New Assimilation Approach, CONUS 12 km Evaluation and Ensemble FDDA

US Environmental Protection Agency, ORD, NERL, Atmospheric Modeling and Analysis Division (AMAD)

Outline of Discussion

- Overview of recent efforts at the US EPA to improve our WRF modeling for Air Quality research and applications
- New very high resolution landuse datasets for better modeling of land-surface processes
- WRF-CMAQ: a fully coupled modeling system of the future
- AMAD's WRF new assimilation (nudging) strategy
- Recent model performance of US EPA's annual CONUS 12 km simulations
- WRF-CMAQ ensemble modeling

Weather Research and Forecast Model: Historical Contributions

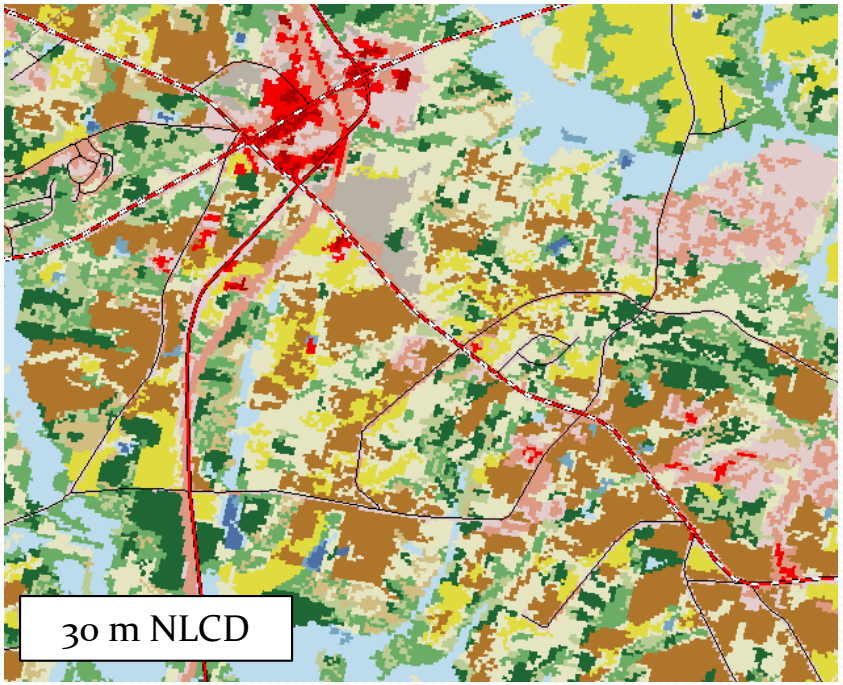
- Involved in initial workgroups that were formed to guide the development of WRF in late 90's, early 2000's
- Contributed to the funding of the development of grid nudging/data assimilation in WRF (~2006-2007)
- Implemented AMAD developed physics in WRF
  - Asymetric Convective Model V2 (Pleim 2007)
  - Pleim-Xiu Land surface model (Xiu and Pleim, 2001; Pleim and Xiu, 2003; Pleim and Gilliam, 2009)
- Meteorology-Chemistry Interface Processor (MCIP)
- WRF-Chem (NCAR)

Current WRF Research and Contributions

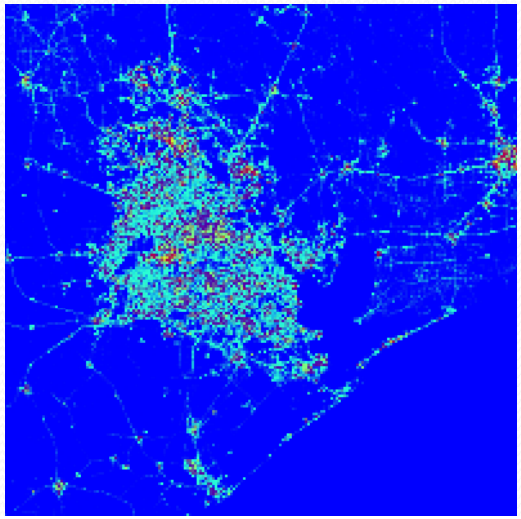
- Continued updates and improvement to ACM2, P-X LSM
- Development of land-surface dataset for WRF
  - NLCD 1992, 2002, 2006; MODIS 2006
- WRF-CMAQ (US EPA/AMAD)
  - Direct (SW/LW rad) and indirect effects (microphysics) of aerosols on meteorology
- Assimilation of wind profiler observations to improve lower troposphere transport
- Ensemble FDDA using SREF or other weather forecast ensemble systems
- Other active AMAD research that may yield significant model improvements
  - Use of impervious surface, canopy fraction and canopy height in LSM
  - WRF Regional Climate Modeling
  - Subgrid scale cloud fraction from convective to radiation scheme
  - Nudging of moisture added to spectral nudging scheme in WRF
  - More flexibility in vertical nudging coefficients to allow lower or no nudging in the upper troposphere and lower stratosphere

Land-surface Datasets

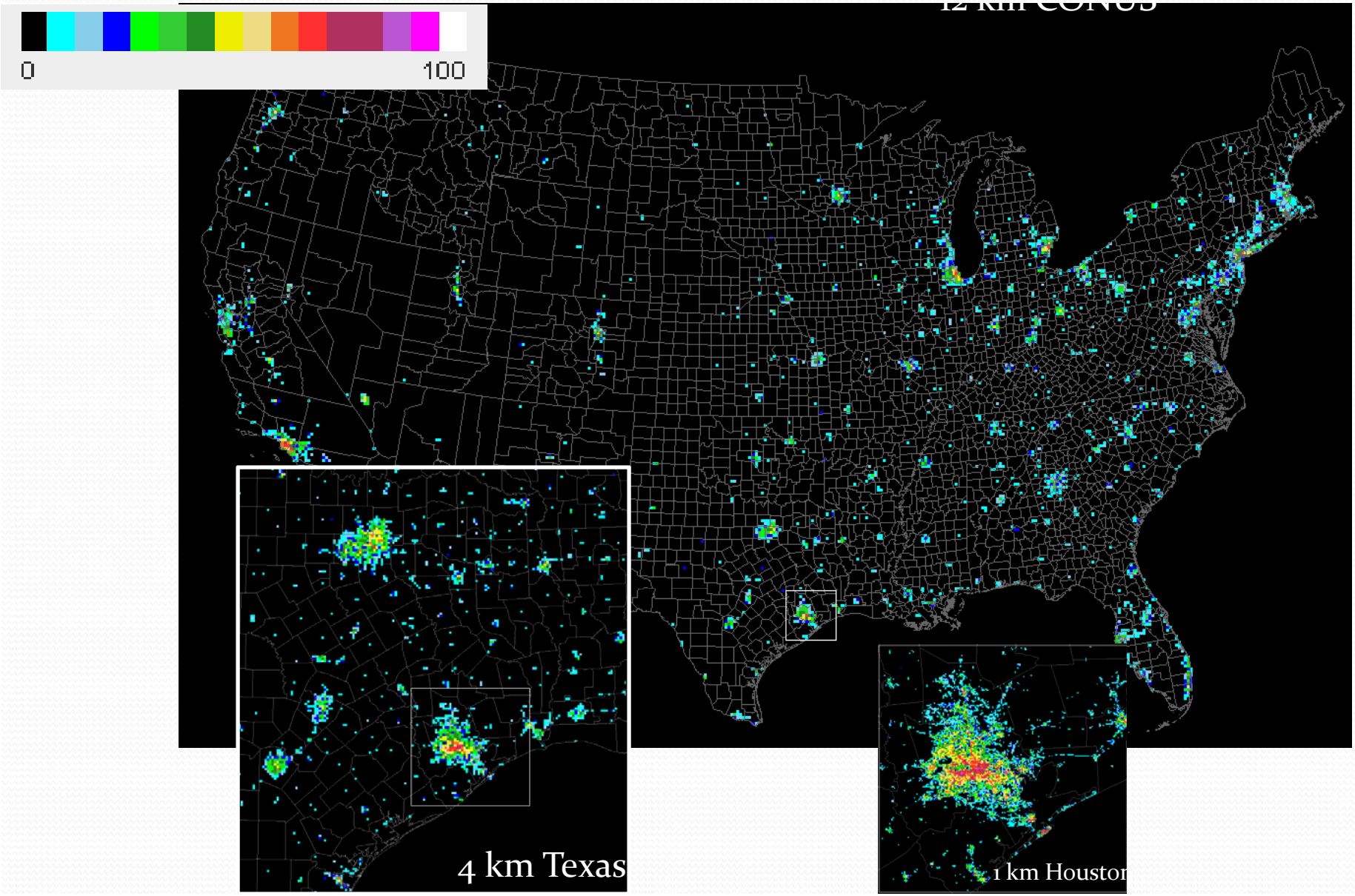
- Very high resolution National Land Cover Dataset (NLCD): approx. 30 m data for US with 4 urban categorizations
- Utilized in P-X LSM fractional land use scheme
- Developed a tool to map these data to user defined model domains
- Developed datasets (NLCD 1992, NLCD 2002, NLCD 2006) for distribution with the WRF model this summer
- Other NLCD-based data is available and will be leveraged in the future; i.e., impervious sfc. frac., forest canopy coverage and height



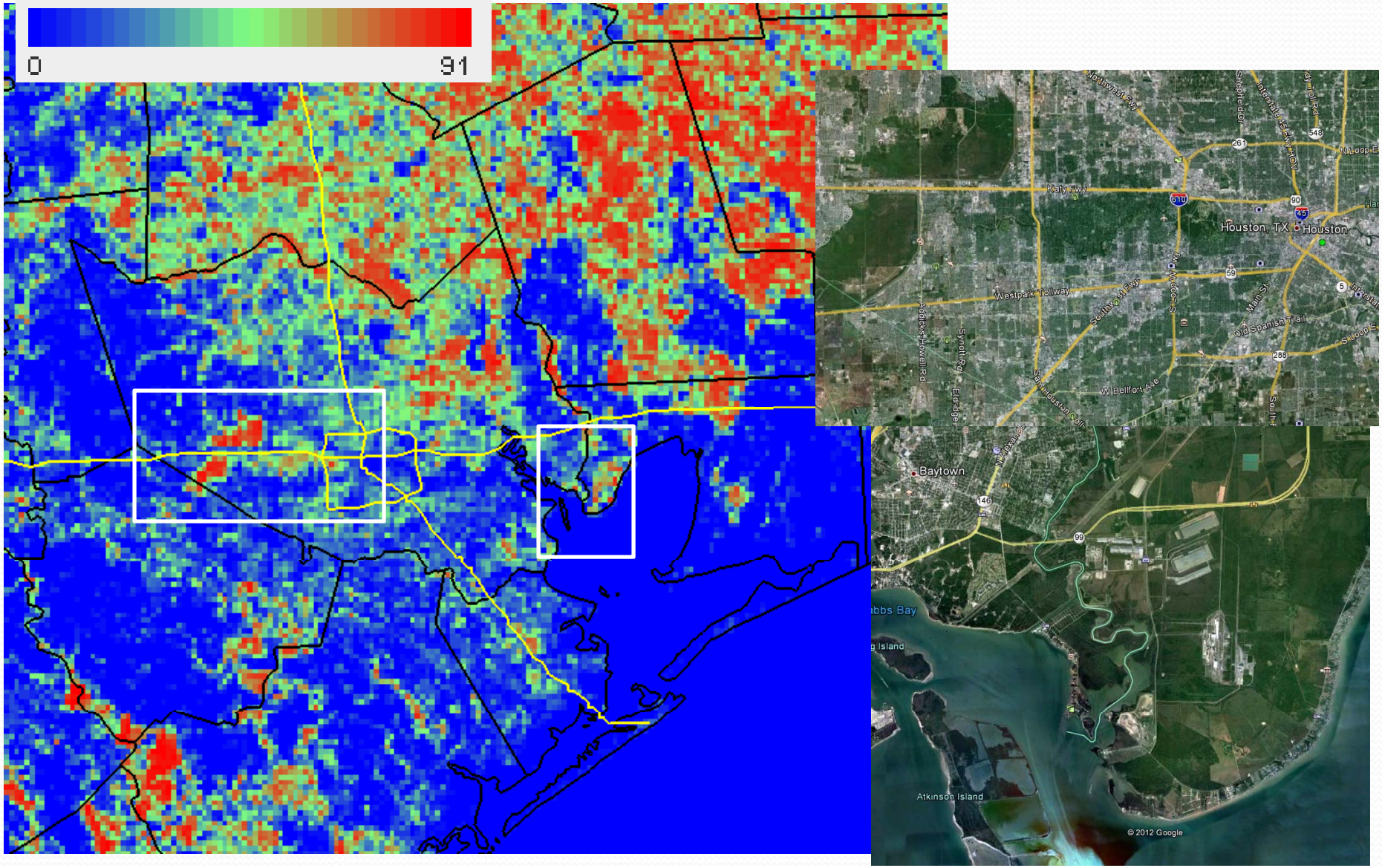
Houston, Tx
Gridded 1 km
Medium
Developed
Urban



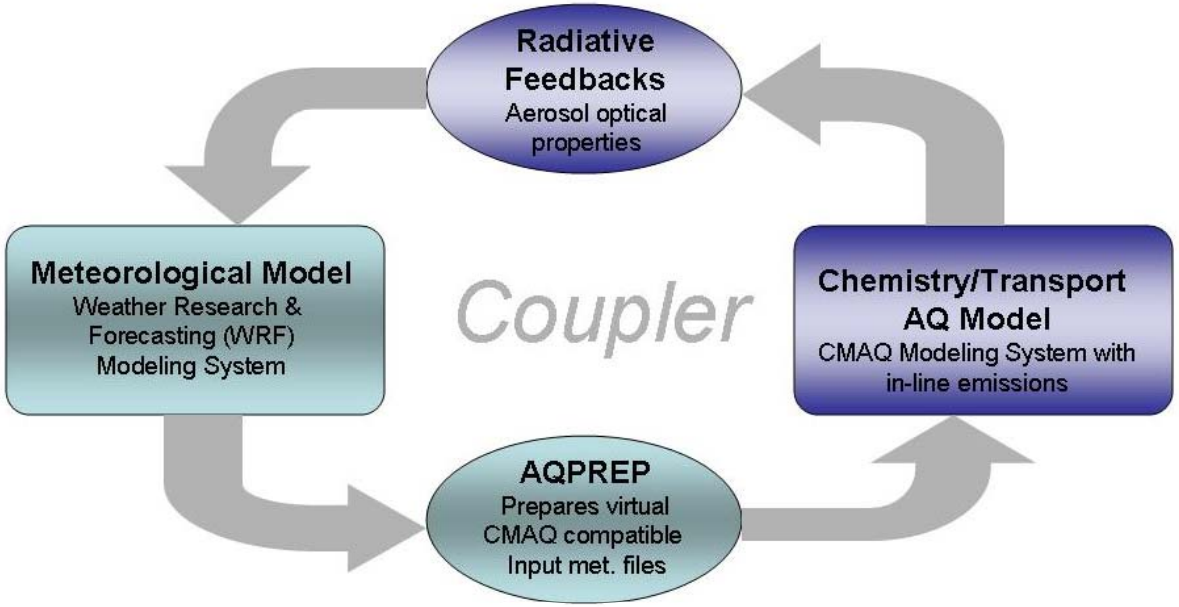
Impervious Fraction (%) for Multiple Grid Scales



Canopy Fraction (%)



WRF-CMAQ (tightly coupled met-aq modeling system)



Aerosol Optics & Feedbacks

- Volume weighted refractive indices for each wavelength based on
  - Composition and size distribution
  - SO_4^{2-}, NO_3^-, NH_4^+, Na^+, Cl^-, EC, POA, anthropogenic and biogenic SOA, other primary, water
- Both RRTMG and CAM Shortwave radiation schemes in WRF
- Effects of aerosol scattering and absorption on photolysis
- Effects of O_3 on long-wave radiation

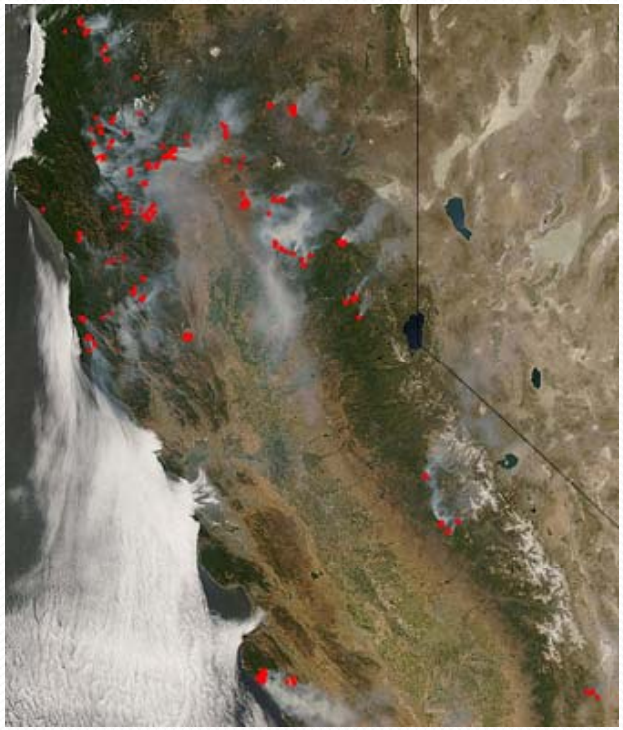
***Flexible* design of model coupling allows**

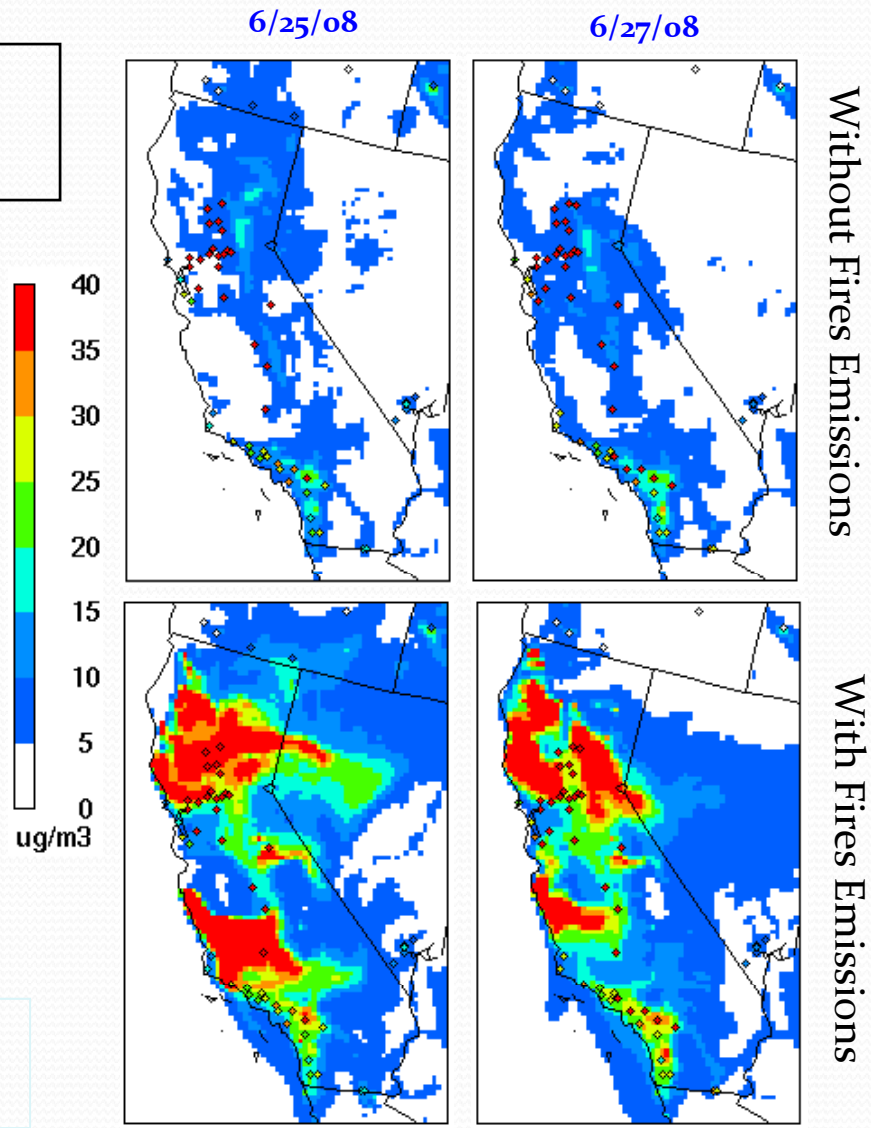
- data exchange through memory resident buffer-files
- flexibility in frequency of coupling
- identical on-line and off-line computational paradigms with minimal code changes
- both WRF and CMAQ models to evolve independently;

  Maintains integrity of WRF and CMAQ

WRF-CMAQ: California Fire Case Study

Widespread wildfires resulted in significant PM pollution during mid/late June 2008 in California and surrounding states





Daily-avg. $PM_{2.5}$

- Fuel loading: National Fire DangerRating (NFDR) system
- Emission Factors: Fire Emission Production Simulator (FEPS) Function of fuel class

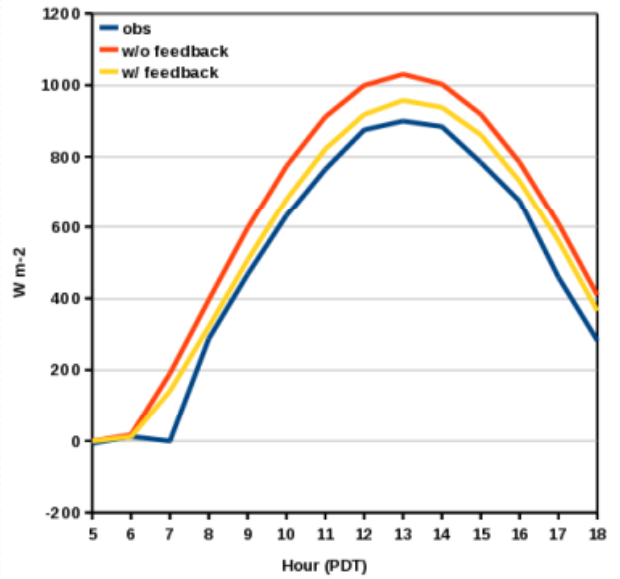
WRF-CMAQ: California Fire Case Study

Shortwave Radiation Reaching the Surface

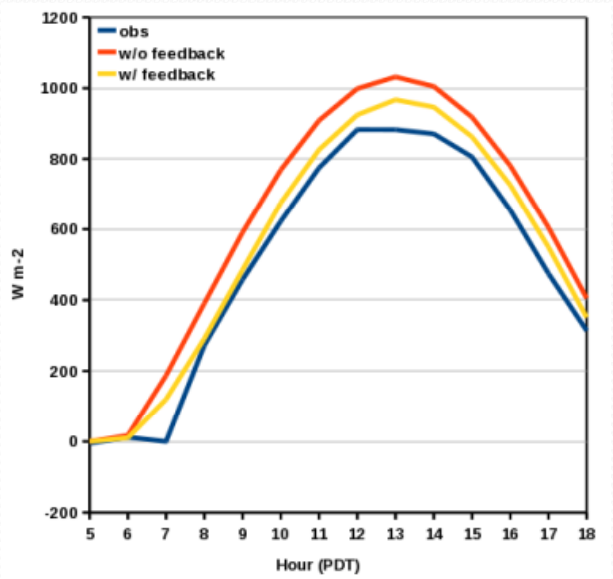
With and Without Feedbacks

Comparison with measurements at ISIS site at Hanford, CA

June 26



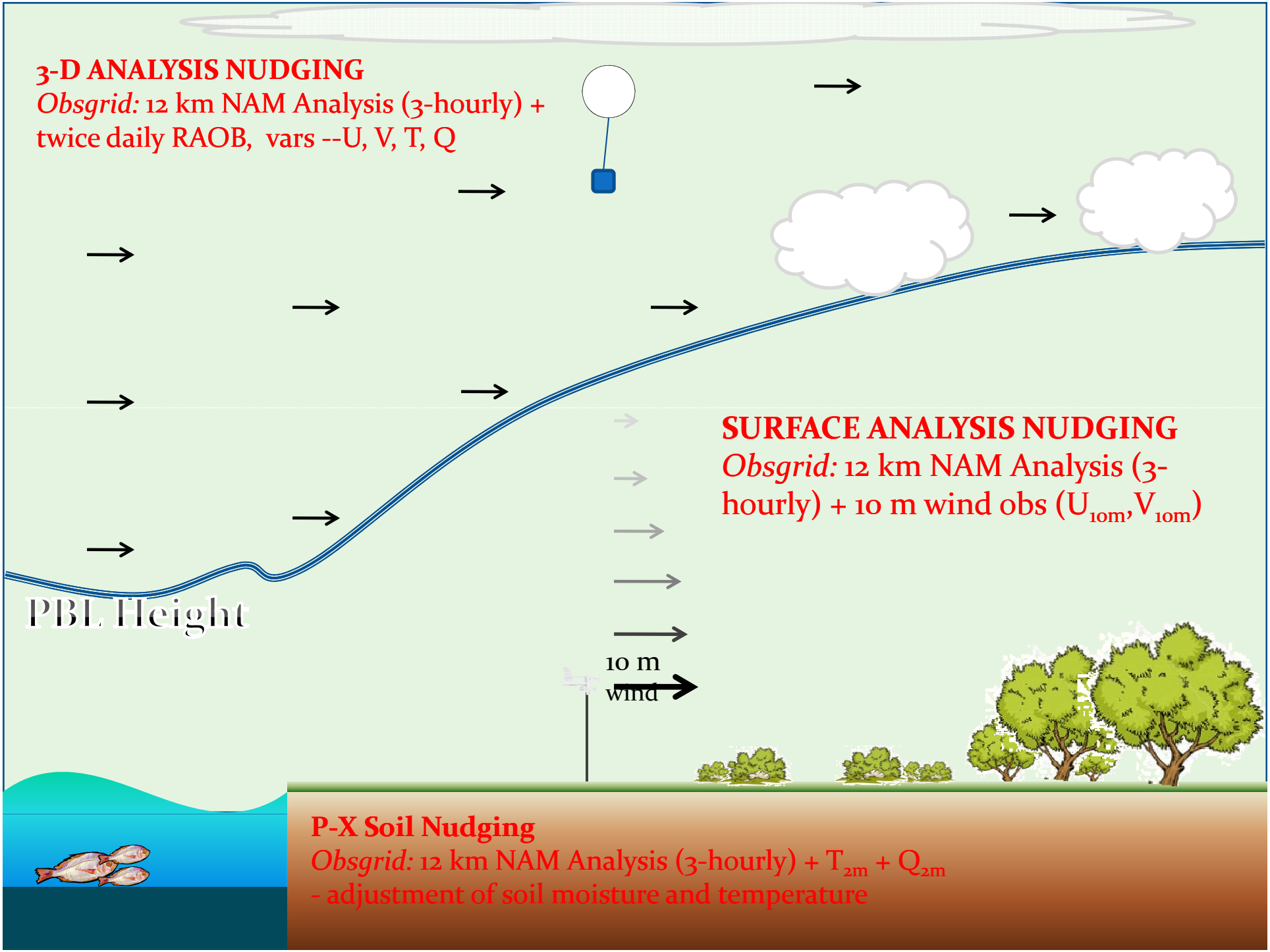
June 27



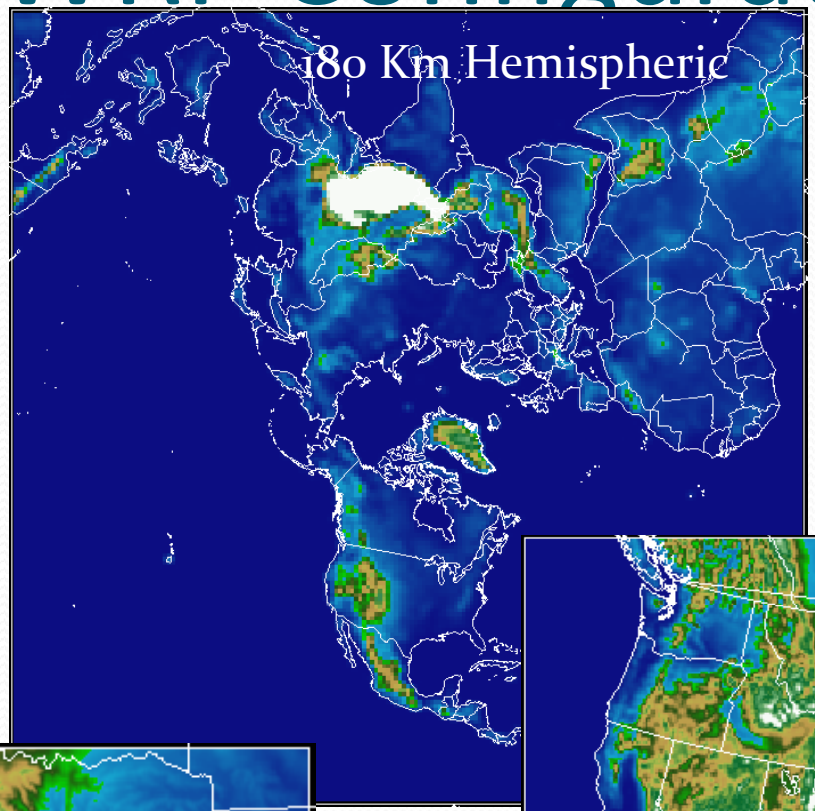
- More pronounced reduction in shortwave radiation due to aerosol loading
- Including aerosol direct forcing improves simulation of SW radiation

