Advancements in Operational CMAQ MODIS AOD data-assimilation at Baron Advanced Meteorological Systems During Forecast Year 2013

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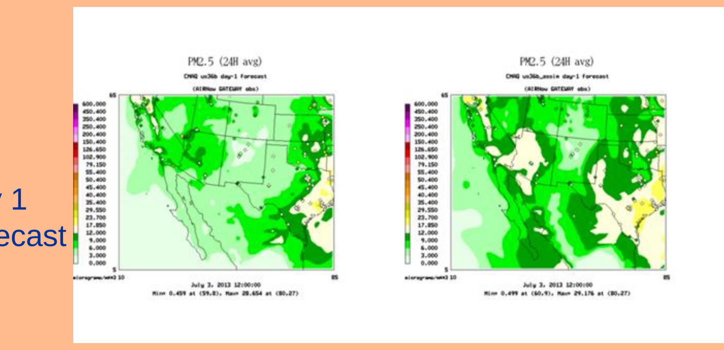
CMAS 2014 Model Development: P21

1. Operational CMAQ forecasting with MODIS AOD Data Assimilation:

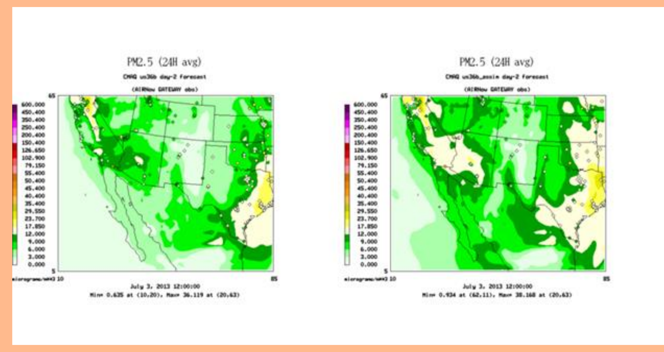
Baron Advanced Meteorological Systems (BAMS) has been engaged in operational numerical air quality prediction (NAQP) for well over a decade. Recently, under a NASA grant, an observation-space variational data-assimilation sub-system was developed and implemented to provide the CMAQ model with remotely-sensed aerosol information. The initial CMAQ-DA was run offline for approximately a year, showing good promise in some areas of the country, but more equivocal results in others. Detailed examination of the results suggested that improvements could be made by utilizing available surface PM2.5 observations within the assimilation system. This approach was implemented and based on significant improvements in the cycled-analysis model, forecast runs were then initiated. This poster describes improvements to the DA subsystem and quantitative improvements in day-1 and day-2 24-hr average surface PM2.5 forecast results as compared to the non-data-assimilating CMAQ forecast model.

No MODIS Assimilation | MODIS TAU Assimilation

Day 1 Forecast



Day 2 Forecast



- Partnering with the VISTA RPO, NCDENR and NASA, BAMS developed/tested/evaluated assimilation of MODIS AOD data into CMAQ V4.51 (soamods, CB4) using 2002 surface observations and annual run-results.

- MODIS AOD is captured using both "Dark Target" and Deep Blue" algorithms, the "Deep Blue" providing additional coverage over bright reflecting surfaces

In light of improvements described herein, BAMS now makes the new CMAQ-DA analysis and forecast routinely available to clients and customers. Applications for both operational forecasting and exceptional event analysis are available.

2. MODIS AOD Acquisition, Q/A and Assimilation into CMAQ

"Forward Operator" $T_{b\lambda} = H_{mt}(C_m) + \varepsilon_{b\lambda}$ (1) Model Mass Concentration to AOD

- Requires a method for calculating AOD as the vertical integral of light extinction due to modeled aerosols through the depth of the model atmosphere: REVISED IMPROVE METHOD (e.g. Morris (2009))

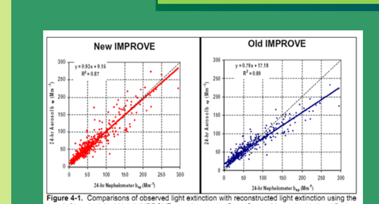


Figure 4-1. Comparisons of observed light extinction with reconstructed light extinction using the new (left) and original (right) IMPROVE equations at the Great Smoky Mountains National Park.

