Incorporating Space-borne Measurements to Improve Air Quality Decision Support Systems

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Collaborators
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1. University of Alabama in Huntsville (UAH)
2. University Space Research Association (USRA)
3. National Aeronautics and Space Administration (NASA)
4. USEPA/ORD/NERL/AMAD/AMDB
5. Harvard-Smithsonian Center for Astrophysics
6. JPL
7. NOAA
• Deceased, 9 February 2011

Presented at:
Health and Air Quality Applications Program Review
September 24 – 26, 2013, St. Paul, MN
PROJECT SUMMARY

TOPIC: Incorporating Space-borne Measurements to Improve Air Quality Decision Support Systems

POP: 10/1/2009 – 9/30/2013 (ROSES-08-AQ)
NCE till 9/30/2014

PI: Arastoo Pour Biazar (University of Alabama – Huntsville)
Co-Iss: Dick McNider (UAH), Mike Newchurch (UAH), M. Khan (USRA), Bill Koshak (NASA)

Partners: USEPA, Texas Commission on Environmental Quality (TCEQ), Georgia Environmental Protection Division (GA-EPD)

NASA Assets: NASA’s GOES Product Generation System; OMI ozone, formaldehyde, and nitrogen dioxide observations; MODIS Aerosol Products; NASA Lightning NOx-production Model (LNOM)

Objective: To employ NASA assets and satellite products to improve the air quality management Decision Support Tools (DSTs) used in defining emission control strategies for attainment of air quality standards.
Overall Objective: To Reduce the Uncertainties in Regulatory Air Quality Simulations Through the Use of NASA Science and Satellite Data Products

In SIP modeling it is imperative to reproduce the observed atmosphere. Model uncertainties translates into uncertainties in emission control strategy which has significant economic consequences.

**Physical Atmosphere**

- Models: WRF, MM5, RAMS
- Recreates the physical atmosphere (winds, temperature, precipitation, moisture, turbulence etc) during the design period
- Clouds and microphysical processes
- Atmospheric dynamics
- Boundary layer development
- Fluxes of heat and moisture
- LSM describing land-atmosphere interactions

**Chemical Atmosphere**

- Models: CMAQ, CAMx
- Recreates the chemical atmosphere
- Heterogeneous chemistry, aerosol
- Transport and transformation of pollutants
- Photochemistry and oxidant formation
- Natural and anthropogenic emissions, Surface removal
Contribution of This Project in Reducing Simulation Uncertainties

- Physical Model (WRF or MM5)
  - Recreates Physical Atmosphere
  - Initial/Boundary conditions

- Standard surface and upper air meteorological observations

- Special Observations
  - Profiler/Sodar

- Chemical Model (CMAQ or CAMx)
  - Recreates Chemical Atmosphere
  - Initial/Boundary conditions

- Emissions (SMOKE)
  - Anthopogenic & Natural

- Cloud Assimilation (GOES cloud activity)

- Lightning Generated NOx (LNOM activity)

- Aerosol/Trace Gas adjustments (OMI, MODIS activity)
Specific Objectives – Three Projects in One

In This Project NASA Assets and Satellite Data Will Be Used to Improve the Quality and Accuracy of Retrospective Baseline Simulation in Which Proposed SIP Emission Reductions Are Tested

**Improving Model Emissions**
- **Utilization of NASA Lightning NOx-production Model (LNOM):** This activity utilizes LNOM to account for Lightning NO Production (LNOx) in convective clouds.

**Improving Chemical Atmosphere**
- **Satellite Trace Gas/Aerosol Utilization:** This activity improves chemical transboundary and initial conditions in the air quality model. The satellite products such as MODIS aerosol and newly available OMI ozone profiles can significantly impact the realization of the chemical state of the atmosphere.