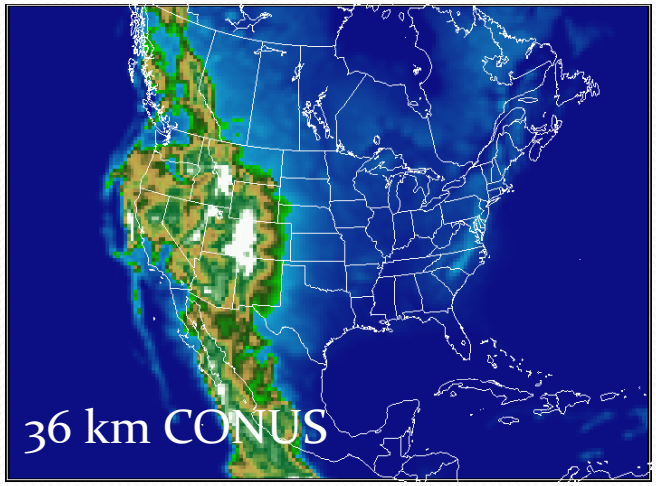
WRF Configuration: General

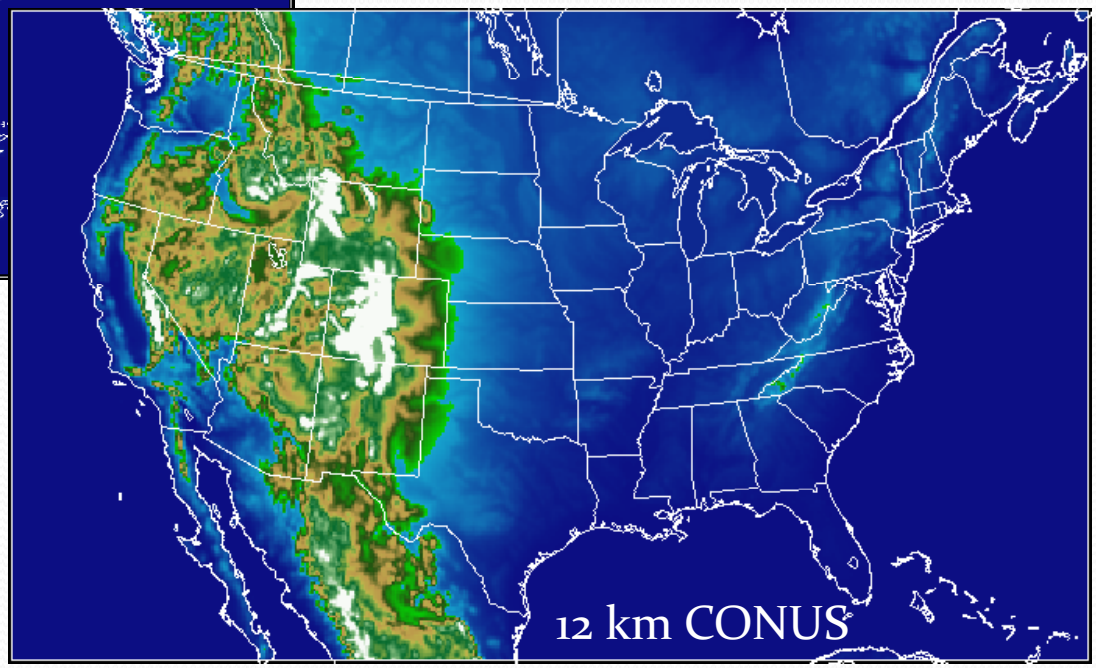
- Other than Air Quality Forecast initiative in the mid-2000's, the US EPA simulates meteorology for retrospective cases
  - Full annual US simulations for 2002-2009
- Our data assimilation methodology is "grid nudging", which leverages model analyses and observations; can be thought of as a "dynamic analysis"
- WRF is used to drive annual CMAQ simulations in an offline, non-coupled mode

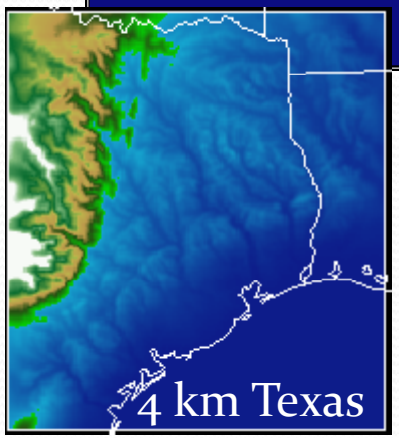

3-D ANALYSIS NUDGING
Obsgrid: 12 km NAM Analysis (3-hourly) + twice daily RAOB, vars --U, V, T, Q
SURFACE ANALYSIS NUDGING
Obsgrid: 12 km NAM Analysis (3-hourly) + 10 m wind obs (U_{10m},V_{10m})
PBL Height
10 m wind
P-X Soil Nudging
Obsgrid: 12 km NAM Analysis (3-hourly) + T_{2m} + Q_{2m}
- adjustment of soil moisture and temperature

WRF Configuration: Model Domains









WRF Configuration: Physics Options

Model Configuration

- 12 km North American domain pictured above
- Annual simulations for 2002, 2006 and 2007; 2008 in progress and 2009-2010 are planned
- 472 (nx) x 312 (ny) grid cells with 34 layers; first layer is ~40 m thick with about 17 layers below 2000 m
- High resolution (30 m) National Land Cover Dataset used for landuse; fractional landuse used to derive surface characteristics within the PX LSM
- Time varying sea surface temperature
- 6th order diffusion (opt. 1), w_damping, w-Rayleigh damping, km_opt (opt. 4), positive definite advection for scalars and moisture
- Simulations were split into 5.5 day run segments that overlapped by 12 hours. The 12 hours is used for model spin-up, but not used by the air quality model or in the evaluation
- Analysis nudging of U,V, T and Q was enabled with the specific options provided to the right; no temperature and moisture nudging in the PBL
- Surface analysis nudging was enabled per namelist options to the right
- Pleim-Xiu LSM soil moisture and temperature nudging enabled
- All nudging fields including 3-D wind, temperature and water vapor mixing ratio; 10-m wind, 2-m temperature and 2-m mixing ratio were derived from the ***Obsgrid*** re-analysis program, which used the 12 km NAM as the base analysis and standard surface observations and rawinsonde soundings for the upper air data

Physics	Parameterization
Microphysics	Morrison
Longwave radiation	RRTMG
Shortwave radition	RRTMG
Surface-layer	Pleim
Land-surface	Pleim-Xiu
Boundary-layer	ACM2
Cumulus	Kain-Fritsch 2

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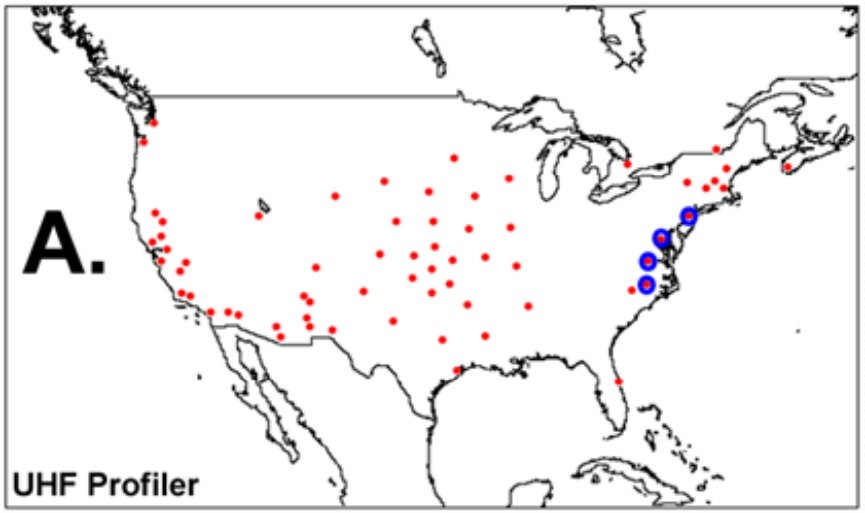
Model Evaluation: The Atmospheric Model Evaluation Tool (AMET), developed by the US EPA and the Univ. of North Carolina's Institute for the Environment, was used to match the annual WRF simulations with point measurements from surface networks and wind profilers. AMET uses the observations collected by the Meteorological Assimilation Data Ingest System (MADIS). For the comparisons to MM5 it must be understood that the MM5 simulation was for a different year (2005) and that domain only covered the eastern US, while the WRF domain covered the difficult to model western US.

New Assimilation Strategy

- Need: Evaluations showed important features for pollution transport, like nocturnal jets, were not simulated well
- Test 1: Elimination of nudging within the PBL as suggested in the past by Zhang et al. (2001)
- Test2: Utilize more upper-level observational data like UHF and VAD wind profiles in the data assimilation (Michelson and Seaman 1999; Godowitch et al., 2011)
- It was found that this combination not only improved the winds in nocturnal jets and at the top of the convective boundary layer, but this improved forcing lowered error in wind within the PBL

Unused wind profiler observation are available that could improve FDDA



UHF Profiler

Pros: high vertical (10's of m) and temporal resolution (sub-hourly), good coverage in the more critical air sheds

Cons: inconsistent spacing

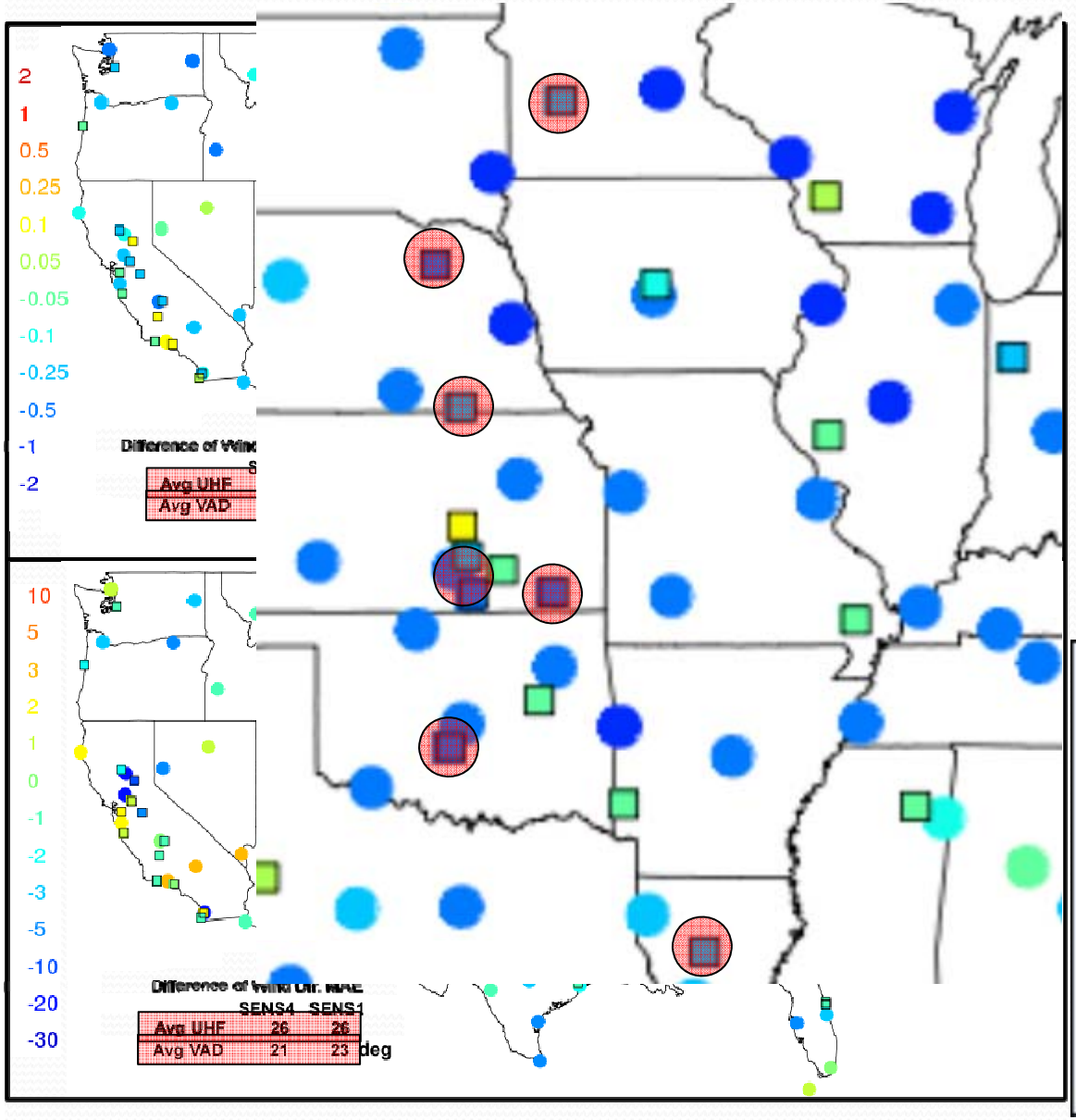
Velocity Azimuth Display (VAD)

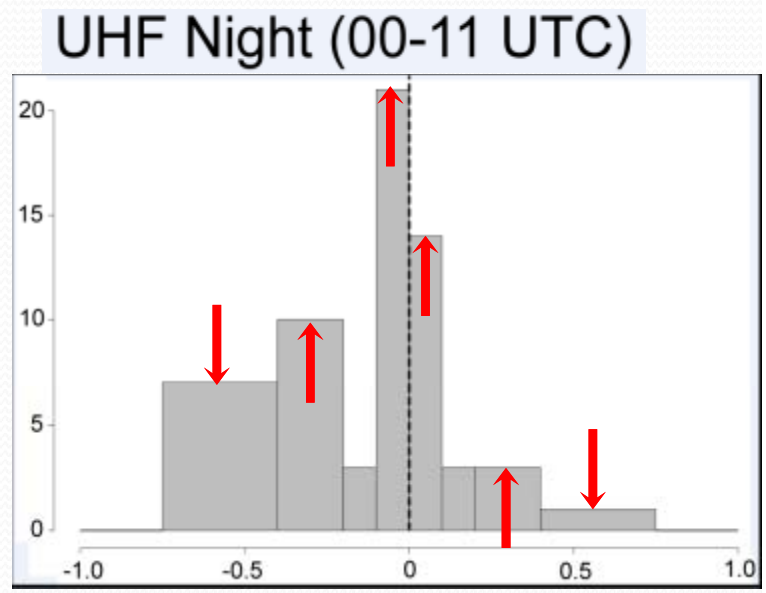
Pros: Consistent and full US spatial coverage, sub-hourly and easily accessible

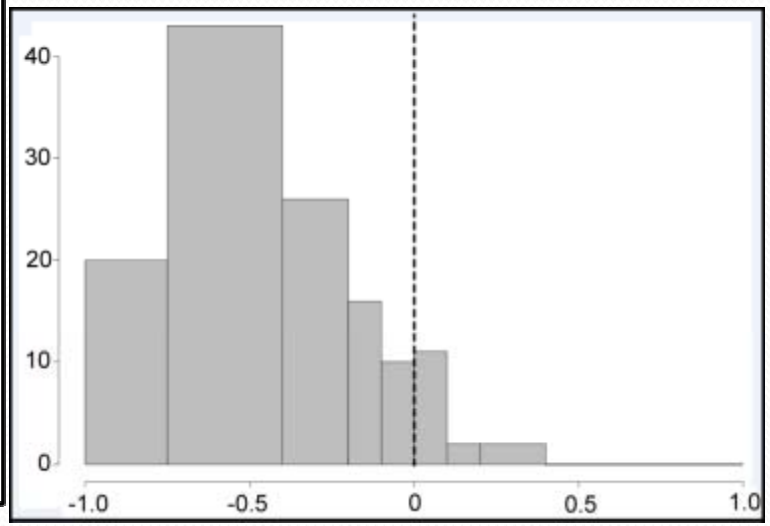
Cons: Coarse vertical resolution, can be influenced by birds and precip

SENS4 vs. SENS1

Impact of VAD Nudging

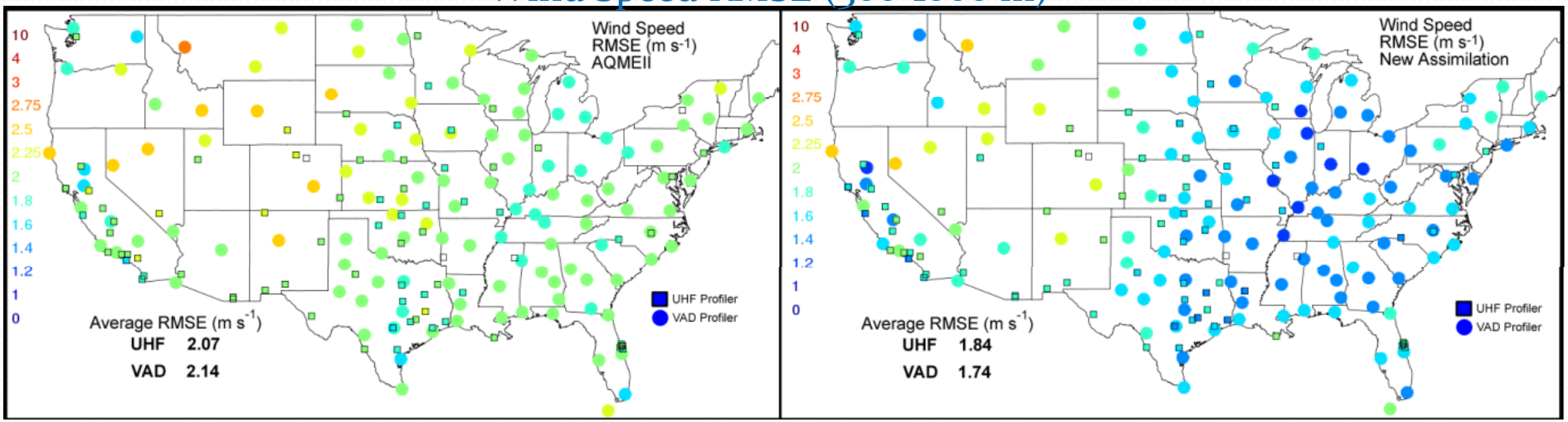


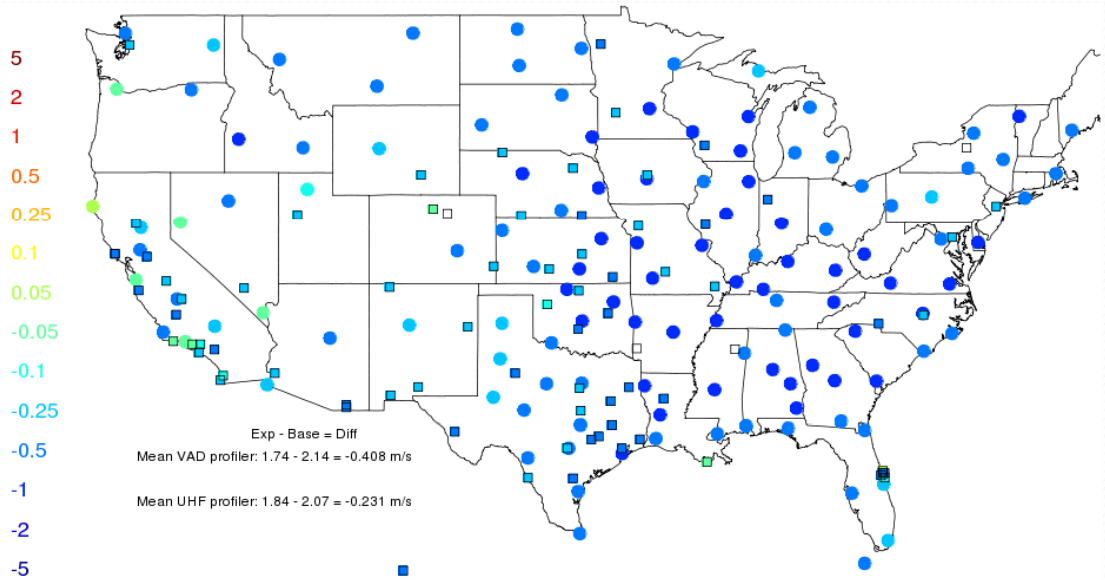




Testing the New Assimilation Strategy

Wind Speed RMSE (300-1000 m)





Error difference (NewAssim-AQMEII) (300-1000 m)

