Aerosol Data Assimilation with the WRF/Chem for air quality analysis and forecast

Zhiquan Liu (liuz@ucar.edu)
NCAR/NESL/MMM

NCAR/MMM: Hui-Chuan Lin, Craig Schwartz
JCSDA: Quanhua Liu

Outline

- Scientific/Technical background
- Results for a dust storm event over East Asia
  - Only assimilate MODIS AOD
- Results over North America
  - Assimilate both MODIS AOD and AIRNow PM2.5
- Summary and Future work

GOCART and WRF/Chem

- The GOCART aerosol module is available within the WRF/Chem model and produces forecasts for 14 aerosol species:
  - Hydrophobic and hydrophilic organic carbon (OC1, OC2)
  - Hydrophobic and hydrophilic black carbon (BC1, BC2)
  - Sulfate
  - Dust in 5 particle-size bins [dust{1,2,3,4,5]
  - Sea salt in 4 particle-size bins [seas{1,2,3,4}]

- WRF-Chem "P25" aerosol variable also an analysis variable
  - P25 is unspeciated aerosols contributing to $PM_{2.5}$

15 aerosol variables (mass concentration) to be analyzed

MODIS AOD DA: previous work

- Collins et al. (2001), Adhikary et al. (2008), Zhang et al. (2008, NAAPS)
  - Two-step procedure:
    - first use 2D-OI or 2D-VAR to analyze 2D AOD field
    - then adjust 3D aerosol concentration profiles from updated AOD fields.
  - Usually do a scaling in the second step by assuming constant weight of each species to total aerosol mass concentration.

- Benedetti et al. (2009, ECMWF): 4DVAR, but use total aerosol mass as analysis variable

Surface PM DA: previous work

1) Lin et al. (2008): Assimilated PM_{10} over China with an EnKF

2) Tombette et al. (2010): Assimilated PM_{10} over Europe with OI

3) Pagowski et al. (2010): Assimilated $PM_{2.5}$ over USA with 3DVAR (two-step method, NOT same as our 3DVAR)

NOT see previous study to assimilate both AOD and surface PM.

Our approach: 3D Variational data assimilation

- 3DVAR is to minimize a cost function (in a least square sense)

$$J(x) = \frac{1}{2}(x - x_b)^{\mathrm{T}} \mathrm{B}^{-1}(x - x_b) + \frac{1}{2}[H(x) - y]^{\mathrm{T}} \mathrm{R}^{-1}[H(x) - y]$$

which measures the weighted distance of the model state x to the model "background" x_b and the observations y.

X are 15 aerosol species mass concentration in 3D space.

X_b the "background" of X, short-term forecast from WRF/Chem.

Y can be any aerosol-related observations (in our case, MODIS AOD and surface PM2.5).

H is "observation operator", which transforms the model state to observation space.

The background error covariance B (having spatial correlation) and observation error covariance R (no spatial correlation).

Observation Operator

- Directly analyze 3D aerosol mass concentration with a one-step procedure of 3DVAR minimization (just like usual meteor. DA)
  - Do NOT apply any assumption about vertical shape and relative weight of individual species.

- Use Community Radiative Transfer Model (CRTM) of Joint Center for Satellite Data Assimilation (JCSDA) as the AOD observation operator, including both forward and Jacobian models to calculate the gradient of cost function.

- Linear formula for model-simulated $PM_{2.5}$ (from WRF-Chem)
  - $PM_{2.5} = \rho[p25 + bc1 + bc2 + 1.8(oc1 + oc2) + dust1 + 0.286*dust2 + seas1 + 0.942*seas2 + 1.375*sulf]$

Advantages of our 3DVAR approach

- Straightforward to add more AOD data from multi-sensor/angle products and also other aerosol related observations (e.g., PM10/PM2.5, Lidar ext. profiles).

- Allow simultaneous assimilation of aerosol and meteor. observations (e.g., humidity and hydrophilic aerosols).
  - though NOT for the results shown here

http://modis-atmos.gsfc.nasa.gov/index.html

MODIS Aerosol Products

MOD - Terra

MYD - Aqua

MOD04_L2: MODIS Level 2 Aerosol Product at 10 km spatial resolution

MOD08_D3: MODIS Level 3 Daily Atmosphere Gridded (1°X1°) Product

MOD08_E3: MODIS Level 3 Eight Day Atmosphere Gridded (1°X1°) Product

MOD08_M3: MODIS Level 3 Monthly Atmosphere Gridded (1°X1°) Product

Collection 51

Acquisition date YYYYDDD

Start time HHMM

Collection version

Processing date and time YYYYDDDHHMMSS

Index of ftp://ladsweb.nascom.nasa.gov /allData/51/MYD04_L2/2010/045/

Up to higher level directory

Name	Size	Last Modified	
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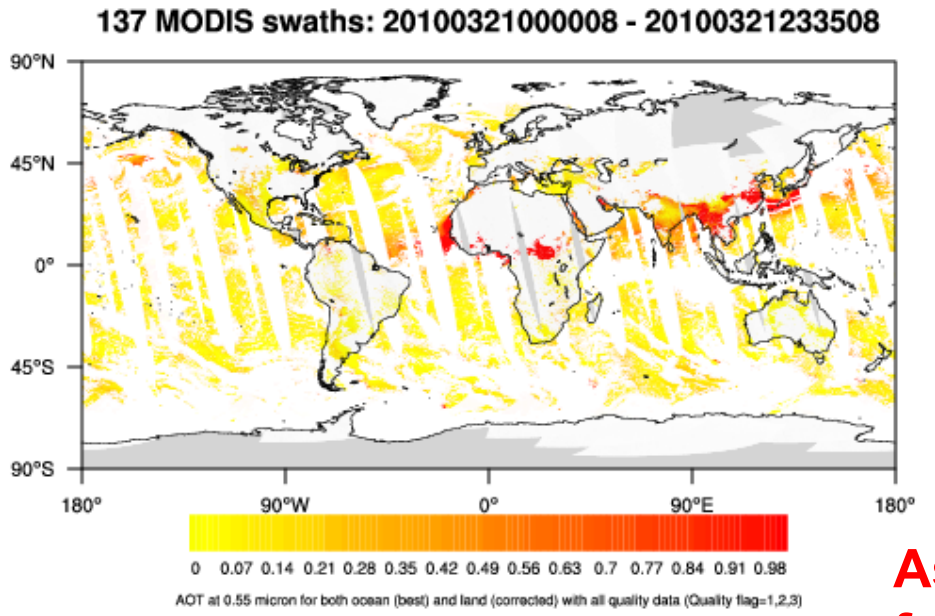
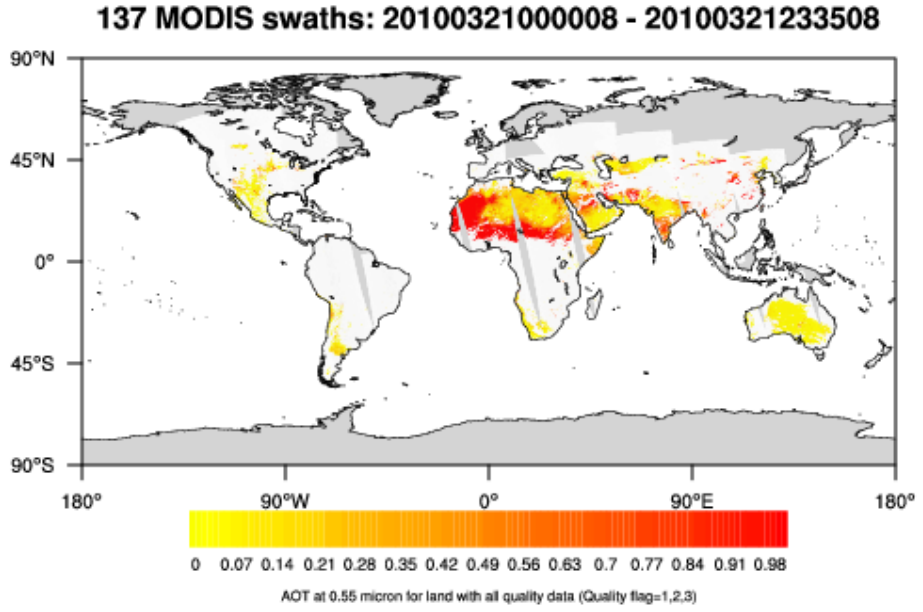
MYD04_L2.A2010045.0120.051.2010046235818.hdf		2/15/10	7:05:00 PM
MYD04_L2.A2010045.0125.051.2010047000238.hdf		2/15/10	7:07:00 PM

One HDF file consists of 5 min data ("Granule")



