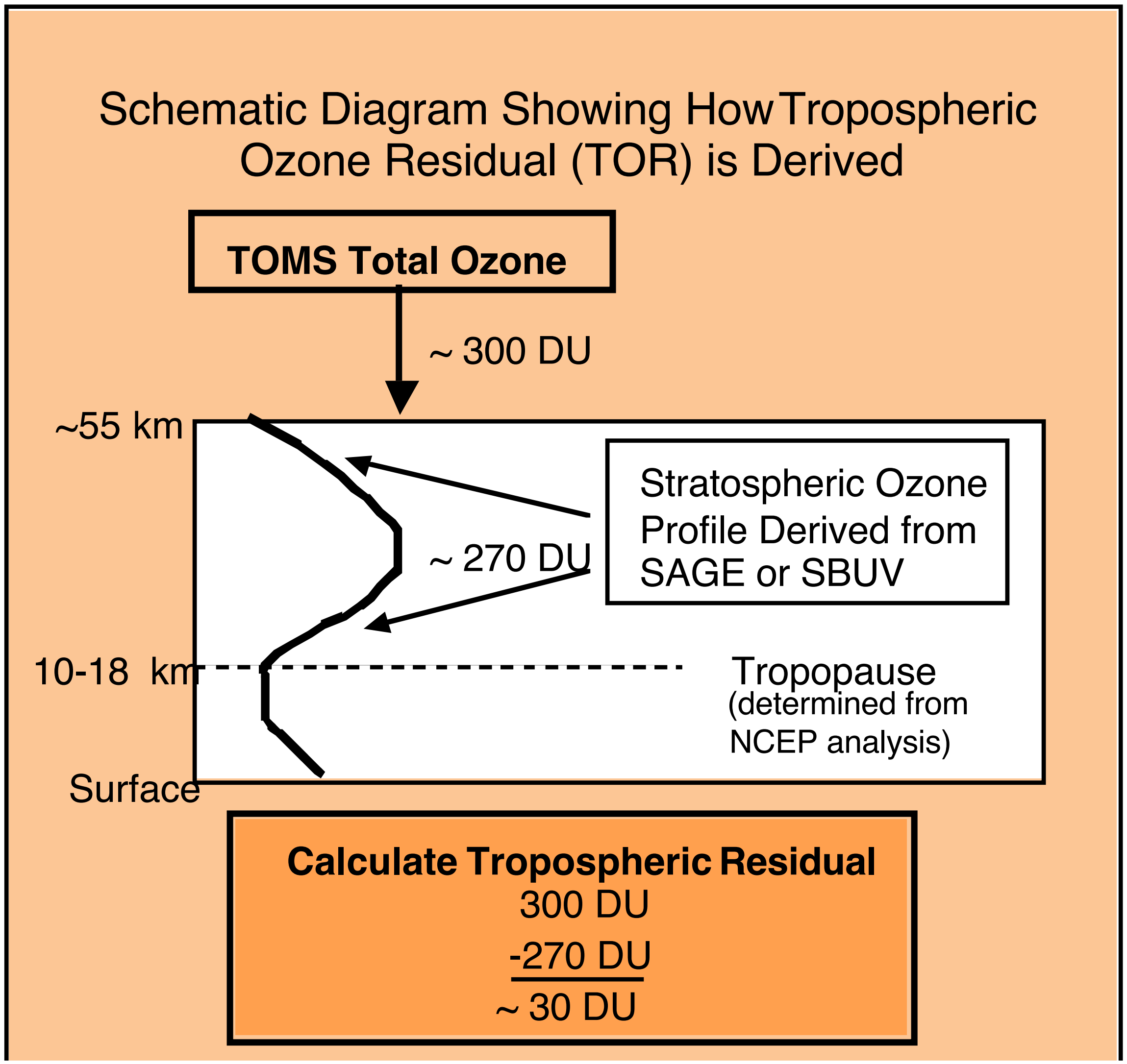
The IGOS/IGACO "Grand Challenge"