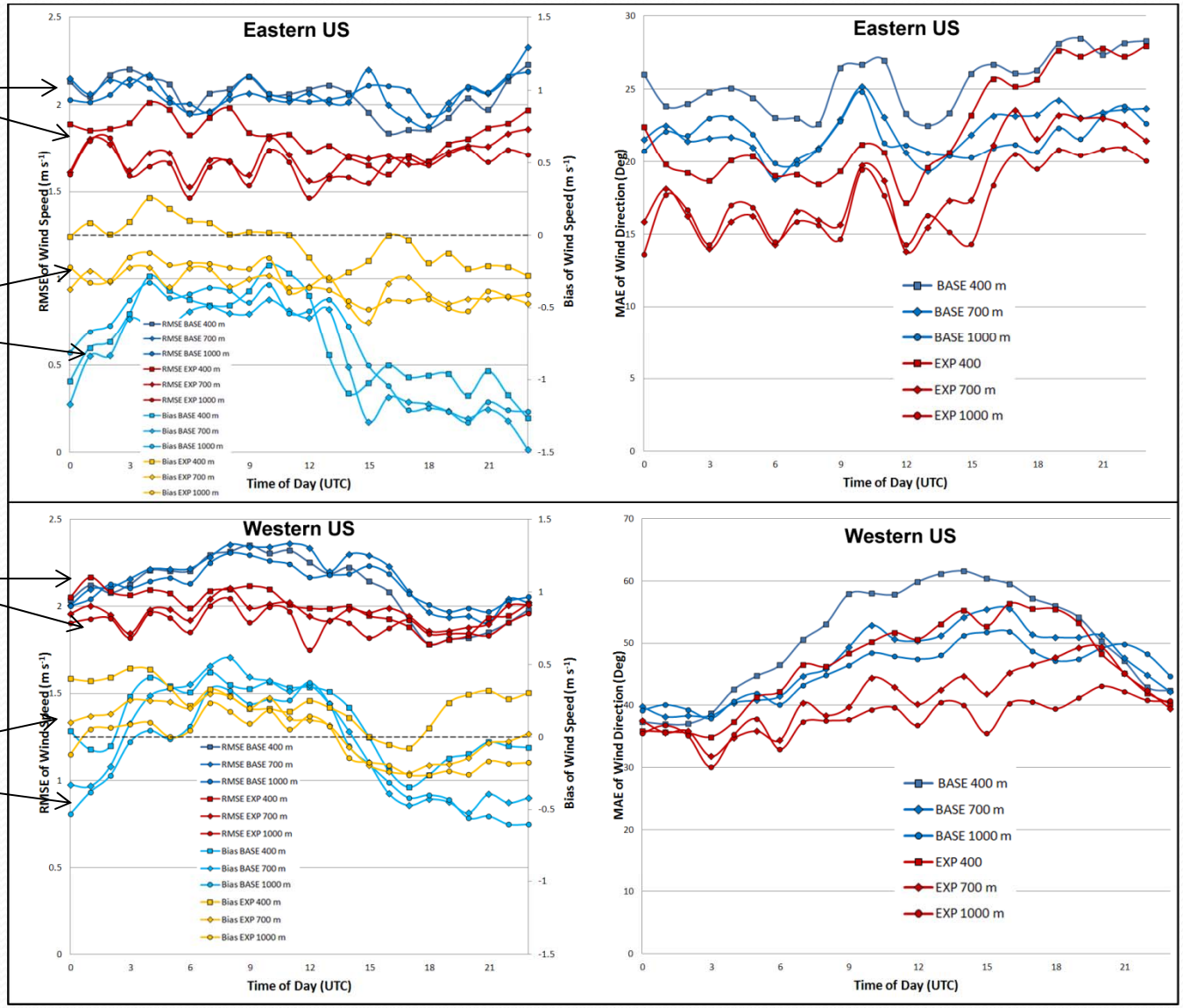
Jun-Aug 2006:Diurnal Statistics

RMSE Wind Speed
BASE NewAssim

Bias Wind Speed
BASE NewAssim

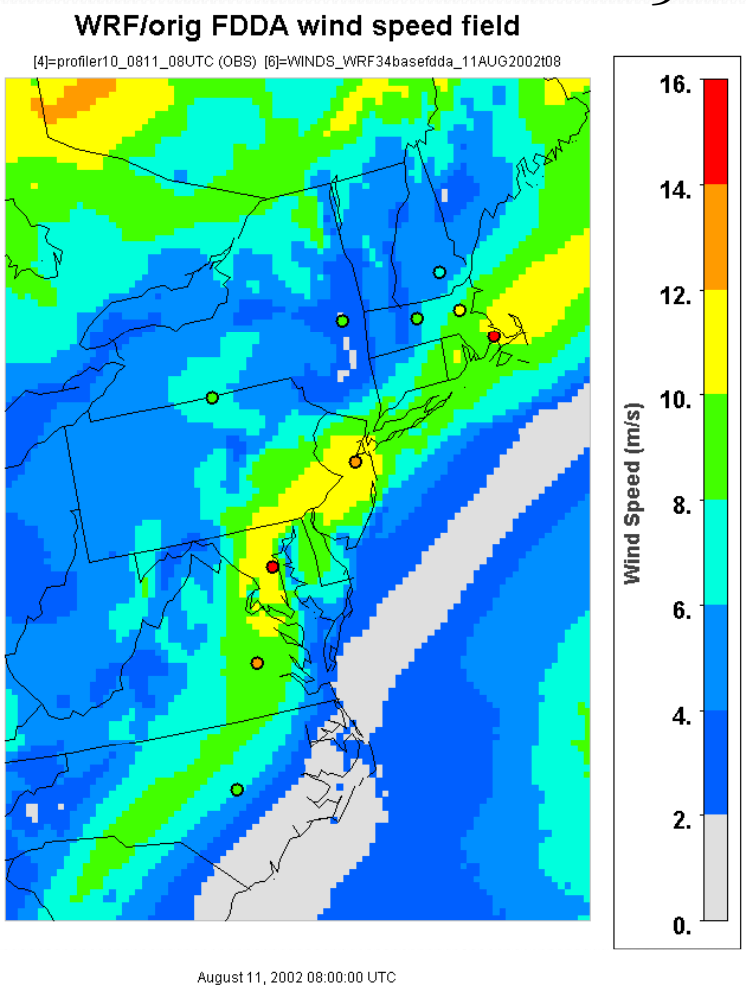
RMSE Wind Speed

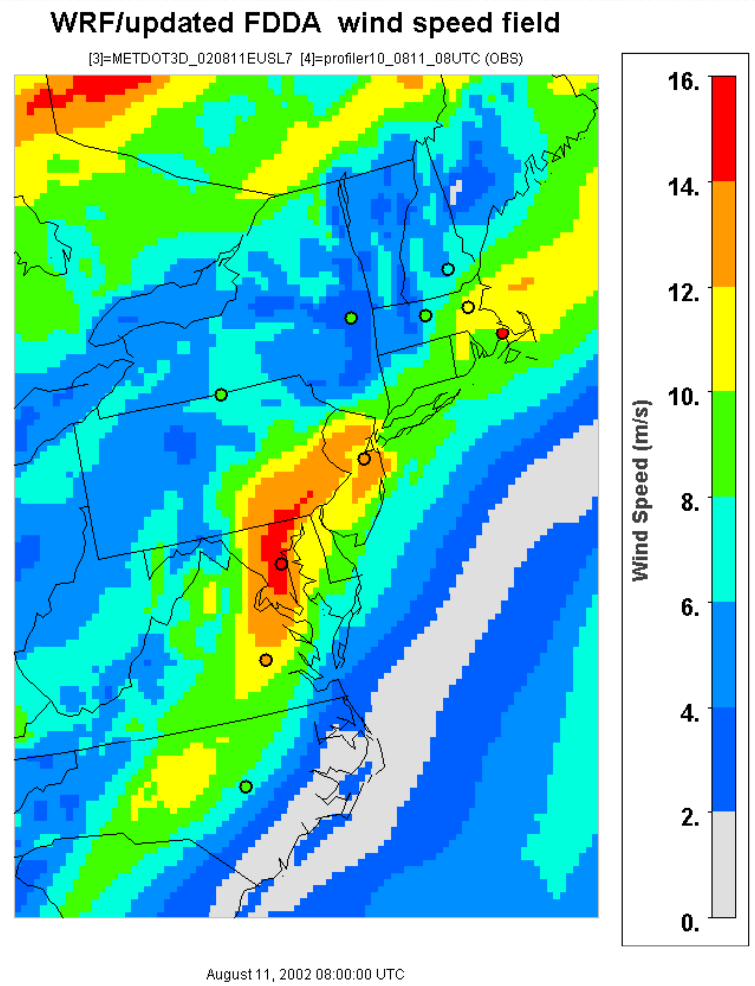
Bias Wind Speed



Testing the New Assimilation Strategy

Z ≈ 300 m AGL

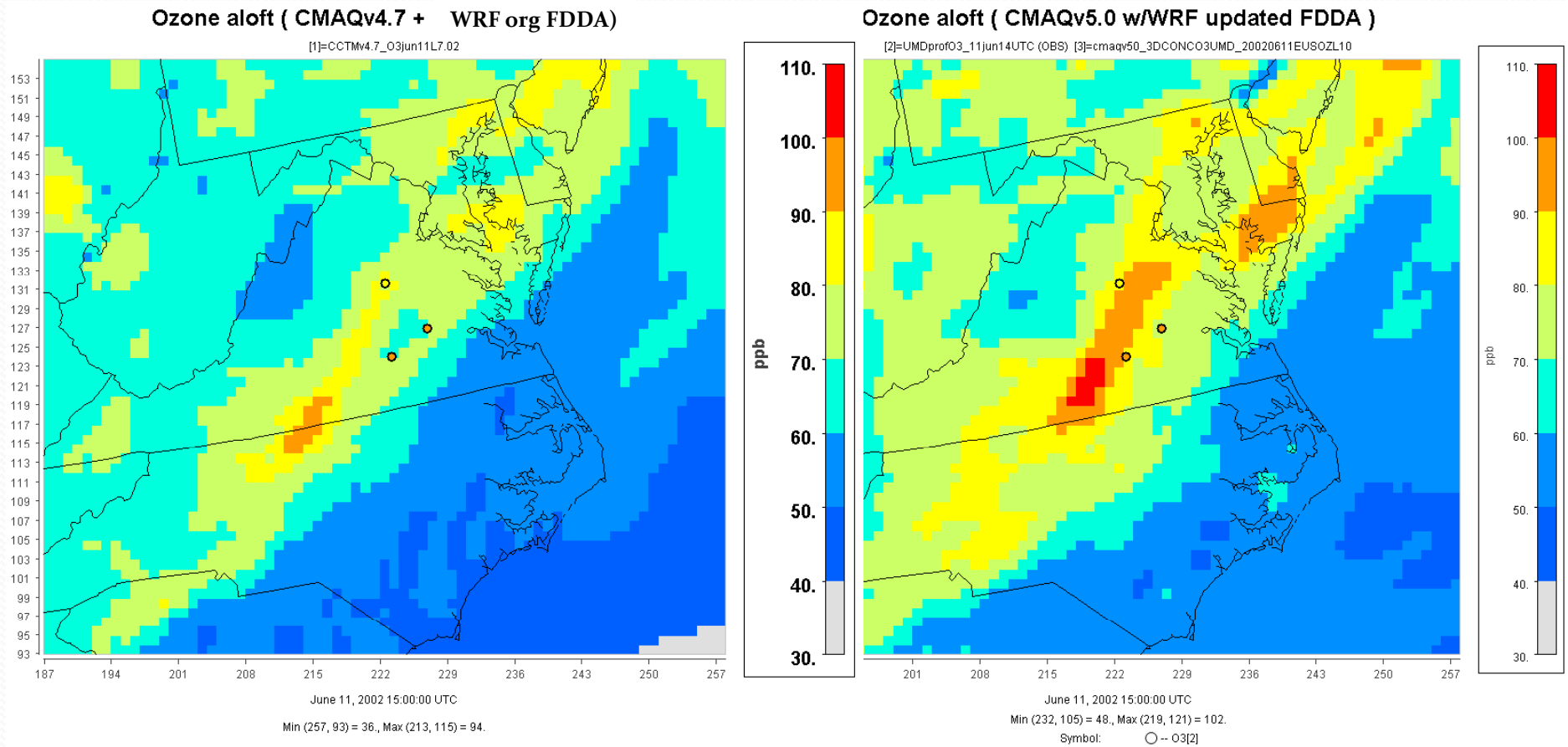




Godowitch et al (2011) – Figure A3

> Stronger winds in mid-Atlantic jet agree with obs

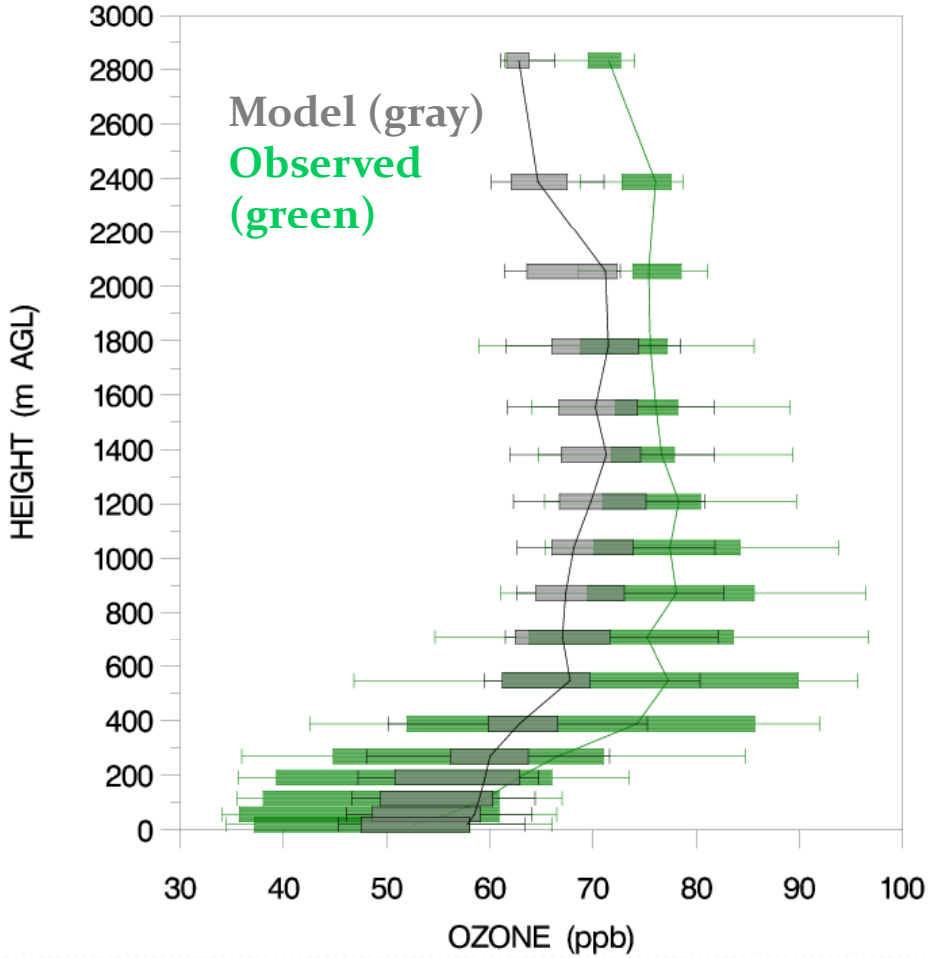
Testing the New Assimilation Strategy



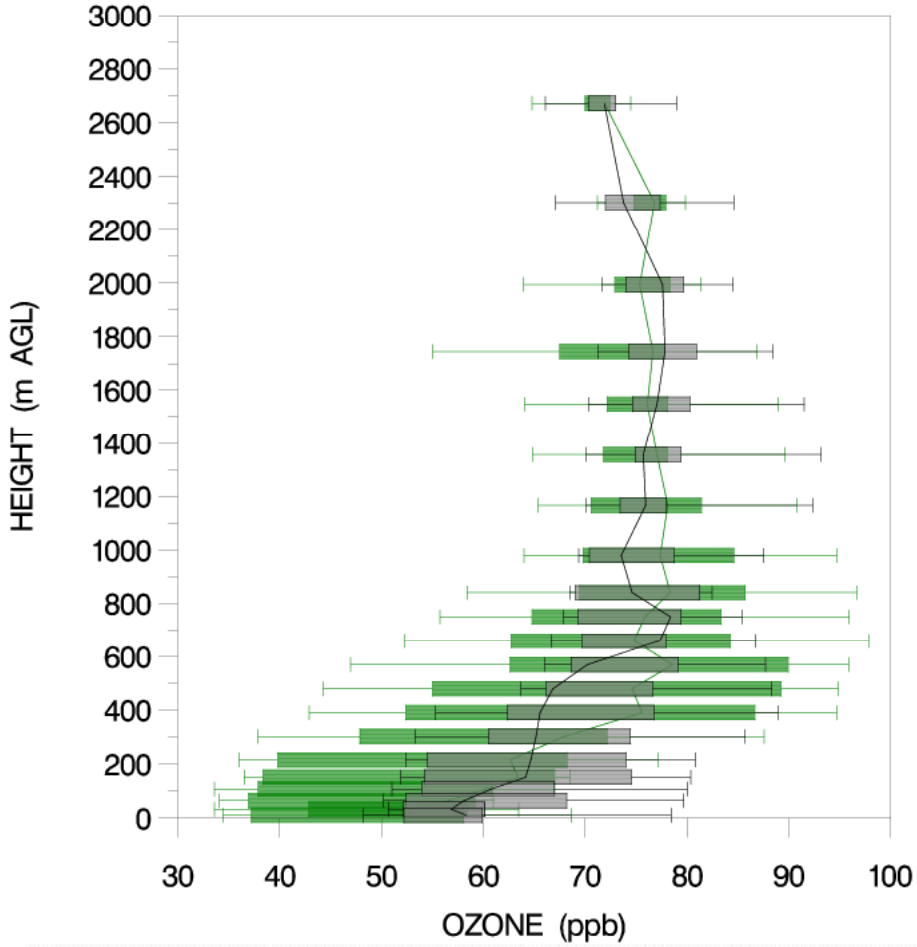
ozone aloft in residual urban plume in close proximity to values at observed profile sites in VA than previous model results

Testing the New Assimilation Strategy

CMAQv47 w/WRF origFDDA

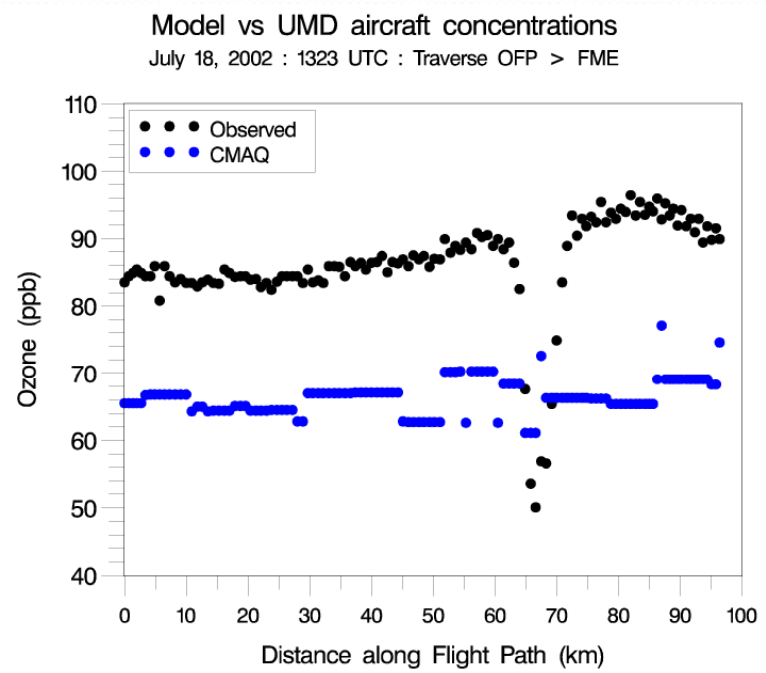


CMAQv50 w/WRF new FDDA

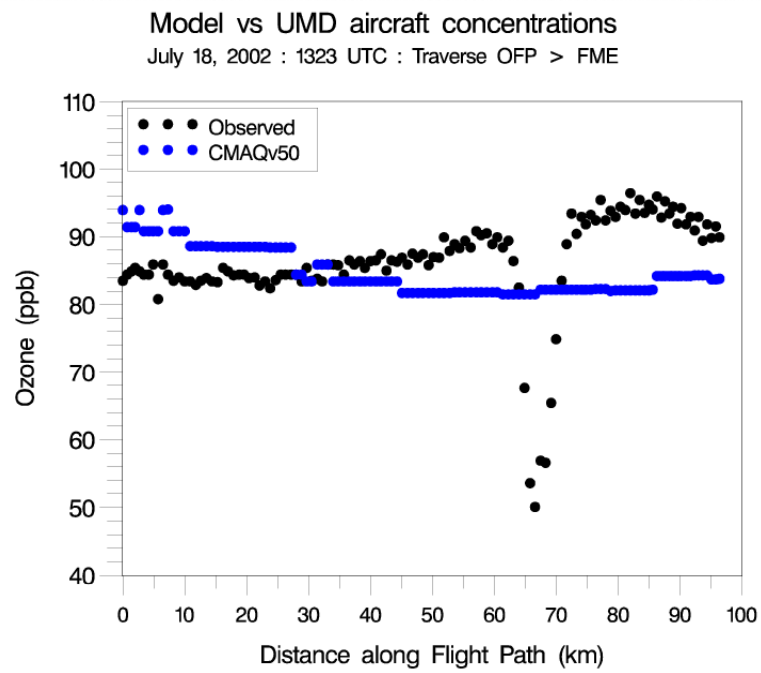


CMAQ vs UMD Aircraft Ozone Measurements
Morning Horizontal Flight Path – Richmond,VA to Ft. Meade,MD

CMAQv47 w/WRF orig.FDDA

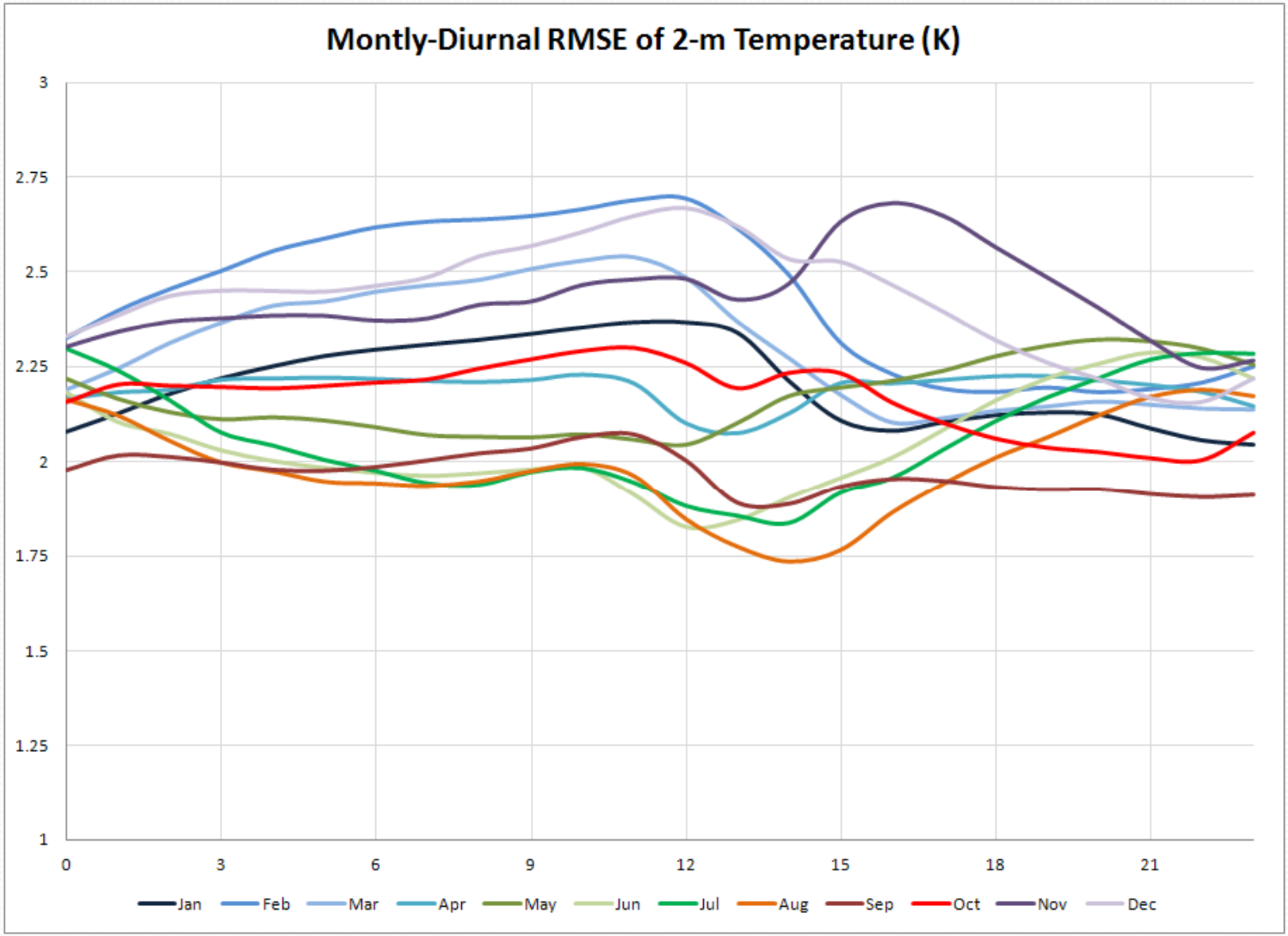


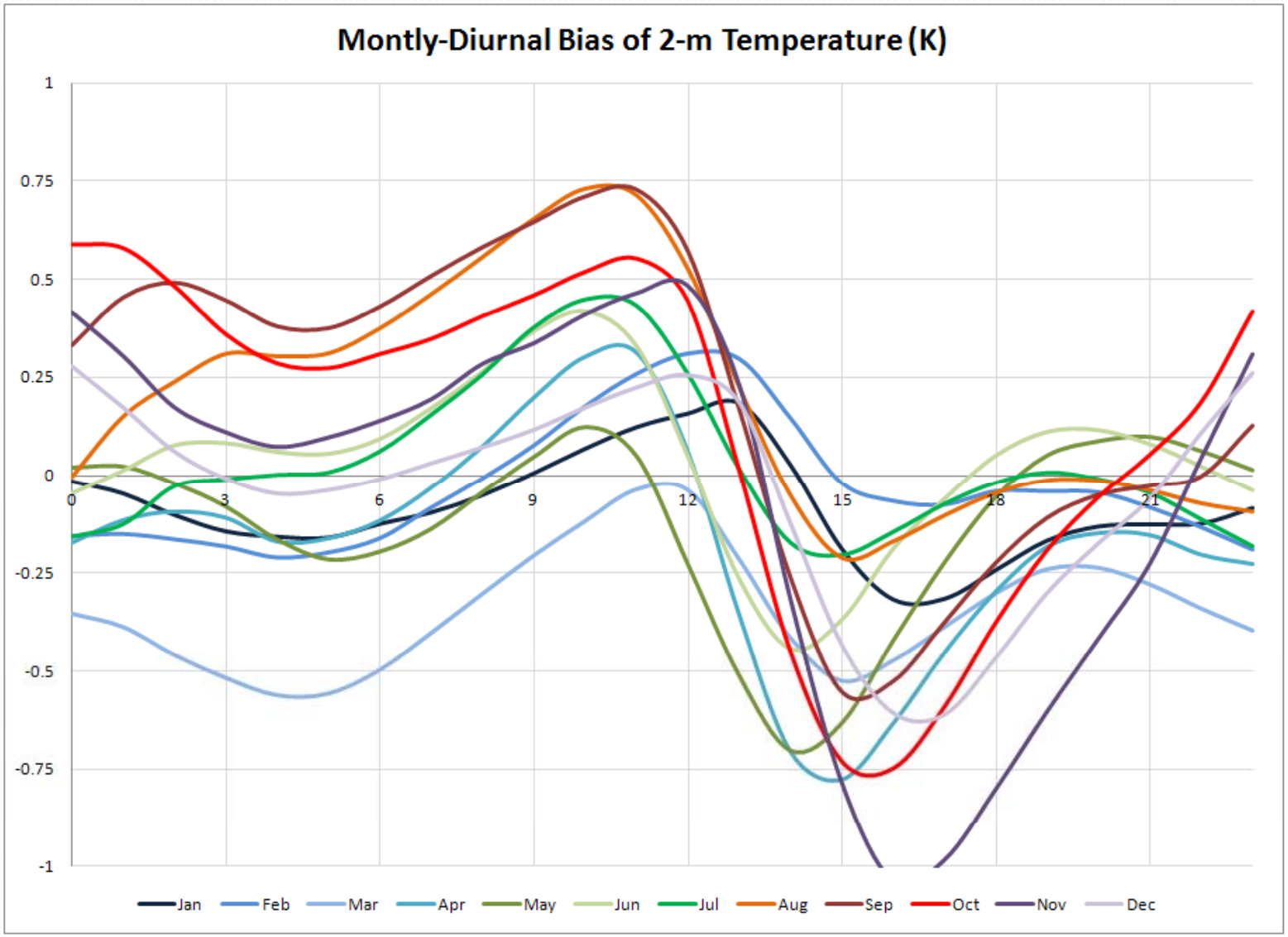
CMAQv50 w/WRF new FDDA



> **Modeled O_3 values from CMAQv50 are in much closer agreement to observed values along this horizontal path aloft than previous model results**