**Improving Physical Atmosphere**
- **Improving Model Location and Timing of Clouds:** Clouds have a profound role in photolysis activity, boundary-layer development, and deep vertical mixing of pollutants and precursors. Satellite products will be utilized to improve model cloud simulation.
LNOM ACTIVITY
(Bill Koshak)

North Alabama Lightning Mapping Array

Use with NLDN to create CMAQ emissions
LNOM ACTIVITY

- Five year August statistics (2005-2009) used to construct the profile.
- CG: 484 mole/flash; IC: 35 mole/flash; Average: 101 mole/flash

Wang et al. (1998) (laboratory)
Cooray et al. (2009) (theoretical)
Implemented in WRF/CMAQ and evaluated the impact on ozone

Collaborating with Ken Pickering for incorporation in official release of CMAQ
ARL PROGRESS

<table>
<thead>
<tr>
<th>LNOM Activity</th>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
</tr>
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<tbody>
<tr>
<td>Starting ARL</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<tr>
<td>Ending ARL</td>
<td>2</td>
<td>3</td>
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<td>5</td>
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</table>

ARL 5: Validation in Relevant Environment (Potential Determined)

- Application components integrated into a functioning prototype application system with realistic supporting elements: The data and documentations are readily available at: http://ghrc.nasa.gov/us/sds_docs/ldar/ldar_dataset.html

- LNOM LNOx was included in WRF/CMAQ simulations for August 2006.

- The application system’s potential to improve the decision making activity determined and articulated: The results were evaluated and the impact on ozone predictions were demonstrated. The technique and its application within WRF/CMAQ is documented in Wang et al., 2013 and Koshak et al., 2013.


Utilization of OMI ozone and MODIS Aerosol products

The observations were successfully incorporated in CMAQ

The improvements for SIP applications were documented in Pour-Biazar et al., 2011, and Wang et al., 2011.

Incorporation of MODIS aerosol products in CMAQ substantially reduced model error with respect to PM2.5. Mean Fractional Bias was reduced by about 30%

The impact of incorporating OMI observations in CMAQ simulation on the boundary layer ozone for August 16, 2006.

OMI is able to explain mid./upper tropospheric ozone. An example of re-sampling ozonesonde and OMI ozone profiles onto CMAQ’s 39 vertical layers at Huntsville, AL on August 1, 2006.

OMI is not able to neither explain elevated surface concentrations nor the large variations experienced by the surface monitors. The correlation coefficient is 0.14.

### ARL PROGRESS

<table>
<thead>
<tr>
<th>Trace Gas/Aerosol Assimilation</th>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
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</thead>
<tbody>
<tr>
<td>Starting ARL</td>
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<td>2</td>
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<tr>
<td>Ending ARL</td>
<td>2</td>
<td>3</td>
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<td>5</td>
</tr>
</tbody>
</table>

**ARL 5: Validation in Relevant Environment (Potential Determined)**

- Application components integrated into a functioning prototype application system with realistic supporting elements: OMI ozone profiles and MODIS aerosol products are readily available. Data products were successfully incorporated in MM5/CMAQ air quality modeling system.

- The application system’s potential to improve the decision making activity determined and articulated: The results were evaluated and the impact on ozone predictions were demonstrated. The technique and its application within MM5/CMAQ is documented in Pour-Biazar et al., 2011 and Wang et al., 2011.


Clouds:

• Impact photolysis rates (impacting photochemical reactions for ozone and fine particle formation).
• Impact transport/vertical mixing, LNOx, aqueous chemistry, wet removal, aerosol growth/recycling and indirect effects.

Temperature:

• Impacts biogenic emissions (soil NO, isoprene) as well as anthropogenic evaporative losses.
• Affects chemical reaction rates and thermal decomposition of nitrates.

Moisture:

• Impacts gas/aerosol chemistry, as well as aerosol formation and growth.

BL Heights:

• Affects dilution and pollutant concentrations.

Winds:

• Impacts transport/transformation
Use satellite cloud top temperatures and cloud albedoes to estimate a **TARGET VERTICAL VELOCITY** ($W_{\text{max}}$).