$b_{Sulfate}$ = 2.2 x f_S(RH) x [Small Sulfate] + 4.8 f_L(RH) x [Large Sulfate]
$b_{Nitrate}$ = 2.4 x f_S(RH) x [Small Nitrate] + 5.1 f_L(RH) x [Large Nitrate]
b_{EC} = 10 x [Elemental Carbon]
b_{OCM} = 2.8 x [Small Organic Mass] + 6.1 x [Large Organic Mass]
b_{Soil} = 1 x [Fine Soil]
b_{CM} = 0.6 x [Coarse Mass]
b_{NaCl} = 1.7 x f_{SS}(RH) x [Sea Salt]
b_{NO2} = 0.33 x [NO_2 (ppb)]

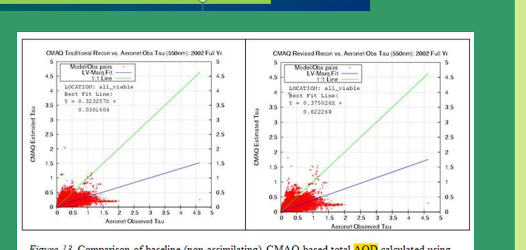


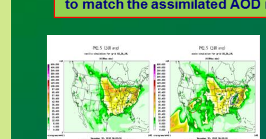
Figure 13. Comparison of baseline (non-assimilating) CMAQ-based total AOD calculated using the revised-IMPROVE method (right) and with the traditional IMPROVE method (left) against all viable surface AERONET observations for the 2002 annual VISTAS simulation.

"Optimal Analysis" of estimated Tau $T_{a\lambda} = T_{b\lambda} + P_b H^T [H P_b H^T + R_o]^{-1} [T_{o\lambda} - H(T_{b\lambda})]$ (2) Data Assimilation Step

- Implemented as an "observation space" formulation following the NRL NAVDAS; Zhang et al. (2008); Daly and Barker (2001)
- Requires RMSE error models for both MODIS AOD and CMAQ AOD. Surface AERONET AOD observations are used as "ground truth"
  - For MODIS AOD; adapted from Zhang and Reid (2006, Table 4), Zhang et al. (2008, eq. 5), and Hyer et al. (2011, Table 3).
  - For CMAQ AOD, adapted from Zhang et al. (2008).
  - Because MODIS AOD error model divides east and west US, CMAQ error equations were subdivided at -100W.
  - An error correlation model was adapted (Zhang et al, 2008) to compute the ECV matrix for CMAQ errors

Initial "Inverse Operator" Had only linear-scaling in the vertical to match the assimilated AOD result

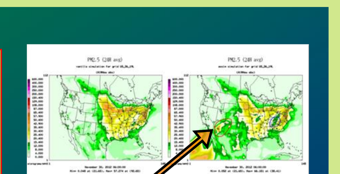
$C_m = H_{tm}(T_{a\lambda}) + \varepsilon_m$ (3) Analyzed AOD to Model Mass Concentration



Once the Tau increment is known in each CMAQ vertical column, the non-linear revised-IMPROVE equations are iterated to recover the newly analyzed aerosol optical depth by adjusting the aerosol constituents:

- For increasing Tau, all background accumulation or coarse mode aerosol species concentrations are adjusted upwards except:
  - Over the ocean: sulfates, nitrates, and chlorine
  - Near the coastline: sulfates
  - Inland: sulfates, sea-salts
- For decreasing Tau, all accumulation and coarse mode species may be adjusted downward
- Nothing is done to adjust modeled NO2, which is assumed "as good as can be" in the model due to its short life-time and relatively local nature
- Further species discrimination in the iterated-inverse adjustment is made based on "smoke" versus "dust" categorizations available from MODIS

Revised "Inverse Operator" preferentially nudges concentrations in the vertical with different weights to match both the assimilated (final analyzed) total column AOD result *and* to ensure the surface PM2.5 values do not exceed the observations – when TAU increases due to the assimilation. Further, over the ocean, TAU increases always result in nudged model concentrations above the PBL only.