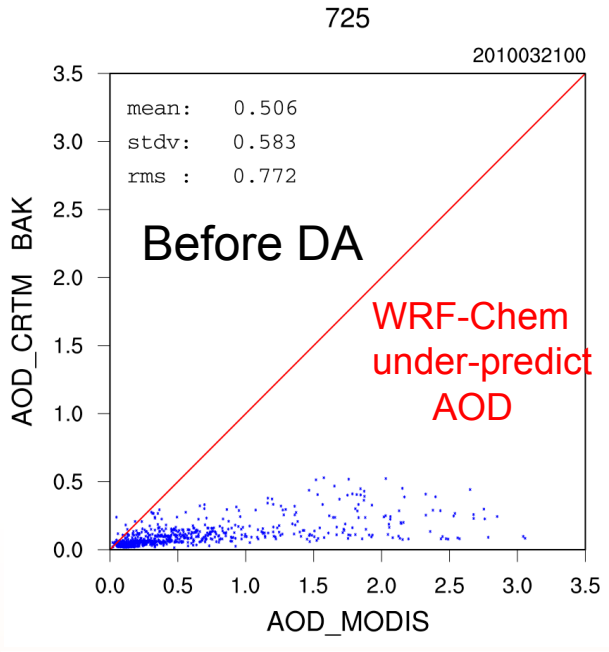
Standard AOD product over ocean & land

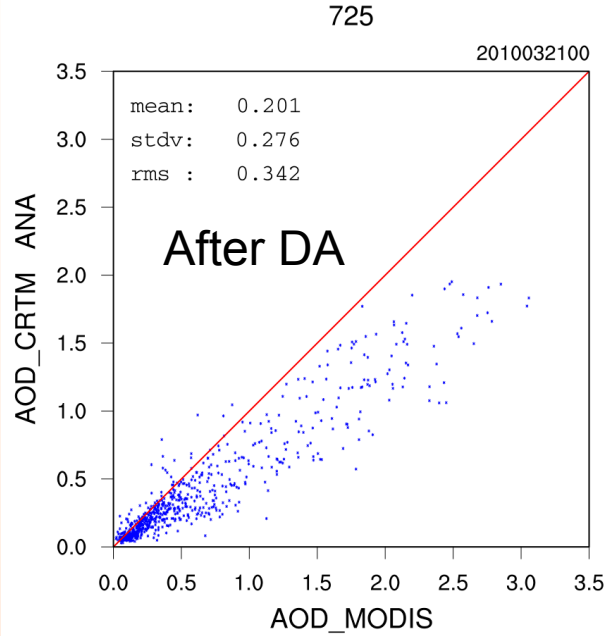
Assimilate only 0.55 μm band from both Terra and Aqua.

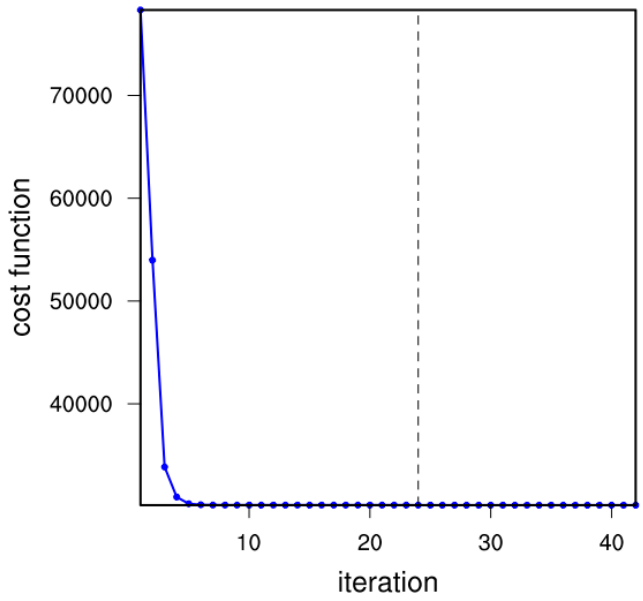


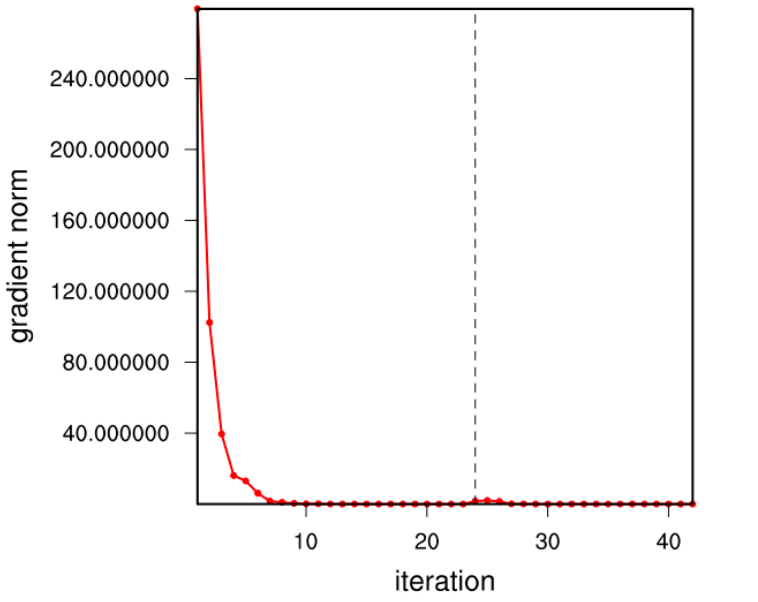
"Deep Blue" AOD product over bright land surface

Minimization









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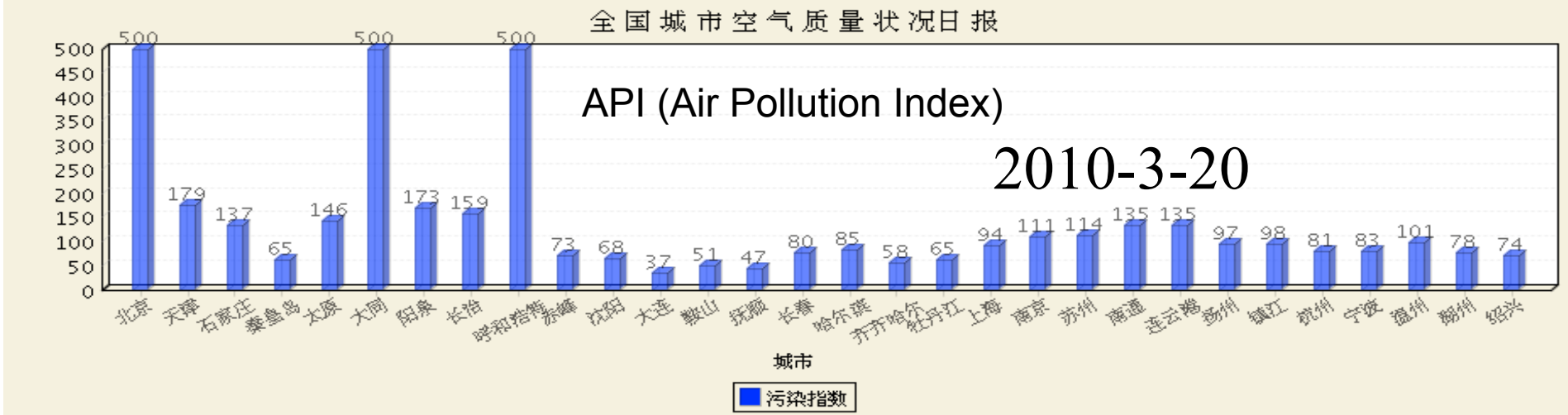
Liu Z. et al., (2011): Three-dimensional variational assimilation of MODIS aerosol optical depth: Implementation and application to a dust storm over East Asia. JGR. In press.

Dust storm affected Nanjing on Mar. 21, 2010

昨天北方沙尘来到南京，使南京蒙上灰蒙蒙的"沙帐"。张鸽 摄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API (Air Pollution Index)
2010-3-20
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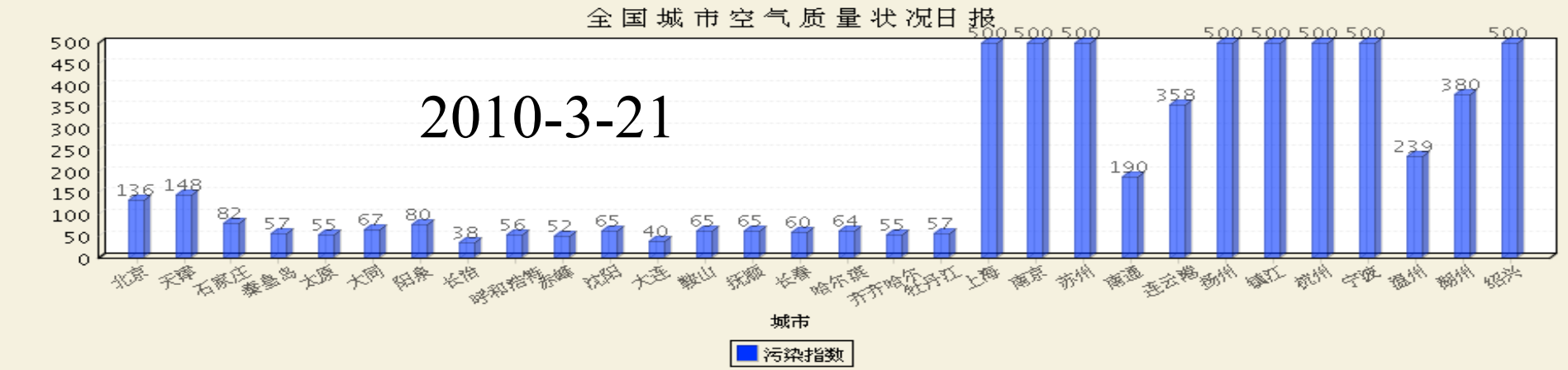
北京 天津 石家庄 秦皇岛 太原 大同 阳泉 长治 呼和浩特 赤峰 沈阳 大连 鞍山 抚顺 长春 哈尔滨 齐齐哈尔 佳木斯 上海 南京 苏州 南通 连云港 扬州 镇江 杭州 宁波 温州 湖州 绍兴
城市
污染指数