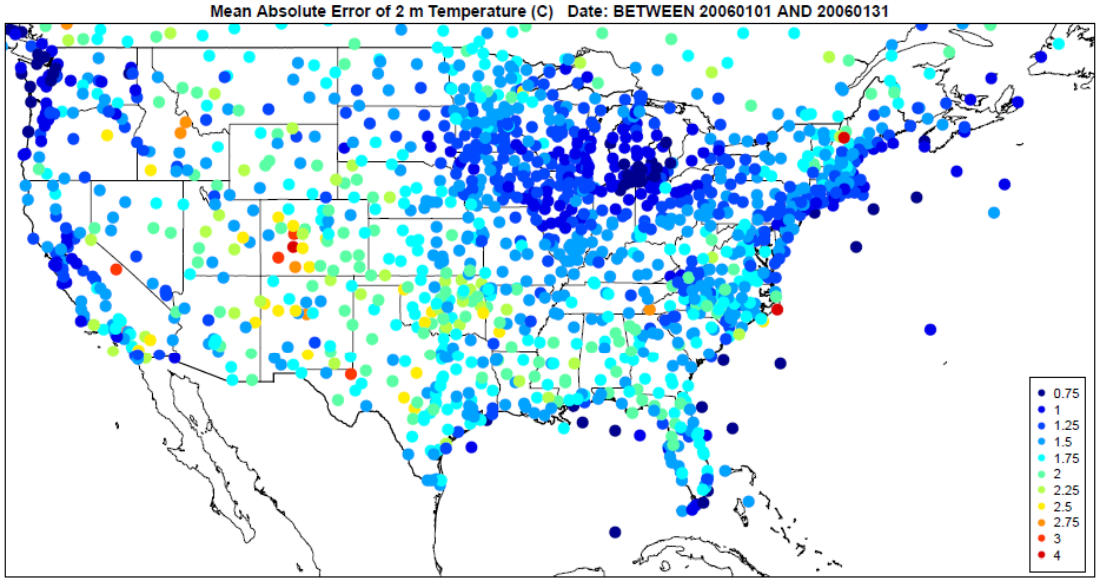
Model Performance of Recent US EPA Annual CONUS (12km) Simulations


Montly-Diurnal RMSE of 2-m Temperature (K)
3
2.75
2.5
2.25
2
1.75
1.5
1.25
1
0
3
6
9
12
15
18
21
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Montly-Diurnal Bias of 2-m Temperature (K)
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
0
3
6
9
12
15
18
21
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

WRF Model Performance: Surface

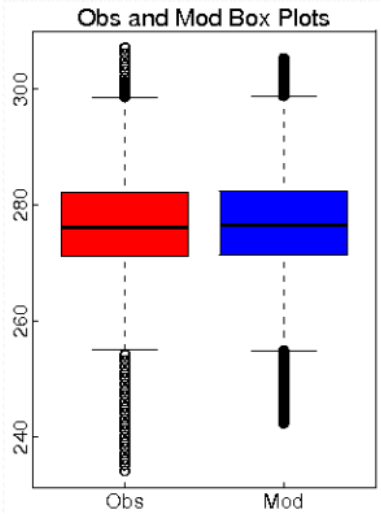
January 2006

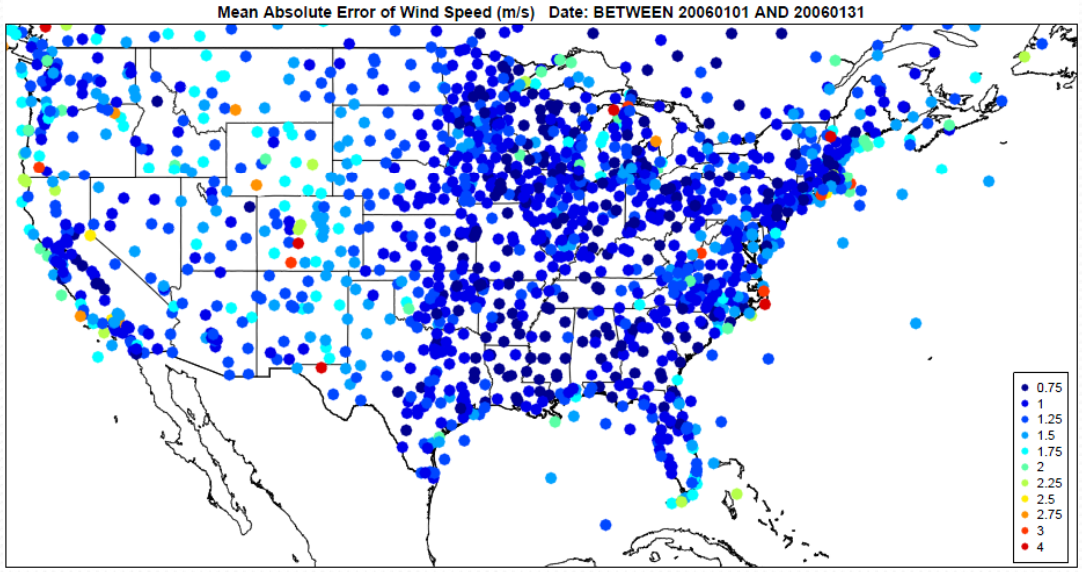


Model Performance Statistics

Data count	1337640
Correlation	0.96714
Standard Deviation	2.202
Mean Absolute Error	1.6686
Mean Bias	–0.087491
*Mean Fractional Bias (%)	–0.02718
*Mean Normalized Bias (%)	–0.090984
*Mean Normalized Error (%)	2.2918
*Normalized Mean Bias (%)	–0.11985
*Normalized Mean Error (%)	2.2858
Root–Mean–Sqr–Error	2.2037
Index of Agreement	0.96709

* Stats are normalized by observation range

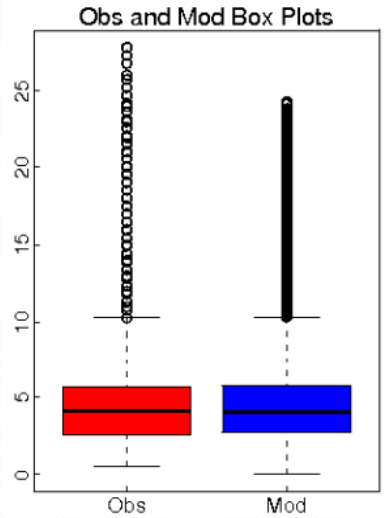




Model Performance Statistics

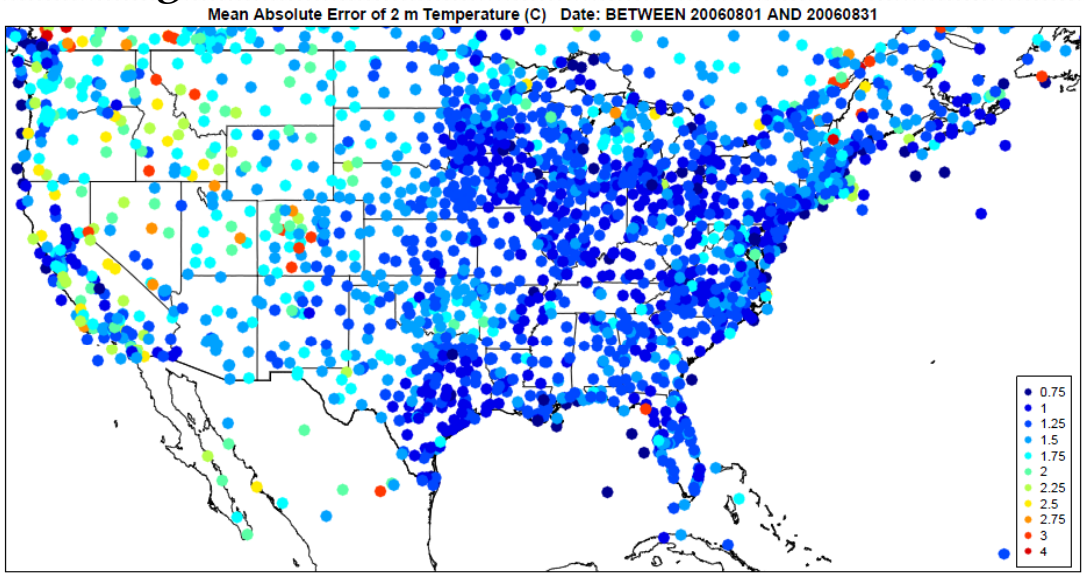
Data count	1107446
Correlation	0.73355
Standard Deviation	1.8119
Mean Absolute Error	1.3584
Mean Bias	0.085745
*Mean Fractional Bias (%)	2.9652
*Mean Normalized Bias (%)	2.7857
*Mean Normalized Error (%)	6.7294
*Normalized Mean Bias (%)	0.30871
*Normalized Mean Error (%)	4.8908
Root–Mean–Sqr–Error	1.8139
Index of Agreement	0.7331

* Stats are normalized by observation range



WRF Model Performance: Surface

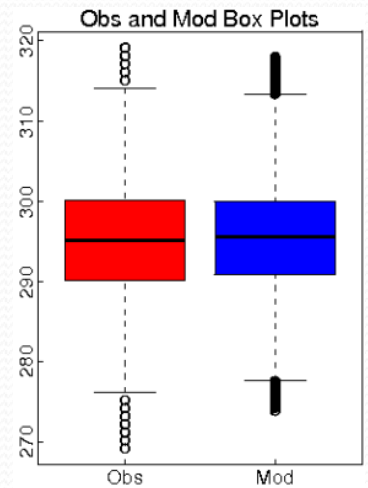
August 2006

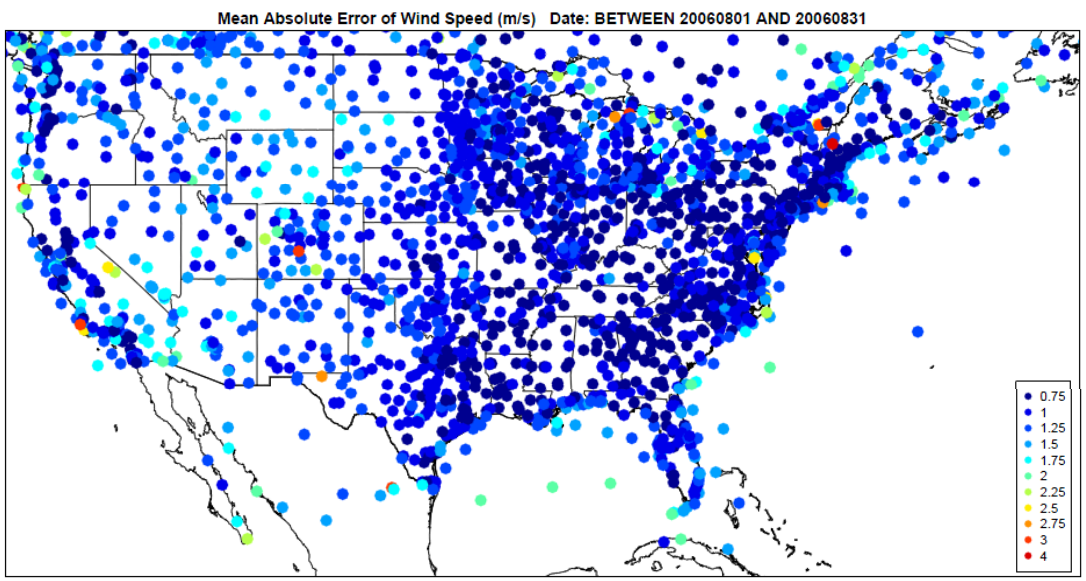


Model Performance Statistics

Data count	1679262
Correlation	0.9549
Standard Deviation	1.9875
Mean Absolute Error	1.4931
Mean Bias	0.18091
*Mean Fractional Bias (%)	0.065214
*Mean Normalized Bias (%)	0.39895
*Mean Normalized Error (%)	2.9967
*Normalized Mean Bias (%)	0.36181
*Normalized Mean Error (%)	2.9862
Root–Mean–Sqr–Error	1.9957
Index of Agreement	0.95448

* Stats are normalized by observation range

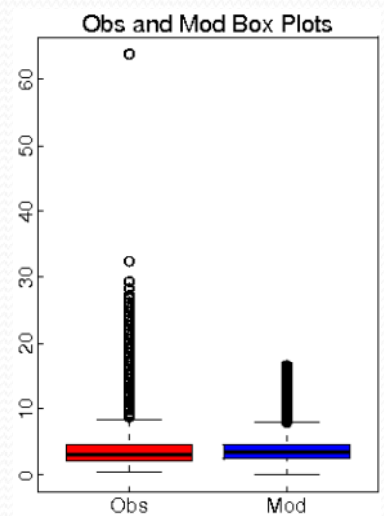




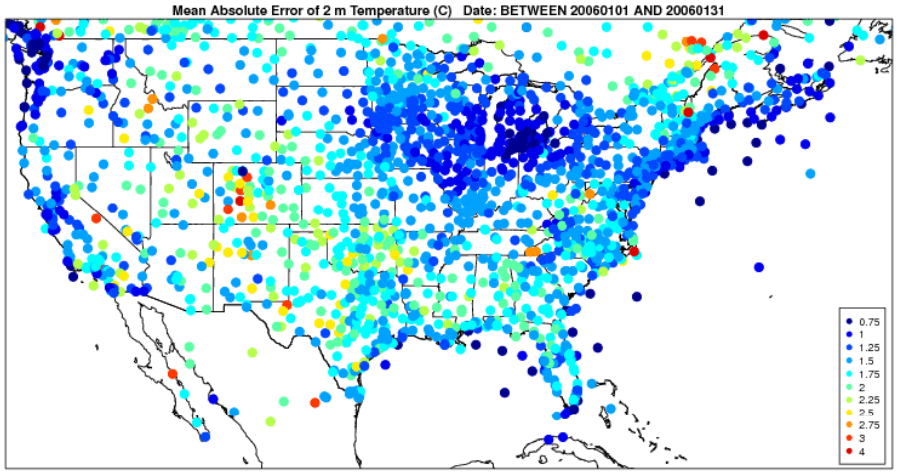
Model Performance Statistics

Data count	1289322
Correlation	0.60458
Standard Deviation	1.6258
Mean Absolute Error	1.2357
Mean Bias	0.067266
*Mean Fractional Bias (%)	2.8877
*Mean Normalized Bias (%)	1.0557
*Mean Normalized Error (%)	2.559
*Normalized Mean Bias (%)	0.10545
*Normalized Mean Error (%)	1.9372
Root–Mean–Sqr–Error	1.6272
Index of Agreement	0.60414

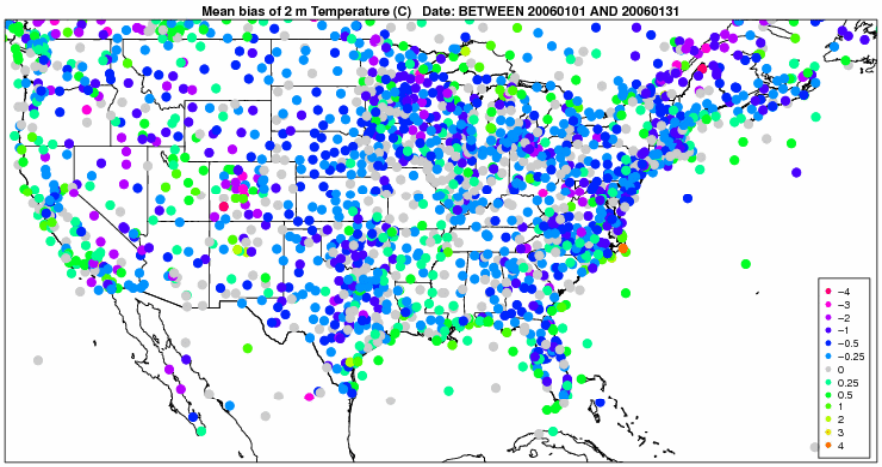
* Stats are normalized by observation range



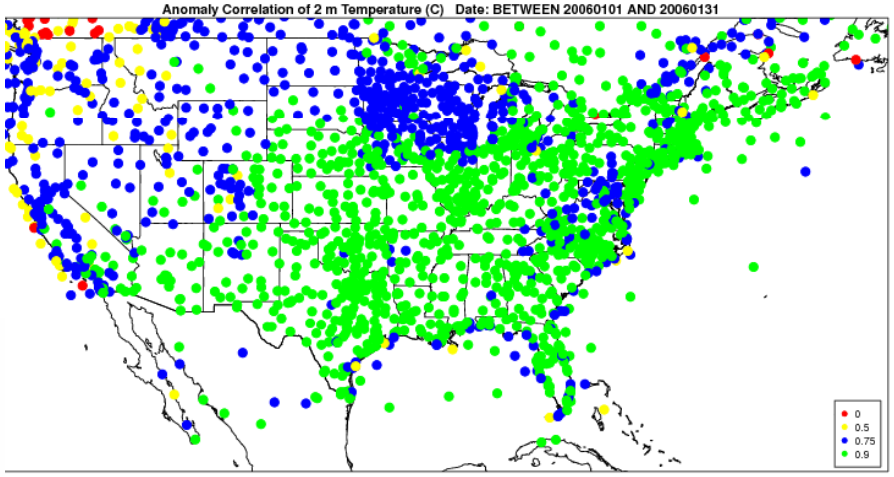
RMSE (K)



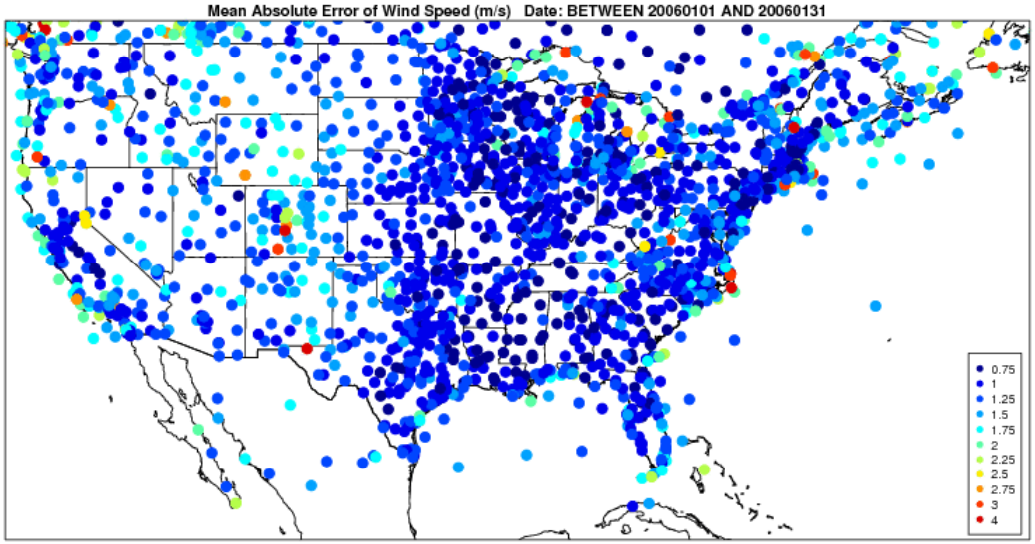
Bias (K)



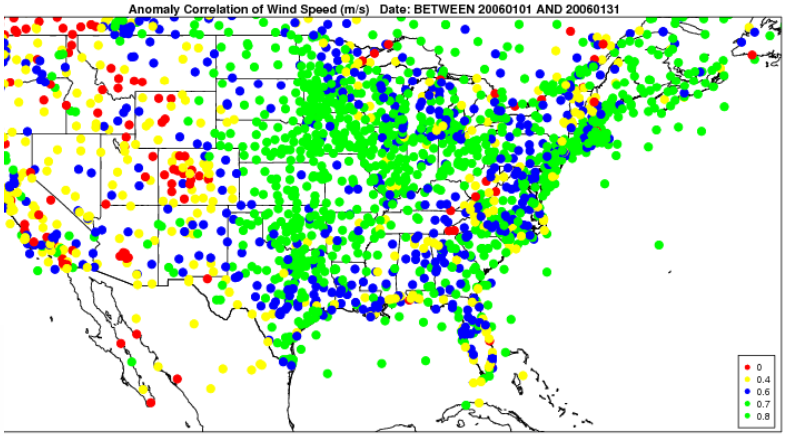
Index of Agreement



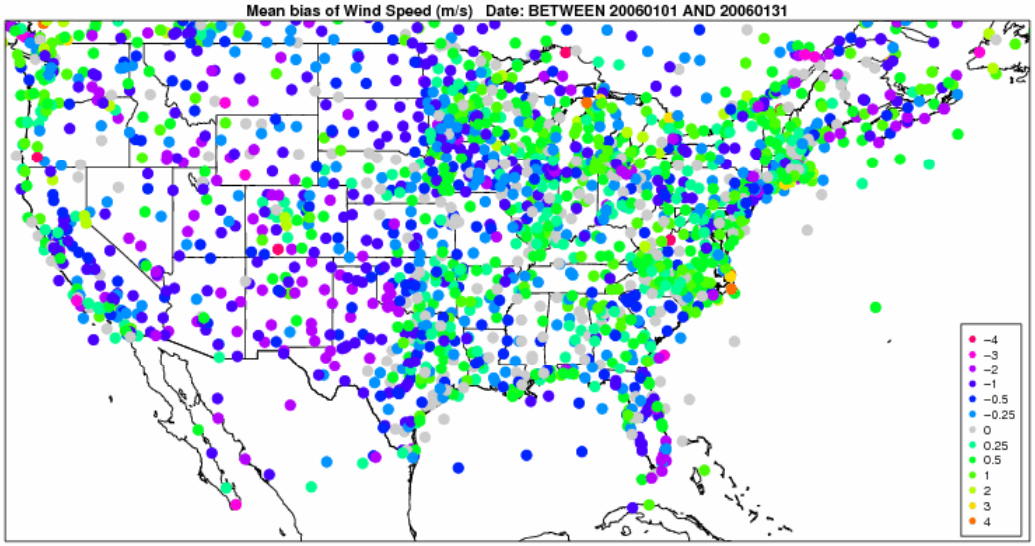
RMSE (m/s)



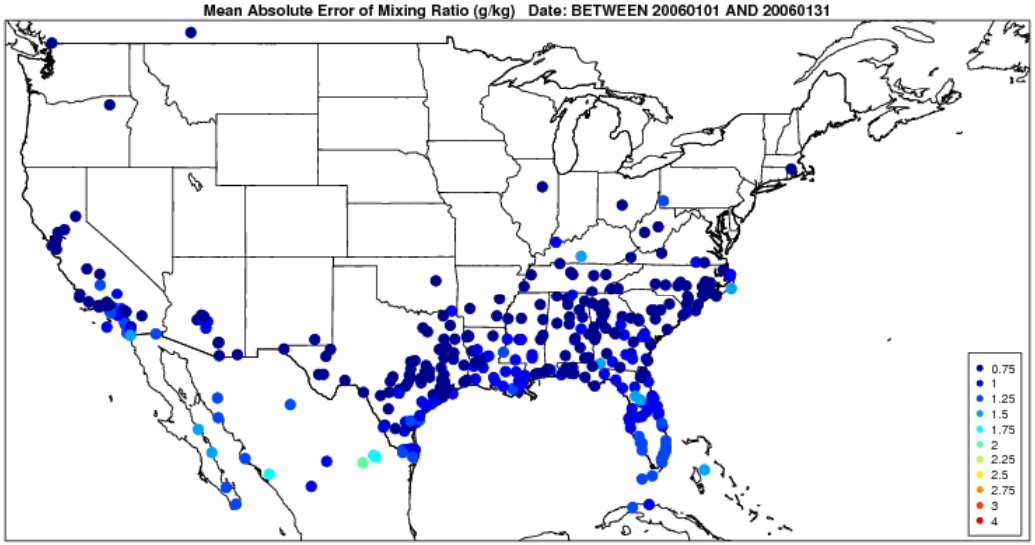
Index of Agreement



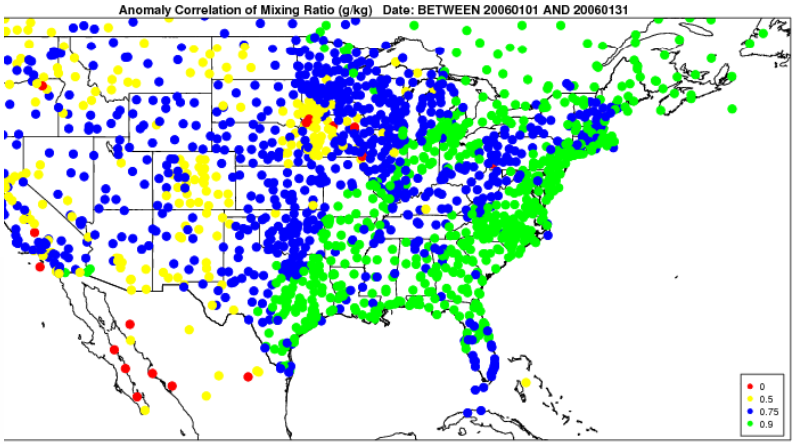
Bias (m/s)



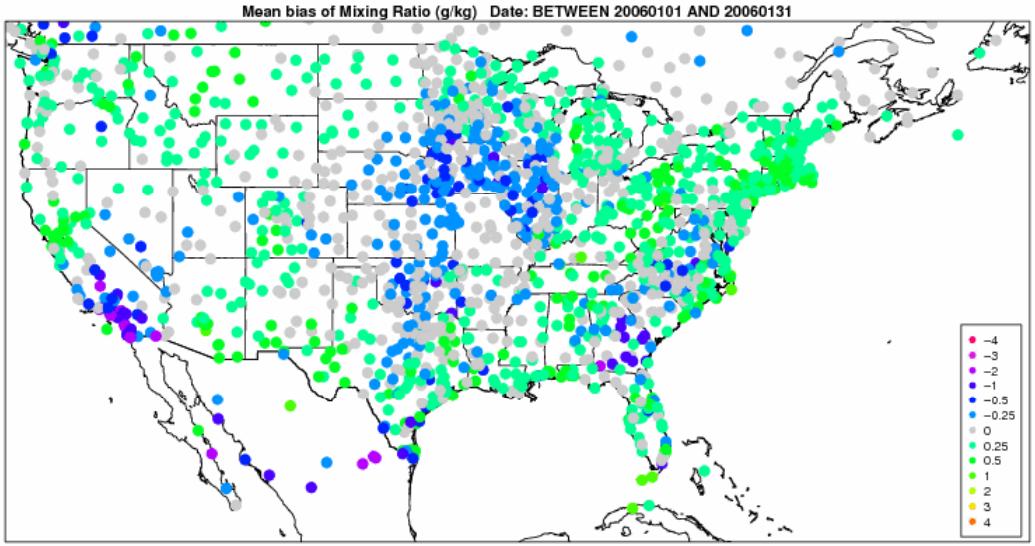
RMSE (g/kg)