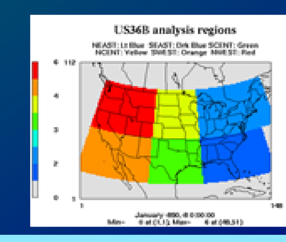
- Analysis showed that when MODIS detected a higher AOD than the initial CMAQ estimate, the inversion-step back to model concentrations sometimes resulted in CMAQ surface PM2.5 that was "too hot". This implied that relatively more of the increased concentration should be place above the PBL.

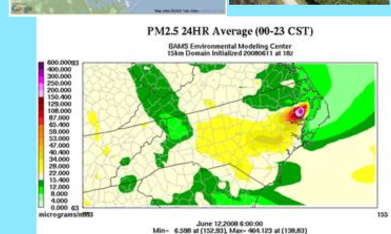
- The revised inversion step makes use of surface PM2.5 to mitigate the above: modeled PBL heights are used to preferentially nudge model concentrations above the PBL more heavily such that the resulting modeled surface PM2.5 does not exceed the "gridded-observed" PM2.5. This is a first improvement – with more to come (discussed later).

3. Initial Performance Analysis of Improved System

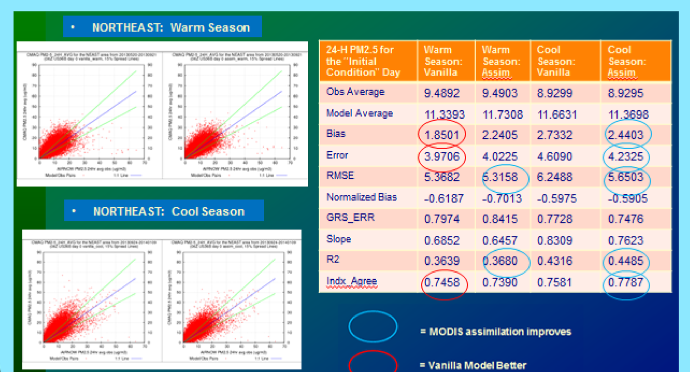
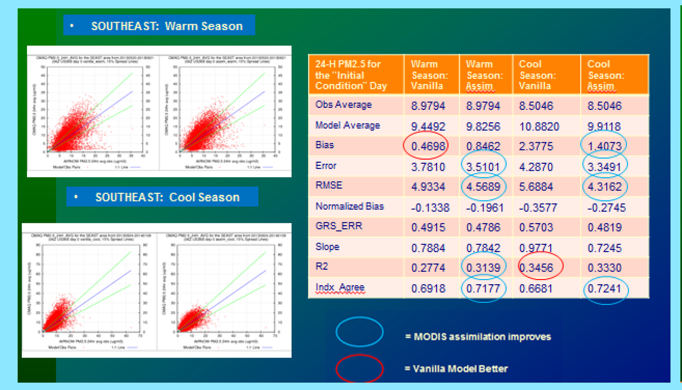
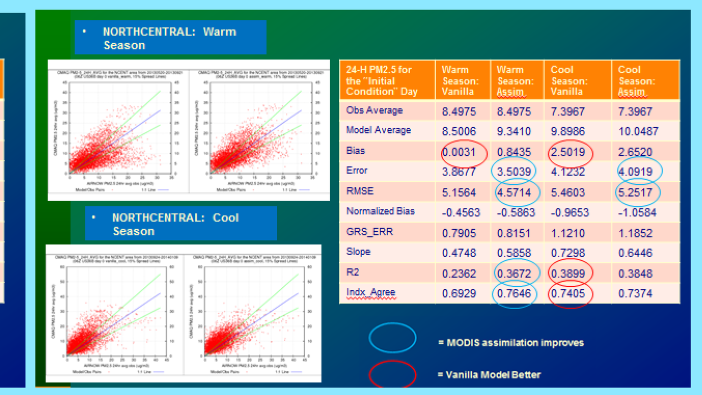