- Adjust divergence to comply with $W_{\text{max}}$ in a way similar to O’Brien (1970).
- Nudge model winds toward new horizontal wind field to sustain the vertical motion.
- Remove erroneous model clouds by imposing subsidence (and suppressing convective initiation).
Cloud Correction

- Improved Characterization of Clouds
  - The most difficult activity among three component of this project.
  - The technique was implemented in WRF modeling system.
  - Simulations for August 2006 were performed.
  - TCEQ continues to provide complementary funding for this work.

Model performance with respect to cloud simulation was improved by 7-10% for August 2006 as measured by Agreement Index.


The Impact on Surface Temperature and Humidity

**Temperature (K)**  (Temperature bias is reduced)

<table>
<thead>
<tr>
<th>Day</th>
<th>Control</th>
<th>Assimilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/04</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>8/05</td>
<td>1.1</td>
<td>1.0</td>
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<tr>
<td>8/06</td>
<td>1.0</td>
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<tr>
<td>8/07</td>
<td>0.9</td>
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<tr>
<td>8/08</td>
<td>0.8</td>
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<tr>
<td>8/09</td>
<td>0.7</td>
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<tr>
<td>8/10</td>
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<td>8/23</td>
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<td>8/25</td>
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<td>1.1</td>
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<tr>
<td>8/28</td>
<td>1.2</td>
<td>1.0</td>
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</tbody>
</table>

**Humidity (g/kg)**  (Slight change in humidity bias)

<table>
<thead>
<tr>
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ARL PROGRESS

Improved Characterization of Clouds

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</table>

DST: WRF/CMAQ Modeling System

ARL 5: Application components integrated into a prototype system and potential to improve the decision-making activity has been determined and articulated.

- Application components integrated into a functioning prototype application system with realistic supporting elements: The technique was integrated into the DST (WRF modeling system).

- The application system’s potential to improve the decision-making activity determined and articulated: Simulations for August 2006 were performed, tested, evaluated, and demonstrated improvement in cloud simulation.

- We are in the process of documenting and transitioning the codes to TCEQ to be tested independently and used in an operational setting.
During testing of Spatial Allocator we noticed a navigation error (surface albedo did not conform to coastal boundaries).

To address the issue we brought NASA/MSFC SPoRT, UAH, and Community Modeling and Analysis (CMAS) together.

The problem was that the Earth’s radius used (and the SW corner) from the GRIB header was not consistent with the internal workings of McIdas.

**Resolution:** From next month, the data will be distributed in ASCII format along with a geolocation file containing the location of data points.

Easy access to data and tools (for manipulation and re-mapping satellite data) remains a major concern for the user community.

We are working on a new web interface to acquire user input about the domain/resolution/format of interest and provide the data in a model friendly (DST compatible) format to the user.
## SCHEDULE / MILESTONES

<table>
<thead>
<tr>
<th>Major Tasks</th>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud Dynamical Support, Implementation/Test &amp; Evaluation/Transition</td>
<td>Preparation, transition from MM5 to WRF</td>
<td>TCEQ Test/Feedback</td>
<td>Revised and Re-Evaluated</td>
<td>Transition to TCEQ started</td>
</tr>
<tr>
<td>OMI/TES ozone and MODIS aerosols, Implementation/Test &amp; Evaluation</td>
<td>Case study identified, data processed, model configured</td>
<td>Model simulation performed, results analyzed</td>
<td>Implemented in CMAQ, Paper Published</td>
<td></td>
</tr>
<tr>
<td>Lightning Generated Nitrogen Oxide from LNOM, Implementation/Test &amp; Evaluation</td>
<td>Data Released to Public, Paper Submitted</td>
<td>Paper published.</td>
<td></td>
<td>Test in CMAQ.</td>
</tr>
<tr>
<td>Website Development for Disseminating Tools &amp; Data</td>
<td></td>
<td></td>
<td>Major overhaul to data format/tools/distribution</td>
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<tr>
<td>Training Workshop for User Community</td>
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<td></td>
<td>Spatial Allocator navigation problem</td>
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<tr>
<td>Benchmarking (multiple activities)</td>
<td>Ozone/Aerosol, Cloud</td>
<td>LNOM, Cloud</td>
<td>Cloud Evaluation for nests</td>
<td></td>
</tr>
<tr>
<td>Transition Activities (CMAS, EPA, TCEQ)</td>
<td>CMAS Activity Started</td>
<td></td>
<td>Holdup due to SA problems</td>
<td></td>
</tr>
</tbody>
</table>

