# Progress on Tiger Team Project: Air Quality Reanalysis


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**Georgia Institute of Technology**


**With thanks to project leaders Greg Carmichael and Pius Lee and other members**

**GT-Emory AQAST Meeting, August 28th, 2015**

# Part 1: Project Team and Major Goals

# Air Quality Reanalysis

## (Configuration for 2010 HTAP production)

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## Concept of Reanalysis

A ‘reanalysis’ is a climate or weather model simulation of the past that includes data assimilation of historical observations. The observations can be very comprehensive (satellite, in situ, multiple variables) or relatively sparse (say, sea level pressure only), and the models themselves are quite varied. Generally these models are drawn from the weather forecasting community (at least for the atmospheric components) which explains the odd terminology. An ‘analysis’ from a weather forecasting model is the 6 hour (say) forecast from the time of observations. Weather forecasting groups realized a decade or so ago that the time series of their weather forecasts (the analyses) could not be used to track long term changes because their models had been updated many times over the decades. Thus the idea arose to ‘re-analyze’ the historical observations with a single consistent model. These sets of 6 hour forecasts using the data available at each point are then more consistent in time (and presumably more accurate) that the original analyses were. - See more at: http://www.realclimate.org/index.php/archives/2011/07/reanalyses-r-us/#sthash.WKOIKeHI.dpuf

# Applications of Reanalysis

## Environments

- Climate Change
- Outdoor Air NEW
- Water
- More

## Health Effects

- Asthma
- Cancer
- Childhood Lead Poisoning
- More Health Conditions

## Population Health

- Population Characteristics
- Health Impact Assessments NEW
- Children's Environmental Health
- More

## Info by Location

Select State:

Select

GO

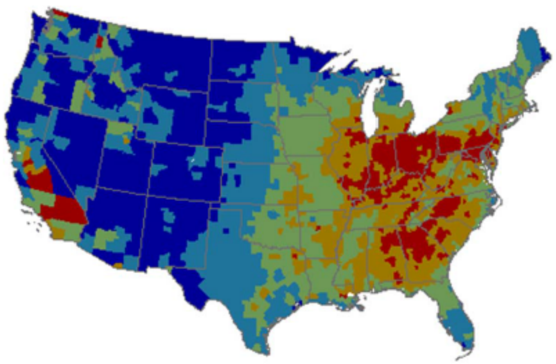
Reanalysis would be able to provide PM2.5 speciation data with national coverage at county level

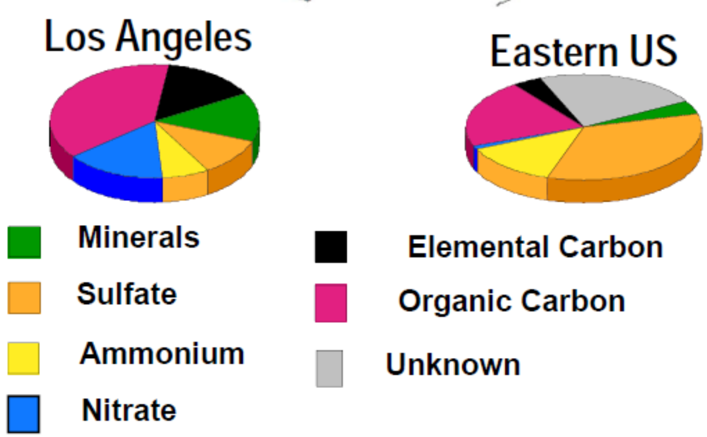
Courtesy: Dan Costa
"New Directions in Air Quality Research at the US EPA"

# *Public Health Burden of $PM_{2.5}$*

## (Fann et al., 2011)

Percentage of $PM_{2.5}$ related deaths due to 2005 air quality levels by county



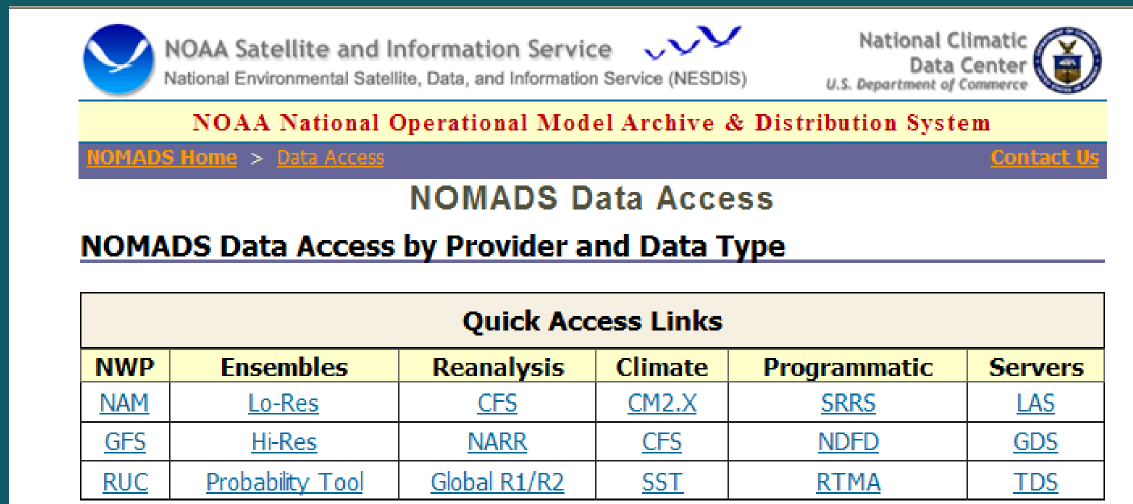



| Summary of National $PM_{2.5}$ impacts due to 2005 air quality | |
|---|---|
| Excess mortalities (adults)[A] | 130 to 320,000 |
| Percentage of all deaths due to $PM_{2.5}$[B] | 5.4% |
| ***Impacts among Children*** | |
| ER visits for asthma (<18 yr) | 110,000 |
| Acute bronchitis (age 8-12) | 200,000 |
| Exacerbation of asthma (age 6-18) | 2,500,000 |

[A] Range reflects use of alternate PM mortality estimates
[B] Population-weighted value using Krewski et al. (2009) PM mortality estimates

# NOAA Service: A user friendly downloadable archive

- NOMADS



NOAA Satellite and Information Service
National Environmental Satellite, Data, and Information Service (NESDIS)
National Climatic Data Center
U.S. Department of Commerce