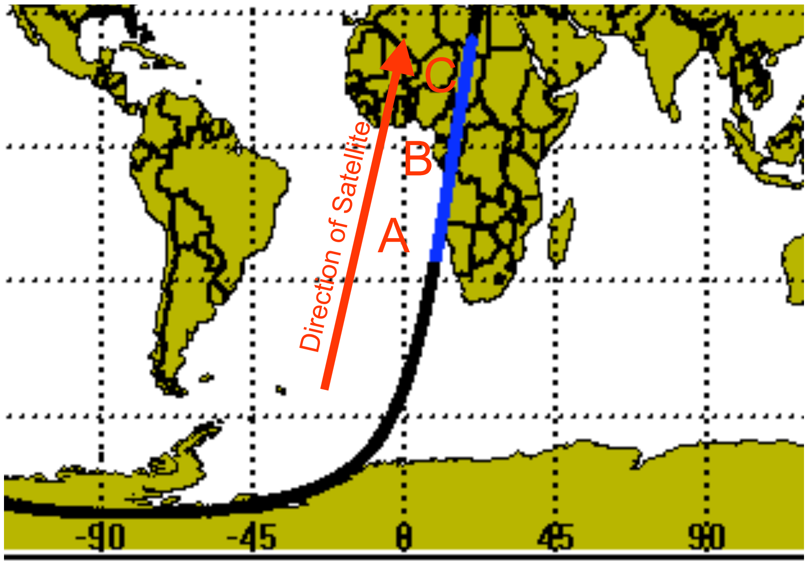


- Develop satellite instrumentation to provide measurements with sufficient temporal and spatial resolution to understand the globalisation of tropospheric pollution
- Develop a comprehensive data modelling system capable of combining data for the chemical and aerosol species with meteorological and other ancillary parameters
- Assimilation techniques for chemical species currently in the demonstration phase need to be developed into operational procedures


Integrated Global Atmospheric Chemistry Observations
IGACO Functions:
I. Collect, Develop Consistent Observations
II. Archive, Distribute, Maintain Data Products
Meteorological Data
Satellite Observations
Aircraft Observations
Profile Measurements
Surface Measurements
Scientific Advances
Quality Control
Chemical Model
Meteorological Model
Data Assimilation System
Initial Assimilated Atmospheric Chemistry Data Set
Atmospheric Chemistry Species Archive and Distribution Center
Improvement of Data through Quality Assurance, Validation and Retrieval Algorithm Refinement
Regulatory Enforcement
Air Quality Prediction
Global Change Studies
Assessment Studies

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





CALIPSO Can Distinguish between, Smoke, Clouds, and Dust Particles

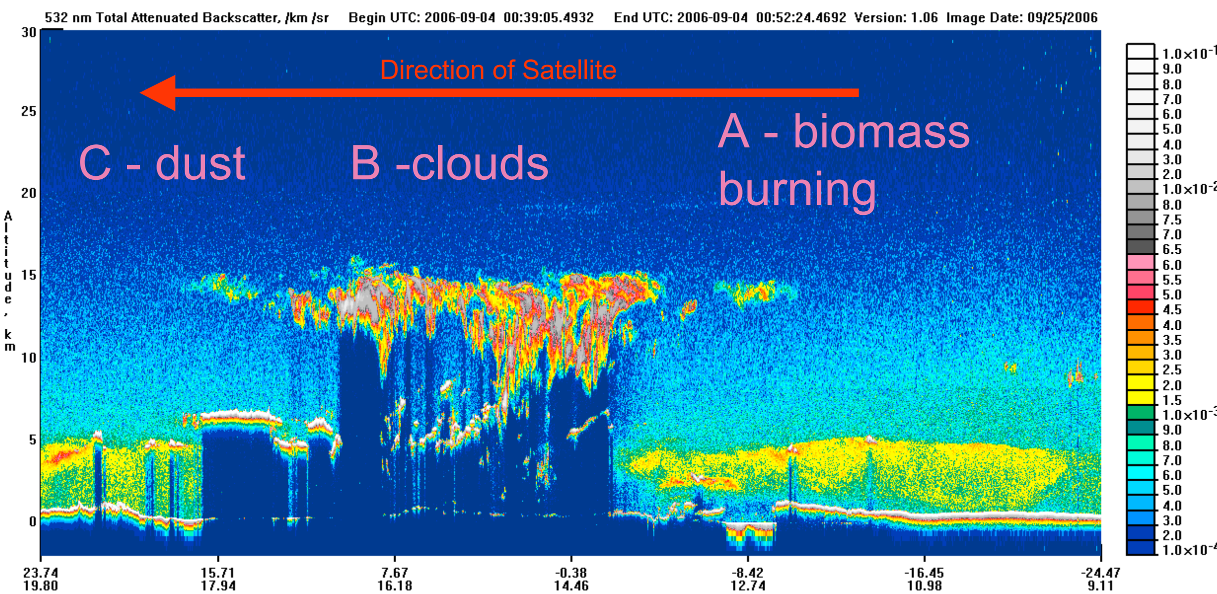
September 4, 2006:

CALIPSO observes:

(A) smoke transported from fires originating from fires over central Africa

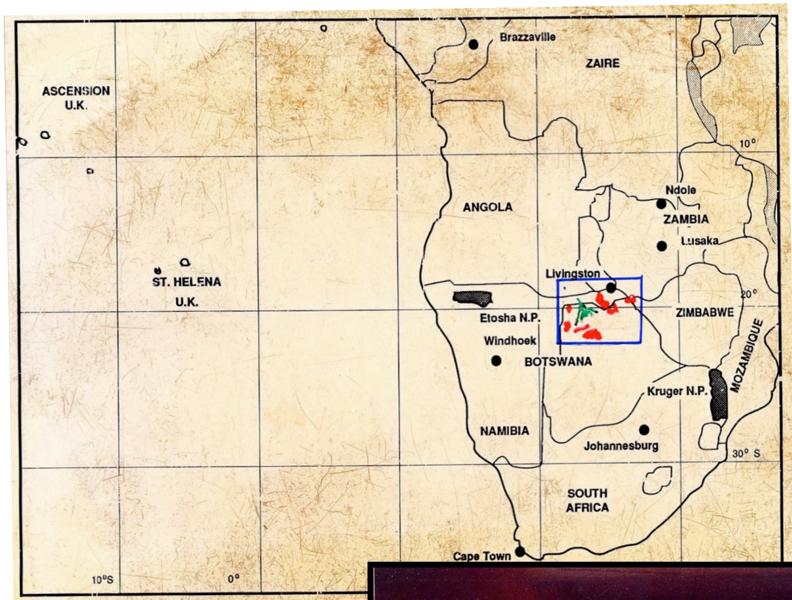
(B) clouds in the Intertropical Convergence Zone