全国城市空气质量状况日报
2010-3-21
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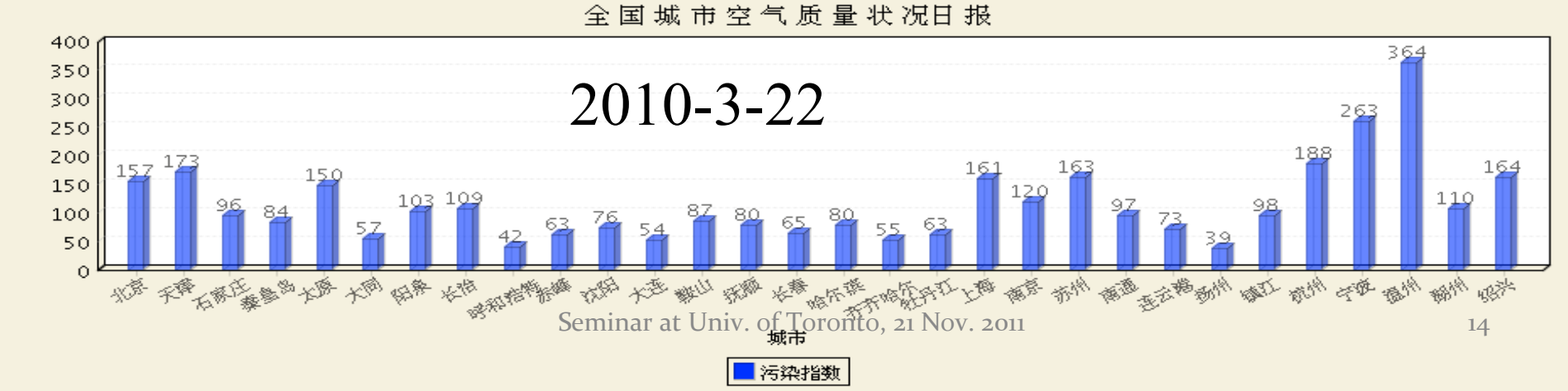
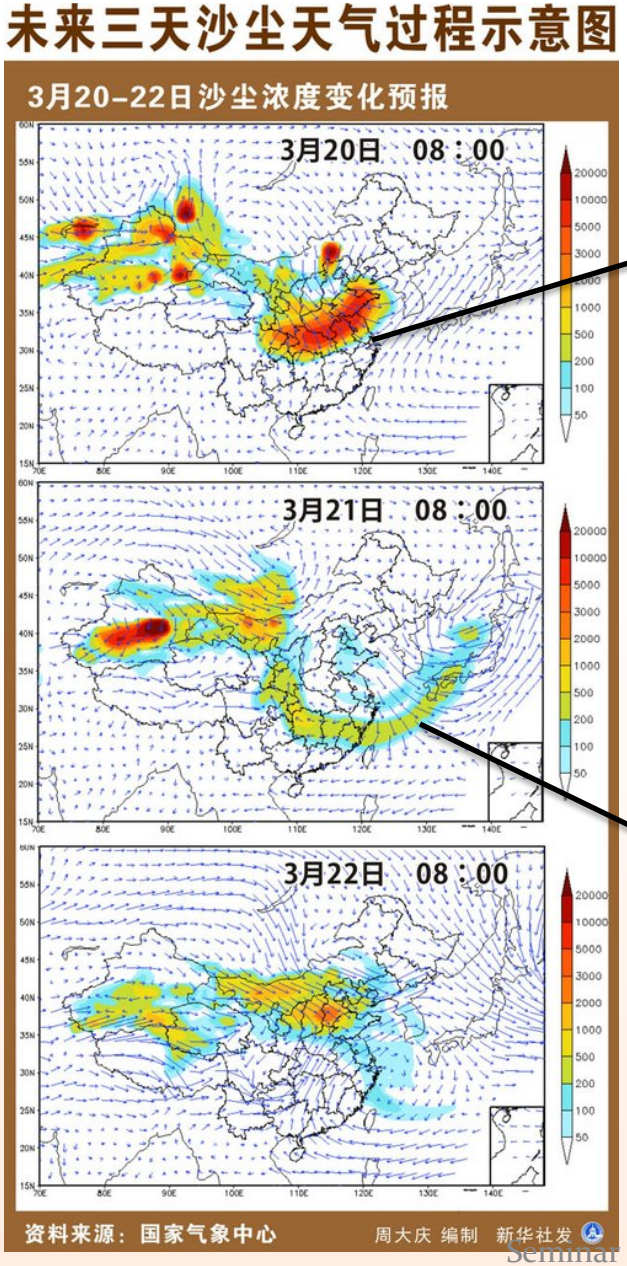
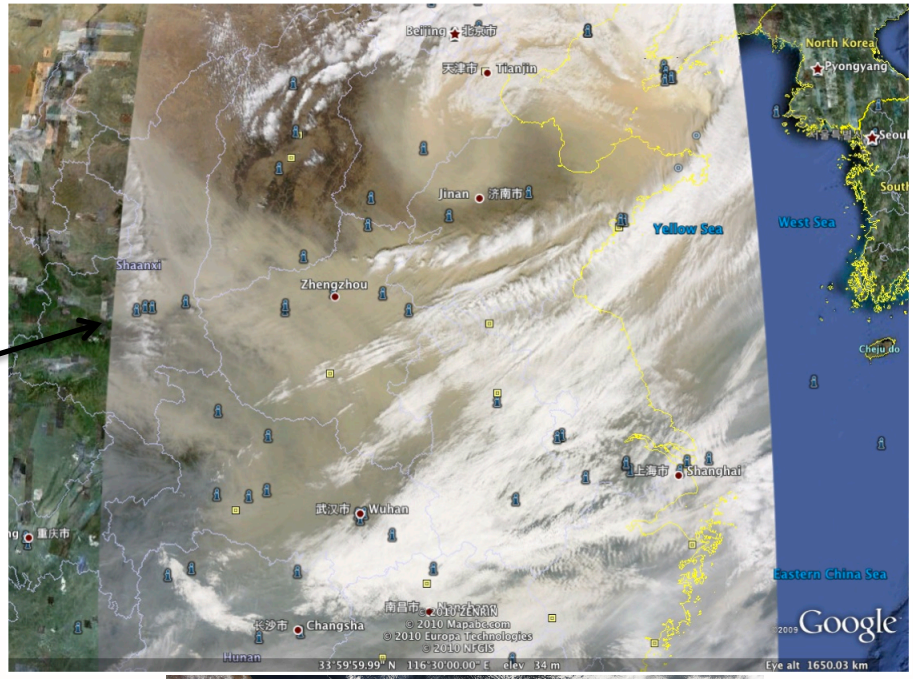
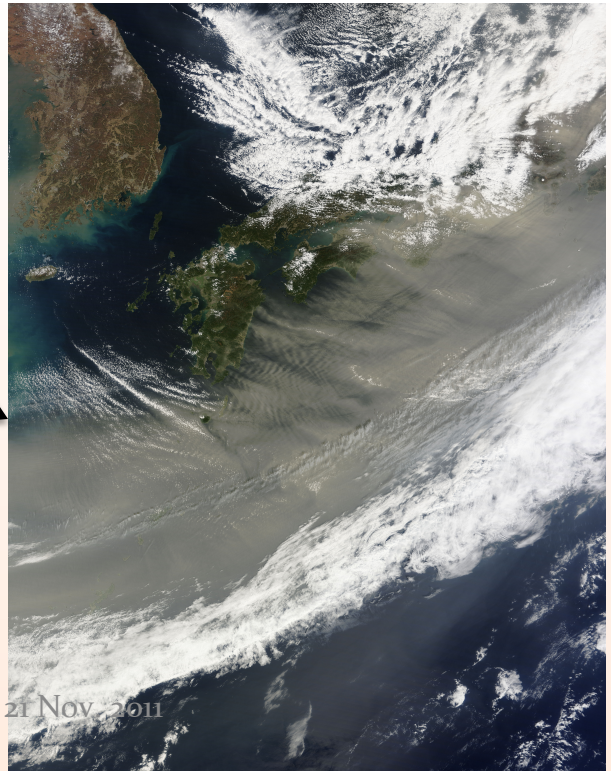
北京 天津 石家庄 秦皇岛 太原 大同 阳泉 长治 呼和浩特 赤峰 沈阳 大连 鞍山 抚顺 长春 哈尔滨 齐齐哈尔 佳木斯 上海 南京 苏州 南通 连云港 扬州 镇江 杭州 宁波 温州 湖州 绍兴
城市
污染指数