NOAA National Operational Model Archive & Distribution System

NOMADS Home > Data Access Contact Us

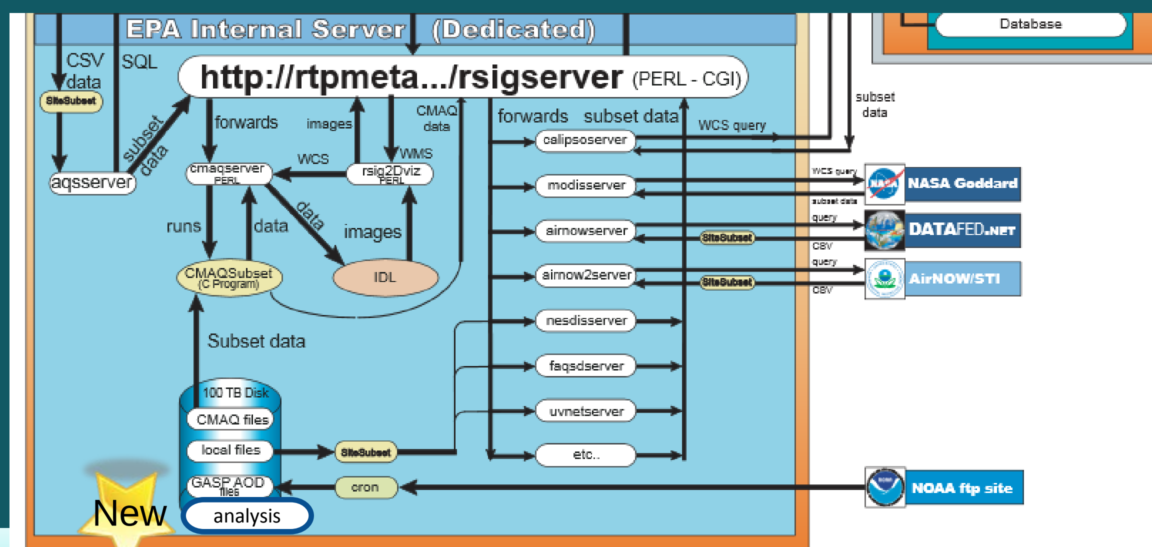
NOMADS Data Access

NOMADS Data Access by Provider and Data Type

Quick Access Links

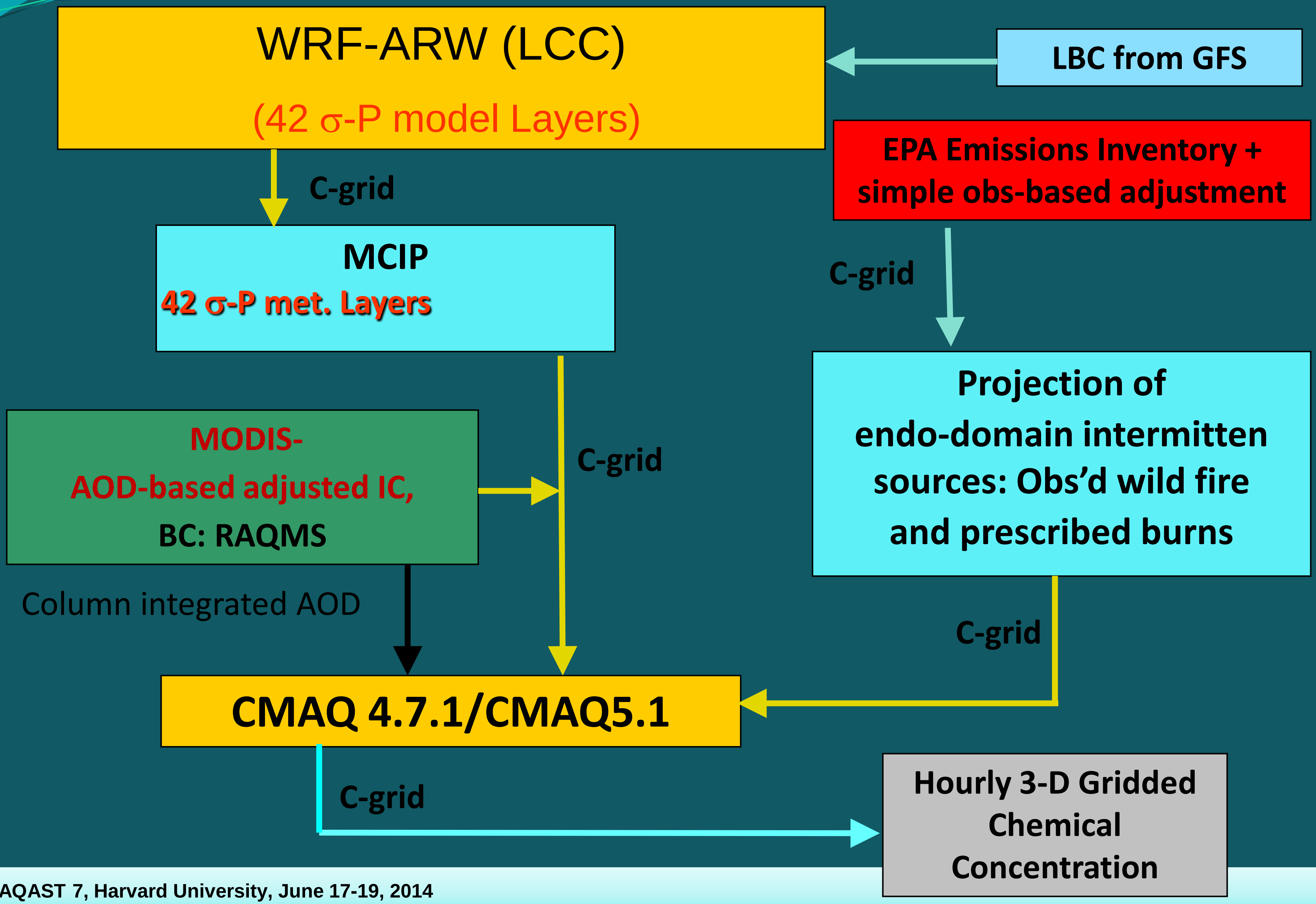
| NWP | Ensembles | Reanalysis | Climate | Programmatic | Servers |
|---|---|---|---|---|---|
| NAM | Lo-Res | CFS | CM2.X | SRRS | LAS |
| GFS | Hi-Res | NARR | CFS | NDFD | GDS |
| RUC | Probability Tool | Global R1/R2 | SST | RTMA | TDS |

- RSIG .



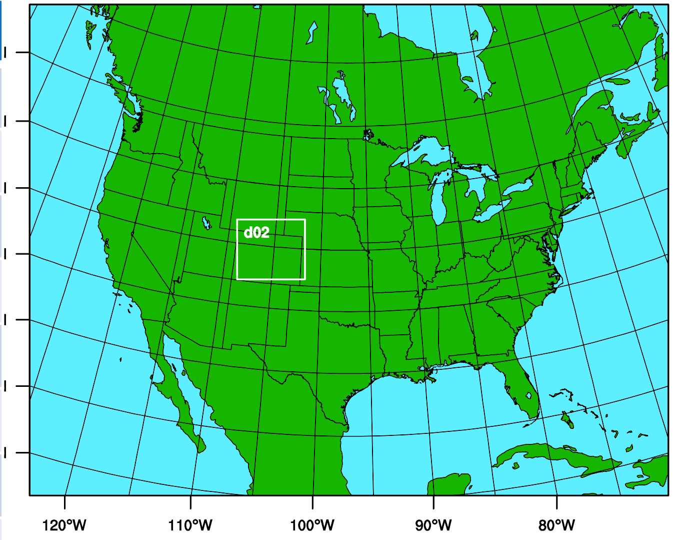
# Part 2: Tasks to make the model more robust

# WRF_ARW-MCIP-CMAQ forward model



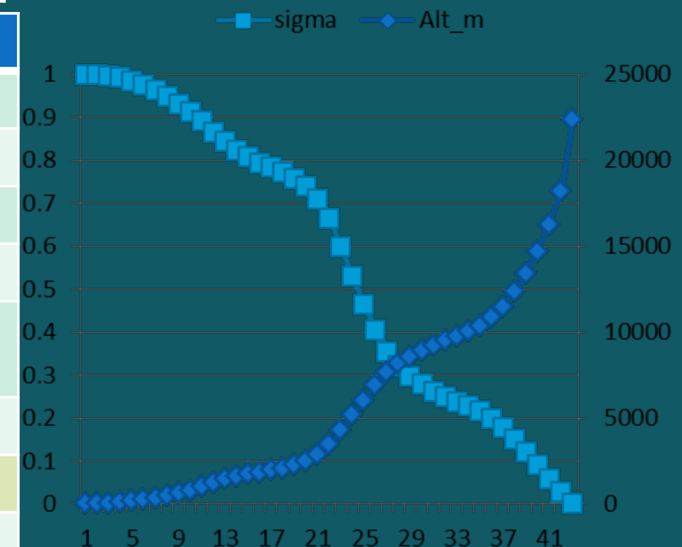
# WRF_ARW-MCIP-CMAQ model physics and chemistry options

| WRF-ARW | Both North America (12 km) & CONUS (4 km) |
|---|---|
| Map projection & grid | Lambert Conformal & Arakawa C staggering |
| Vert. co-ordinate | 42 σ-p unevenly spaced levels |
| advection | RK3 (Skamarock and Weisman (2008)) |
| SW & LW radiation | RRTMG (Iacono et al. 2008)) |
| PBL Physics | Mellor-Yamada-Janjic (MYJ) level 2.5 closure |
| Surface layer scheme | Monin-Obukhov Similarity with viscous sub-layer |
| Land Surface Model | NCEP NOAH |
| Cloud Microphysics | Thompson et al. (2008) |
| Cloud convective mixing | Betts-Miller-Janjic Mass adjustment |




**AQ forecast: ^12 km nested to 4 km**

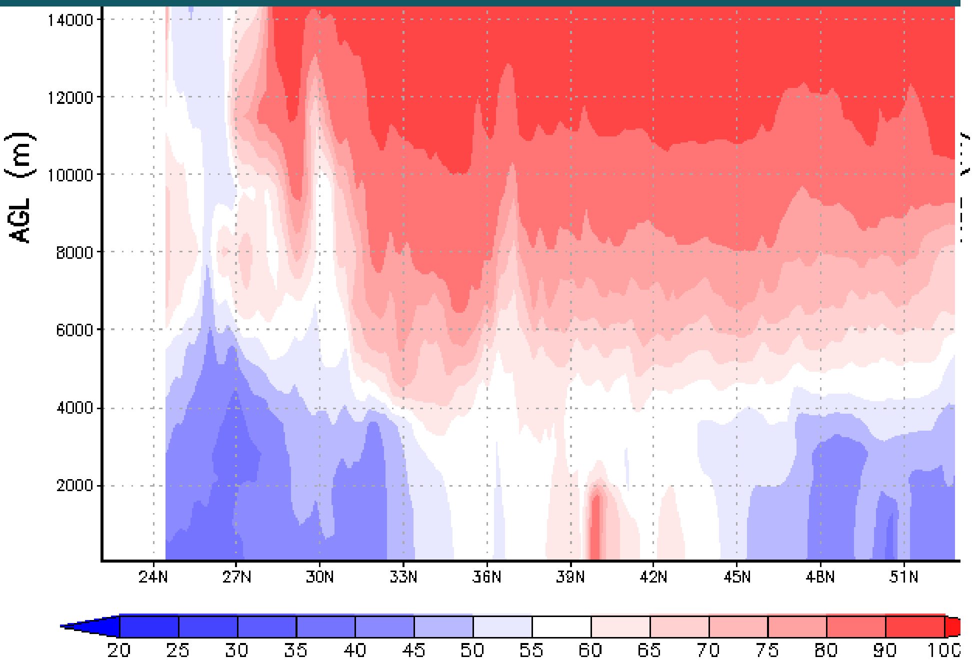
| CMAQ4.7.1 | Both CONUS(12 km) & SENEX (4 km) |
|---|---|
| Map projection & grid | Lambert Conformal & Arakawa C staggering |
| Vert. co-ordinate | 42 σ-p unevenly spaced levels |
| Gas chemistry | Cb05 with 156 reactions |
| Aerosol chemistry | Aero5 with updated evaporation enthalpy |
| Anthropogenic emission | 2005NEI as base year, mobile projected using AQS*, area and off-road used CSPR^, point source uses 2012 CEM data |
| | WRAP oil and gas emissions data |
| Biogenic emission | BEIS-3.14 |
| Lateral BC | RAQM (B. Pierce) |