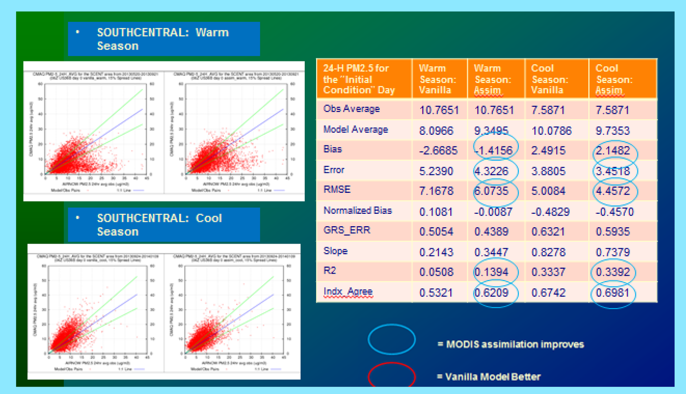
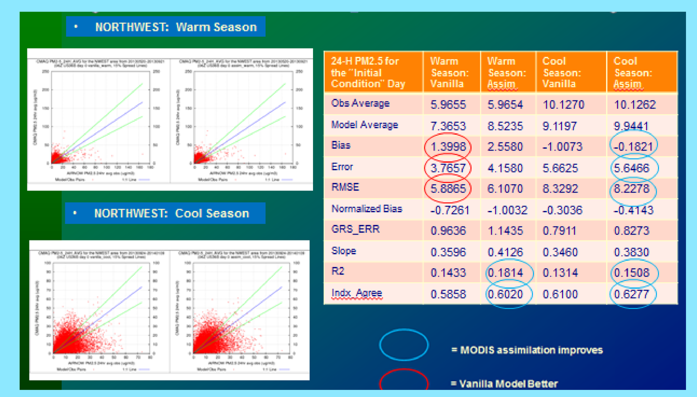
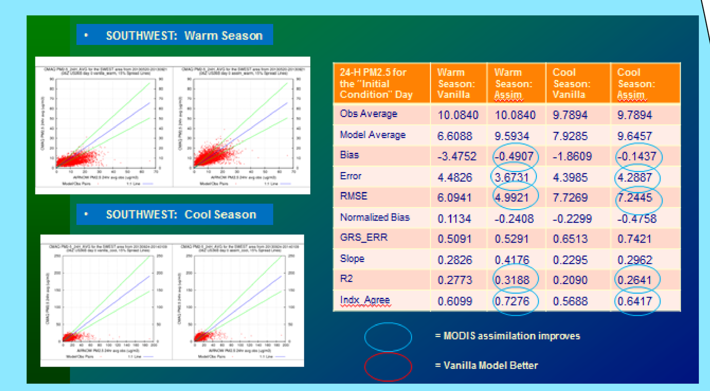
- CMAQ is being run in both "vanilla" mode (non-DA cycling and forecast) and "MODIS-DA" mode (cycling and forecast) using the newly implemented surface PM2.5 data
- Runs began in late Spring of 2013 and continued through Summer/Fall/Winter
- Due to occasional MODIS outages and network glitches, the dataset is not continuous but features about 170 total model days for comparison
- Preliminary analyses of both the final analysis (initial condition) and the day-1 and day-2 forecast results comparing "vanilla" and "MODIS-DA" were completed, with a focus on daily-average total surface PM2.5 observations as reported through the AIRNow "gateway"
- Performance analysis in six CONUS sub-regions and "warm" (87 days) versus "cold" (84 days) season has been conducted.