(C) dust during a storm in the Sahara

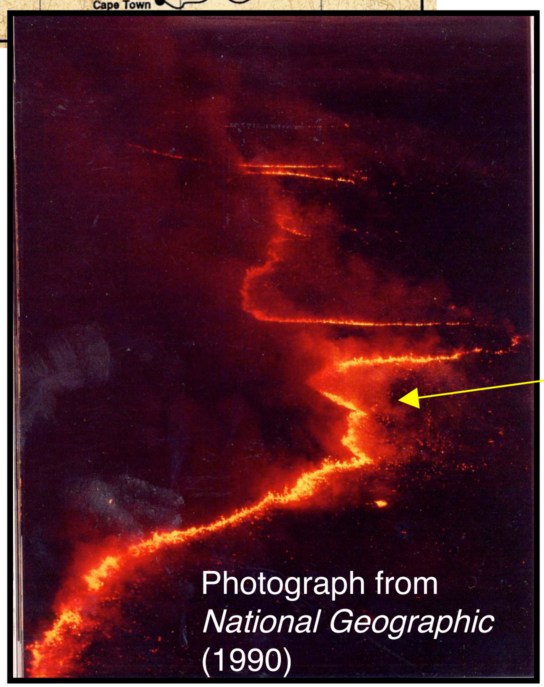


International Expedition Explores Findings over Tropical South Atlantic in 1992

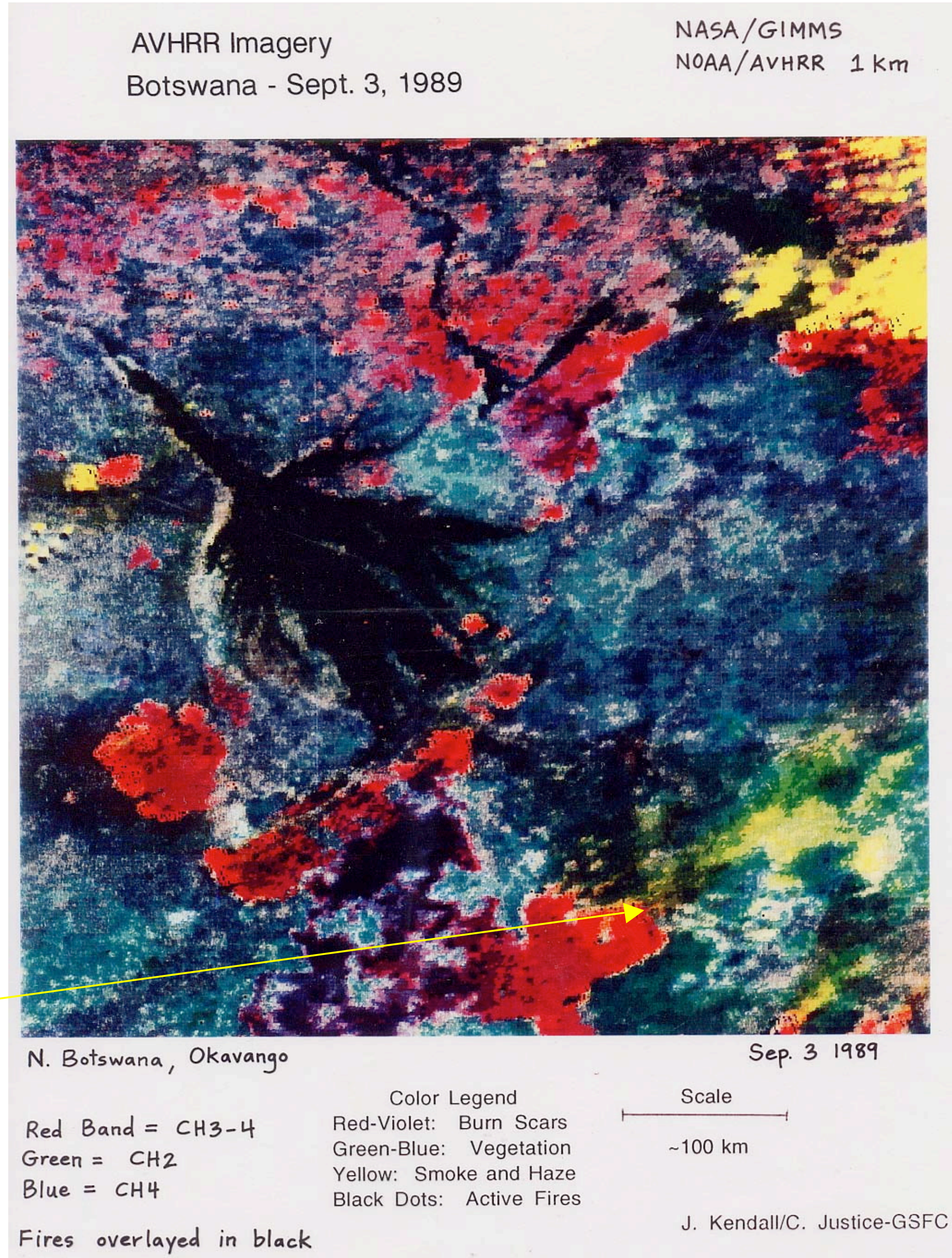
Fires and Burnt Areas Observed by AVHRR



Hot fire pixels saturate image and show as black dots



Photograph from *National Geographic* (1990)