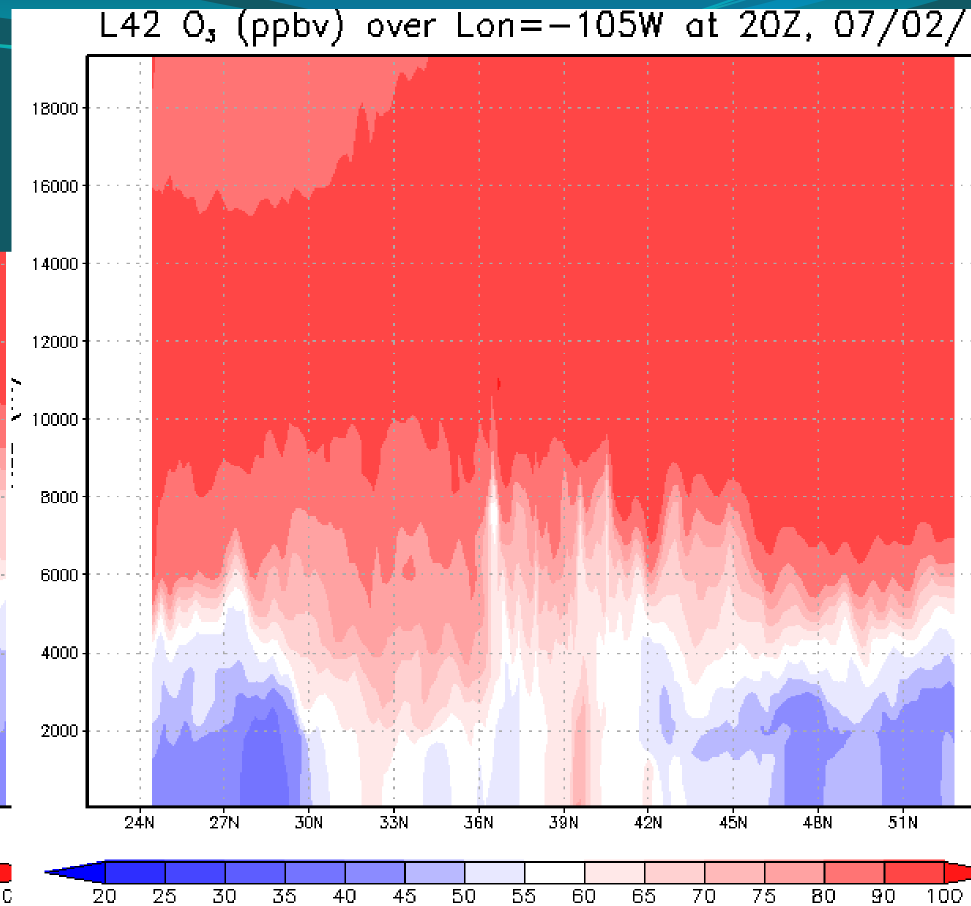



**42 vertical layers**

## WRF_ARW-CMAQ4.7.1 (42L)

## NMMB-CMAQ4.7.1 (22L)

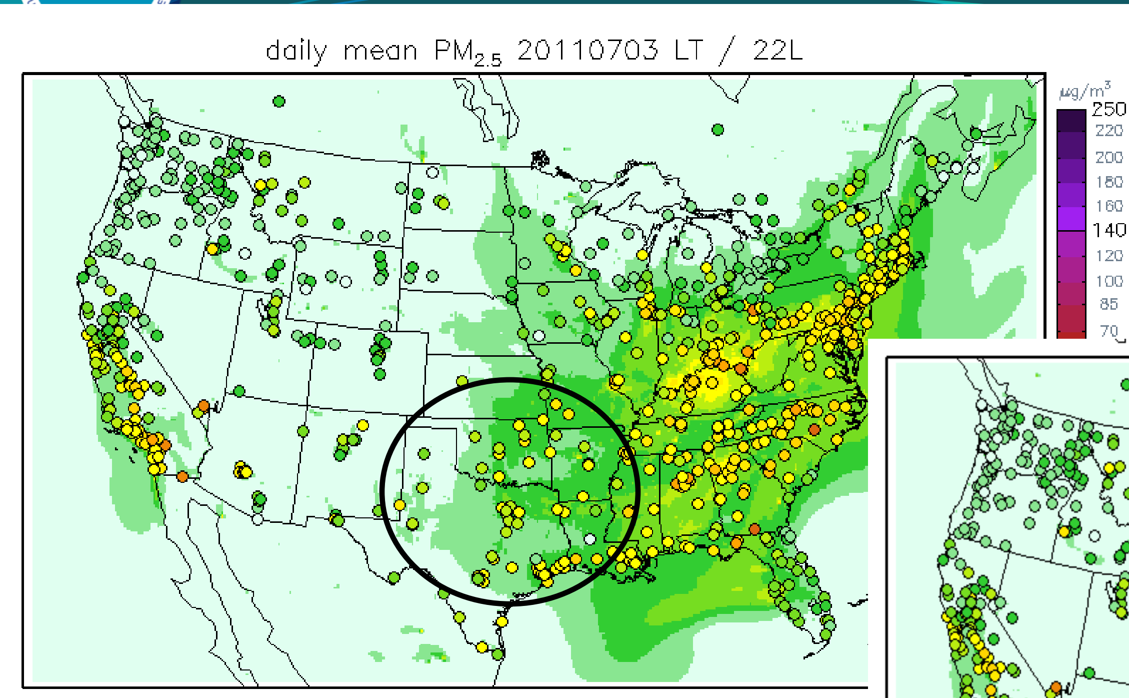


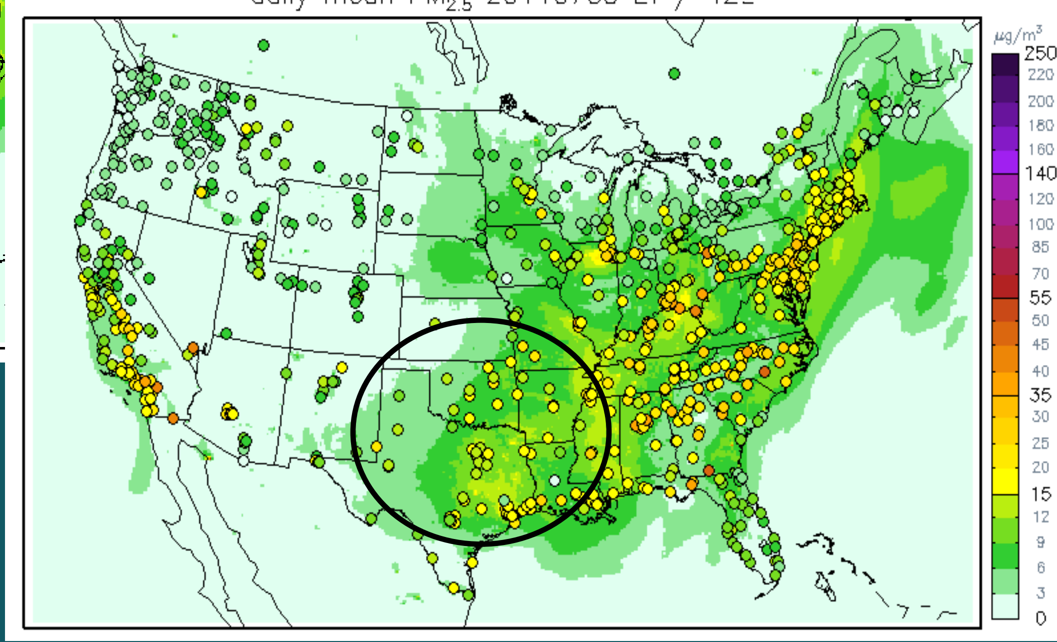

**Longitudinal cross-section along Denver (105W) at 20 UTC July 2, 2011**

**No spurious spikes of vertical gradients over complex terrain for $O_3$ concentration**

## NMMB-CMAQ4.7.1 (22L)




## WRF_ARW-CMAQ4.7.1 (42L)




**24 h averaged surface $PM_{2.5}$ on July 3 2011**
**A mixed result as a general lower predicted value by 42L exacerbated under-bias, but the higher predicted values by 42L in Lower Middle helped.**

# Outline on progress

- *The Regional Chemical Analysis TT started in 2013:*
- *Deliverable in 2014: Analysis fields for July 2011 provided for GaTech and UMD for SIP modeling*
  - *Assimilated exo-domain wild fire, $O_3$ using RAQM*
  - *Upgrade emission based on NEI2011*
  - *Assimilated wild-fire using NESDIS obs, $PM_{2.5}$ constraints using MODIS AOD & AQS $PM_{2.5}$*
  - *Assimilated cloud attenuated photolytic rate*
  - *Mimicked SIP reduced RMSE by 400% for $PM_{2.5}$*
- *Deliverable in 2015: Analysis fields for 2010, support HTAP*
  - *Assimilate lightning NOx, PAR, DYNAMO Isoprene*
- *User friendly portal and archive for chemical analysis fields over Continental U.S.*

# Lightning Process currently used in CMAQ 5.0*

NLDN (National Lightning Detection Network) data

Map to CMAQ grid

Calculate Total monthly Lightning flash Count over each grid

Model's convective Precipitation rate

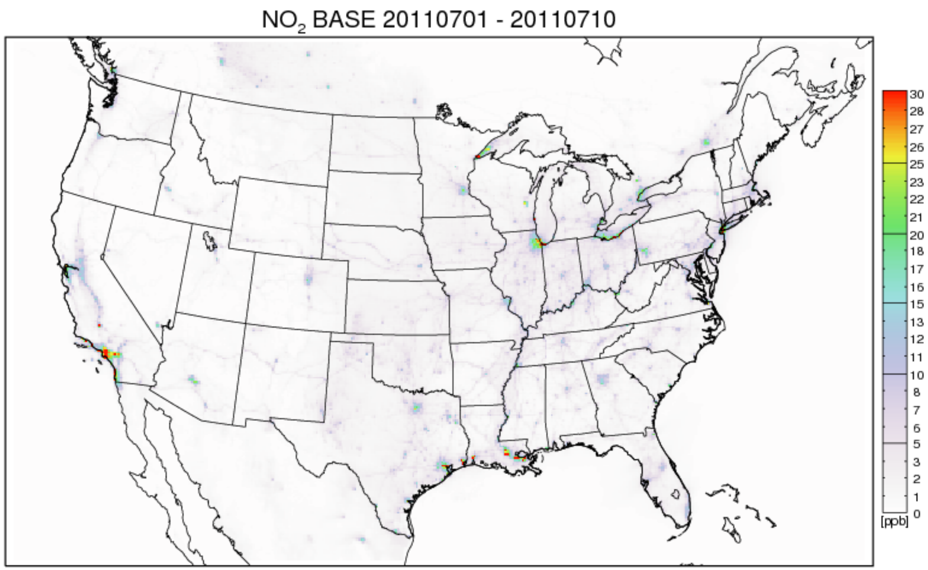
Model's strike count (monthly total)

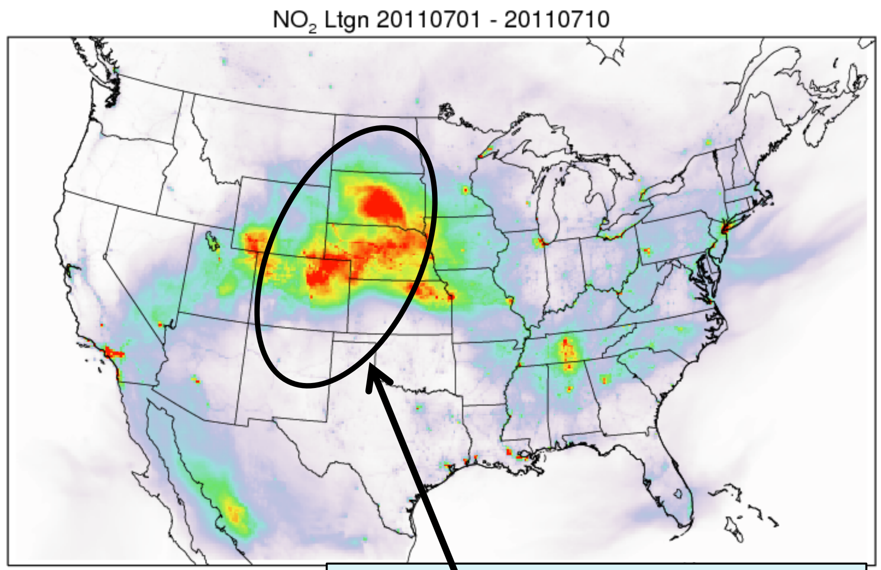
Mean LTratio used in CMAQ NLDN/Model

*CMAQ Version 5.0 and higher contains a scheme based on Allen et al. (2012, ACP) that was funded under NASA Applied Sciences Air Quality Program project (Ken Pickering, PI):