全国城市空气质量状况日报
2010-3-22
157 173 96 84 150 57 103 109 42 63 76 54 87 80 65 80 55 63 161 120 163 97 73 39 98 188 263 364 110 164
北京 天津 石家庄 秦皇岛 太原 大同 阳泉 长治 呼和浩特 赤峰 沈阳 大连 鞍山 抚顺 长春 哈尔滨 齐齐哈尔 佳木斯 上海 南京 苏州 南通 连云港 扬州 镇江 杭州 宁波 温州 湖州 绍兴
城市
污染指数

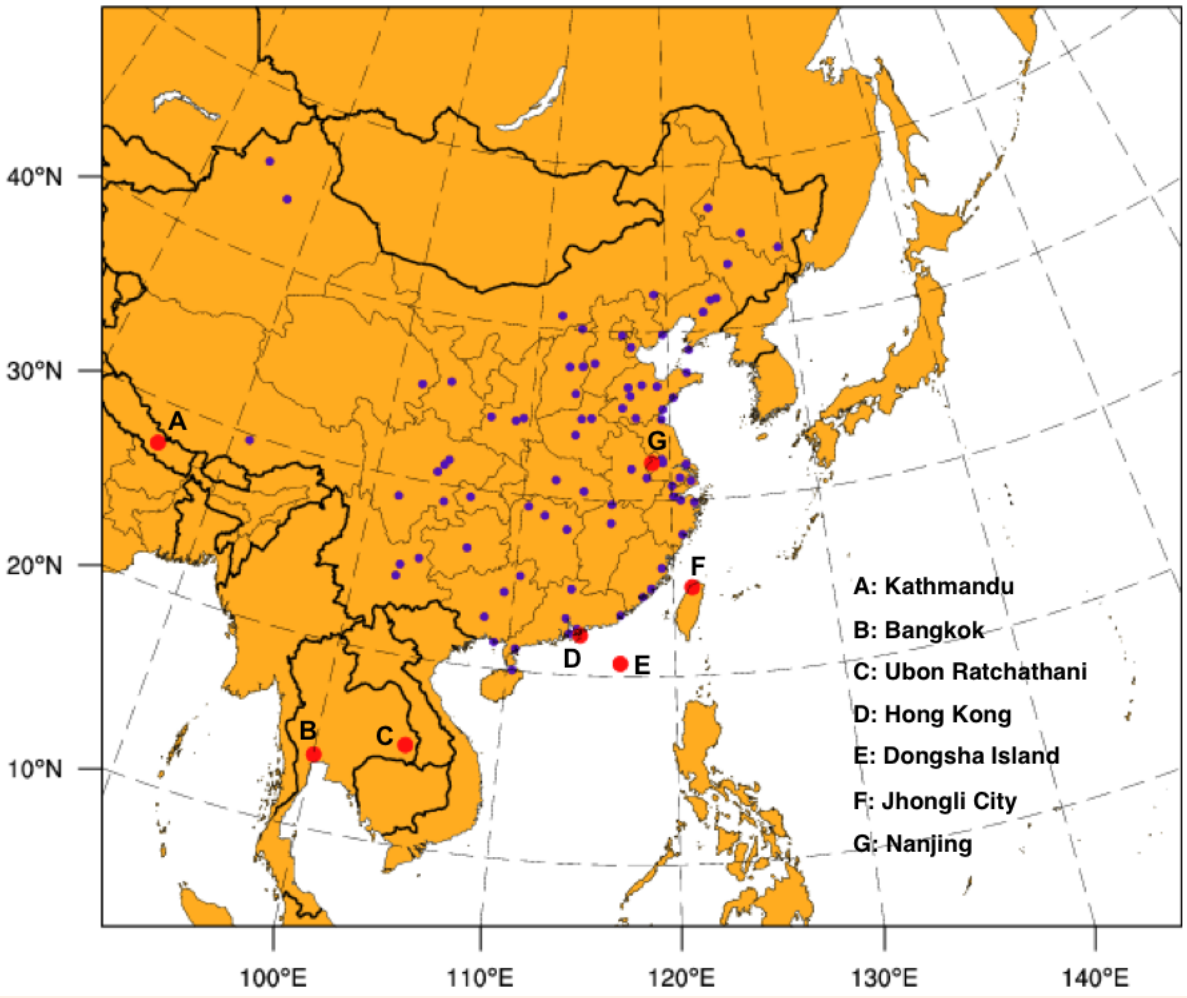
CMA dust model forecast







East Asia domain



261x222 @27 km
45L with top @50 hPa

Validation observations:
- 7 AERONET sites
- CALIPSO AOD

chem_opt=301:
- GOCART+RACM

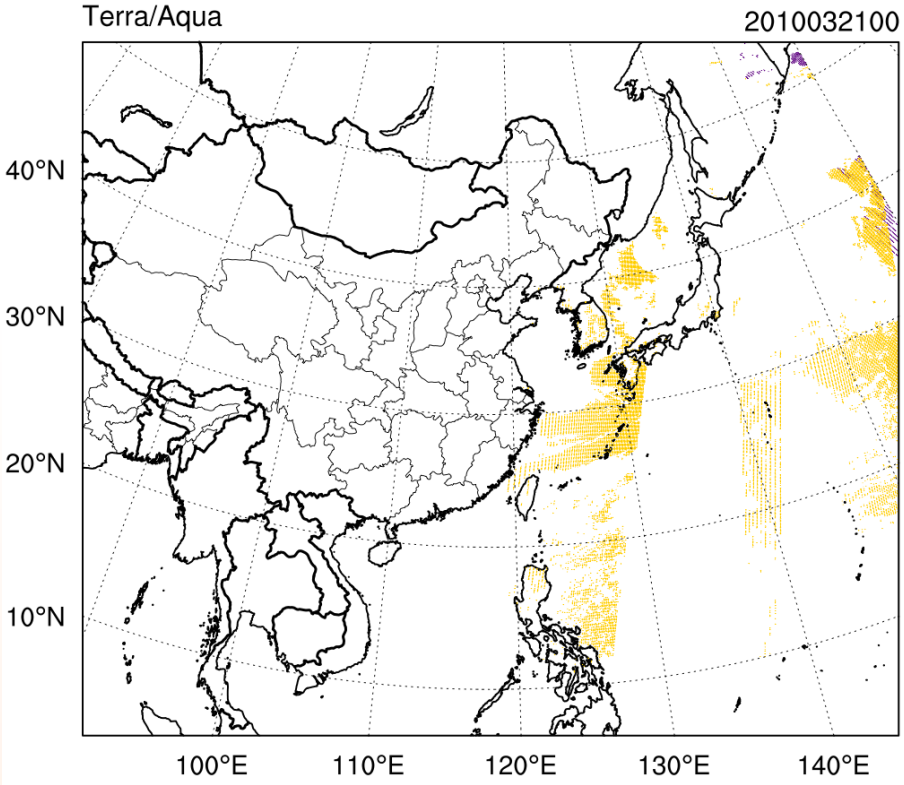
Emissions:
- Online biogenic
- RETRO+"Streets" anthropogenic
- GOCART dust emission

LBC: NCAR CAM-Chem

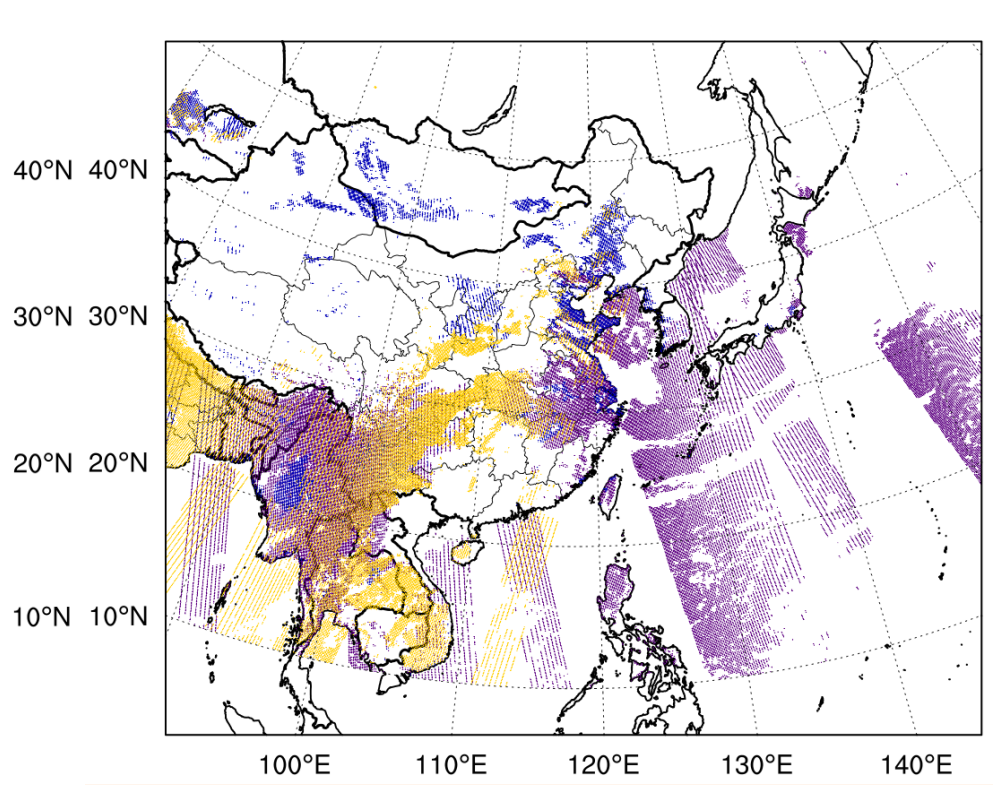
6-hr cycling DA/FC experiment:
- 17~24 March, 2010.
- MET fields updated from GFS.
- Aerosol fields updated from AOD DA.