Defined as	minlat	maxlat	minlon	maxlon
Southeast	25	37	-90	-70
Northeast	37	50	-90	-65
SouthCentral	25	37	-105	-90
NorthCentral	37	50	-105	-90
SouthWest	25	37	-125	-105
NorthWest	37	50	-125	-105

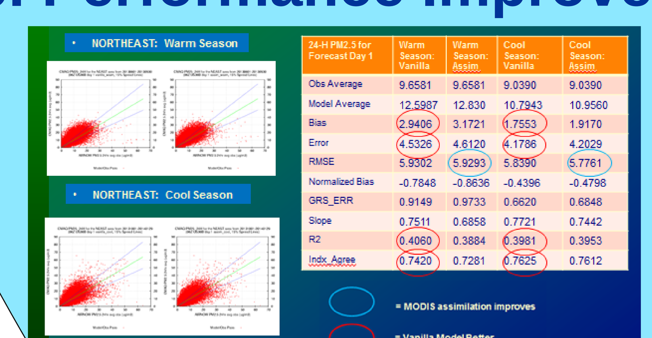
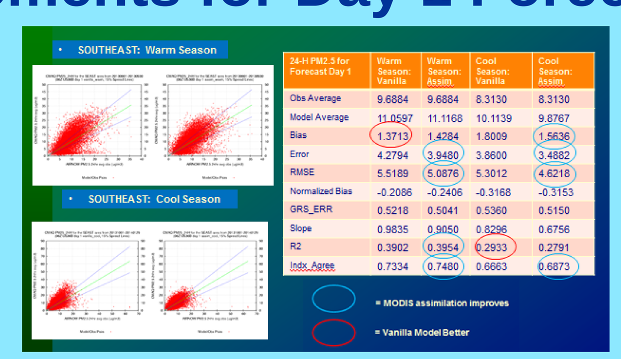
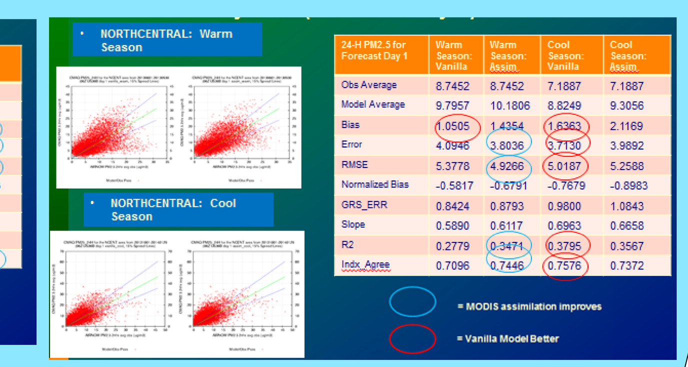
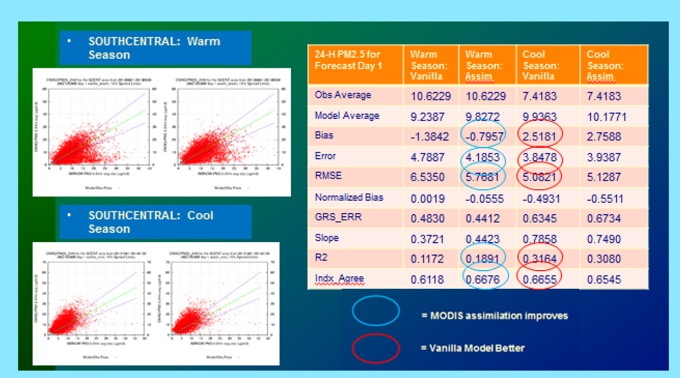
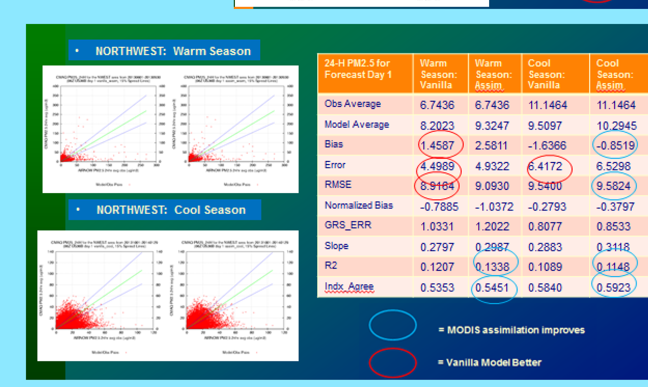
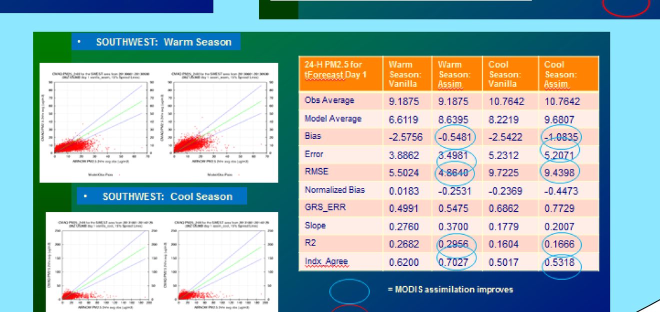