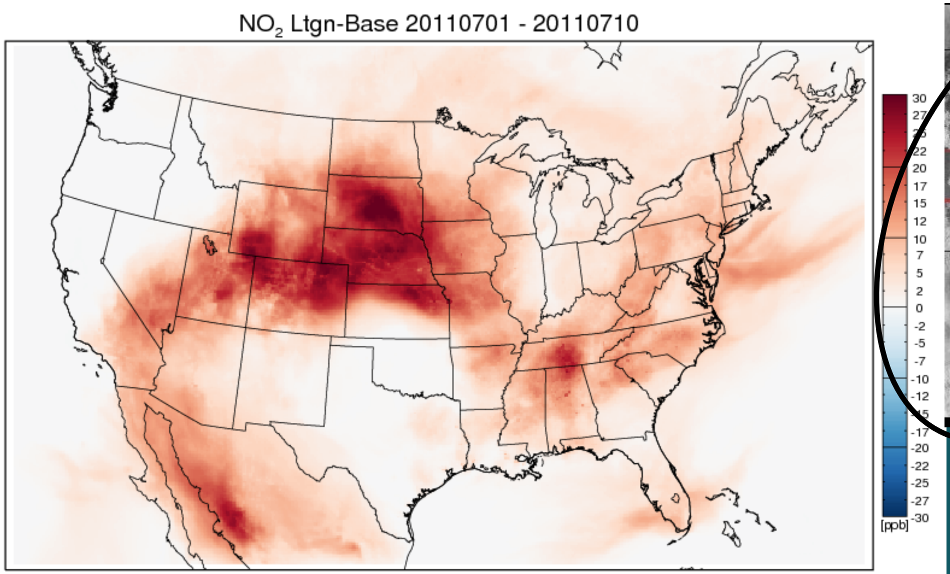
- Method for estimating lightning flash rates
- $LNO_x$ production per flash
- Method of allocating $LNO_x$ production in the vertical

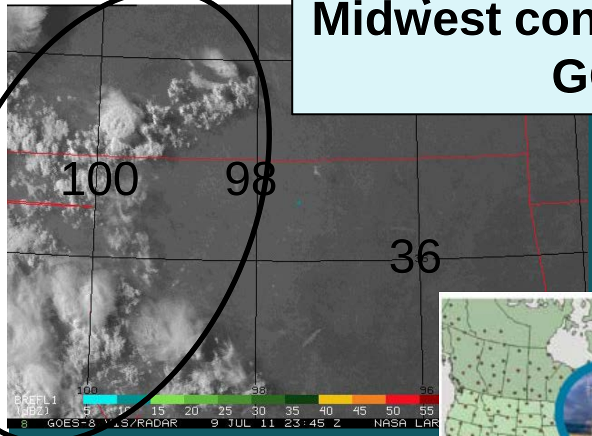
# July 1-10, 2011 $NO_2$ (Left) Base (Right) with LNOx, (Bottom) Difference




**Midwest convections.**
**GOES13**

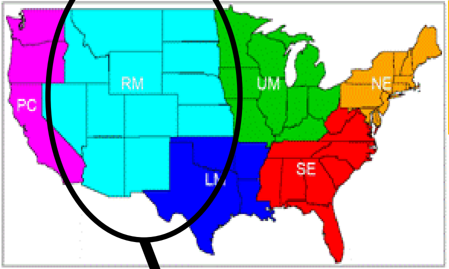


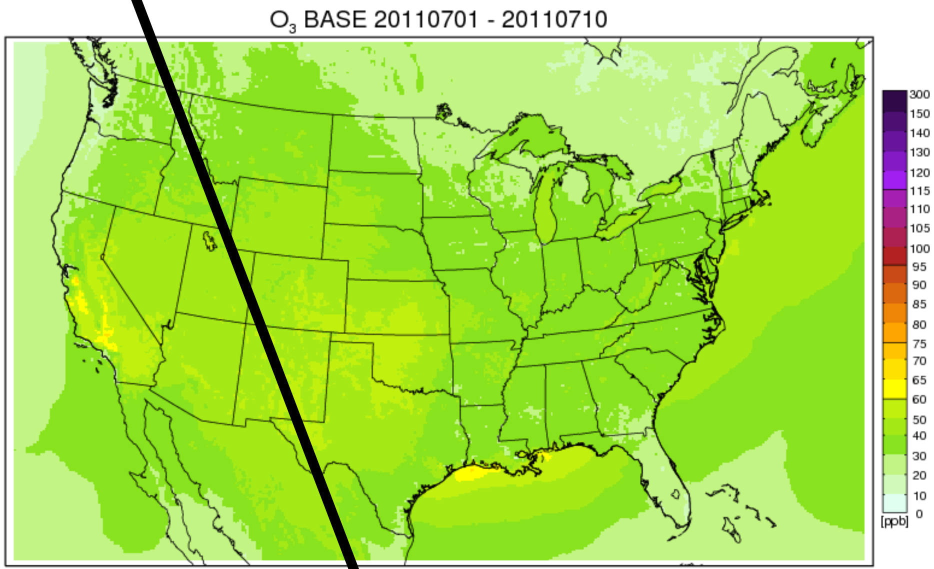



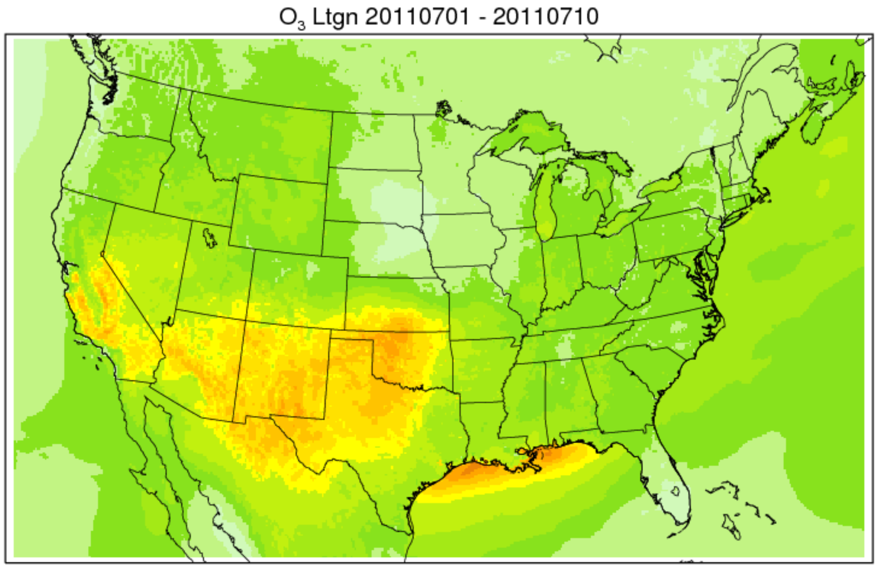

*U.S. NLDN consists of more than 114 remote, ground-based lightning sensors.*

*Sensors instantly detect the electromagnetic signals created when lightning strikes the earth's surface.*

