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 NO₂ 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
Satellite Provide Unique Perspective for Mapping the Extent of Large Pollution Events

Assimilation Models Provide Consistent Picture of Species

Monthly Averages Used for Validation 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 O₃ 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. ... 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

• 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 only 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
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.

Pollution from northern states pools off North Carolina coast

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
- Elevated NO$_2$ from OMI
- Elevated Surface O$_3$ from EPA Sites

Surface O$_3$ Concentrations:
- 0-60 ppb
- 61-79 ppb
- 80-99 ppb
- 100-110 ppb
- 111-124 ppb
- 125+ ppb
Best Method to Observe Pollution is from Geostationary Orbit

Technology Readily Available:
O$_3$, CO, NO$_2$, SO$_2$, CH$_2$O and aerosols
CMAQ Simulation and NO$_2$ from OMI in Good Agreement

June 22, 2005, 1900 Z

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

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

12-km resolution from CMAQ
CMAQ Simulation and NO$_2$ from OMI

June 22, 2005, 1200 Z

12-km resolution from CMAQ

OMI NO$_2$
CMAQ Simulation and NO\textsubscript{2} from OMI

June 22, 2005, 1300 Z
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
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

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
CMAQ Simulation and NO$_2$ from OMI

June 22, 2005, 2200 Z
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

Surface Concentrations and Integrated NO$_2$ Column Calculated by CMAQ Plotted as a Function of Hour: June 22-23, 2005

Measurements from GeoTRACE Capture Daylight Portion of Diurnal Cycle

Observations from GEO: NO$_2$ Measurements Every 30-60 Minutes Throughout Sunlit Hours

Surface NO$_2$ Concentrations Calculated by CMAQ Plotted as a Function of Hour: June 22-23, 2005

Column NO$_2$ Calculated by CMAQ (10$^{15}$ mol. cm$^{-2}$)

Surface NO$_2$ Concentrations Calculated by CMAQ

June 22

Hour of Day (GMT)

June 23
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

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Ozone Increase on U.S. and Global Crop Production


• 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

Proportional Yield Response

Seasonal Ozone Concentration (ppb)

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
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
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    - 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 what is measured from space and how it relates to surface values.

### Monthly Averages:

- June-Sept (2002-2006)
- 20 points

### Data for one box near Indianapolis

\[
\text{Sfc. } O_3 = 0.95 \text{ TOR} + 14.04
\]

### Threshold for onset of crop damage

For human health implications, concentrations are meaningful only at the surface.

\[
Y = 0.95X + 14.04
\]

Data for one box near Indianapolis.
BACK-UP SLIDES
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 (Seidel et al. 1986). Since then, numerous satellite-based instruments have provided important measurements of trace gases in low-earth orbit (LEO), giving nearly global coverage of several key gas species (National Research Council 2008). The Geostationary satellite, originally proposed as a component of the Earth Observing System (EOS) concept in the 1990s, 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 insights and processes that control the observed distribution.

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-
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

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Scientific Advances
Chemical Model
Meteorological Model

Data Assimilation System

Meteorological Data

Profile Measurements
Surface Measurements
Aircraft Observations
Satellite Observations

Atmospheric Chemistry Species Archive and Distribution Center

Initial Assimilated Atmospheric Chemistry Data Set

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)

Schematic Diagram Showing How Tropospheric Ozone Residual (TOR) is Derived

TOMS Total Ozone

~ 300 DU

~ 55 km

~ 270 DU

10-18 km

Tropopause (determined from NCEP analysis)

Stratospheric Ozone Profile Derived from SAGE or SBUV

Calculate Tropospheric Residual

300 DU

-270 DU

~ 30 DU
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

Photograph from National Geographic (1990)

Hot fire pixels saturate image and show as black dots.
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
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

CALIPSO Defines Altitudes of Smoke Particle on 4 Sept.

Trajectories Show Some Smoke Intercepts Cape Town 6-7 Sept.

Smoke rises as it exits Africa
Southern Hemispheric Pollution Transport

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

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