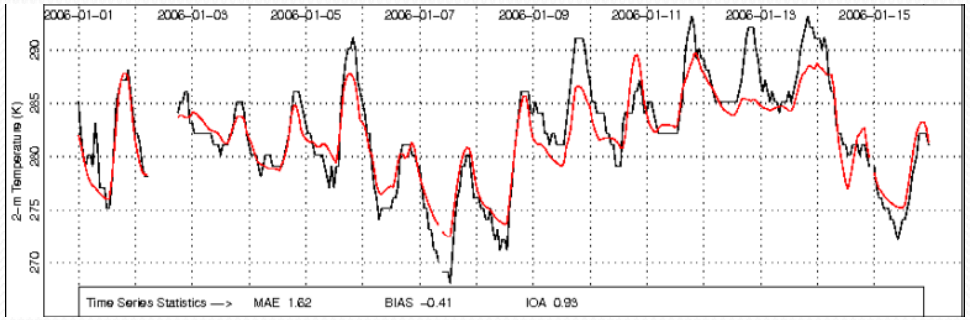
Index of Agreement

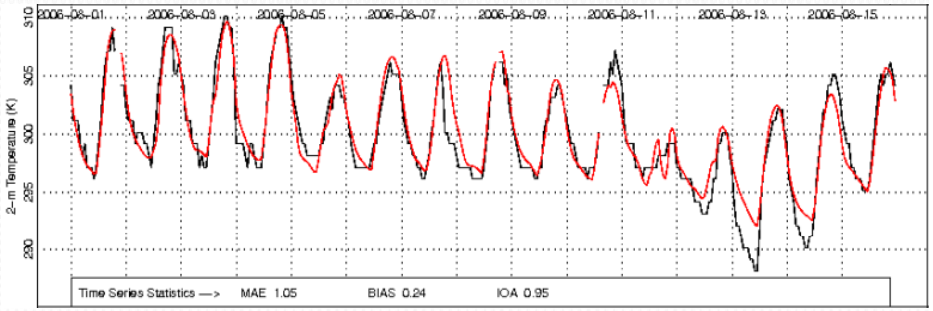


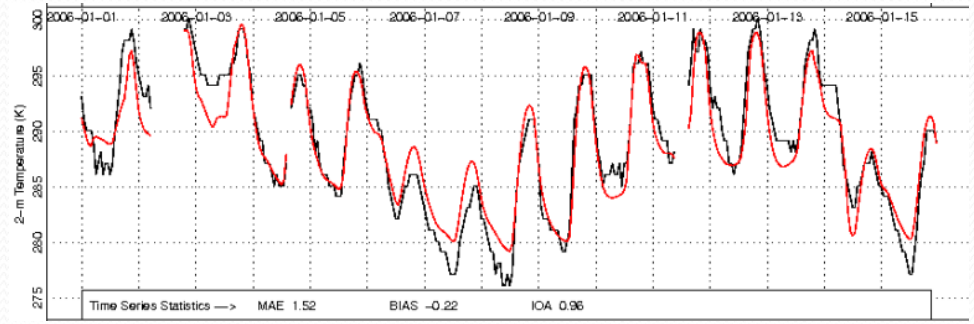
Bias (g/kg)

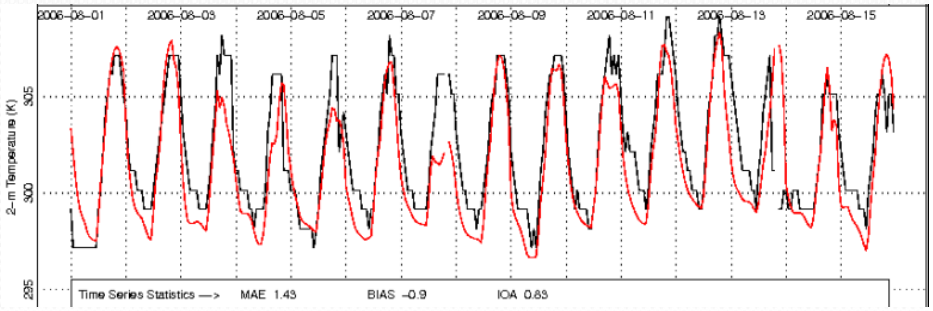


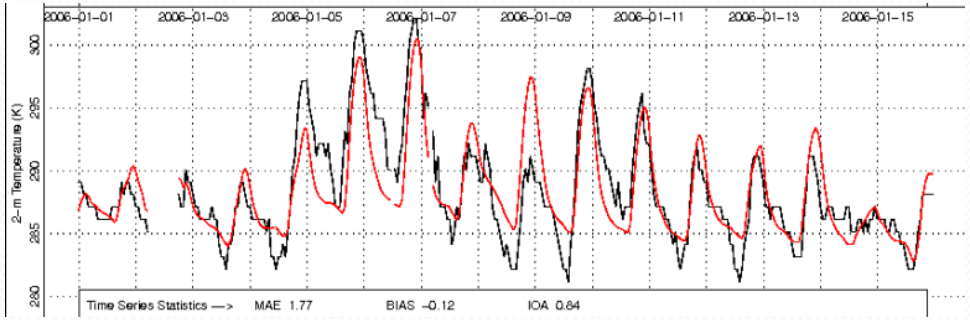
WRF Model Performance

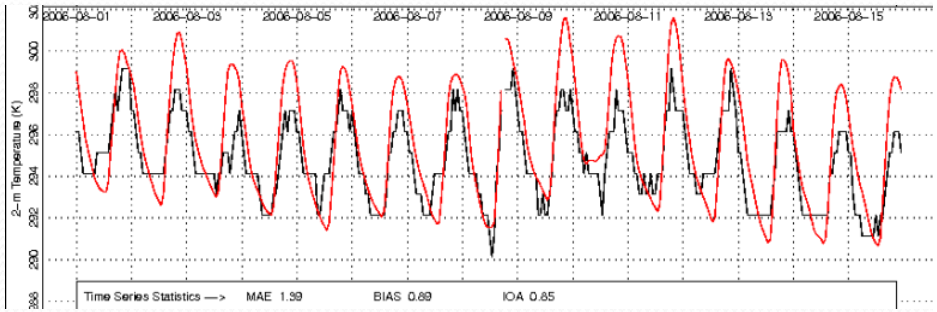




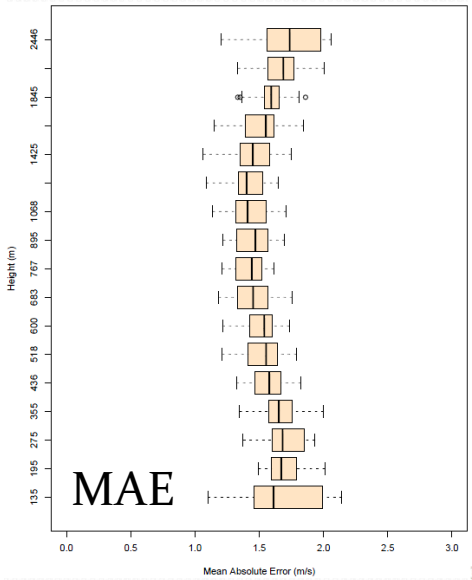


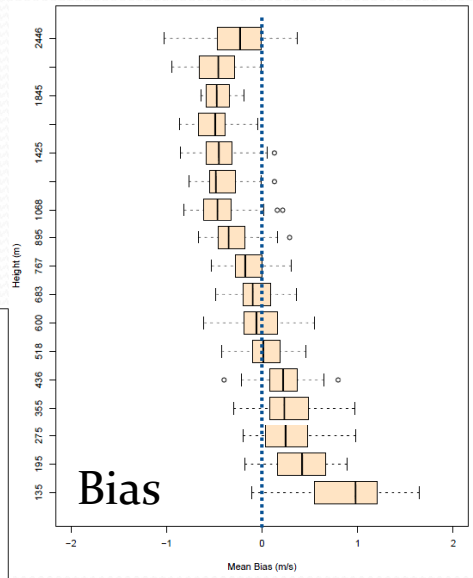


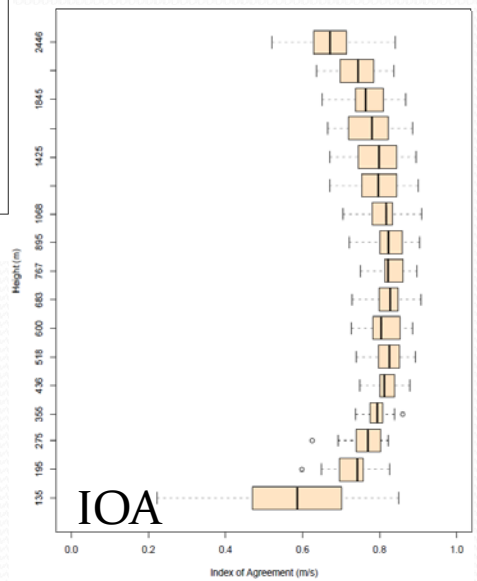


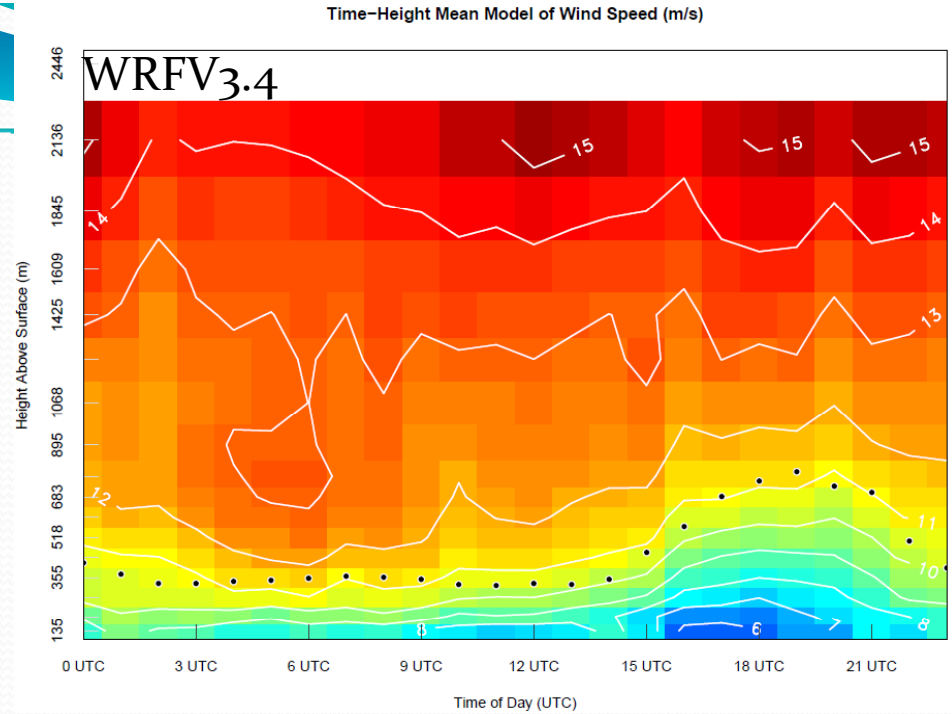


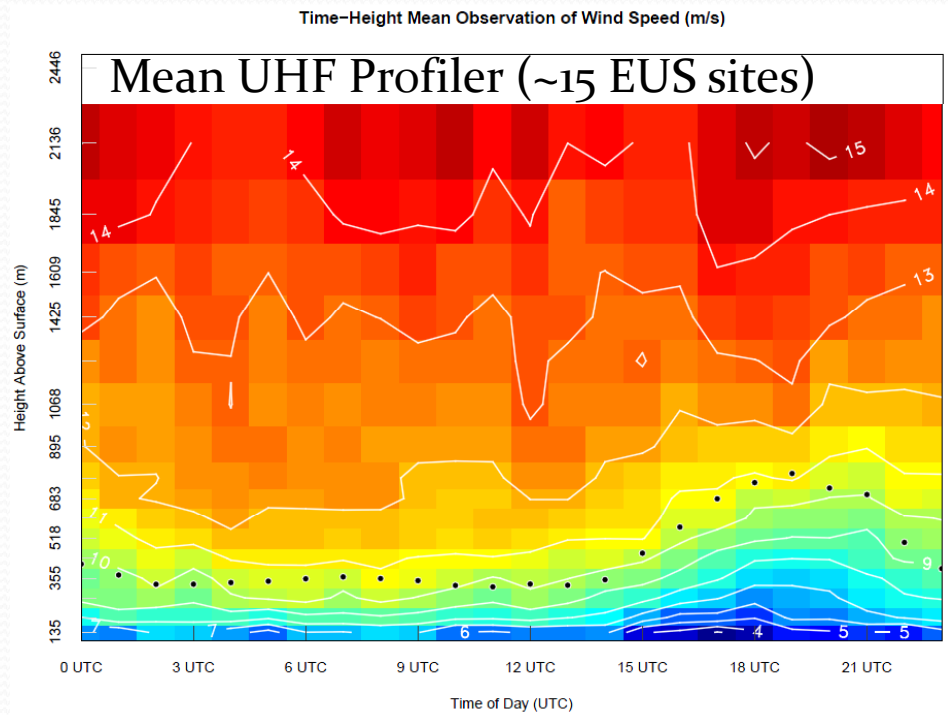
Evaluation of PBL Wind (Jan 2006)



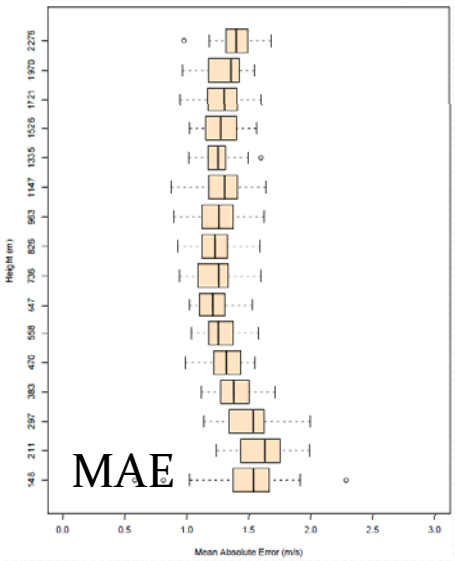


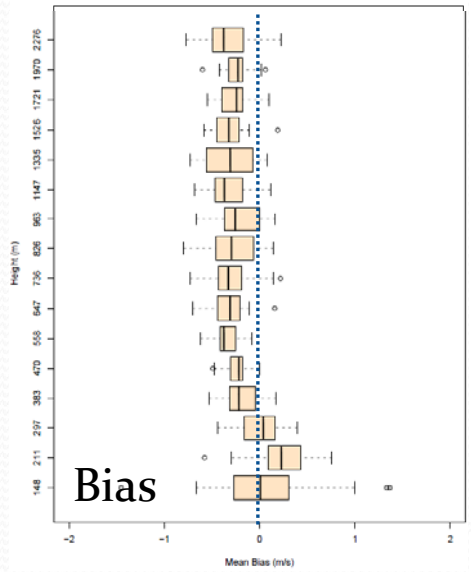


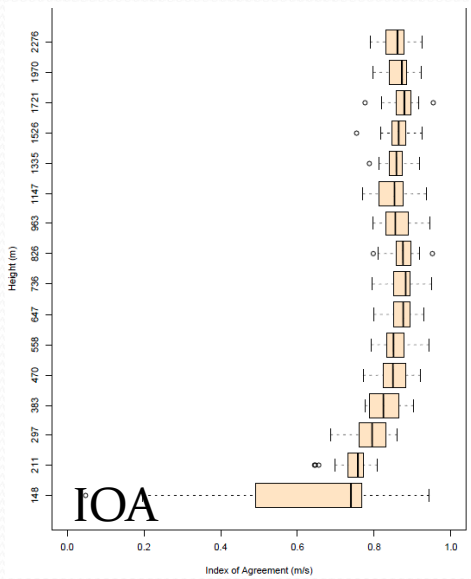


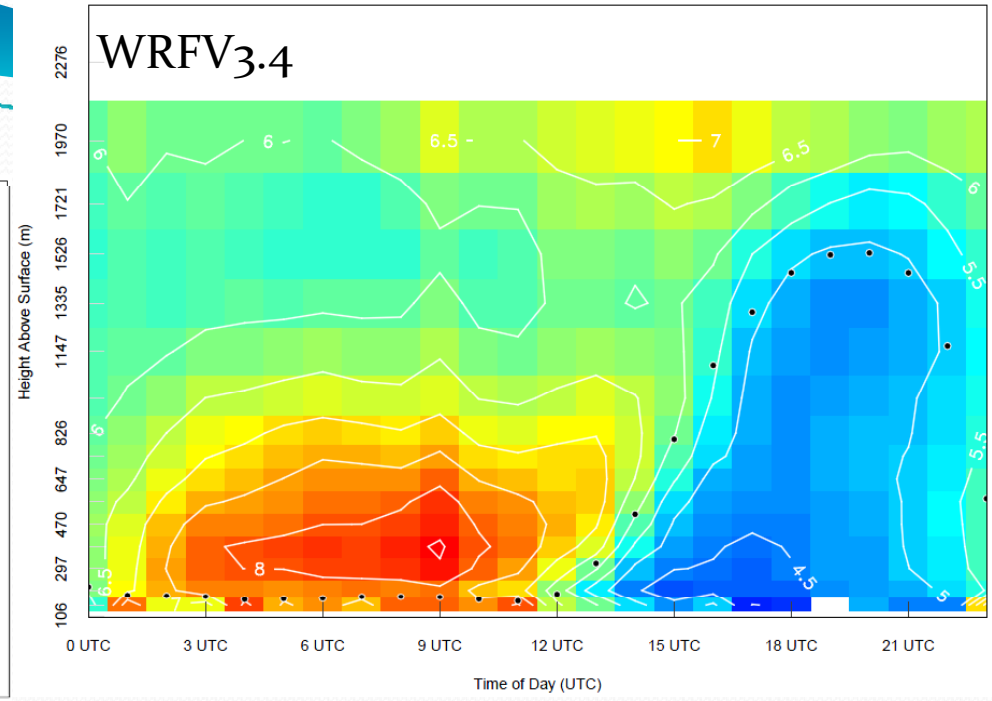


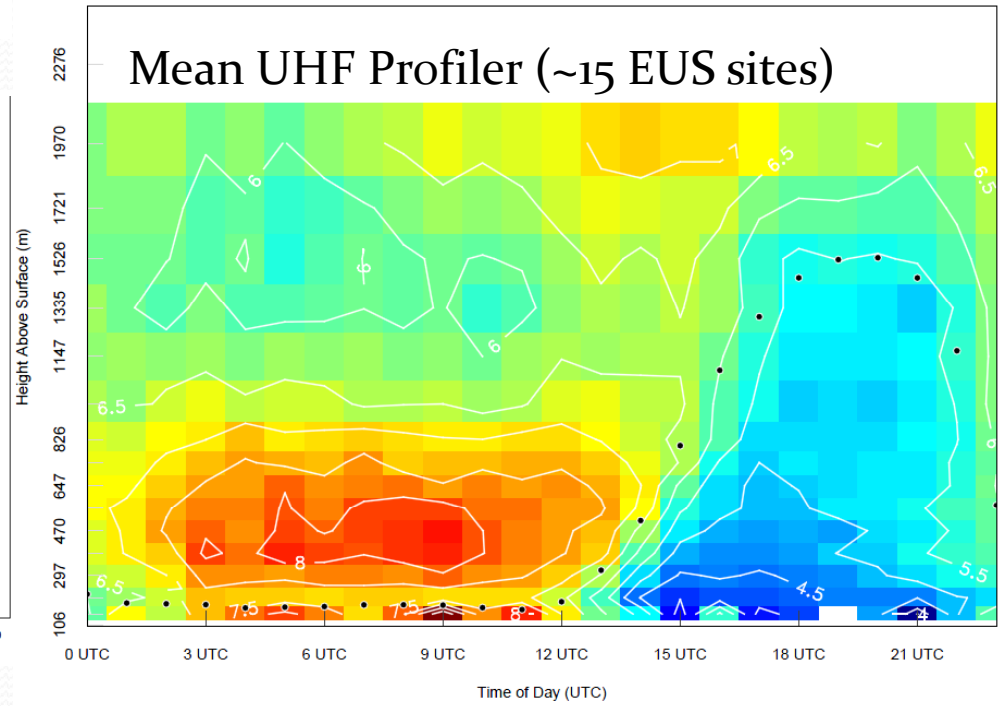
Evaluation of PBL Wind (Aug 2006)



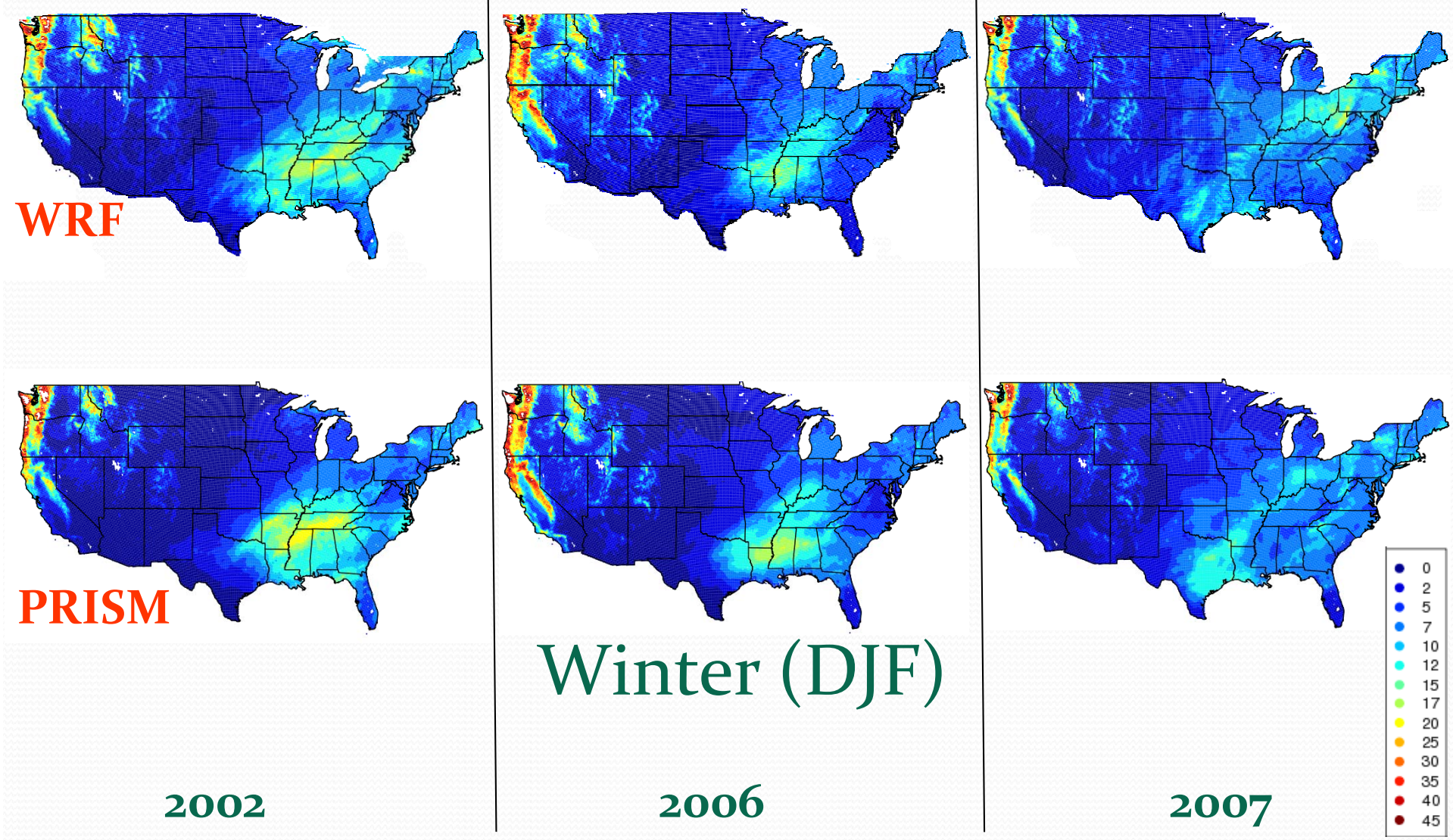




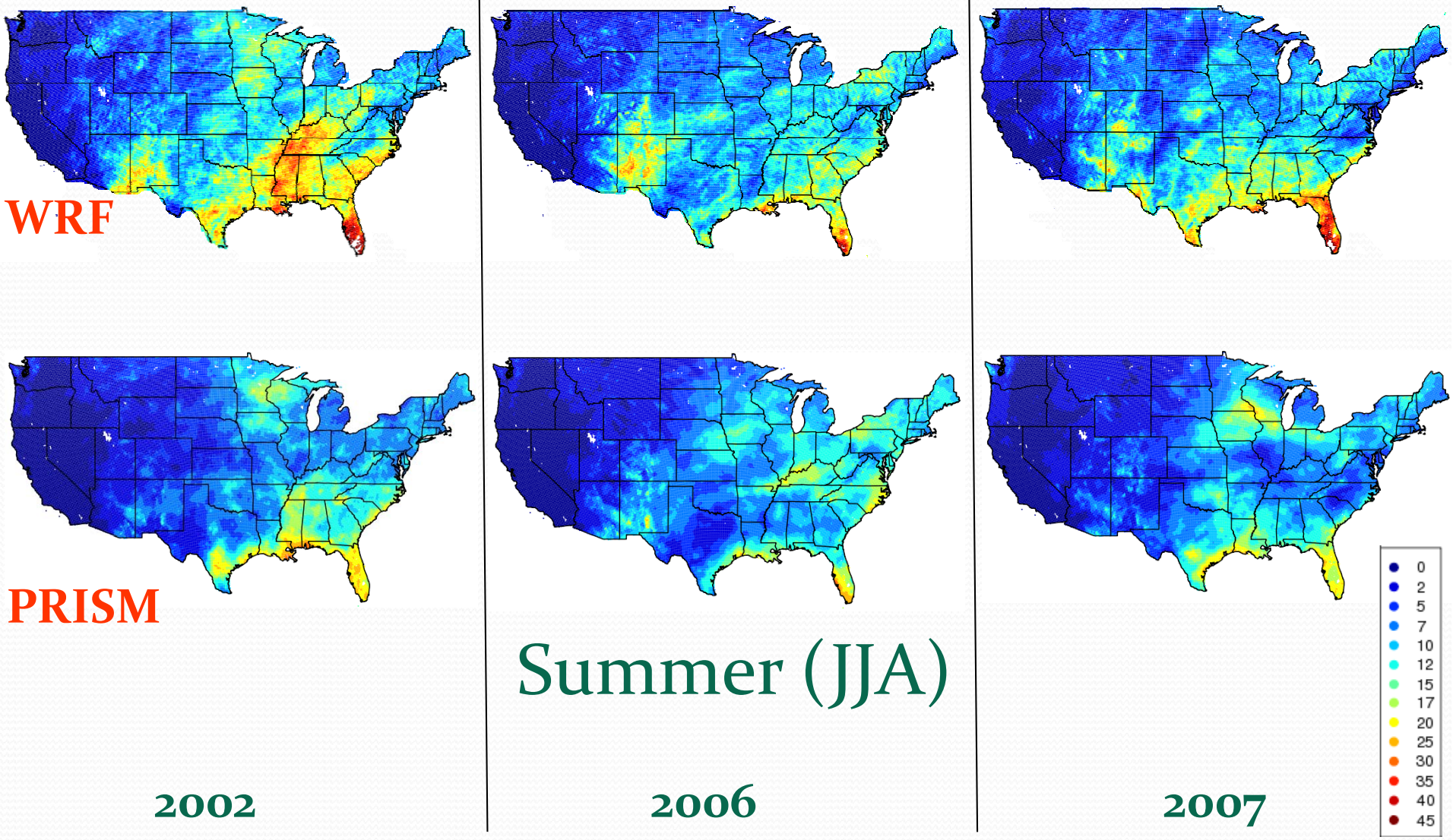




WRF Model Performance: Precip.