L2 MODIS AOD@0.55µm coverage

0000 UTC, 21 March 2010



0600 UTC, 21 March 2010



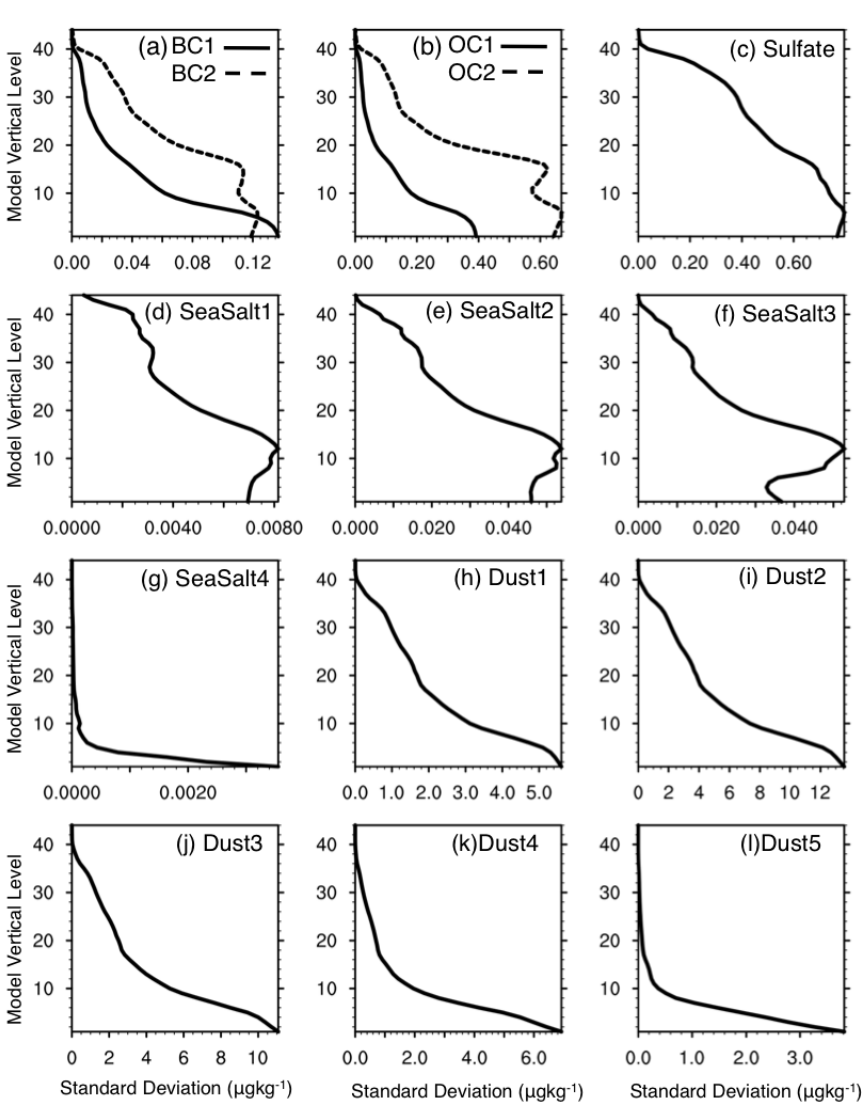
Data only available at day time (00Z and 06Z), visible band.

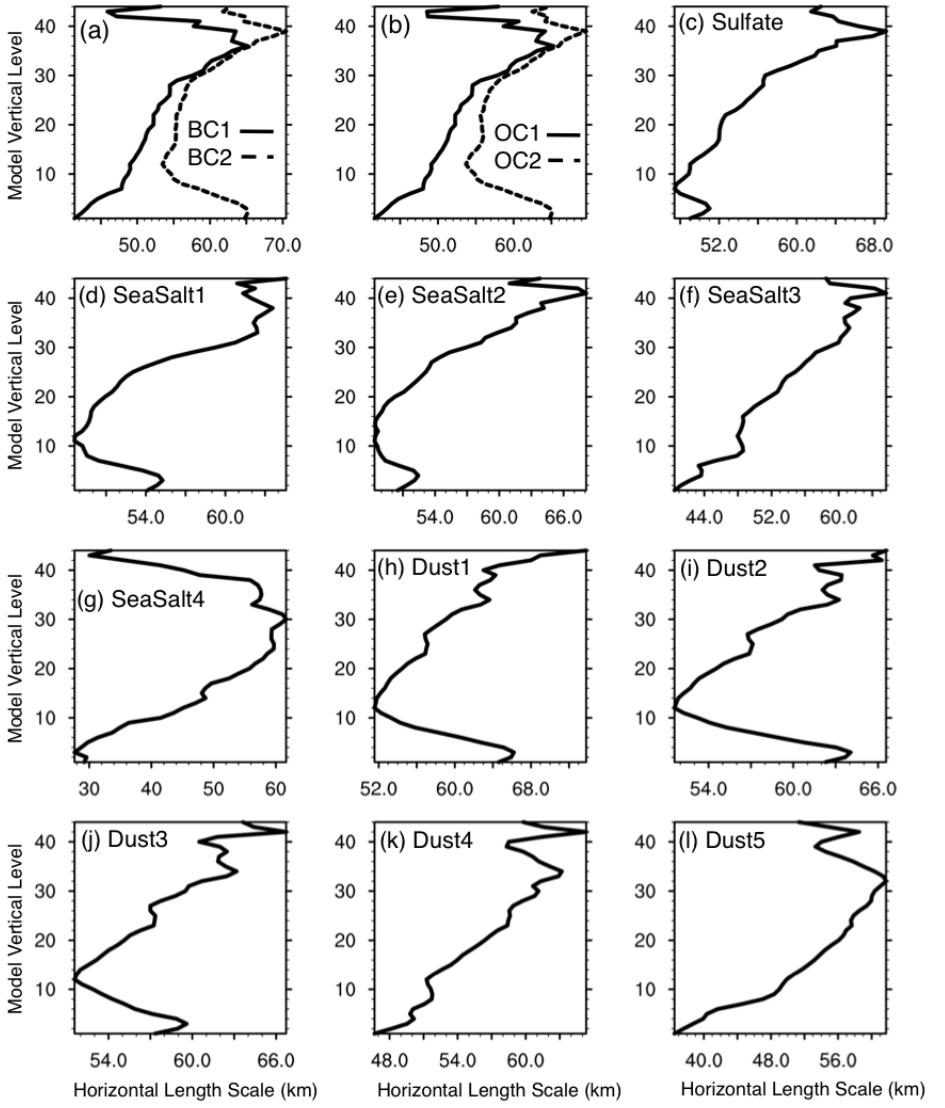
purple: dark-surface retrievals from Aqua;
gold: dark surface from Terra;
blue: deep-blue produced from Aqua.