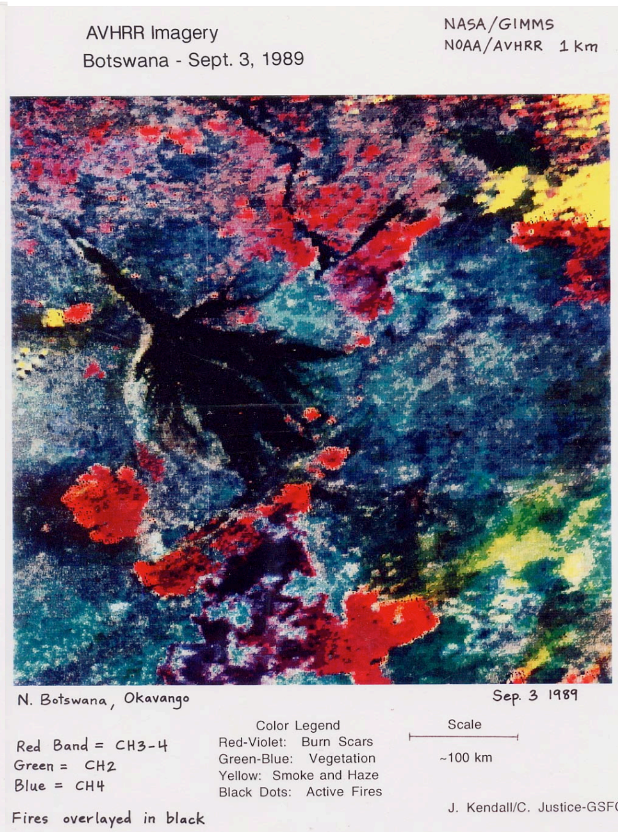


AVHRR Imagery Shows Progression of Burnt Areas

August 31, 1989

Burning just starting in Okavanga Delta region

September 3, 1989



Burning event near peak at this time

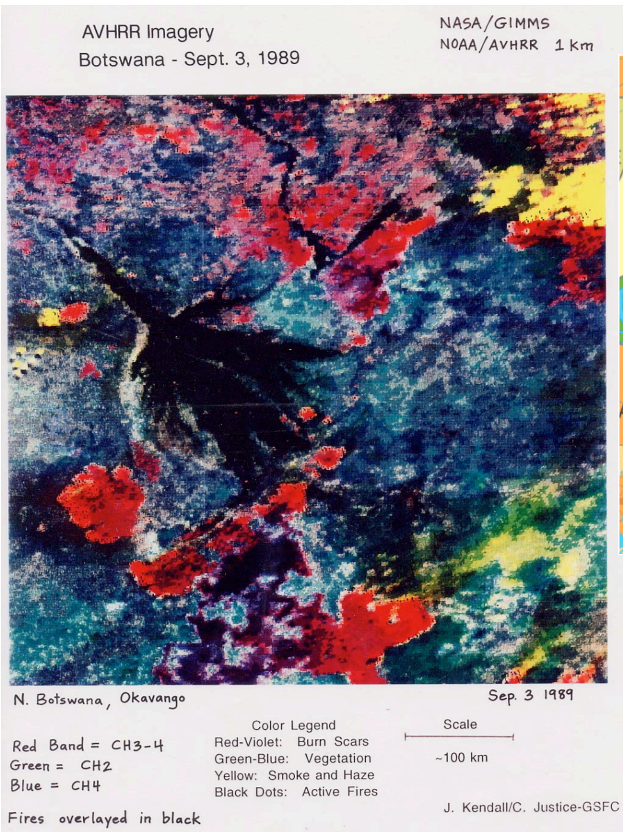
September 8, 1989

Complete extent of burning difficult to see through all the smoke (yellow)

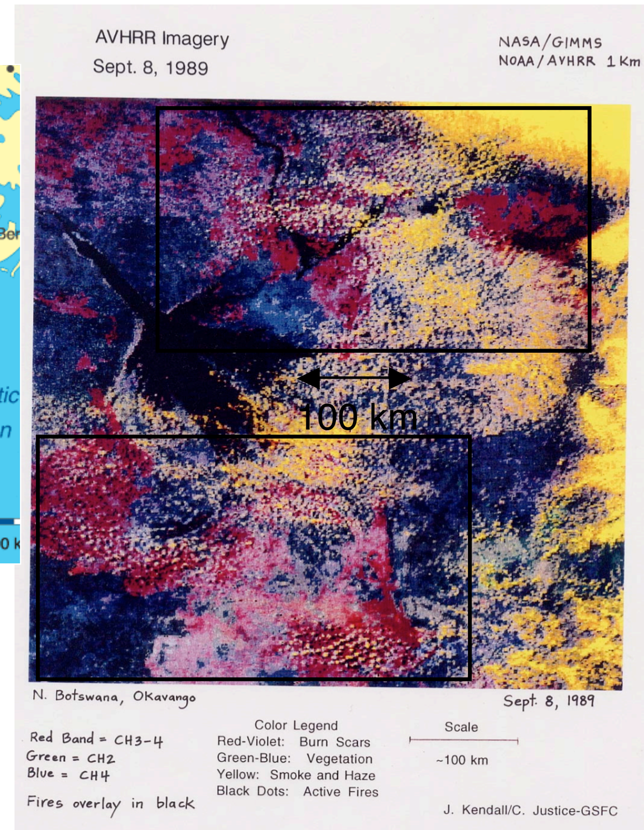
Area Burnt by Fires in Africa Comparable in Size to Large Section of North Carolina