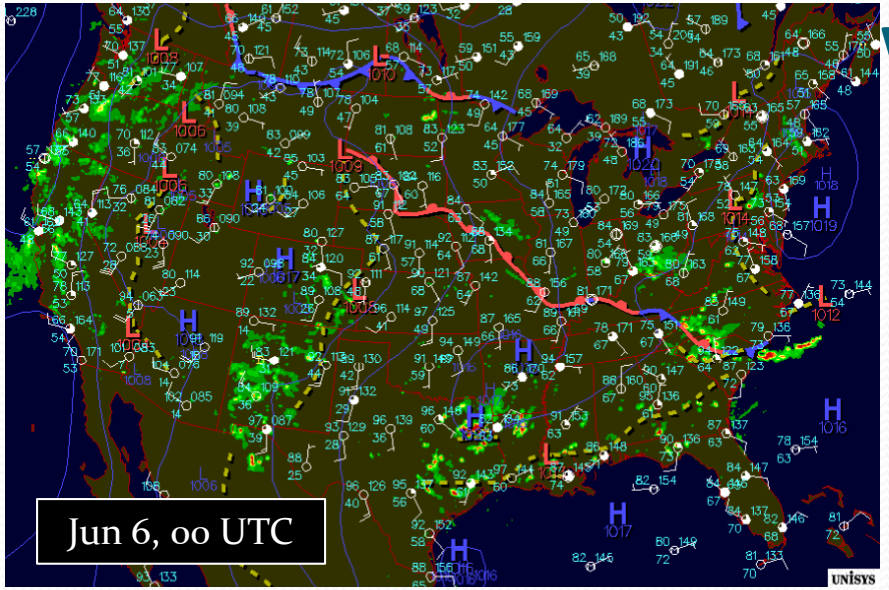


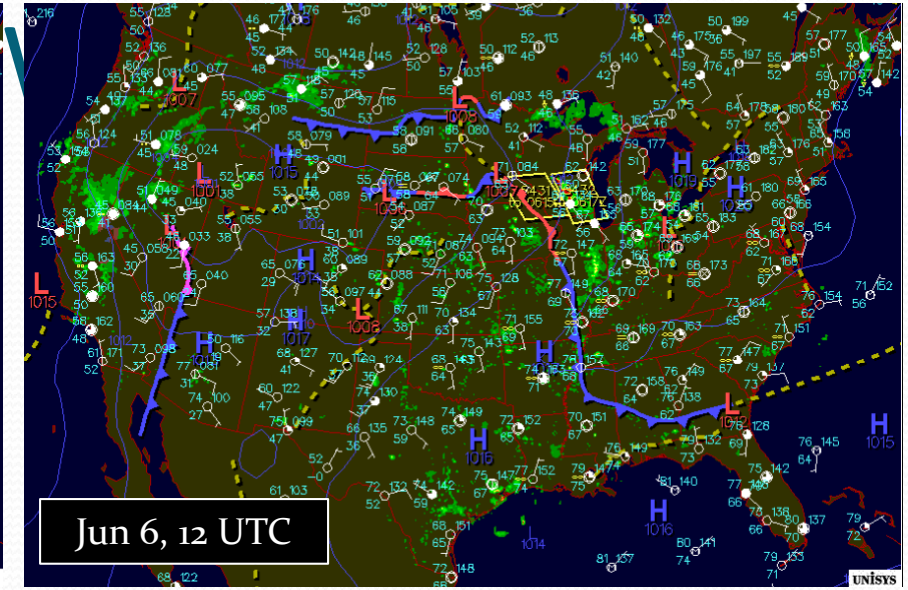
WRF Model Performance: Precip.

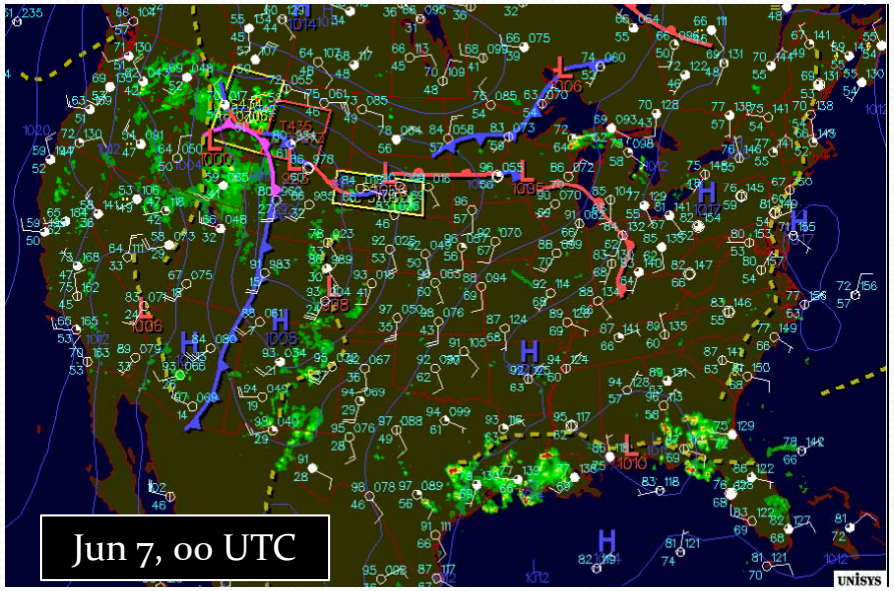


WRF-CMAQ Ensemble Modeling

- Uncertainty in air quality modeling is largely impacted by the uncertain inputs of meteorology and emissions
- In order to account for meteorological uncertainties a more probabilistic approach may be necessary
- Short-Range Ensemble Forecast system (SREF) is a 21 member system ran 4 times each day and can be used to drive multiple WRF-CMAQ simulations via grid nudging
- CMAQ results can not only provide a better assessment of modeled pollutant uncertainty, but a quantitative measure of the impact of meteorology inputs on air quality solutions


Jun 6, 00 UTC
UNISYS


Jun 6, 12 UTC
UNISYS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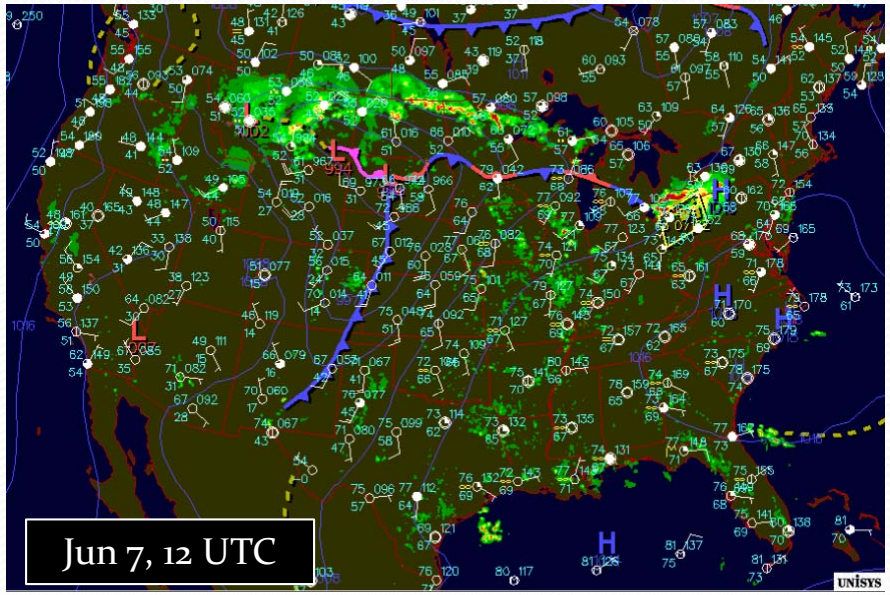
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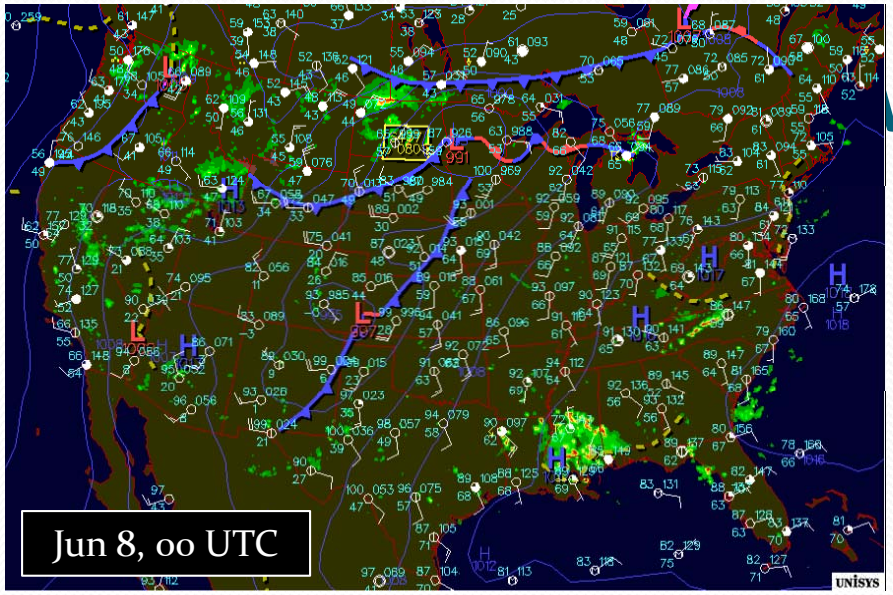
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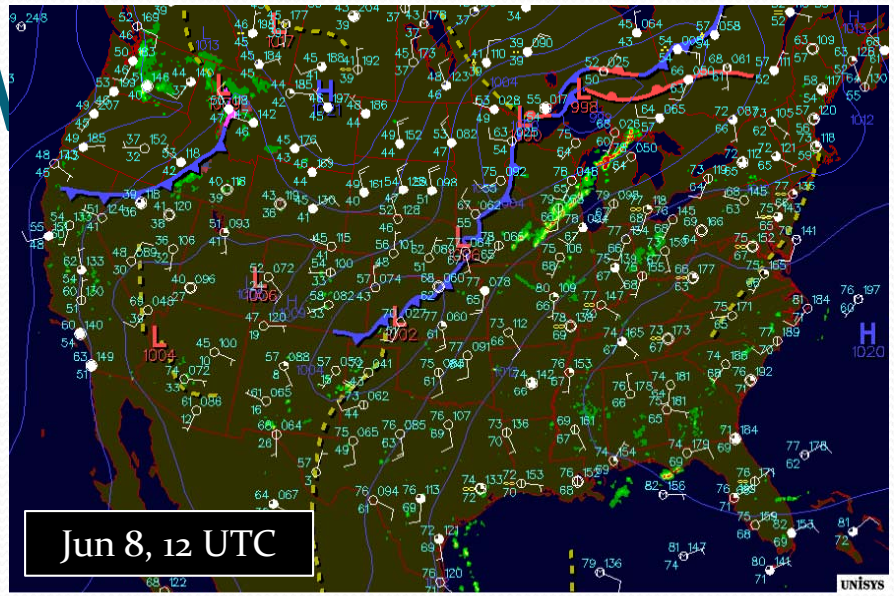
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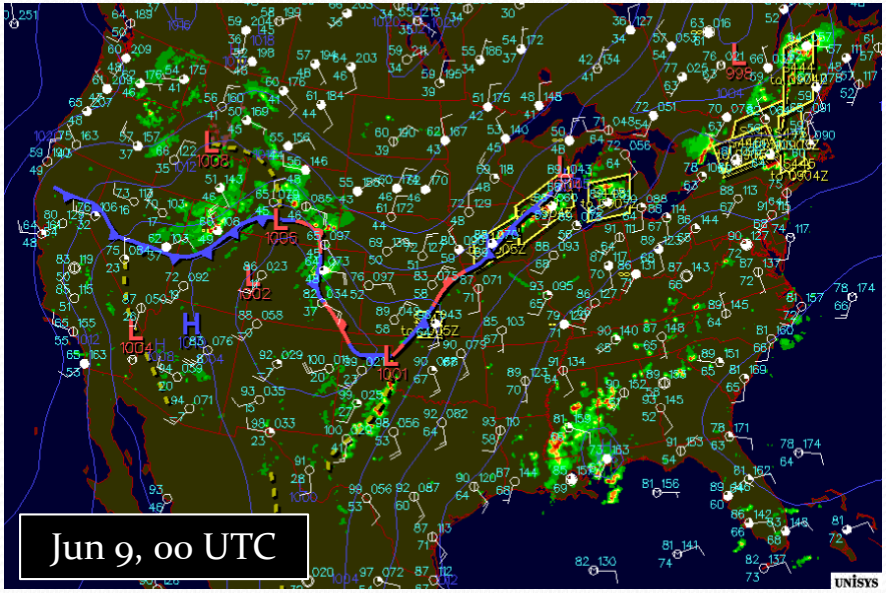
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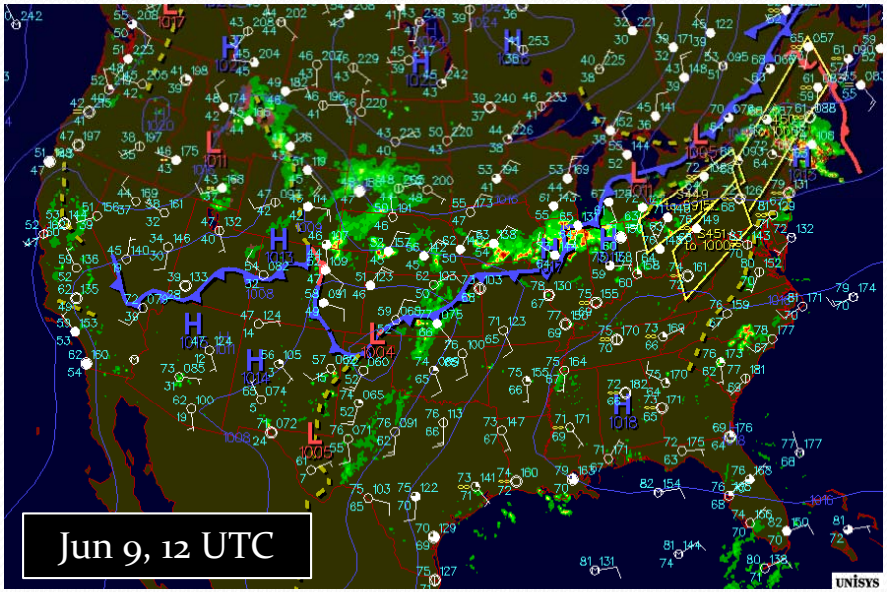
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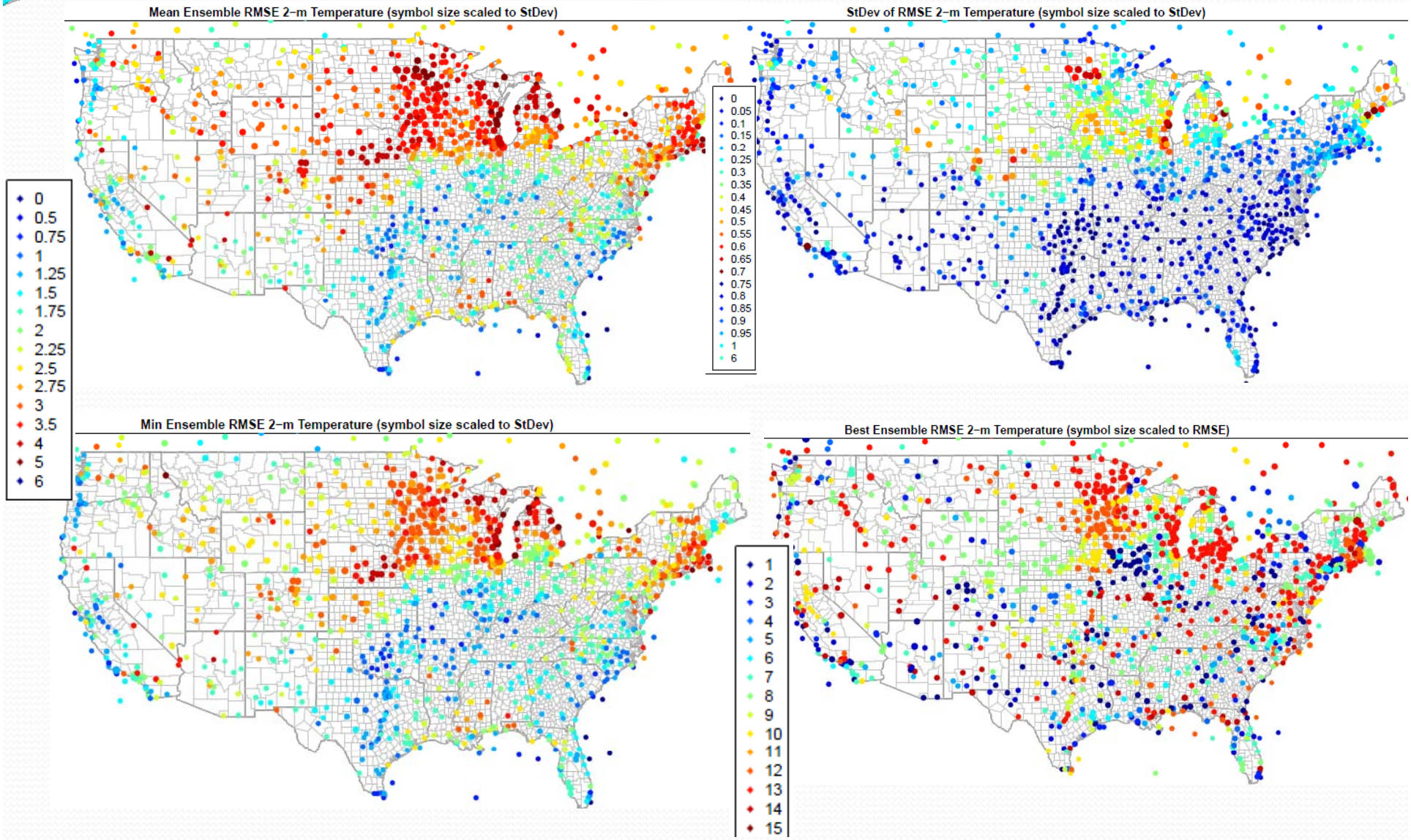
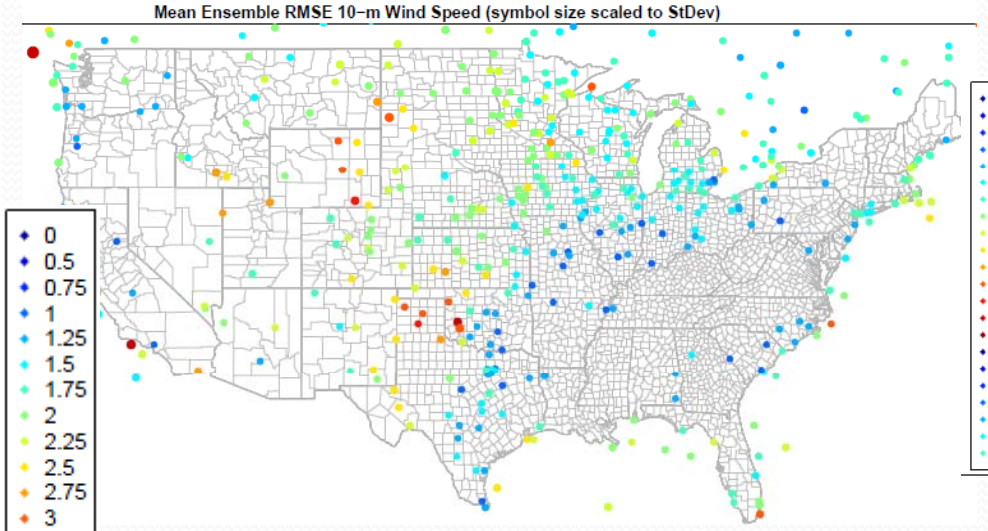
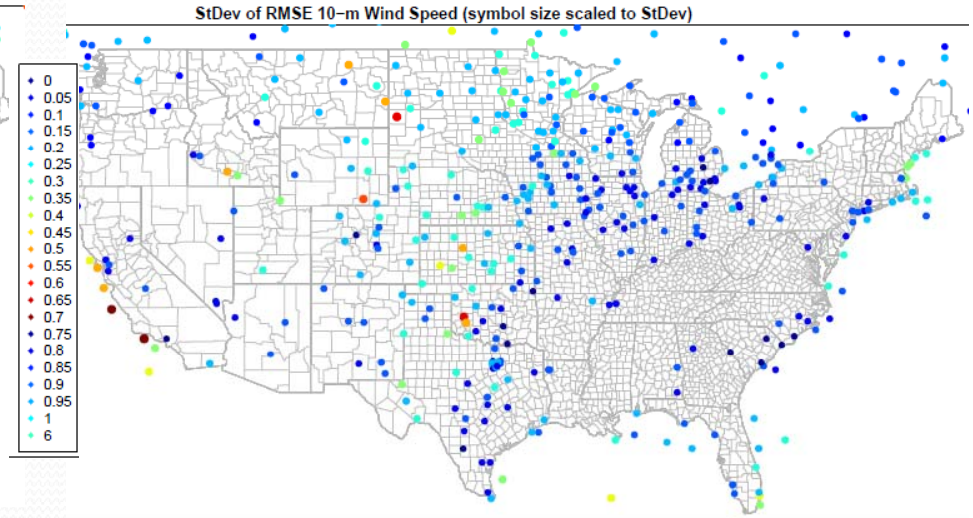
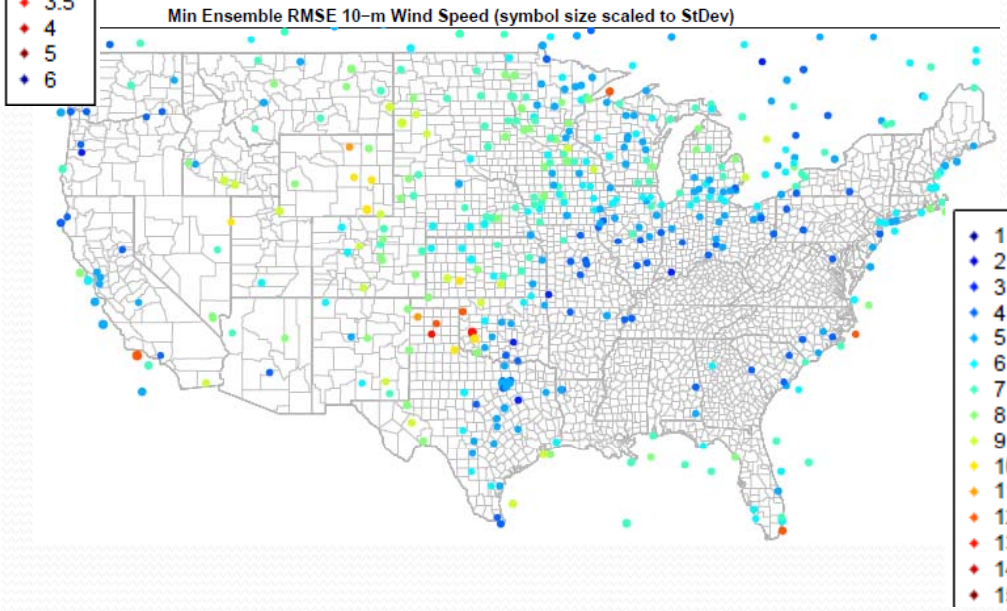
2m Temperature