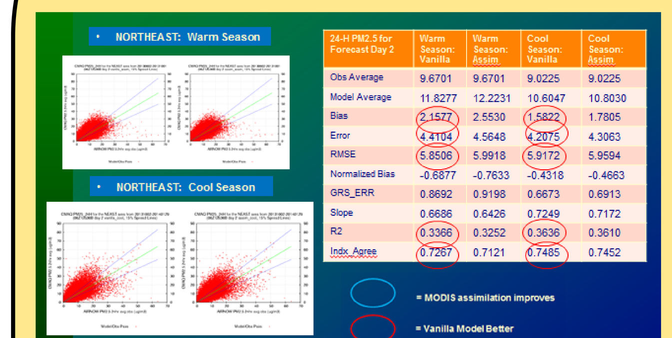
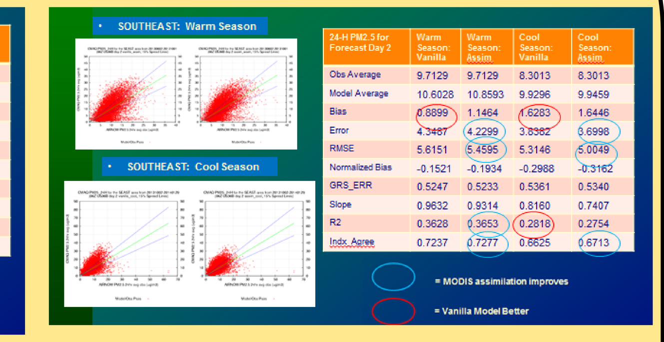
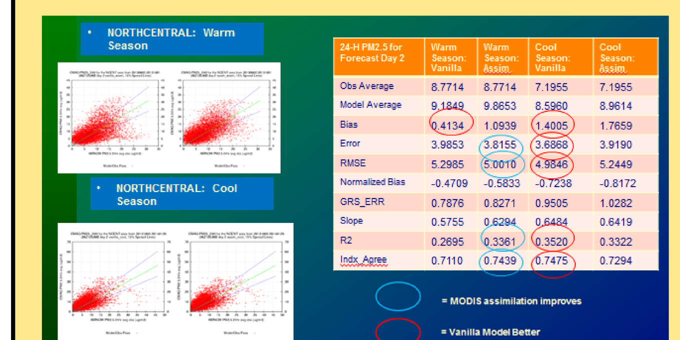
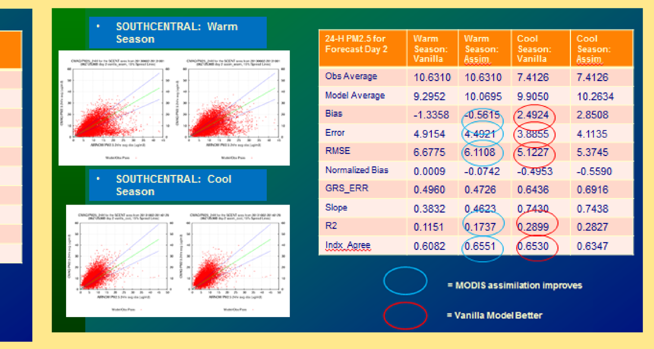
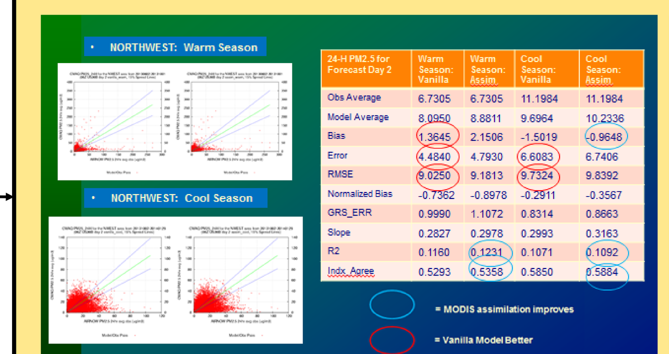
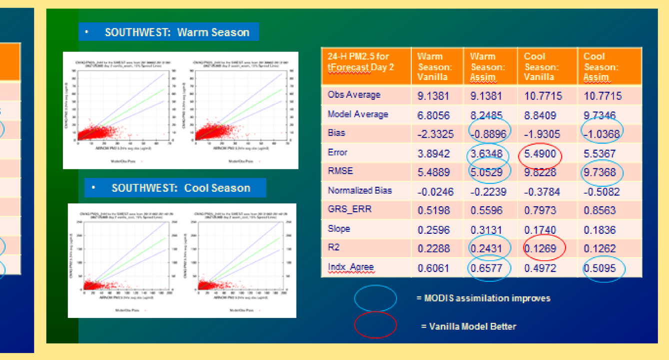
3a. Performance Improvements for Analysis Cycle