# July 1-10, 2011 $O_3$ (Left) Base (Right) with LNOx, (Bottom) Verification

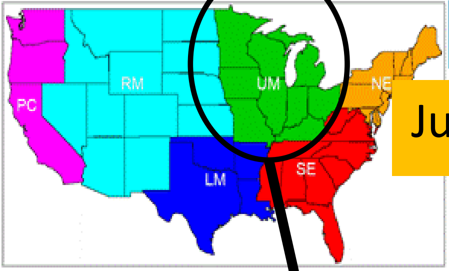


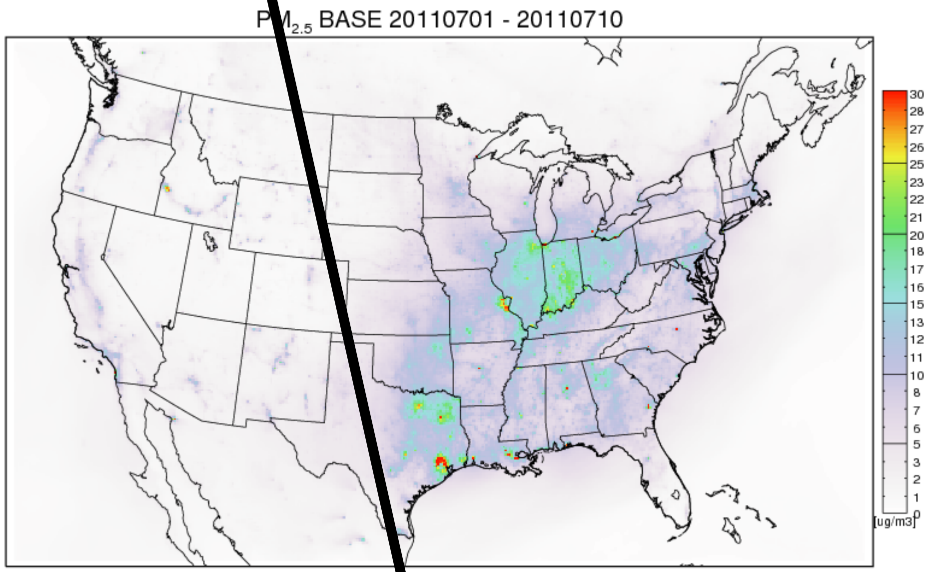



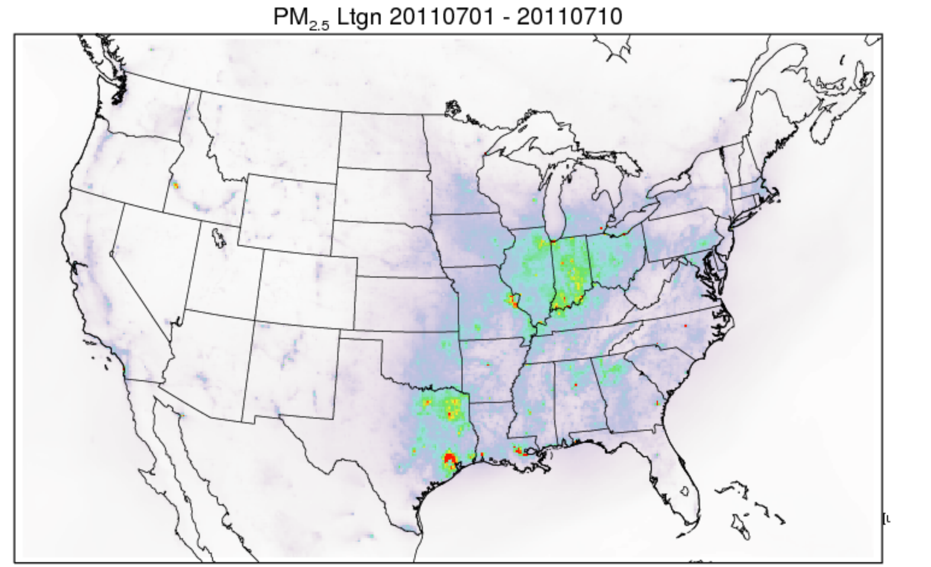

| $O_3$ 10 days avg | Stations | Obs mean | Mean bias | RMSE | Corr. Coef. |
|---|---|---|---|---|---|
| Base | 3222 | 36.45 | -0.17 | 15.81 | 0.66 |
| | | 36.45 | 2.90 | 24.54 | 0.53 |

| $O_3$ 10 days avg (RM) | Stations | Obs mean | Mean bias | RMSE | Corr. Coef. |
|---|---|---|---|---|---|
| Base | 483 | 42.36 | 1.32 | 13.32 | 0.61 |
| Include LNOx | | 42.36 | 6.61 | 29.60 | 0.48 |




## July 1-10, 2011 $PM_{2.5}$ (Left) Base (Right) with LNOx, (Bottom) Verification




| $PM_{2.5}$ 10 days avg | Stations | Obs mean | Mean bias | RMSE | Corr. Coef. |
|---|---|---|---|---|---|
| Base | 1801 | 12.67 | -3.47 | 13.22 | 0.25 |
| | | 12.67 | -3.07 | 13.58 | 0.24 |

| $PM_{2.5}$ 10 days avg (UM) | Stations | Obs mean | Mean bias | RMSE | Corr. Coef. |
|---|---|---|---|---|---|
| Base | 276 | 17.71 | -3.66 | 16.40 | 0.23 |
| Include LNOx | | 17.71 | -2.61 | 17.08 | 0.22 |

# Part 3: Data Assimilation Methodology

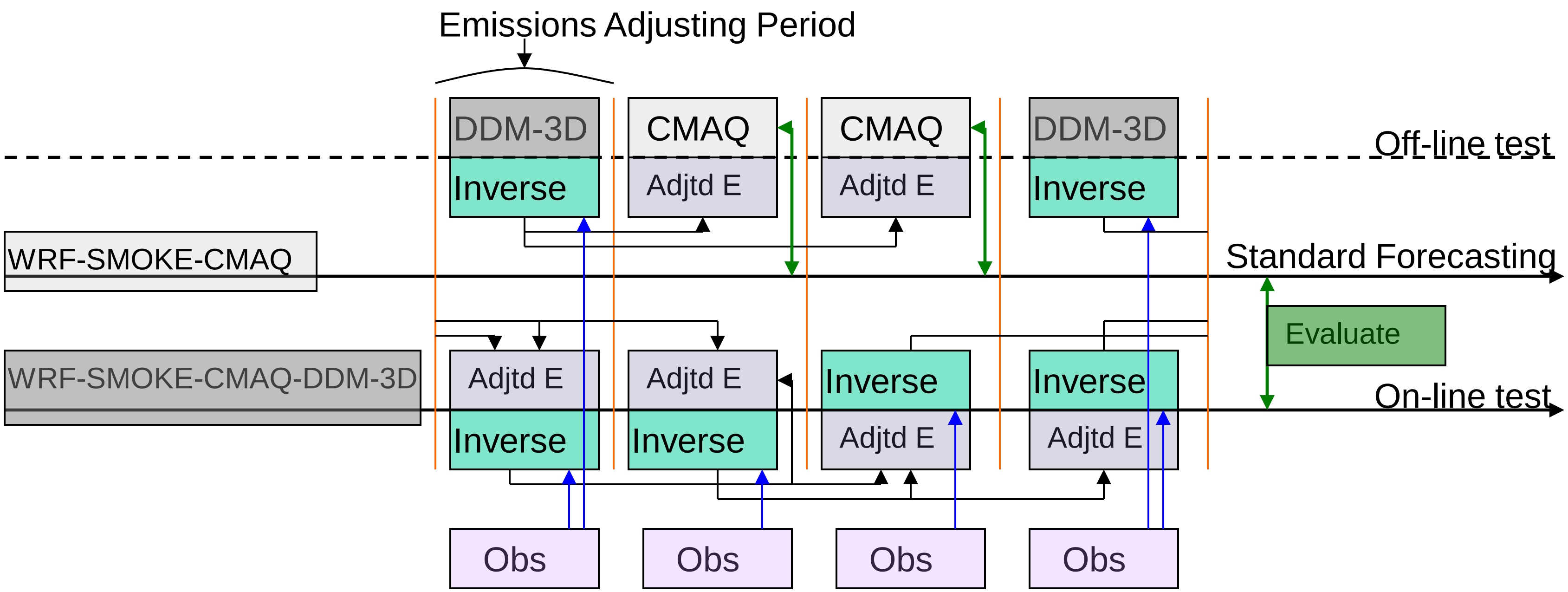
# Optimal Interpolation (OI)

- OI simplifies the extended Kalman filter formulation (Dee et al. *Q. J. R. Meteor. Soc*. 1998) by limiting the analysis problem to a subset of obs.

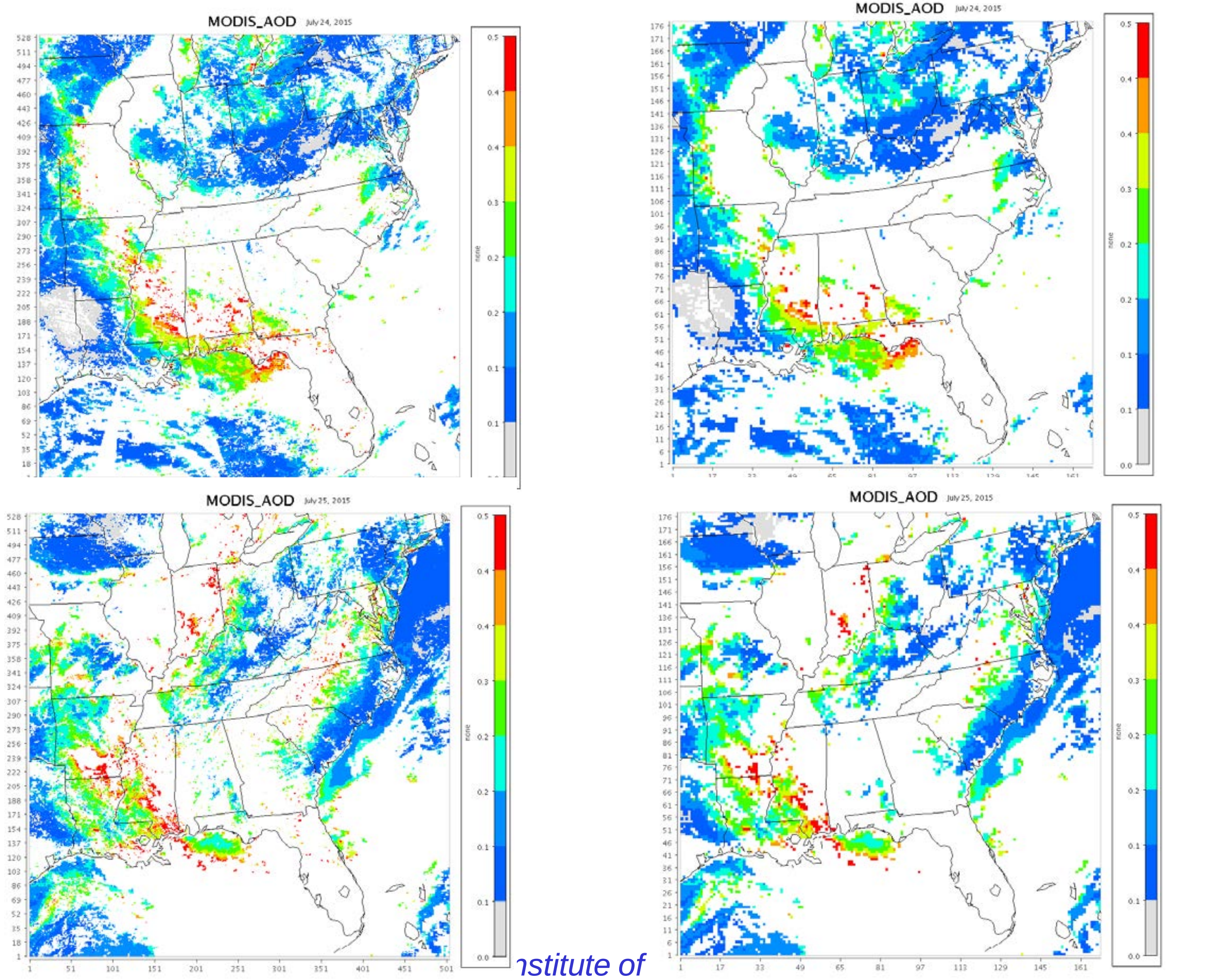
$$X^a = X^b + BH^T(HBH^T + O)^{-1}(Y - HX)$$

- Obs far away (beyond background error correlation length scale) have no effect in the analysis.
- Injection of Obs through OI takes place at 1800 UTC daily.