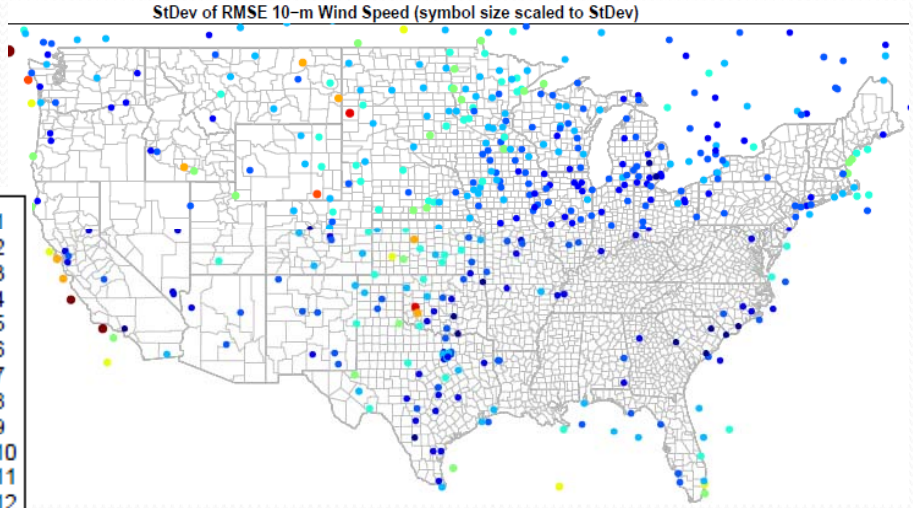


10m Wind Speed

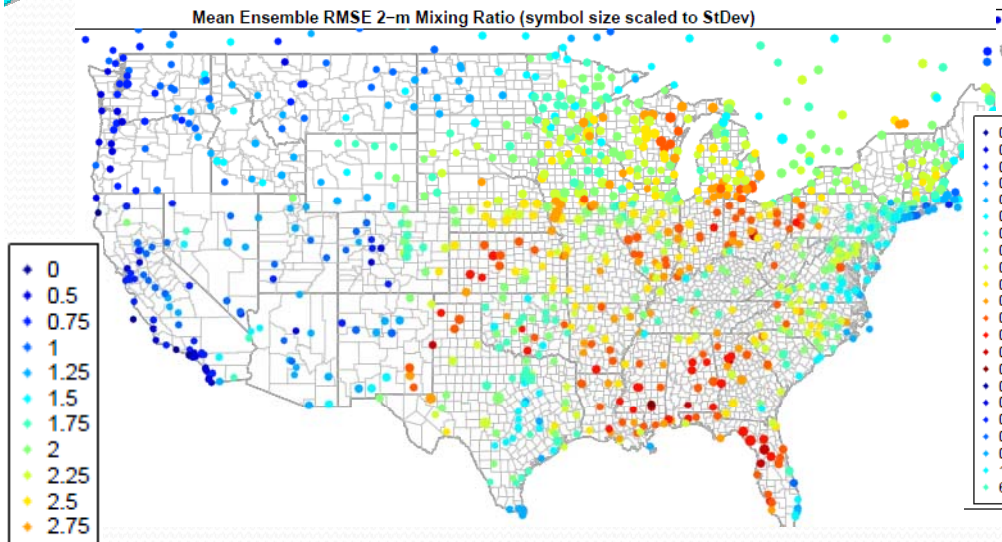


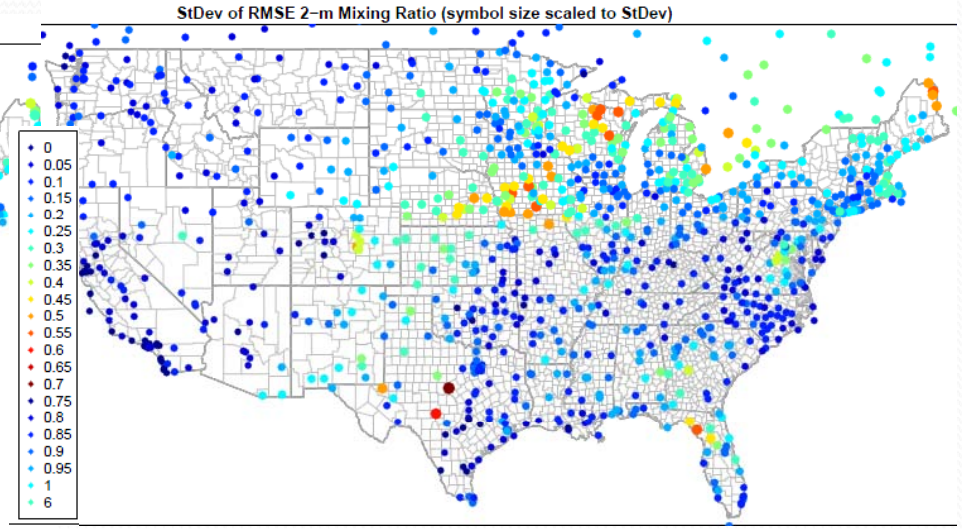


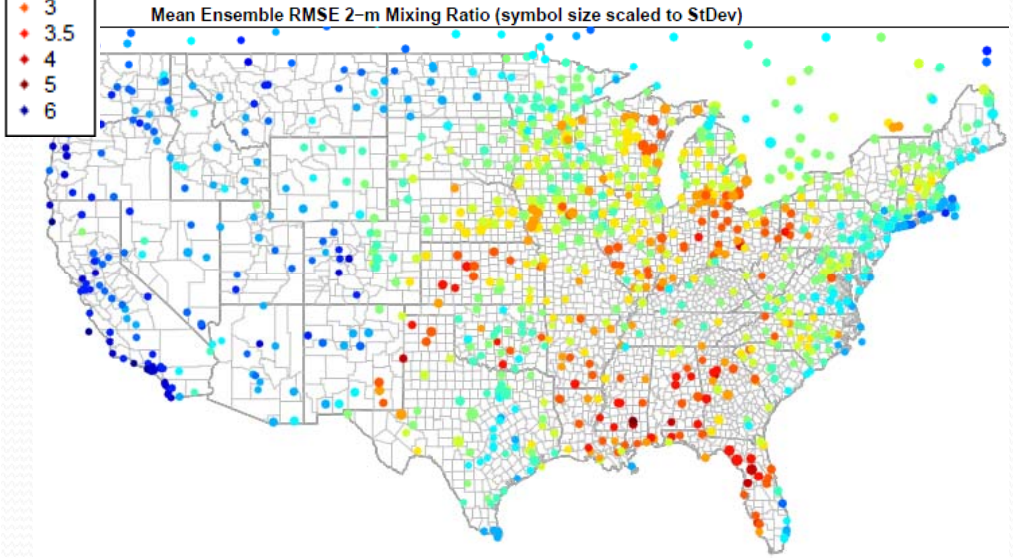


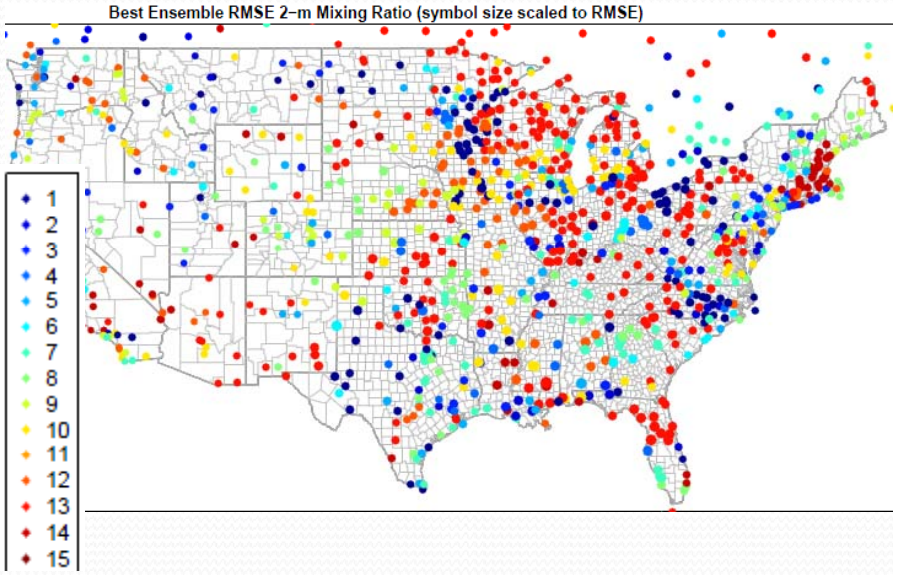


2m Mixing Ratio



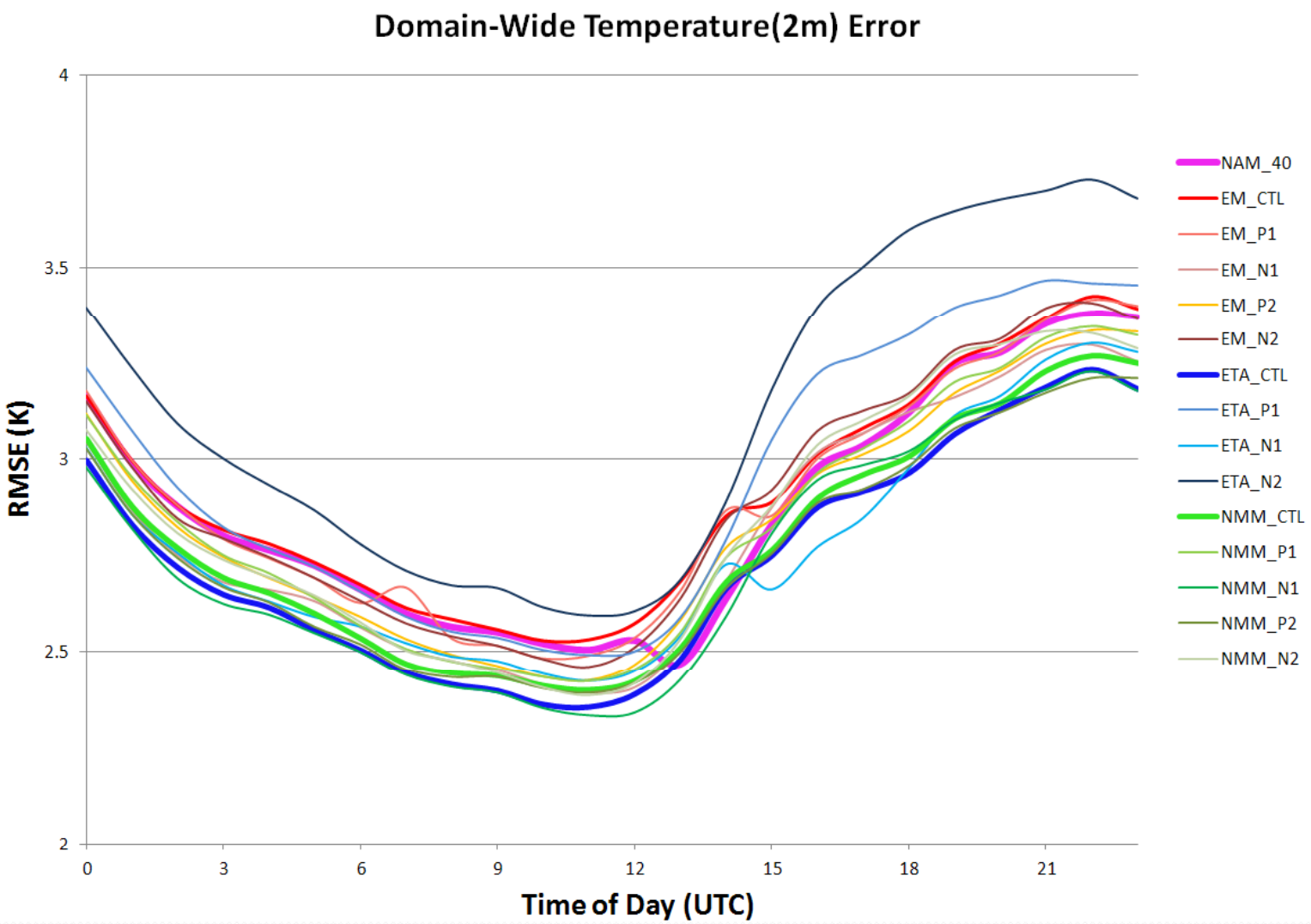


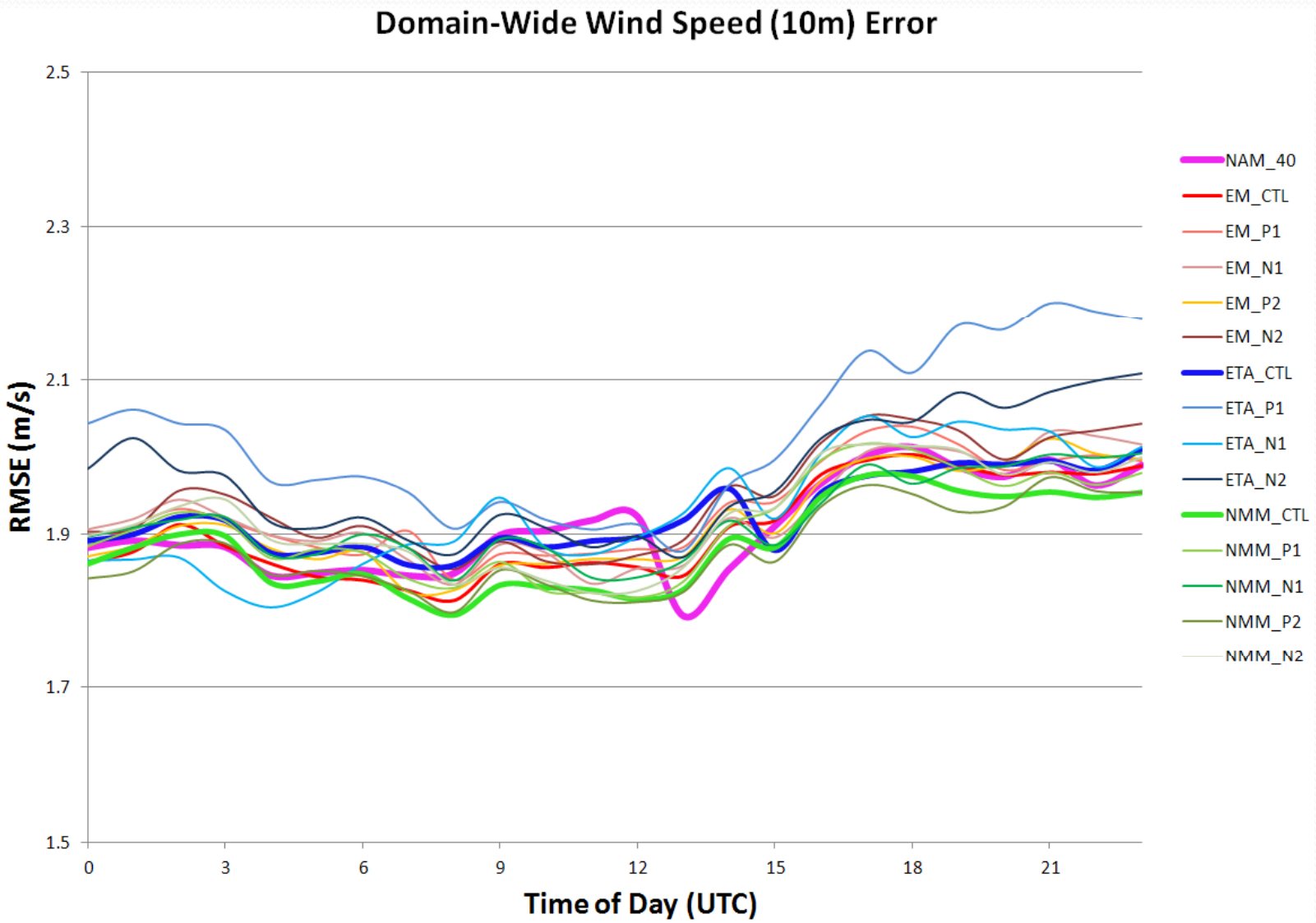




Domain-Wide Error Summary

	RMSE (K, g/kg, m/s, deg)			
ENS Member ID	T2m	Q2m	WS10m	WD10m
NAM (baseline)	2.87	2.24	1.91	41
EM_CTL	2.9	2.23	1.91	41
EM_P1	2.89	2.19	1.93	42
EM_N1	2.8	2.18	1.93	41
EM_P2	2.83	2.19	1.92	41
EM_N2	2.89	2.2	1.95	42
NMM_CTL	2.77	2.15	1.89	40
NMM_P1	2.82	2.2	1.91	41
NMM_N1	2.73	2.17	1.92	40
NMM_P2	2.74	2.19	1.88	40
NMM_N2	2.83	2.2	1.92	41
ETA_CTL1	2.73	2.14	1.92	40
ETA_CTL2	2.73	2.14	1.92	40
ETA_P1	2.94	2.3	2.03	47
ETA_N1	2.77	2.15	1.92	40
ETA_P2				
ETA_N2	3.11	2.38	1.98	44


Domain-Wide Temperature(2m) Error
RMSE (K)
4
3.5
3
2.5
2
0
3
6
9
12
15
18
21
Time of Day (UTC)
NAM_40
EM_CTL
EM_P1
EM_N1
EM_P2
EM_N2
ETA_CTL
ETA_P1
ETA_N1
ETA_N2
NMM_CTL
NMM_P1
NMM_N1
NMM_P2
NMM_N2


Domain-Wide Wind Speed (10m) Error
RMSE (m/s)
2.5
2.3
2.1
1.9
1.7
1.5
0
3
6
9
12
15
18
21
Time of Day (UTC)
NAM_40
EM_CTL
EM_P1
EM_N1
EM_P2
EM_N2
ETA_CTL
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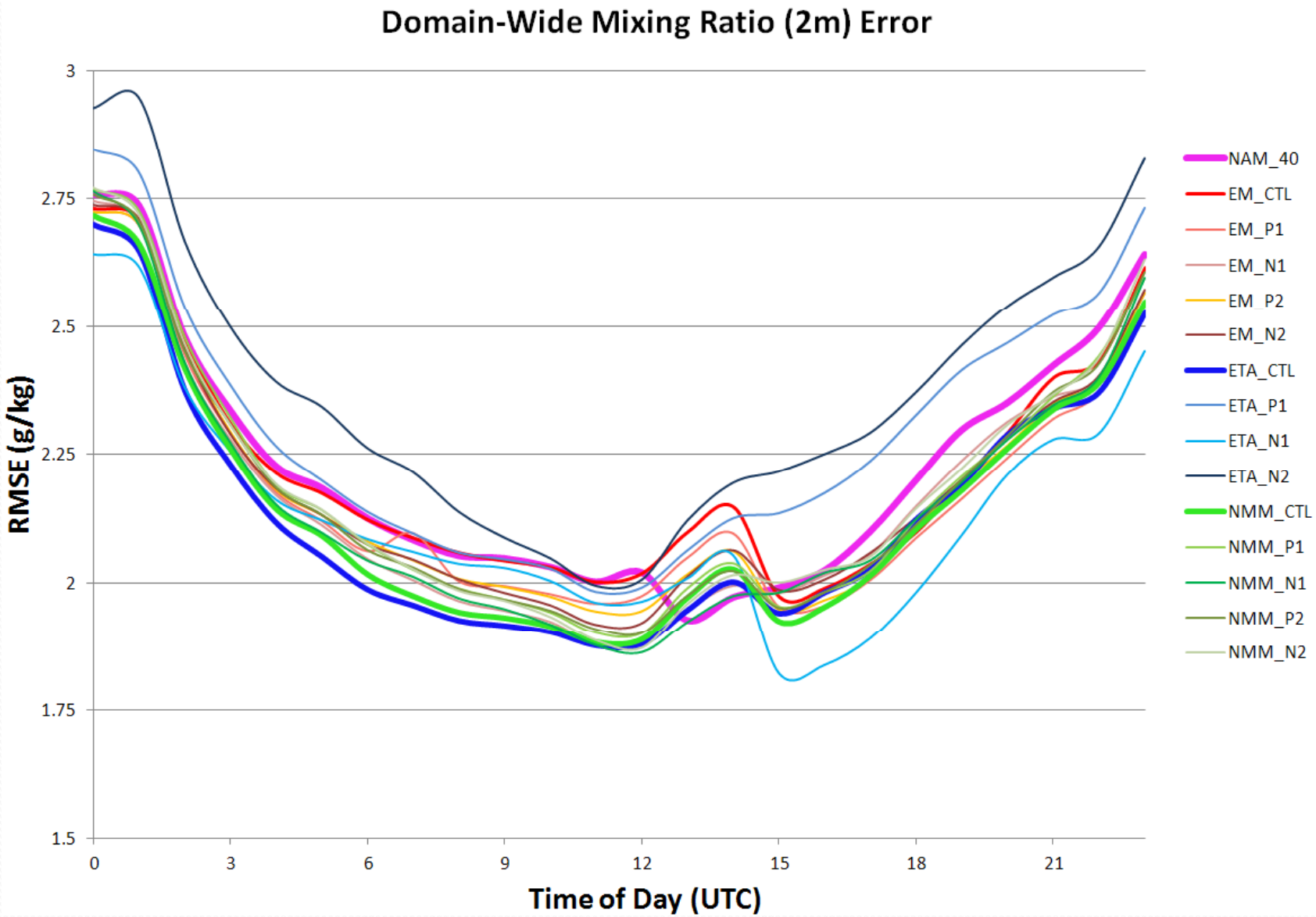
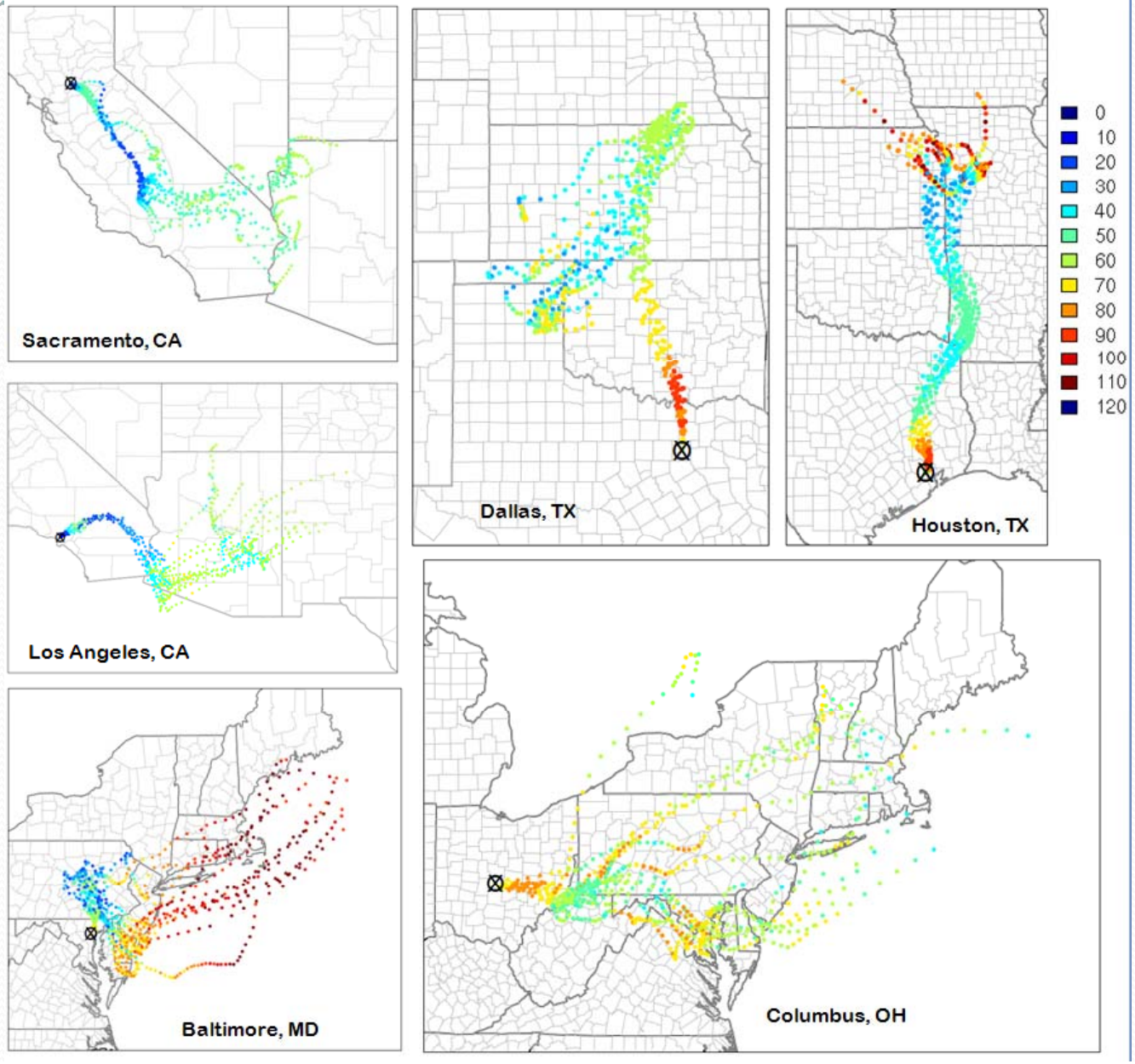
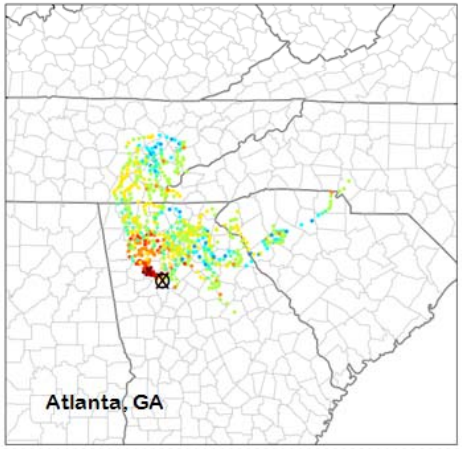
NMM_N1
NMM_P2
NMM_N2

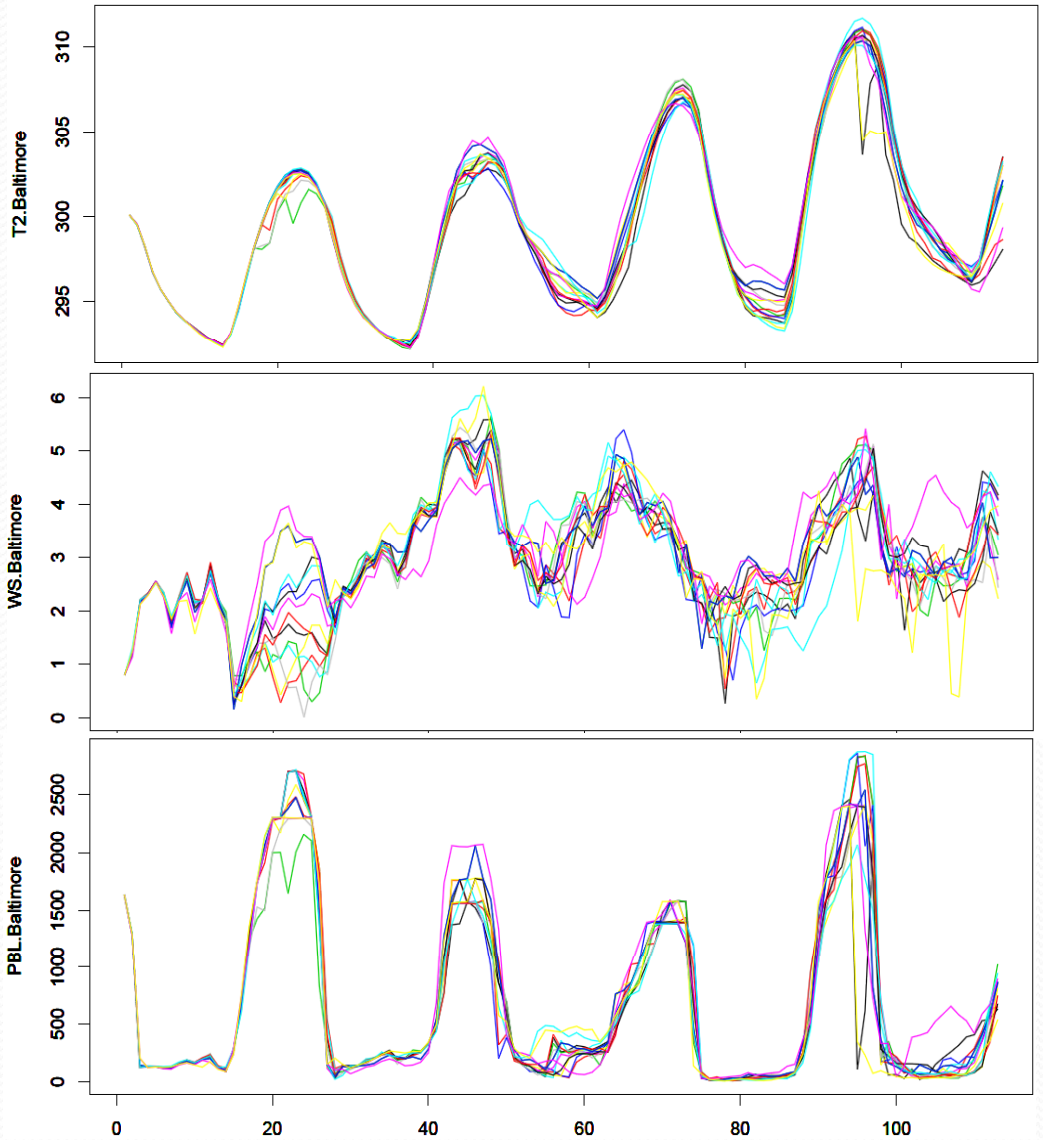

Domain-Wide Mixing Ratio (2m) Error
RMSE (g/kg)
3
2.75
2.5
2.25
2
1.75
1.5
0
3
6
9
12
15
18
21
Time of Day (UTC)
NAM_40
EM_CTL
EM_P1
EM_N1
EM_P2
EM_N2
ETA_CTL
ETA_P1
ETA_N1
ETA_N2
NMM_CTL
NMM_P1
NMM_N1
NMM_P2
NMM_N2