September 3, 1989

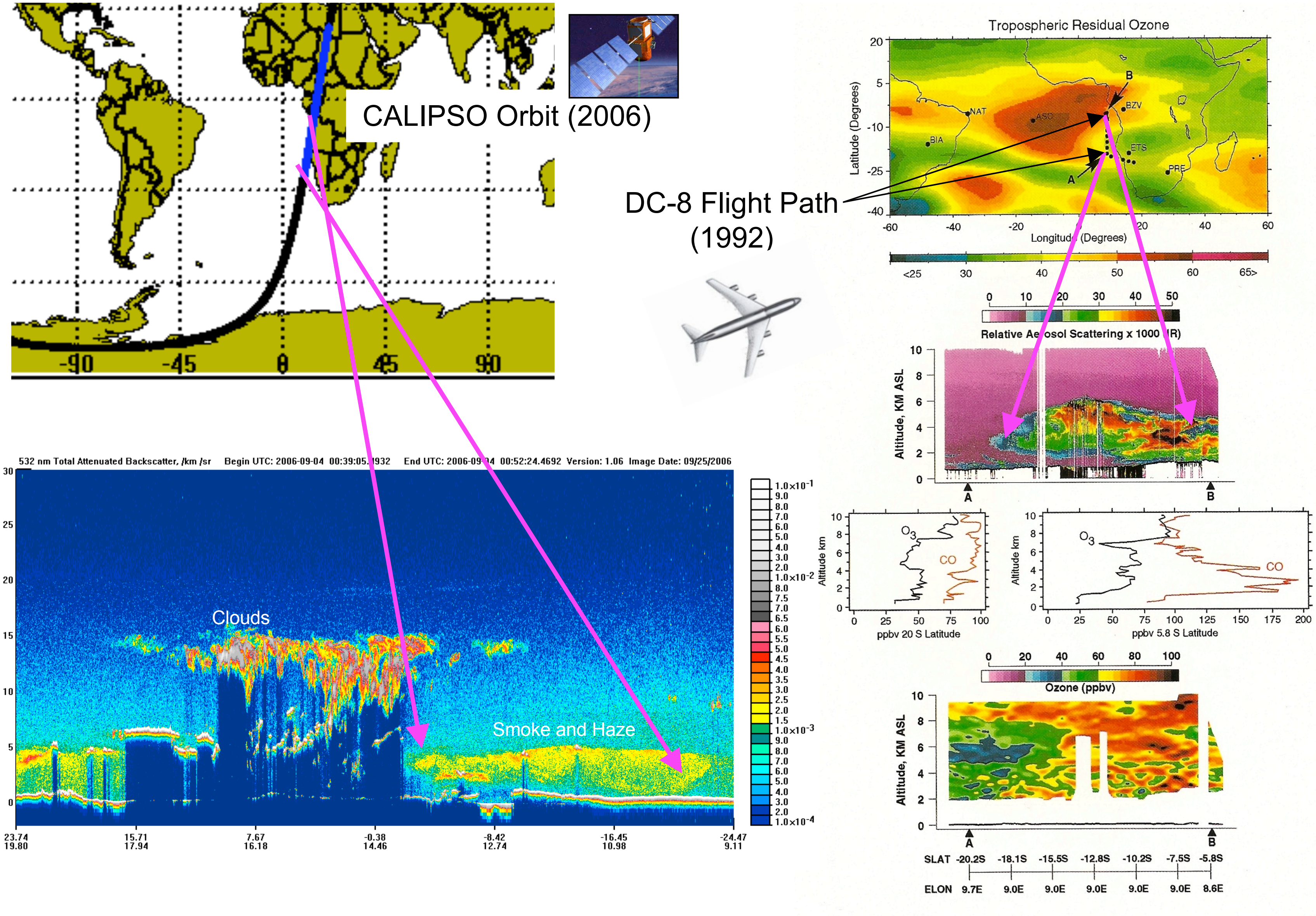
September 8, 1989



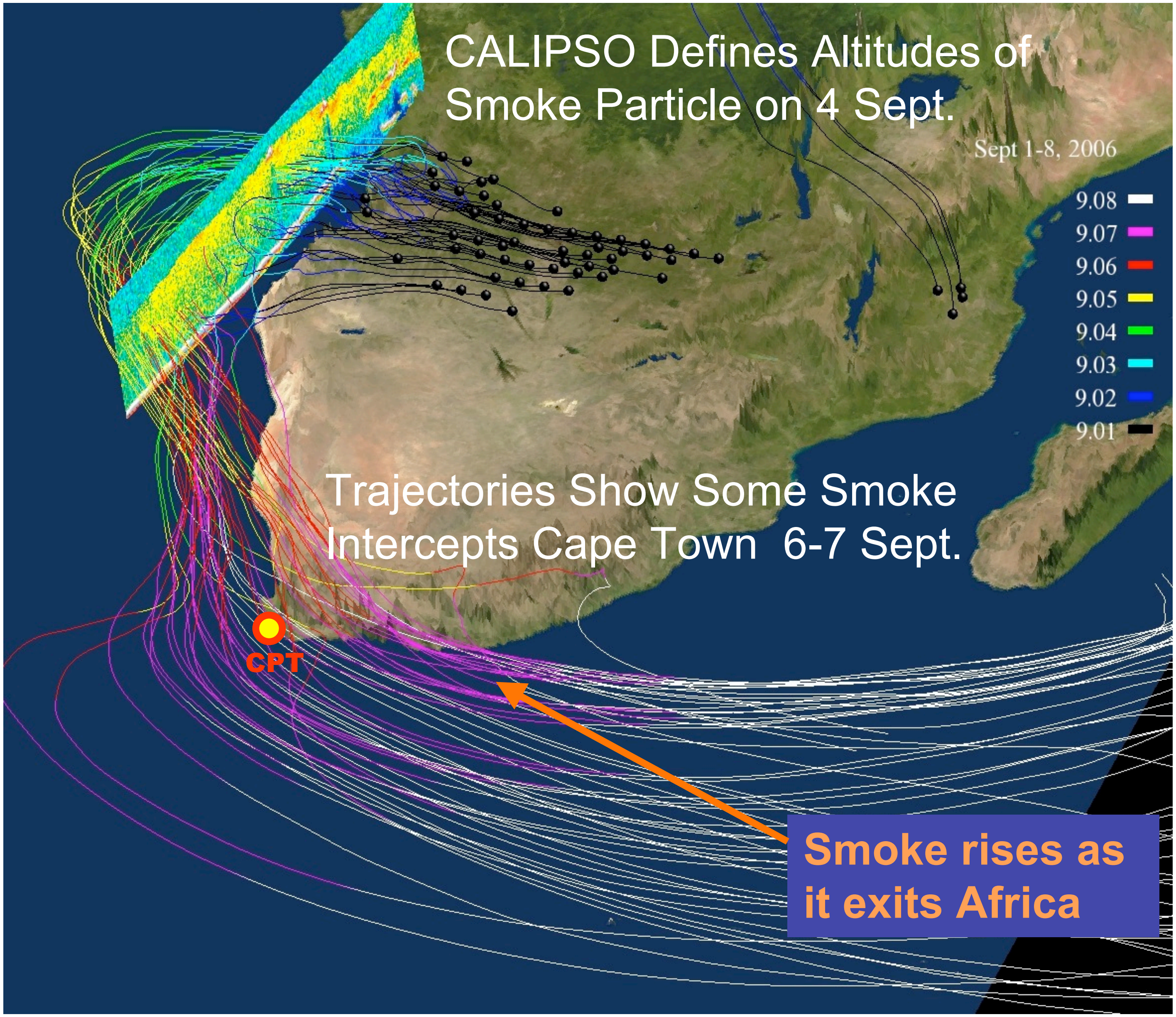
100 km



In 2006 CALIPSO Finds Similar Smoke and Aerosol Feature Off African West Coast Observed by Lidar during TRACE-A