# Alternative methods: Emissions adjustments and model results based data fusion



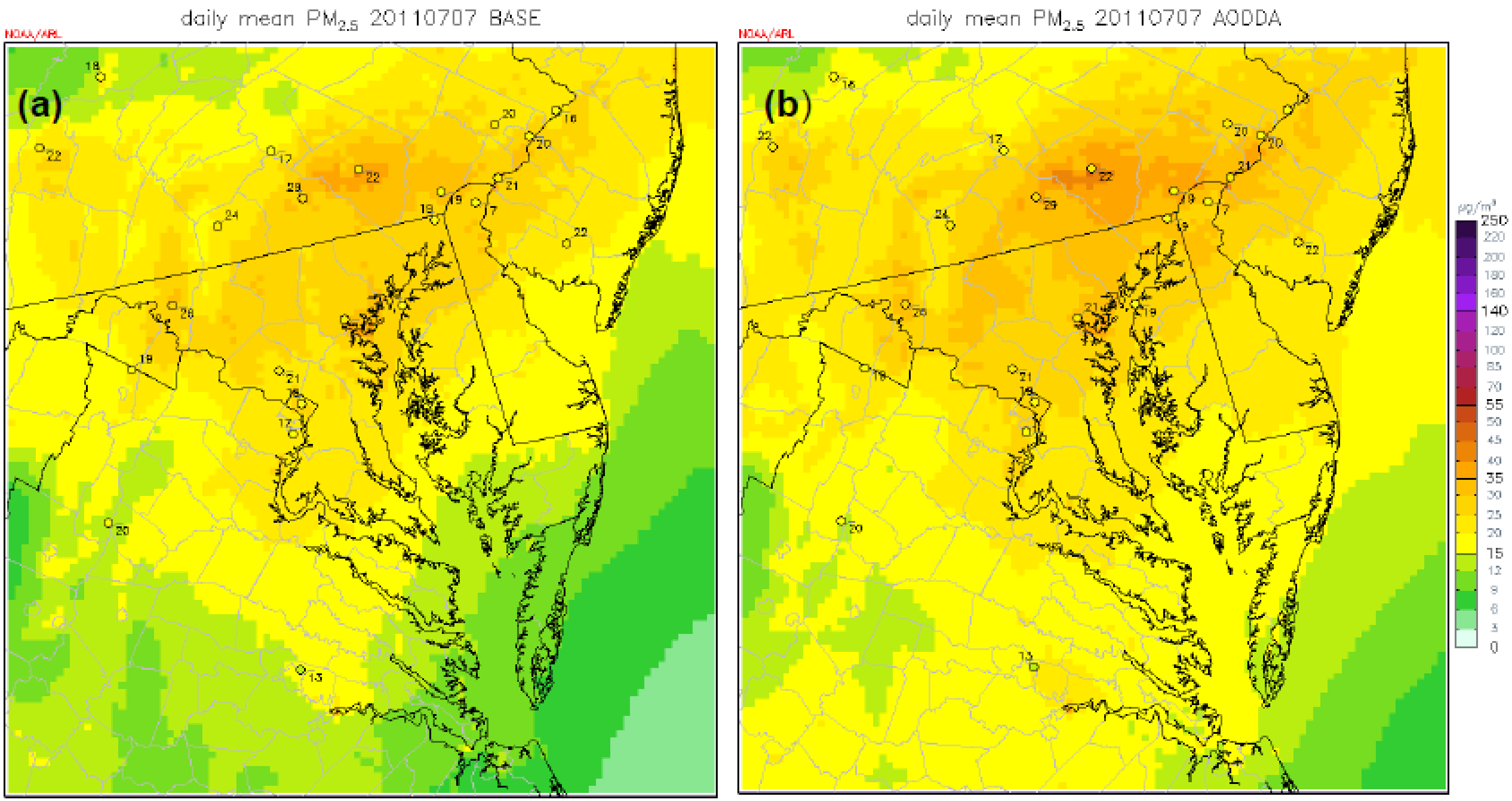
# MODIS L2 C6 AOD Re-gridded Near Real-Time HiRes2 Products: 12-km versus 4-km



# Part 4: Reanalysis fields for SIP modeling and health studies

# Use Reanalysis fields for SIP modeling's initial and boundary conditions

**24 h PM2.5 on 07/07/2013 (a) Base, (b) AOD_DA for DISCOVER-AQ GA_Tech 4 km**




**DISCOVER-AQ GA_Tech 4 km**

| PM2.5 24h avg | Obs mean | Mean bias | RMSE | Corr. Coef. |
|---|---|---|---|---|
| Base | 17.36 | -5.88 | 22.50 | 0.40 |
| With re-analysis field to derive LBC | 17.36 | -3.48 | 22.19 | 0.42 |

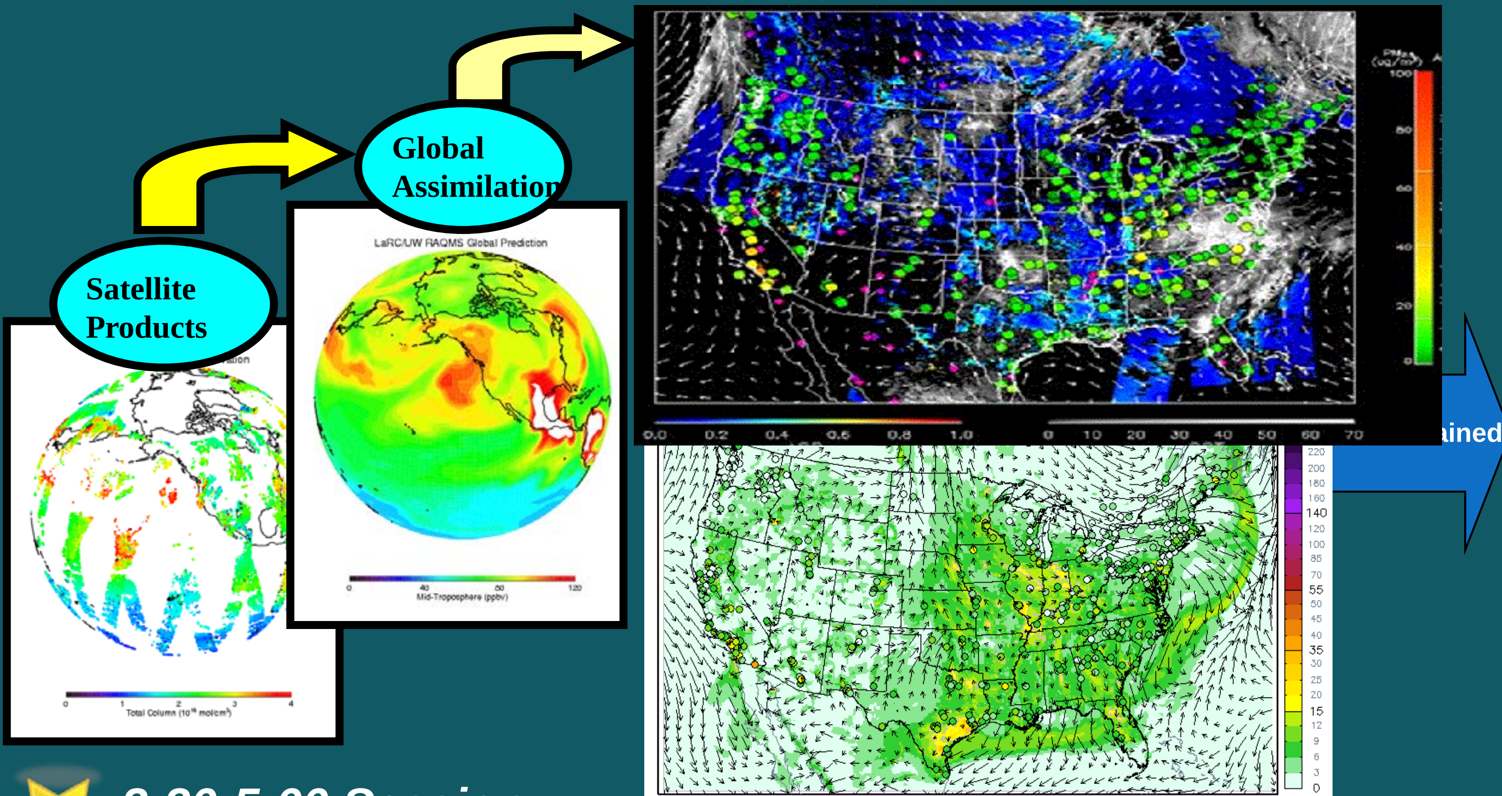
# Summary

- Decision on matching the GFS vertical structure 42-L was made for the chemical reanalysis forward model
  - The reanalysis forward model showed reasonable ozone cross-section in complex terrain
- The reanalysis forward model is tested and used to generate July 2011 reanalysis fields for MDE for SIP modeling
- July 2011 analysis fields was used by Georgia Tech for a 14-day SIP simulation and showed significant improvement in RMSE
- Data Set assimilated: RAQMS (MLS, OMI $O_3$, MODIS AOD); HMS Fire; GOES cloud fraction for photolytic rate correction; MODIS AOD; AQS $O_3$, $PM_{2.5}$
- Assimilate lightning NOx: Use NOAA hourly reporting of the National Lightning Detection Network to derive and distribute LNOx
- Preliminary surface NOx and $O_3$ verification showed over-estimation
- Further improvement of LNOx assimilation algorithm is being test
- Analysis configuration also includes observation set on biogenic emission from the DYNAMO team
- Production FY2010 in conjunction with HTAP support
- Portal via RSIG is being tested

# Supplement

# AQAST Project: Air Quality Reanalysis

## (*Translating Research to Services*)




- \+ AQ Assessments
- \+ State Implementation Plan Modeling
- \+ Rapid deployment of on-demand rapid-response forecasting; e.g., new fuel type,…, etc.
- \+ Health Impacts assessments
- \+ Demonstration of the impact of observations on AQ distributions
- \+ Ingestion of new AQAST products into operations