Estimate B for Aerosol Species

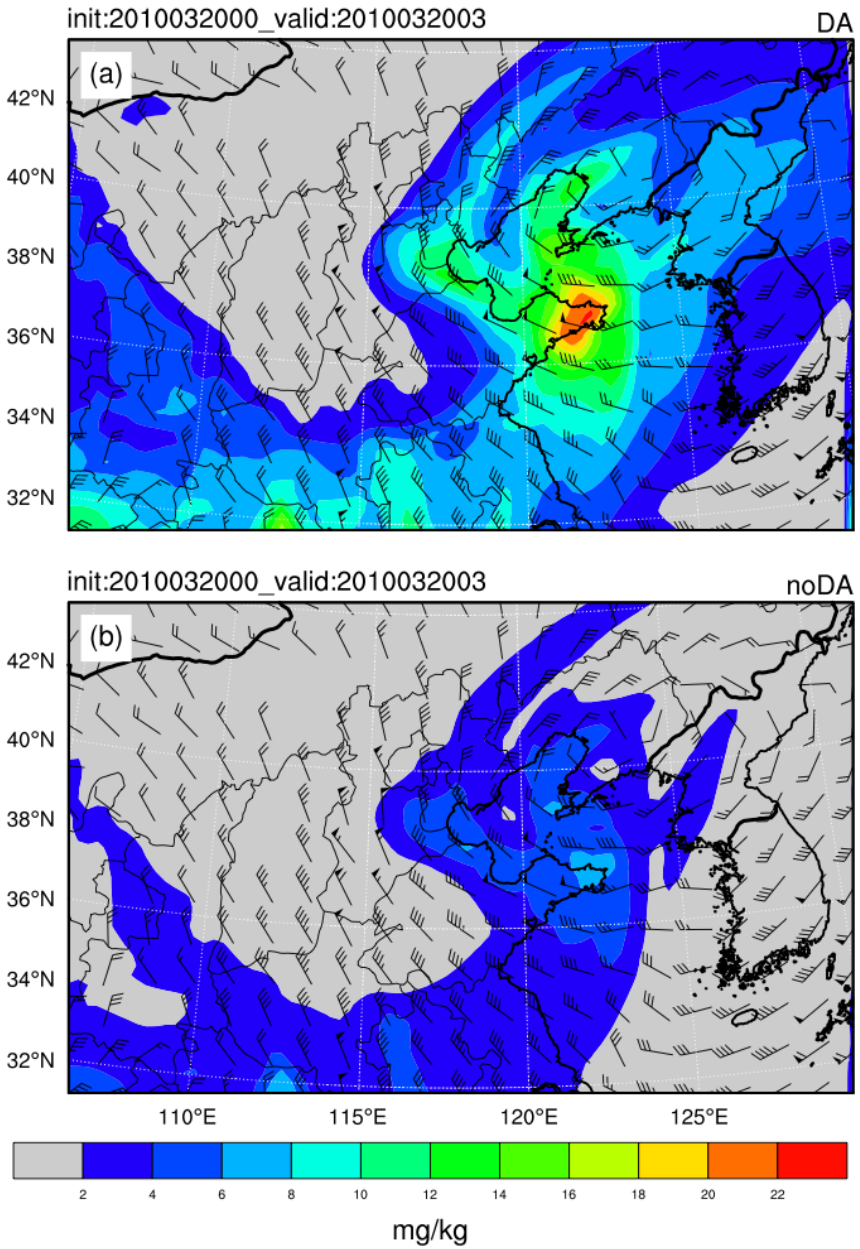
- "NMC" method was used to compute aerosol background error covariance (B) statistics using WRF-Chem model forecasts (at 00Z and 12Z) in March.
  - Uses differences between 24- and 12-hr forecasts valid at the same time
  - Compute standard deviation, vertical and horizontal length-scale for 14 GOCART aerosol variables
  - No multivariate correlation