* [http://ghrc.nsstc.nasa.gov/uso/ds_docs/ldar/ldar_dataset.html](http://ghrc.nsstc.nasa.gov/uso/ds_docs/ldar/ldar_dataset.html)
Requested NCE and it was approved. POP extended to 9/30/2014.

The balance will be used to complete the transition to CMAS and hold a workshop.

TCEQ is providing additional funding of $150K for documentation/transition to TCEQ. This brings the total complementary funding from TCEQ to $500K.

<table>
<thead>
<tr>
<th></th>
<th>UAH</th>
<th>CMAS</th>
<th>NASA/USRA</th>
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<tbody>
<tr>
<td>Total</td>
<td>$855,932</td>
<td>$139,000</td>
<td>$272,911</td>
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<tr>
<td>Balance</td>
<td>$20,050</td>
<td>$33,803</td>
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</table>
Future Tasks

- Resolve the issues with CMAS and hold a workshop.
- Complete transitioning to CMAS and TCEQ.
  - Complete documentation.
  - Work with TCEQ for independent evaluation of tools and techniques.
- Upgrade the current web based data delivery system for the new data format.
- Respond to user community’s request for Photosynthetically Active Radiation (PAR).
  - We had requests from Dave Allen’s group at University of Texas-Austin, Russ Dickerson at University of Maryland and Rice University.
What is PAR

\[ PAR = \int_{0.4}^{0.7} I(\lambda) d\lambda \quad (W \ m^{-2}) \]

\[ PAR = \frac{1}{hc} \int_{0.4}^{0.7} I(\lambda) d\lambda \quad (\text{quanta} \ m^{-2} \ s^{-1}) \]

In most applications (e.g., agriculture related) a conversion factor CF is used:

\[ CF = \frac{PAR}{\text{Insolation}} \]

Direct and diffuse light differences: Highest sensitivity to clouds/aerosols and zenith angle, but not in the same direction. (Adapted from: Frouin and Pinker, 1994; Pinker and Laszelo, 1991)
Simple PAR calculation

$$CF = \frac{PAR}{Insolation} = 0.48 + 0.17 \times C\text{factor} \times Z\text{factor}$$

Where \( C\text{factor} = \sqrt{1 - (\alpha_c - 1)^2} \)

\( \alpha_c \) is cloud albedo
Journal Publications:


Publications

Proceedings:
Koshak, W., and H. Peterson, A summary of the NASA Lightning Nitrogen Oxides Model (LNOM) and recent results, 10th Annual Community Modeling and Analysis System (CMAS) Conference, Chapel Hill, NC, October 24-26, 2011.
Park, Yun-Hee, Arastoo Pour Biazar, Richard McNider, Kevin Doty, Bright Dornblaserr, Satellite Assimilation to Improve Cloud Prediction in WRF Model, 10th Annual CMAS Conference, Chapel Hill, NC, October 24-26, 2011.
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMAQ</td>
<td>EPA’s Community Multiscale Air Quality (CMAQ) Model</td>
</tr>
<tr>
<td>CMAS</td>
<td>Community Modeling and Analysis System</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>LNOx</td>
<td>Lightning Generated Nitrogen Oxides</td>
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<td>LNOM</td>
<td>Lightning Nitrogen Oxides Model</td>
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<tr>
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<td>National Aeronautics and Space Administration</td>
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<tr>
<td>SIP</td>
<td>State Implementation Plan</td>
</tr>
<tr>
<td>TCEQ</td>
<td>Texas Commission on Environmental Quality</td>
</tr>
</tbody>
</table>
Thank You
ADDITIONAL SLIDES
O3 Statistics

Mean BIAS (ppb)