***3:30-5:00 Session***

**Yang Liu: MODIS C6**

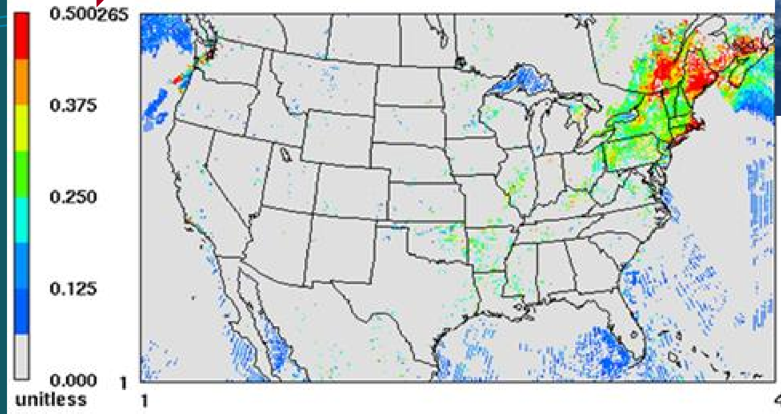
**Alvarado & Hegarty: $NH_3$**

**Huang, McNide, Lee : $T_{Skin}$**

**http://acmg.seas.harvard.edu/aqast/projects.html**

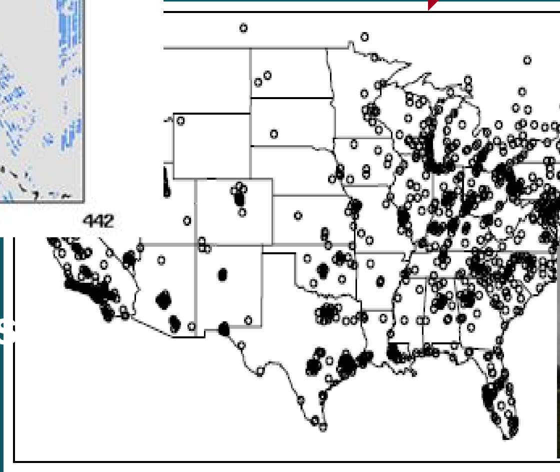
done

## MODIS obs




done

## AIRNow



done

## Cloud-obs Photolysis rates

**GOES-MCIP INTERFACE**

Cloud transmissivity (calculated from satellite retrieved cloud albedo), cloud top pressure, and cloud fraction are prepared for input to MCIP

**MODIFIED MCIP**

GOES retrievals replaces MM5 cloud information being passed to CMAQ. Cloud fraction, transmissivity, cloud base and top heights are passed to CMAQ.

**PHOT in CMAQ**

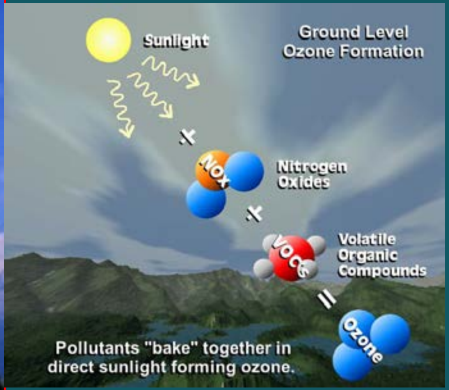
In subroutine PHOT, clear sky photolysis rates will be adjusted for cloud cover based on GOES cloud fraction and cloud transmissivity information.

Interpolated in between.

Cloud Base According to Lifting Condensation Level

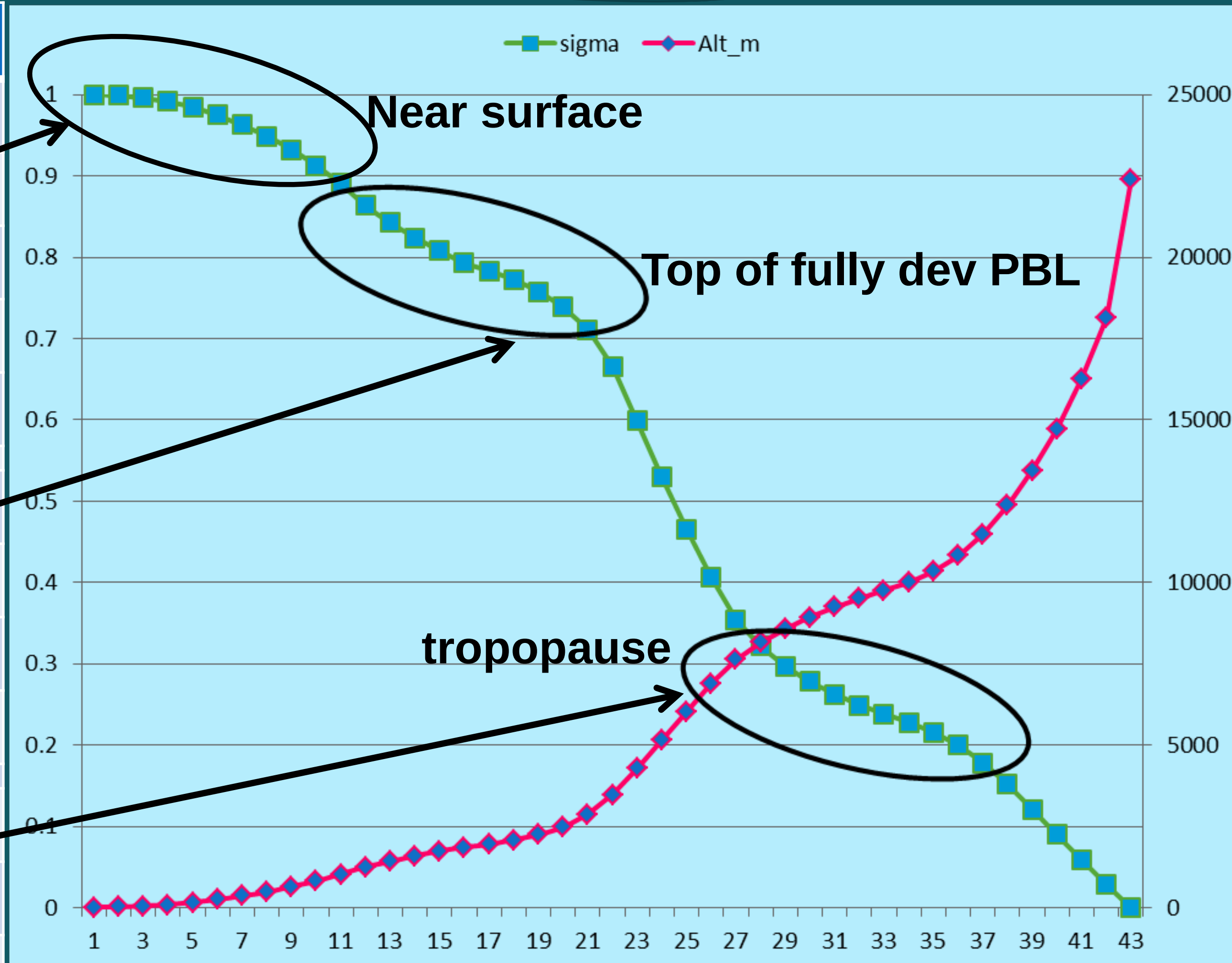
$$T_c = B / \ln\left[\frac{A\varepsilon}{wp_0}\left(\frac{T_0}{T_c}\right)^{1/\kappa}\right]$$


Yet to do Isoprene & PAR

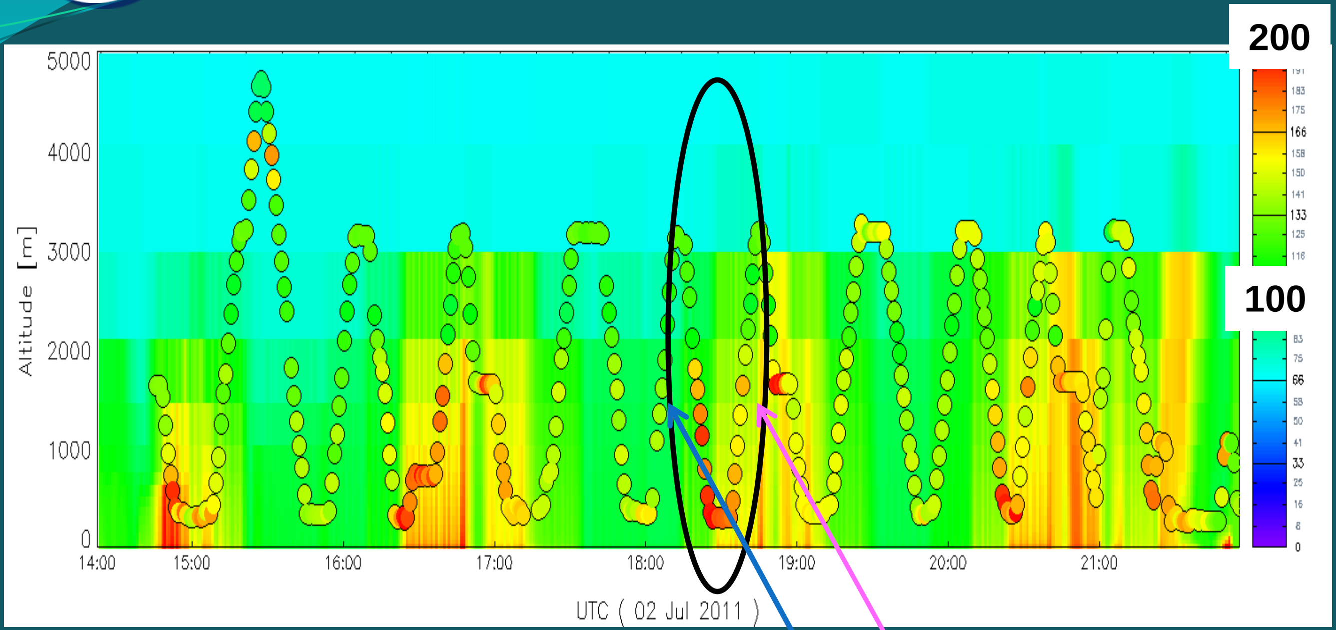


# Re-configuration of vertical structure: Decision to match GFS (NCEP)

| sigma | Pres (hPa) | Z (m) |
|---|---|---|
| 1 | 1013 | 0 |
| 0.999 | 1012 | 4 |
| 0.996 | 1010 | 20 |
| 0.992 | 1007 | 48 |
| 0.985 | 993 | 92 |
| | | |
| 0.864 | 872 | 1245 |
| 0.843 | 852 | 1430 |
| 0.824 | 836 | 1590 |
| 0.808 | 821 | 1735 |
| | | |
| 0.322 | 348 | 8150 |
| 0.297 | 326 | 8580 |
| 0.278 | 310 | 8940 |
| 0.262 | 296 | 8580 |
| | | |