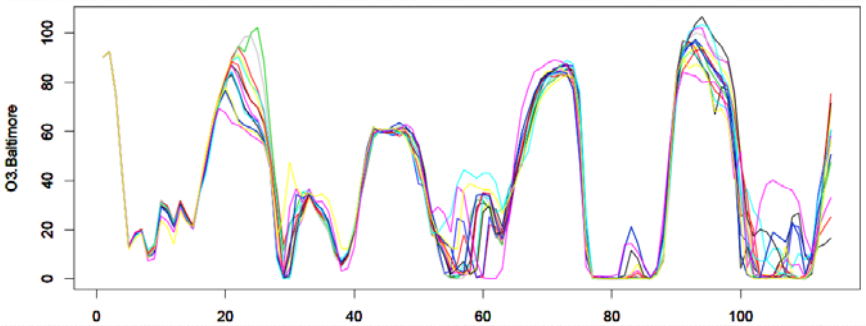
Ensemble Trajectories

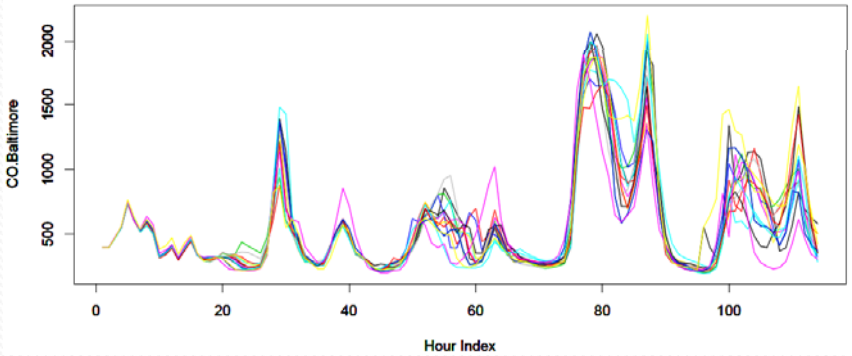




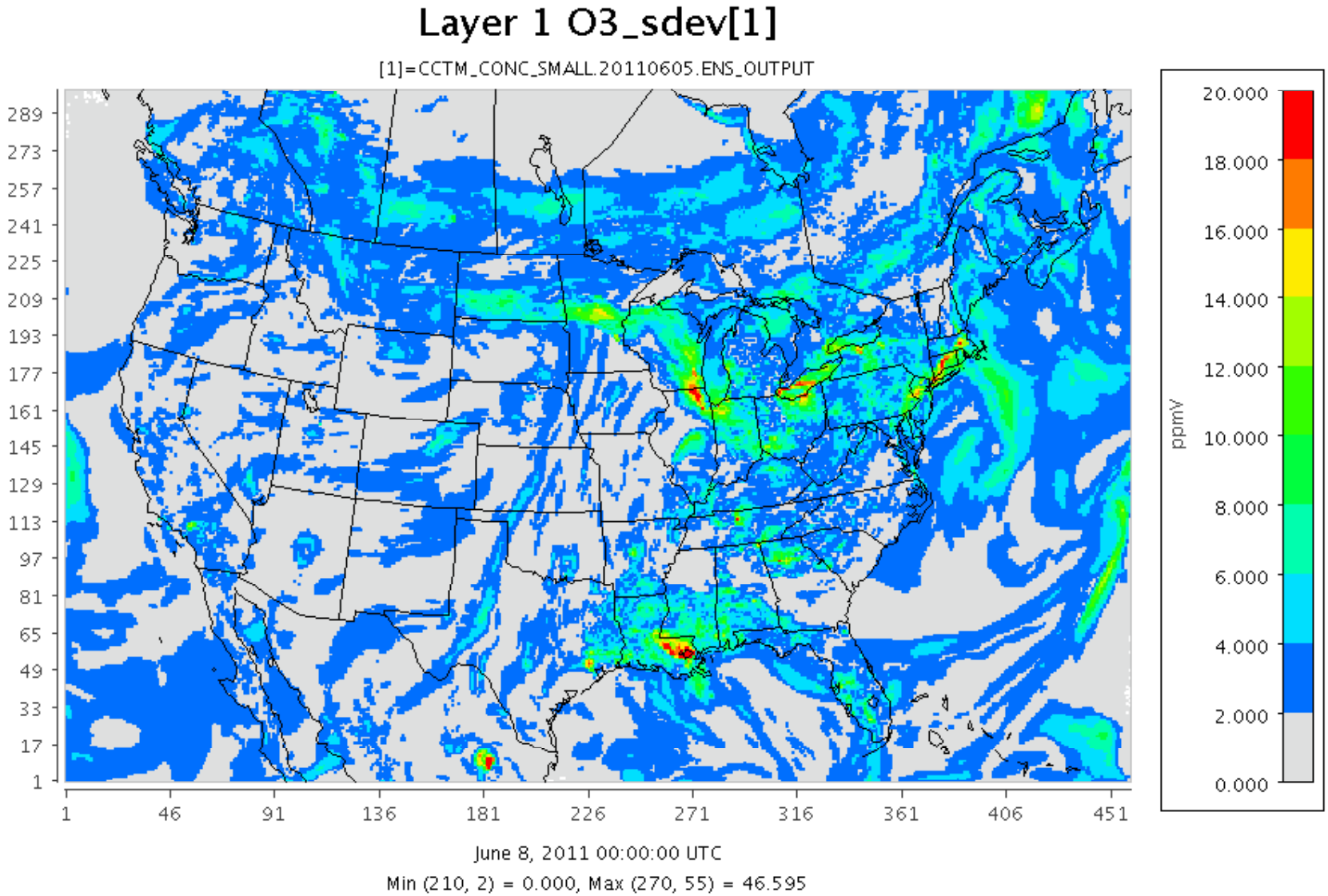
Impact of Ensemble Meteorology on CMAQ



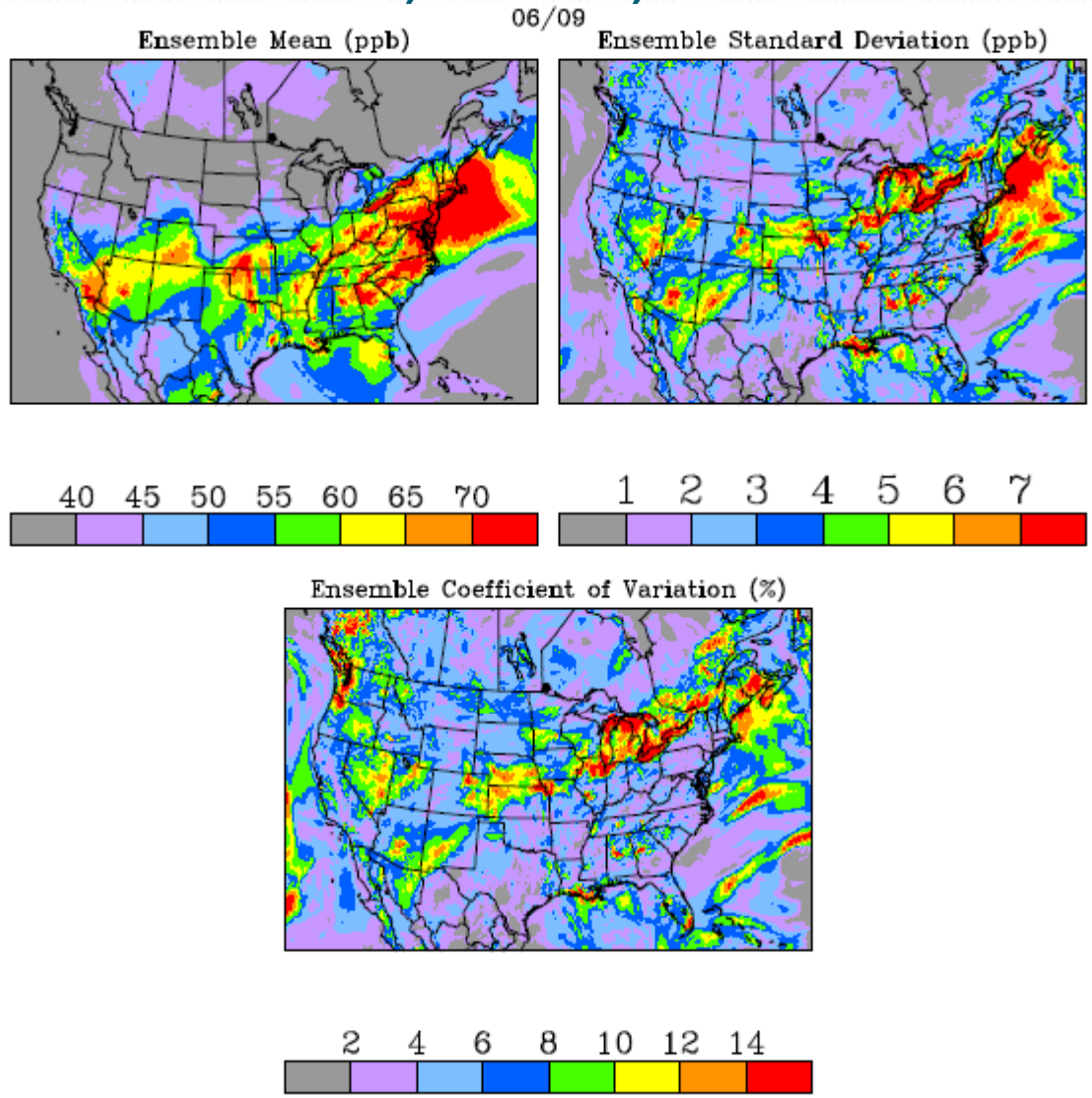




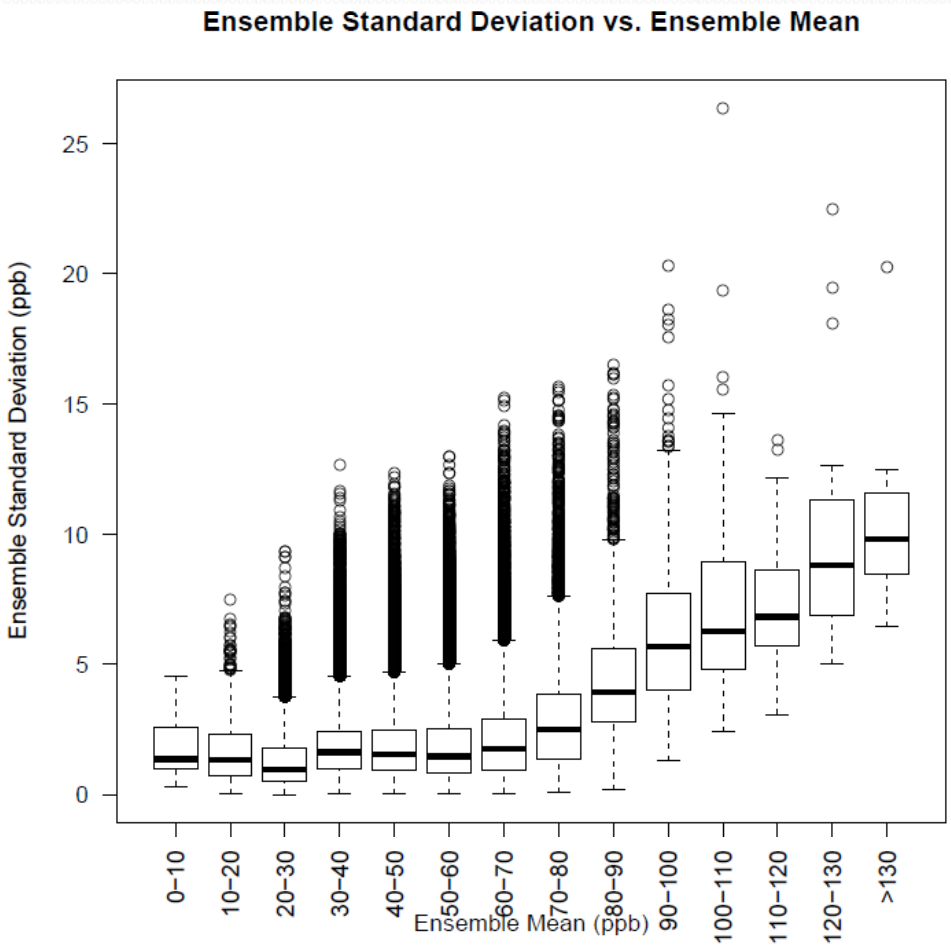
Impact of Ensemble Meteorology on CMAQ

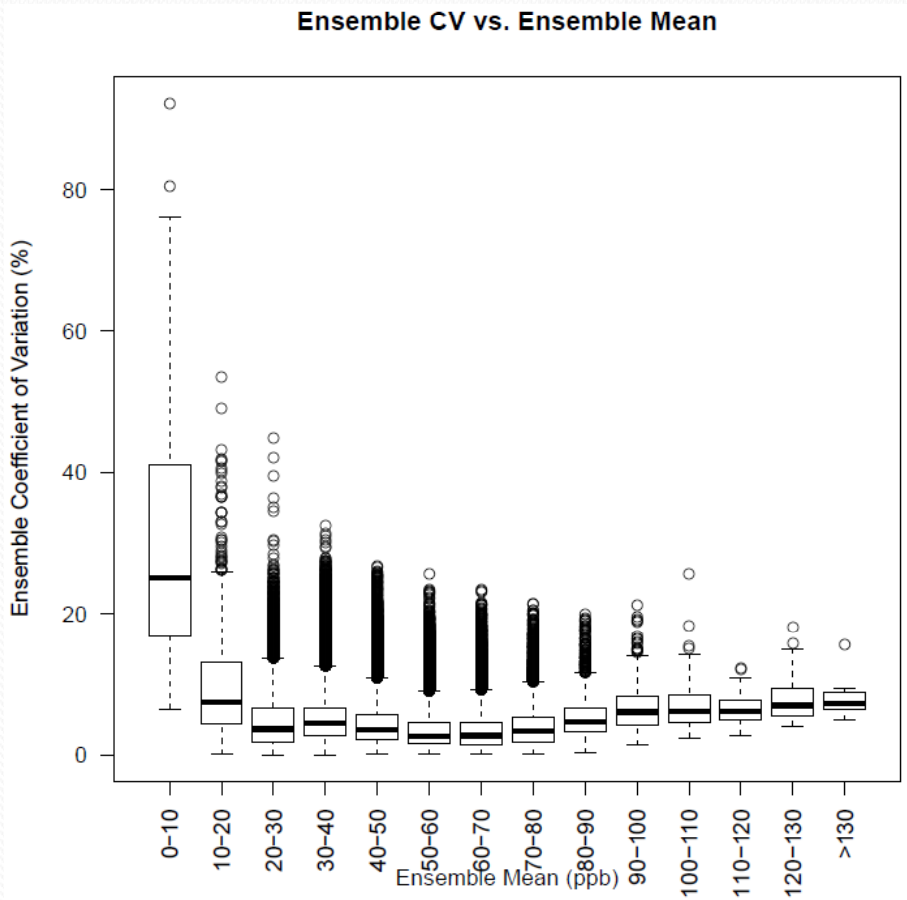


Ensemble Mean, Standard Deviation, and Coefficient of Variation of 8hr DM O3, June 9, 2011

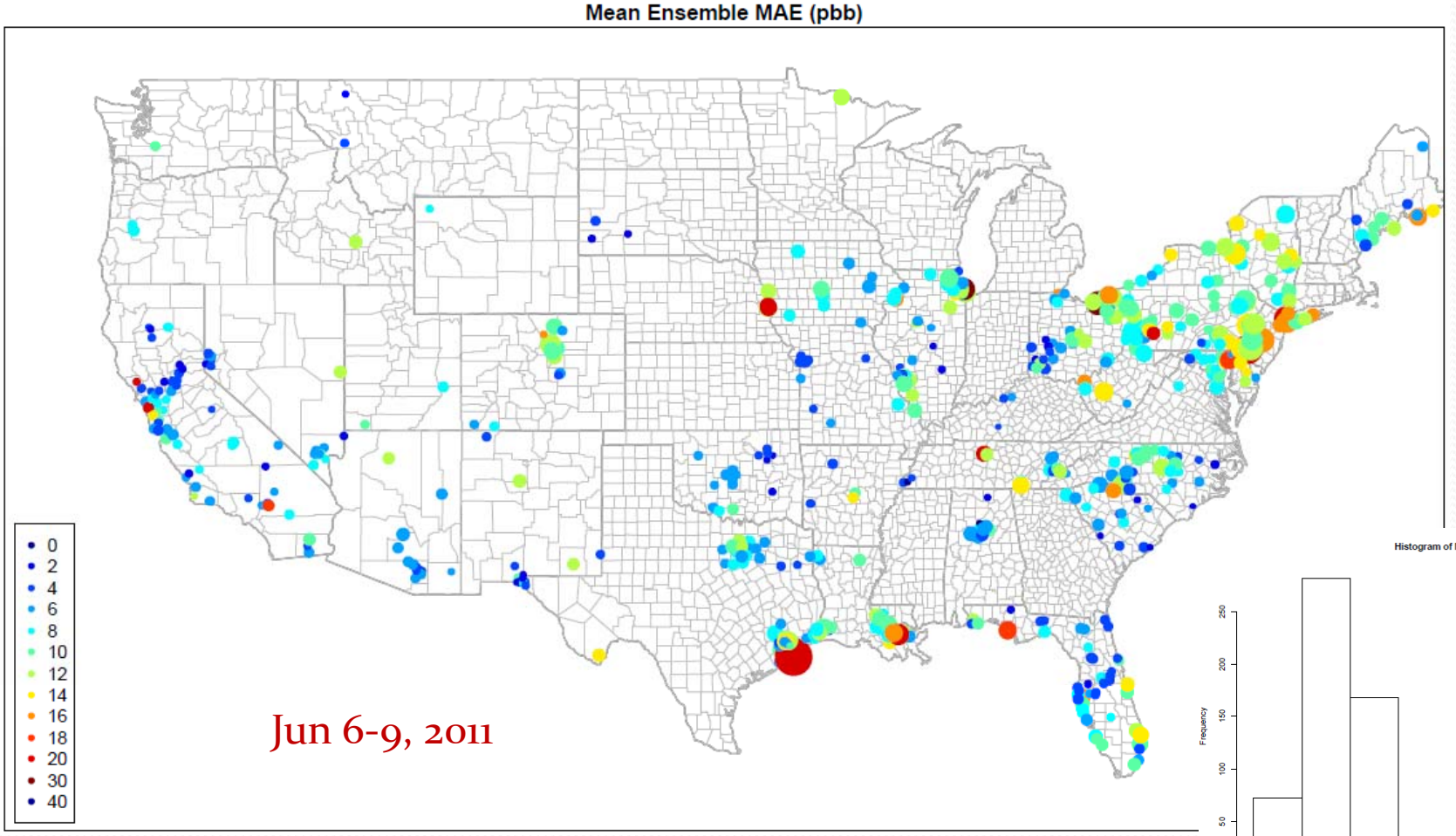


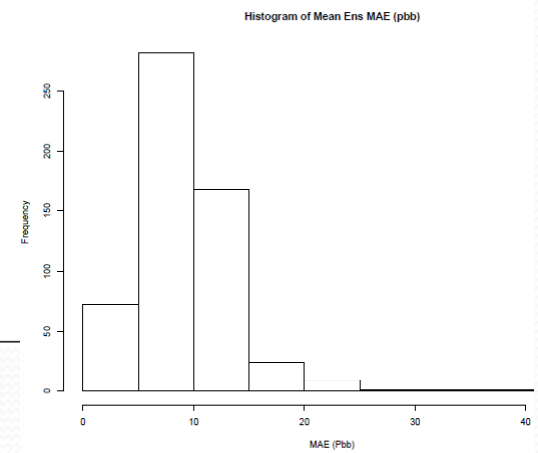
Ensemble Standard Deviation and Ensemble Coefficient of Variation of 8-hr DM O3 as Function of Ensemble Mean Concentration All Days June 6 – 9, All Grid Cells Except 100% Water Cells





Spatial Ensemble Metrics

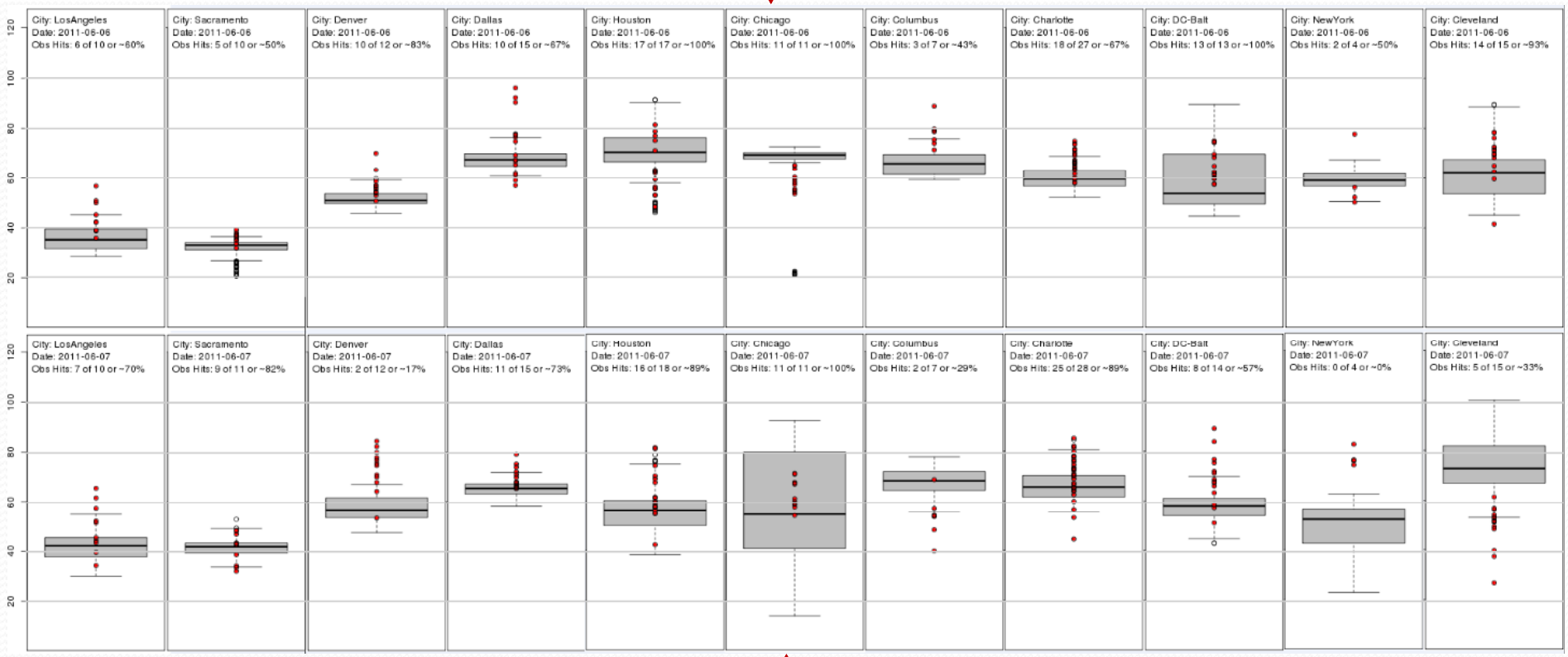




Note: Symbol color is the mean of the MAE of Ensemble Members (8-hr Max Ozone)
Symbol size is proportional to the Std.Dev. Of the Ensemble MAE's

Daily City-based max 8-hr O3 Comparisons

June 6, 2011

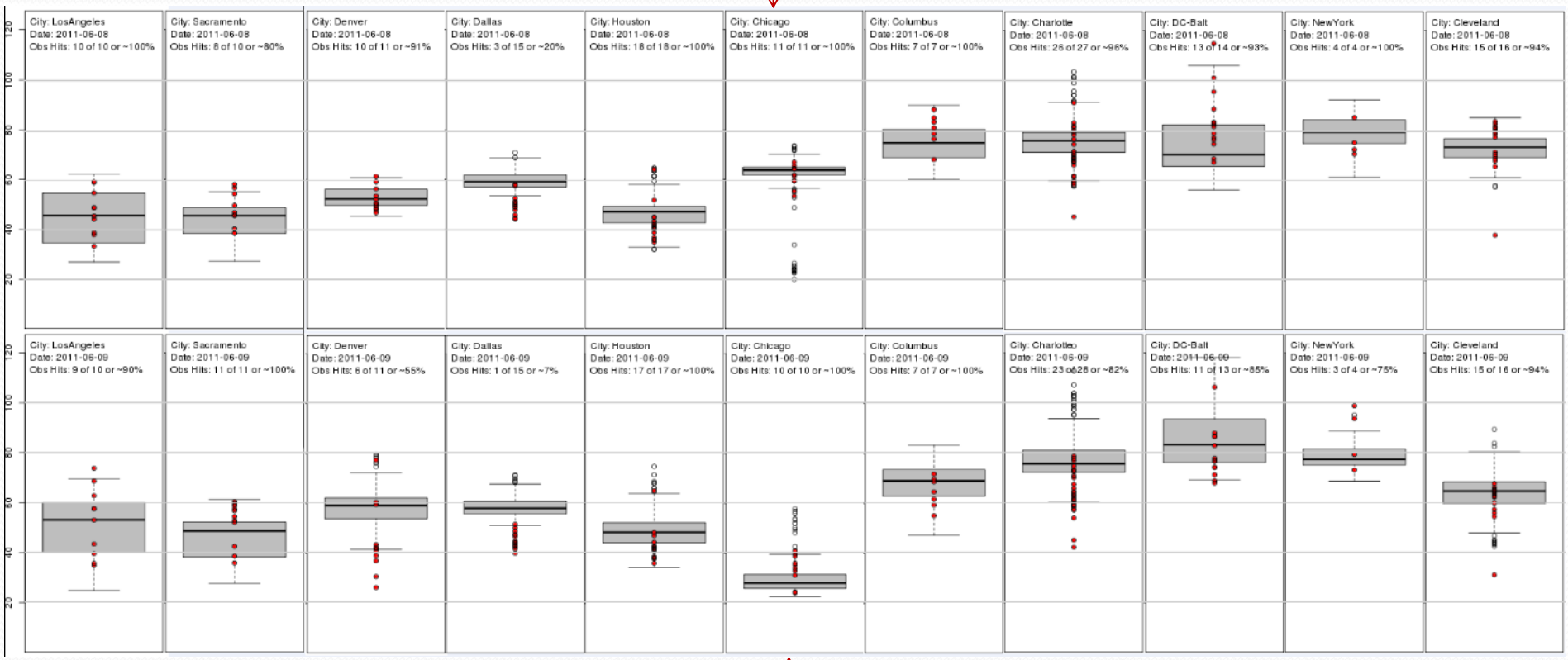


* City-wide 8-hr max O3 can vary widely on a day-to-day basis. It is very difficult for a single model realization to capture this spatial variability on such a small scale. Probabilistic modeling has the capability of making these max 8-hr estimates more likely to cover the observed range.

June 7, 2011

Daily City-based max 8-hr O3 Comparisons

June 8, 2011



June 9, 2011