MODIS Identifies Origin of Smoke on 1 September 2006



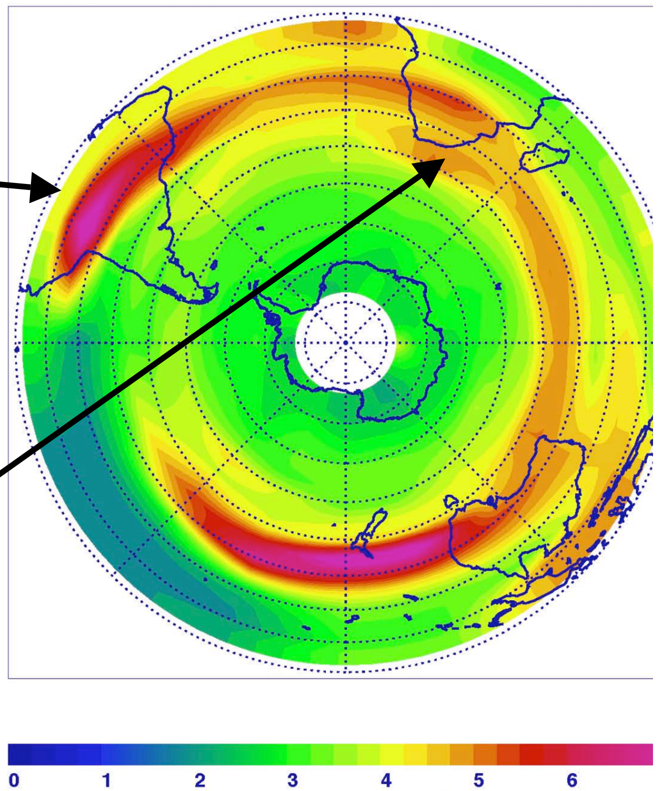
Southern Hemispheric Pollution Transport

Both Aerosols and Ozone Circumnavigate Hemisphere during Burning Season (September-November)

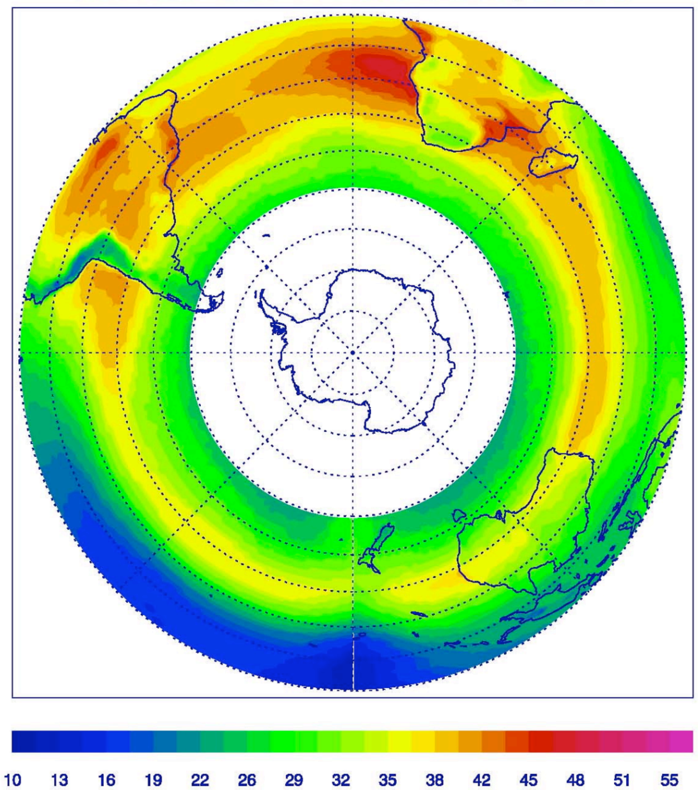
SAGE II aerosol extinction data (6km)

Aerosol Enhancement over Brazil from Convection

Aerosol Enhancement off East coast of Africa after upward transport



TOR TOMS-SBUV 1979-2005 CLIM Sep-Oct-Nov



Tropospheric Ozone (DU)

Improvement of Modeling Capability between 1992 and 2006 Provided Insight into Origin of Secondary Aerosol Maximum off East Coast of South Africa