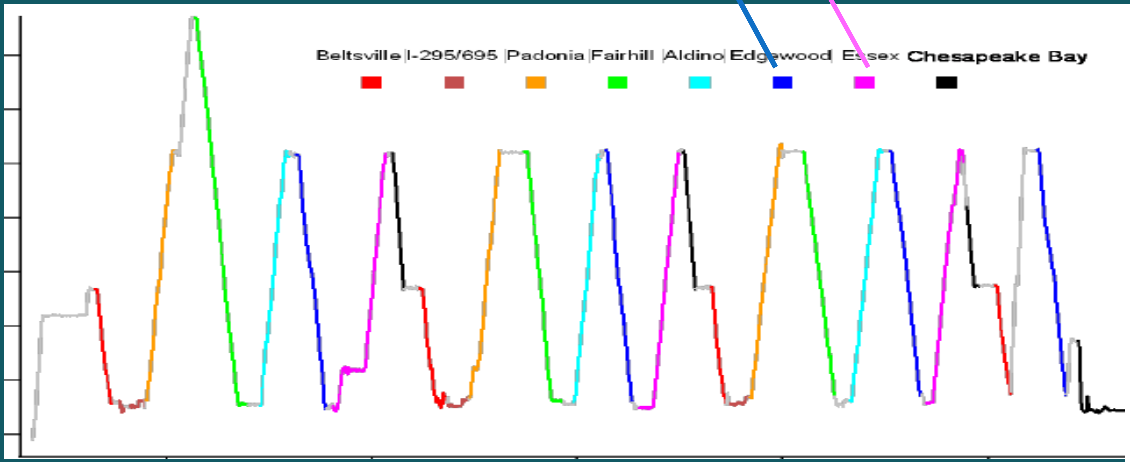


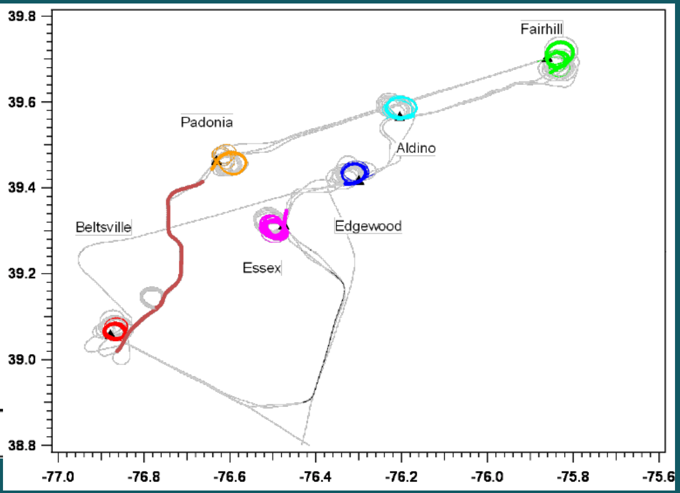
# CO (ppb) along the P3 Flight – July 2 2011: AOD_DA case vs. Obs



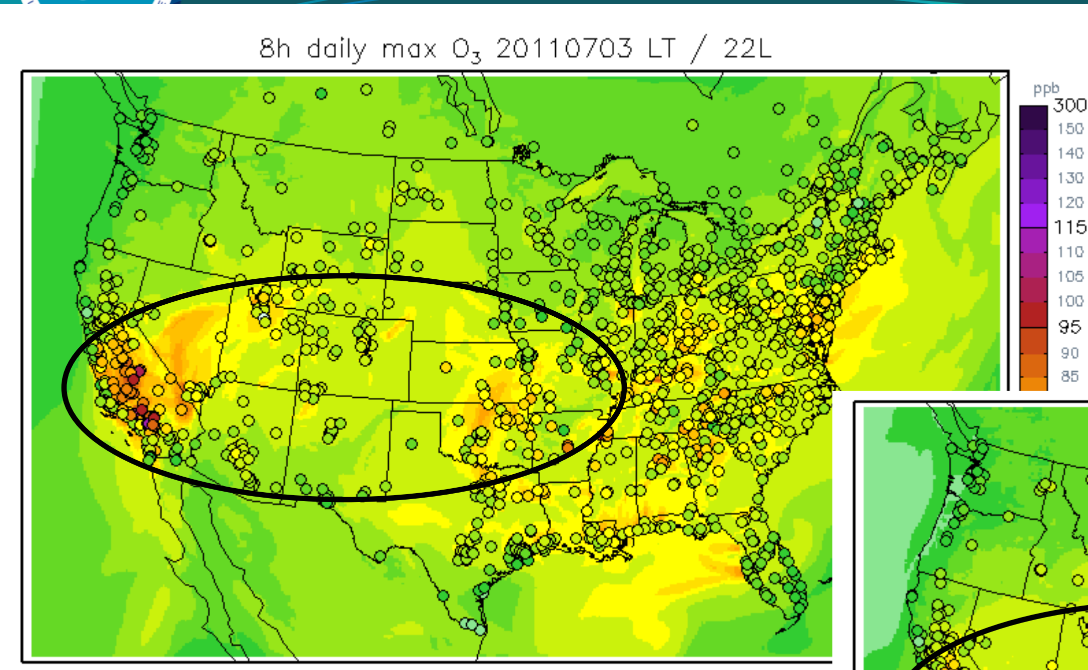

P3 Three and a half loops:
Beltsville
Padonia
Fairhill
Aldino
Edgewood
Essex
Chesapeake Bay

**Pan & Lee et al., AE 2014**

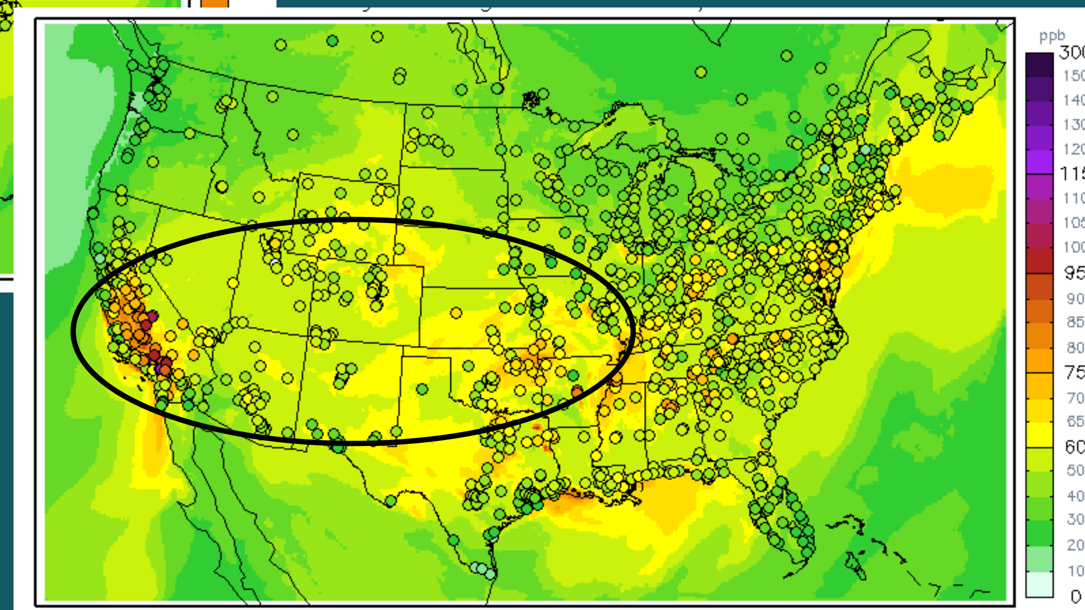


# NMMB-CMAQ4.7.1 (22L)



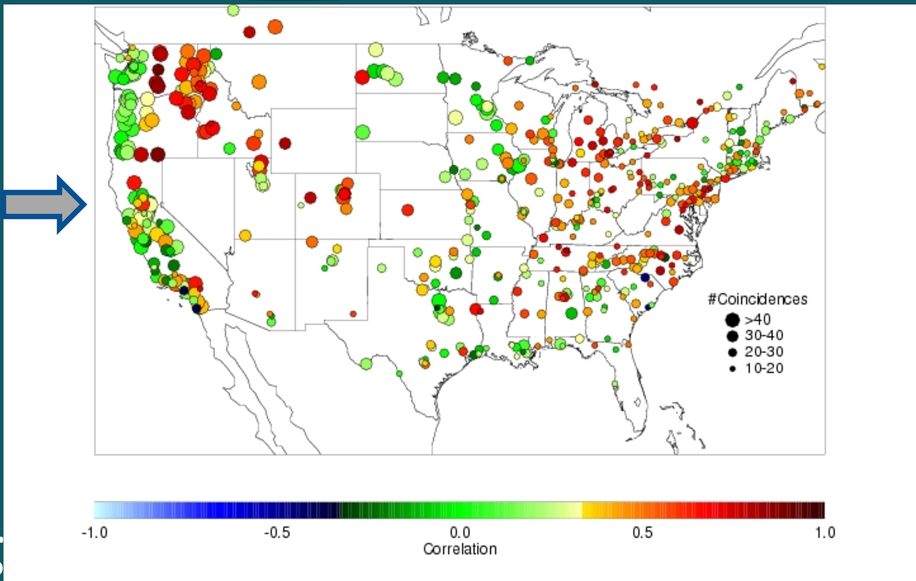

# WRF_ARW-CMAQ4.7.1 (42L)




**Daily maximum 8 h averaged surface $O_3$ on July 3 2011**
**The over bias across a large swath in the Southern U.S. was reduced by 42L**

# National correlation map between AIRNow measurement and MODIS AOD

Typically good correlation between surface $PM_{2.5}$ and AOD retrieved by MODIS




Courtesy :NESDIS

## MODIS (Moderate Resolution Imaging Spectroradiometer) AOD

| | |
|---|---|
| **Orbit:** | **705 km, 10:30 a.m. descending node (Terra) or 1:30 p.m. ascending node (Aqua)** |
| **Swath Dimensions:** | **2330 km (cross track) by 10 km (along track at nadir)** |
| **Spatial Resolution:** | **250 m (bands 1-2)**<br>**500 m (bands 3-7)**<br>**1000 m (bands 8-36)** |

http://terra.nasa.gov/About/