Matrix B: Standard deviation & horizontal length-scale

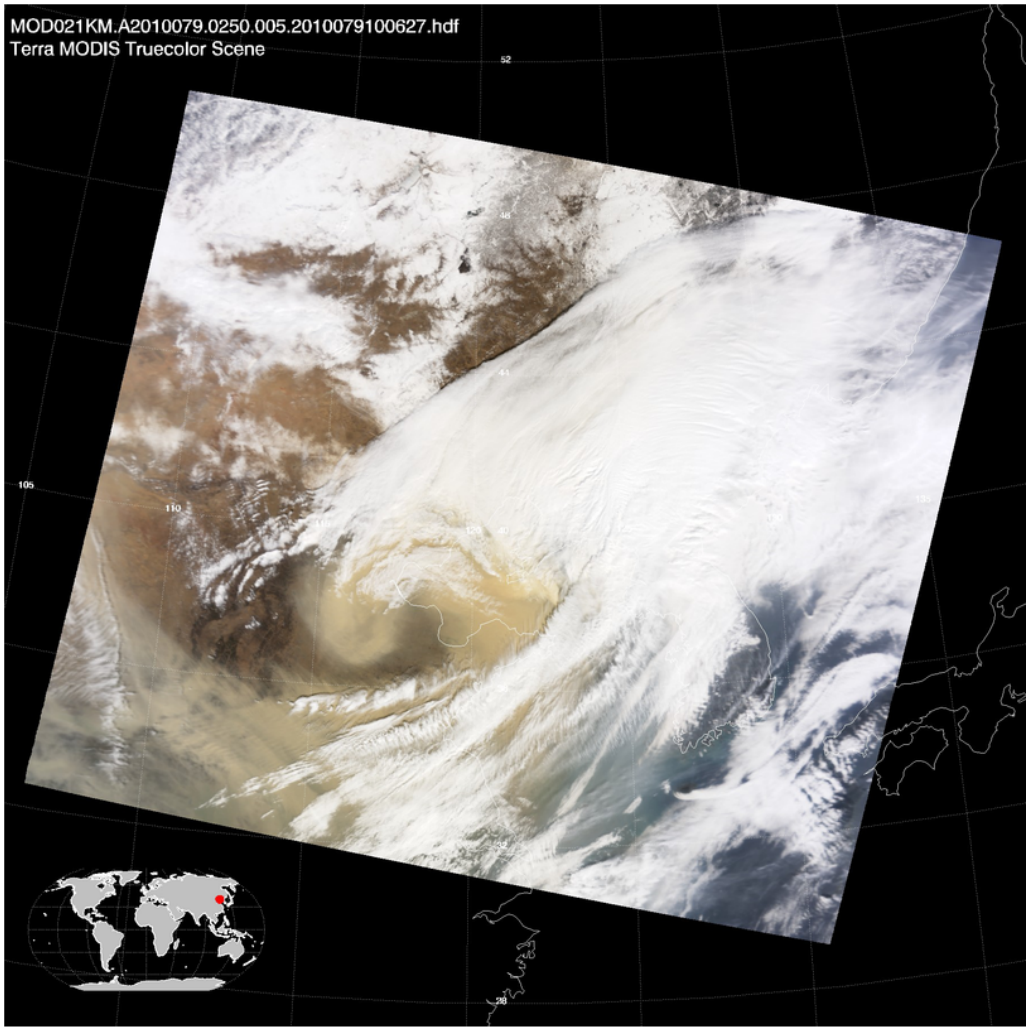


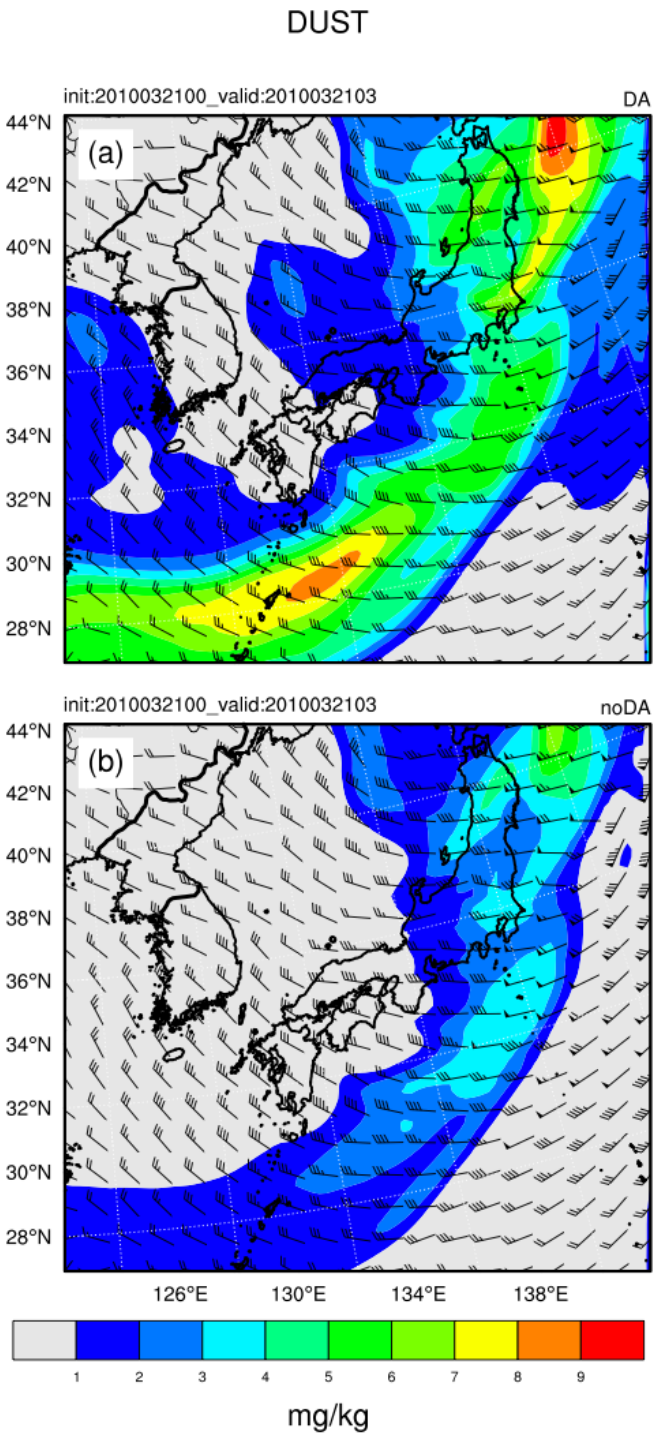


DUST

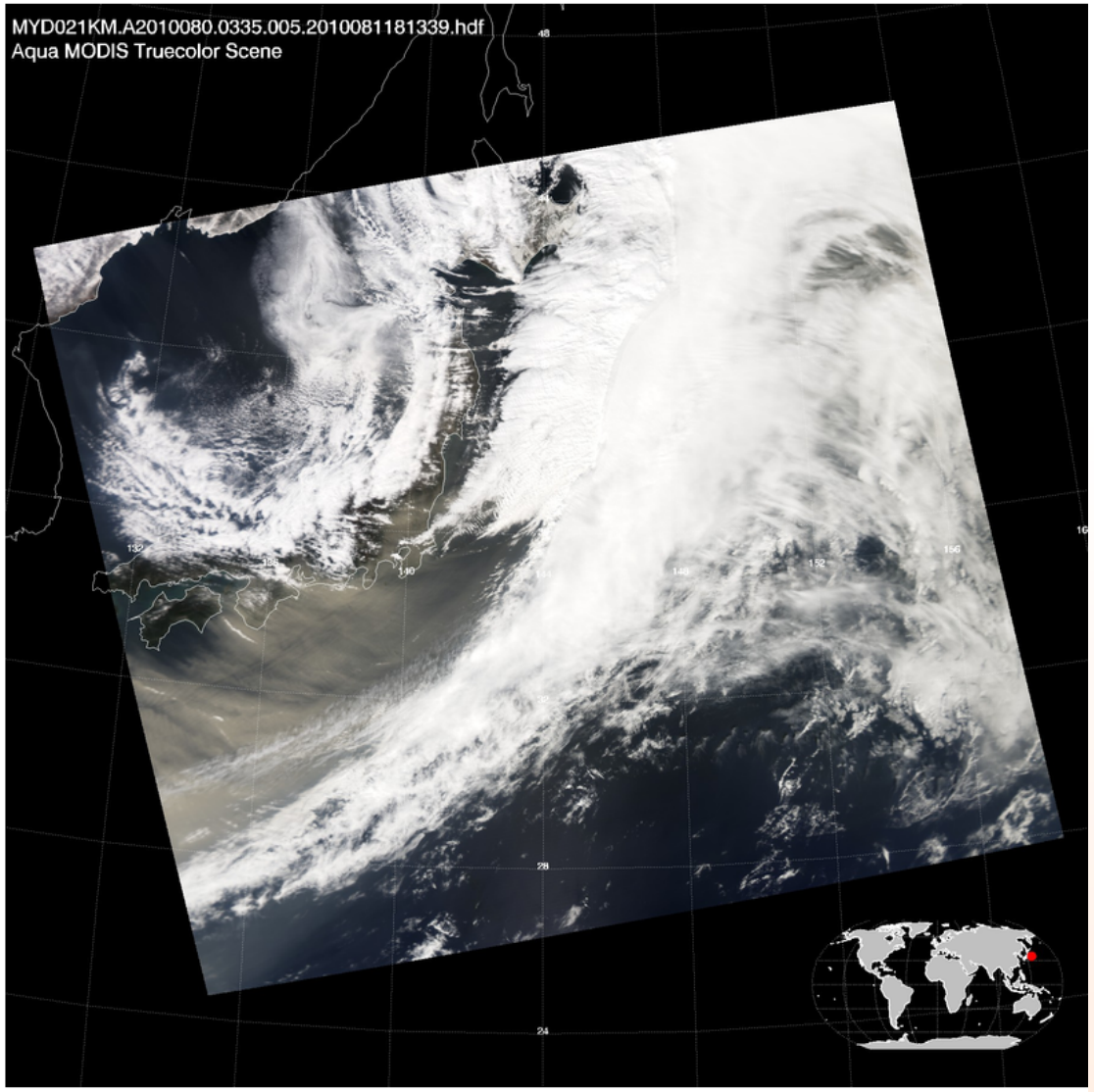


Column dust vs. MODIS true color image. 2010032003

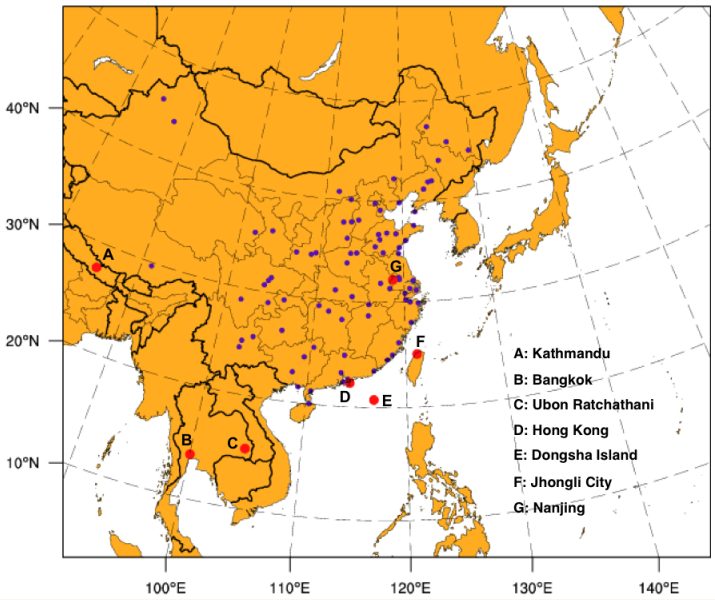


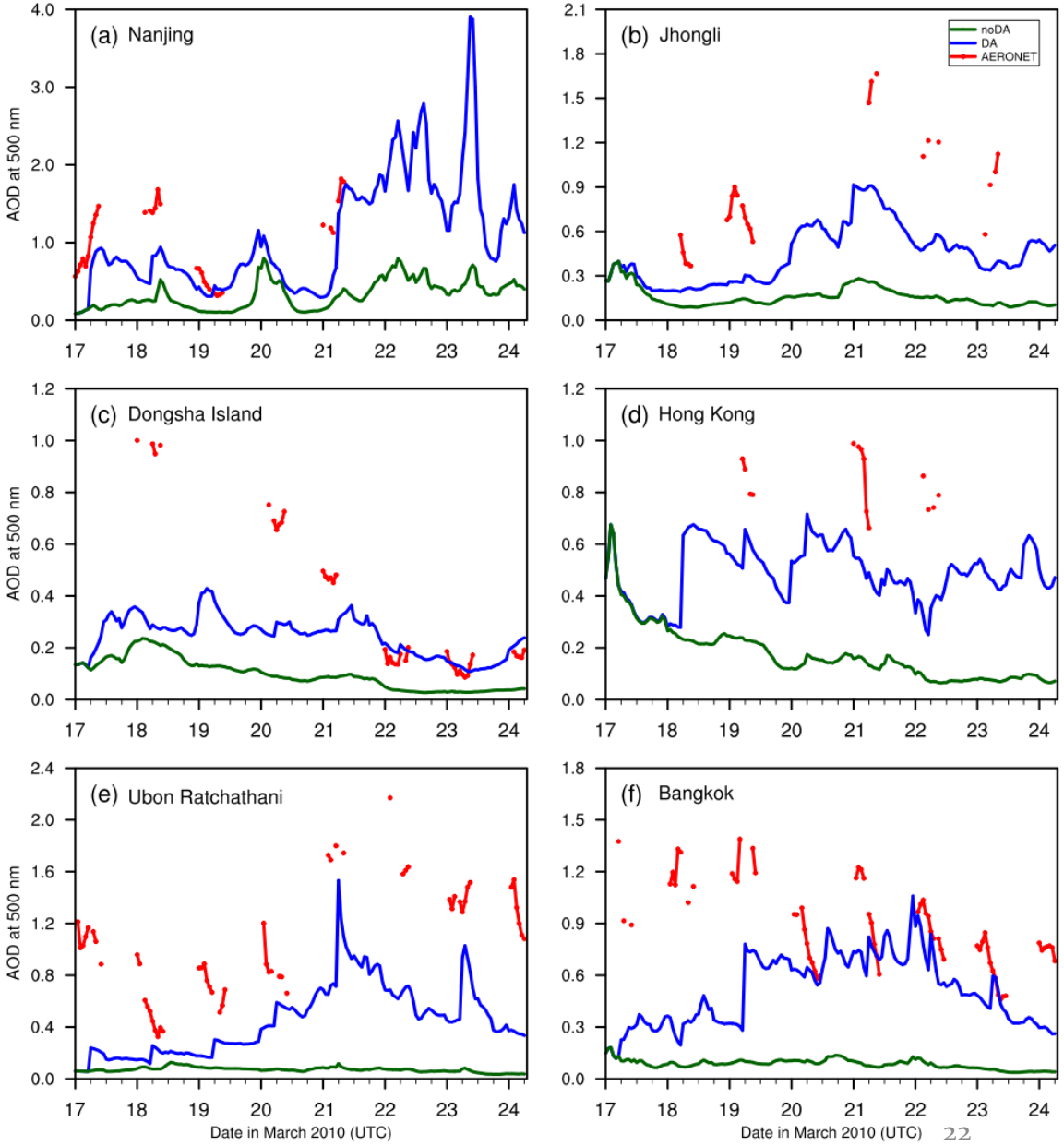


Column dust vs. MODIS true color image. 2010032103

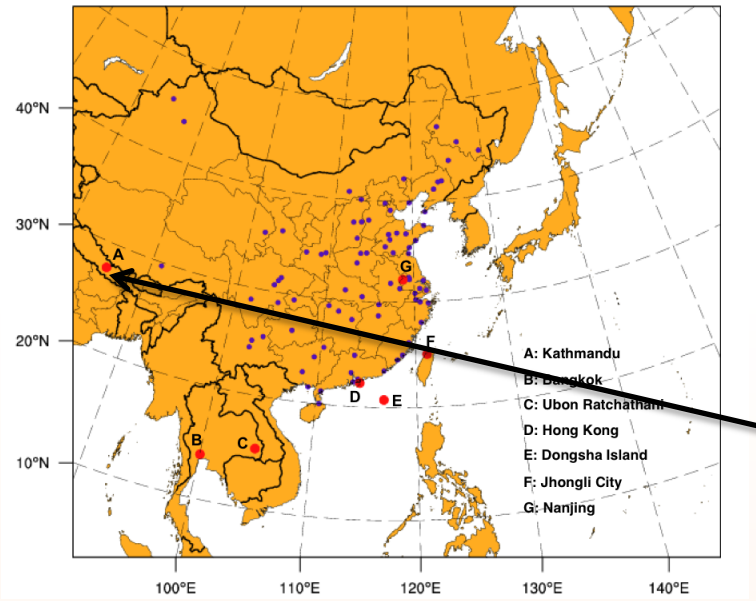