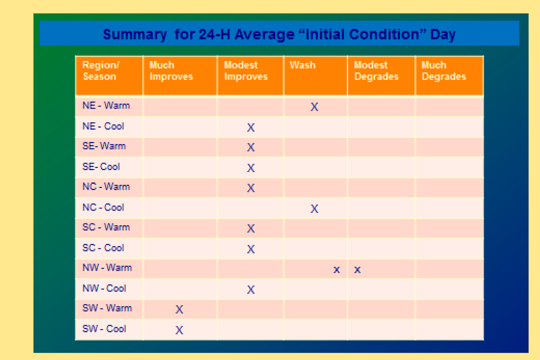
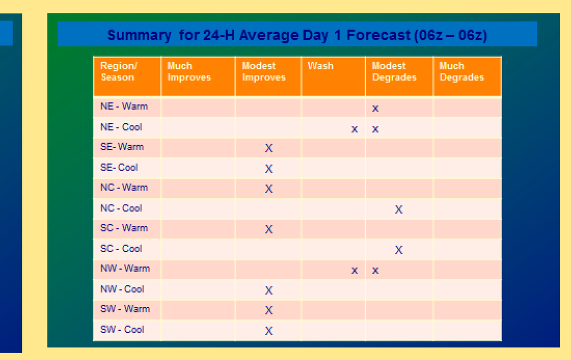
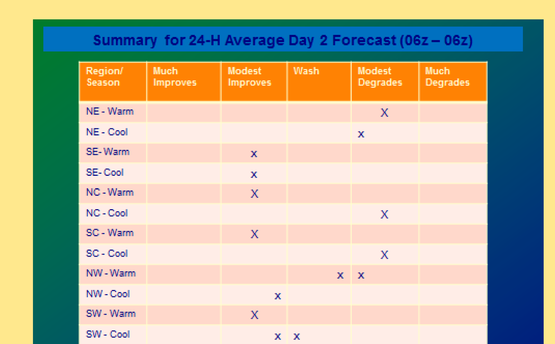
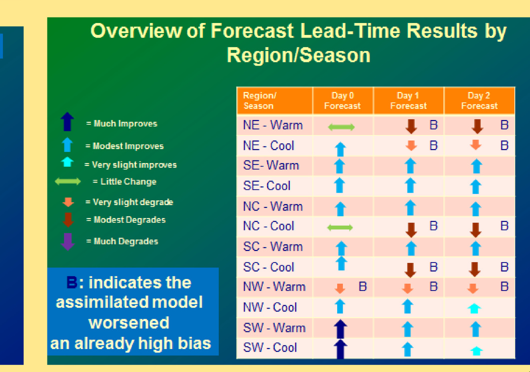
3b. Performance Improvements for Day 1 Forecasts

3c. Performance Results for Day 2 Forecasts

4. Composite and Summary Performance Results

6. Conclusions and Ongoing Work

- Initial Performance Analysis of the BAMS CMAQ-MODIS-DA analysis and forecast model for Warm and Cool Seasons by Six Sub-regions shows:
  - Very encouraging overall improvements, extending out to at least the 2nd forecast day in many regions
    - More consistent improvements during the warm season, when cloudiness is not as much of an issue
    - Impressive improvements in the SW US (all seasons) and South Central during the warm season
  - Some areas of concern –
    - NE US where vanilla performance is already very good
    - The Pacific NW warm season (clouds?)
    - Cool season in the central US (clouds?)
- Analysis of regions/seasons that did degrade show that *increases* in an already high bias played a role in statistical degradation. Thus we have now implemented additional vertically-sensitive improvements in the TAU-inversion step using real-time PM2.5 surface observations. Analysis of these new results is ongoing.