Mean Bias O3>50 (ppb)

Mean Bias O3<50 (ppb)

Mean Norm. Bias O3>50 (%)
A contingency table can be constructed to explain agreement/disagreement with observation.

\[
AI = \frac{A + D}{G}
\]

\[
G = A + B + C + D
\]

- **Clear Cloud**
  - Clear: A
  - Cloud: C

- **Cloud**
  - Clear: B
  - Cloud: D

**Areas of disagreement between model and satellite observation**
Cloud Correction: Agreement Index = (# of cloudy/clear grids in agreement) / (Total # of grids)

Agreement index increased by 7-10%

MODEL

<table>
<thead>
<tr>
<th></th>
<th>Clear</th>
<th>Cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>

G = (A + B + C + D)

MODEL:

\[ \text{AI} = \frac{A + D}{G} \]
Overview of the Data Archive & Delivery system

NSSTC Satellite Ground Station & Data Link

NSSTC Satellite Data Processing & Product Generation
- Insolation
- Skin Temperature
- Surface Albedo
- Cloud Albedo
- Cloud Top Temperature/Pressure
- Cloud Transmittance
- MODIS Emissivity

Web Based Satellite data delivery system (SAT_ASSIM.NSSTC.UAH.EDU)
- Archive and Distribute Data
- Regridding Software
- Data Processing Software

Decision Support Tools
- MM5/WRF
- CMAQ/WRFCHEM

State, Local & Private Sector Users
Web Based Delivery System

Data Link for Satellite Data Assimilation

Retrieve GOES Products
Download Regridding Software
Regridding Software Documentation

sat_assim.nsstc.uah.edu
Username: levl
Password: sparkx
The State Implementation Plan (SIP) Decision Making Process

- **Classification**: Once an area exceeds the National Ambient Air Quality Standard (NAAQS) for a criteria pollutant (e.g., O3, NO2, SO2, particulate matter) and is listed by the USEPA as **non-attainment** the state must develop a plan or strategy to lower the pollutant levels to meet the NAAQS.

- **Design Period**: A design day or design period is selected (usually the period when the highest pollutant levels occur).

- **Best Modeling Practice**: Model simulations are carried out to determine whether the model can reasonably replicate the atmospheric conditions for such episode and the observed pollutant values for that period.

- **Emissions Reduction**: Next various emission reduction scenarios in these models are carried out to determine the most efficient strategy for meeting the air quality standards for the design period. **This defines the SIP.**
Control Strategy Simulations - Inputs

Standard surface and upper air meteorological observations

Special Observations Profiler/Sodar

Physical Model
Recreates Physical Atmosphere

Chemical Model
Recreates Chemical Atmosphere

Emissions are Changed to Reflect Control Programs on Industrial and Mobile Sources

Initial/Boundary conditions

IC/BC

Ambient Levels Compared to NAAQS
Design Period Simulations – Satellite Inputs

Retrospective – Data Assimilated for all Integration Period

Geostationary Satellite
- Insolation
- Cloud Properties
- Skin Temperature

MODIS
- Surface emissivity
- Surface albedo
- Skin temperatures

Satellite derived Cloud properties for photolysis rates

Satellite trace gas and aerosol observations

ASSIMILATION

Physical Model
Recreates Physical Atmosphere

Chemical Model
Recreates Chemical Atmosphere

Geostationary and Polar Orbiting Observations for Evaluation
Under the Southern Oxidant Study it was estimated that SIP control decisions involved $5 billion for 6 southeastern states.

In Texas the cost of the ozone SIP for Houston alone was estimated to be over $1 billion.

Nationally these SIPs amount to ten’s of billions in control costs (http://www.epa.gov/oar/sect812/feb11/fullreport.pdf).
The method and its first application within WRF/CMAQ have been documented (Koshak et al., 2012).

Simulations over 4 summers are underway, quantifying the model error due to lack of LNOx in default CMAQ configuration.

The data and documentations are now available at (http://lightning.nsstc.nasa.gov/data/index.html#LNOM_DATA)