Verify @550nm at other 6 AERONET sites

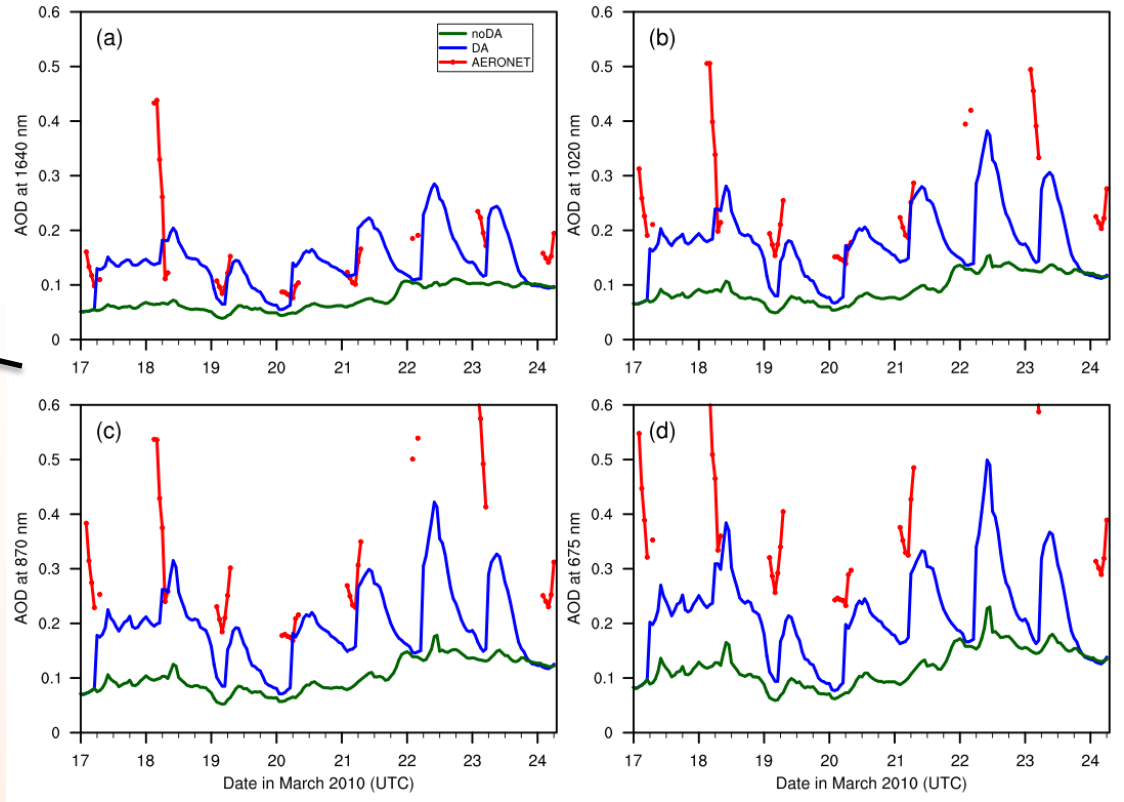




Verify vs. AERONET AOD @1640, 1020, 870, 675 nm

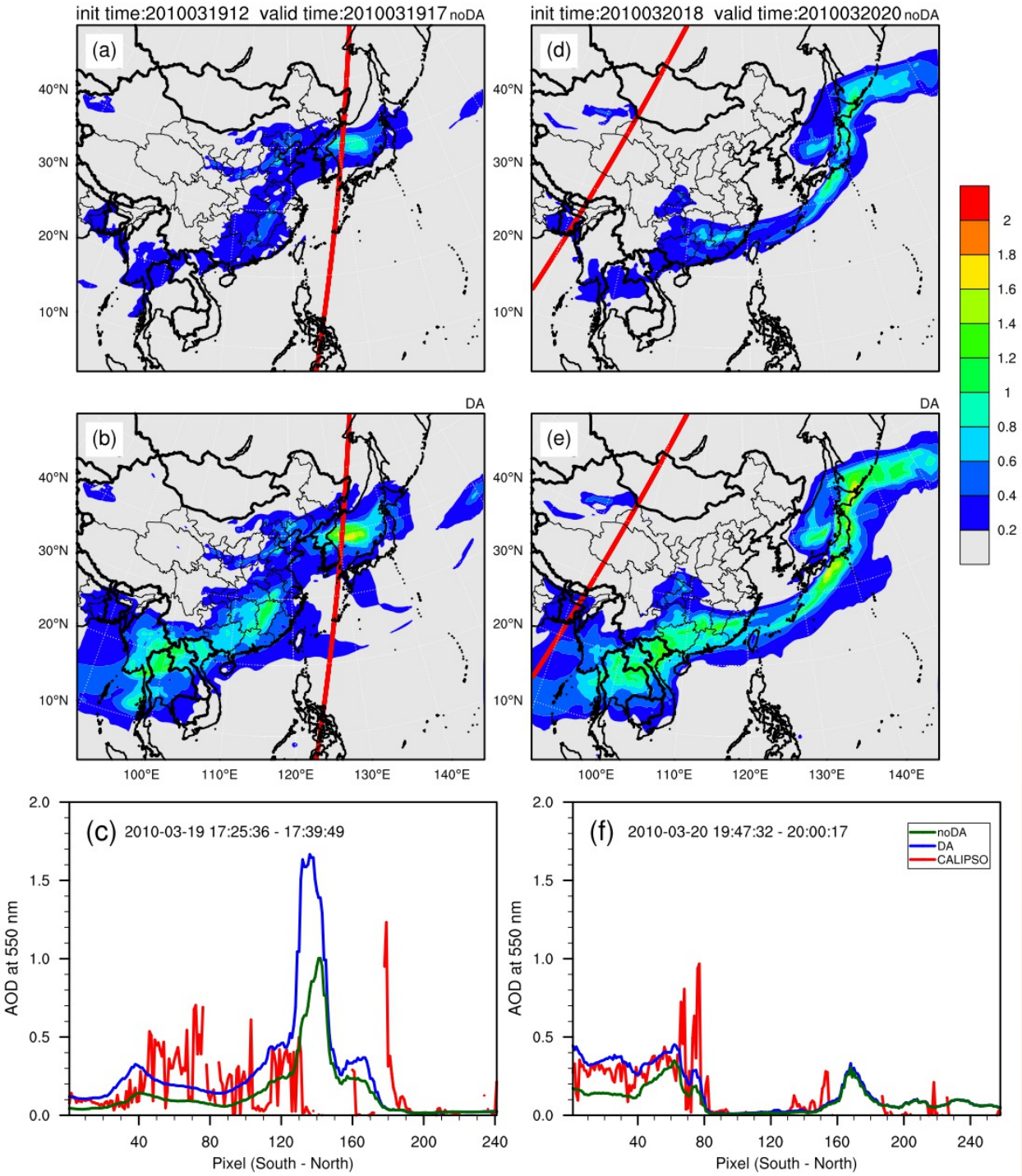


Kathmandu of Nepal



AERONET obs and DA likely reflect air-pollution variation due to the traffic.

Verify vs. CALIPSO AOD



Vertical distribution of AOD

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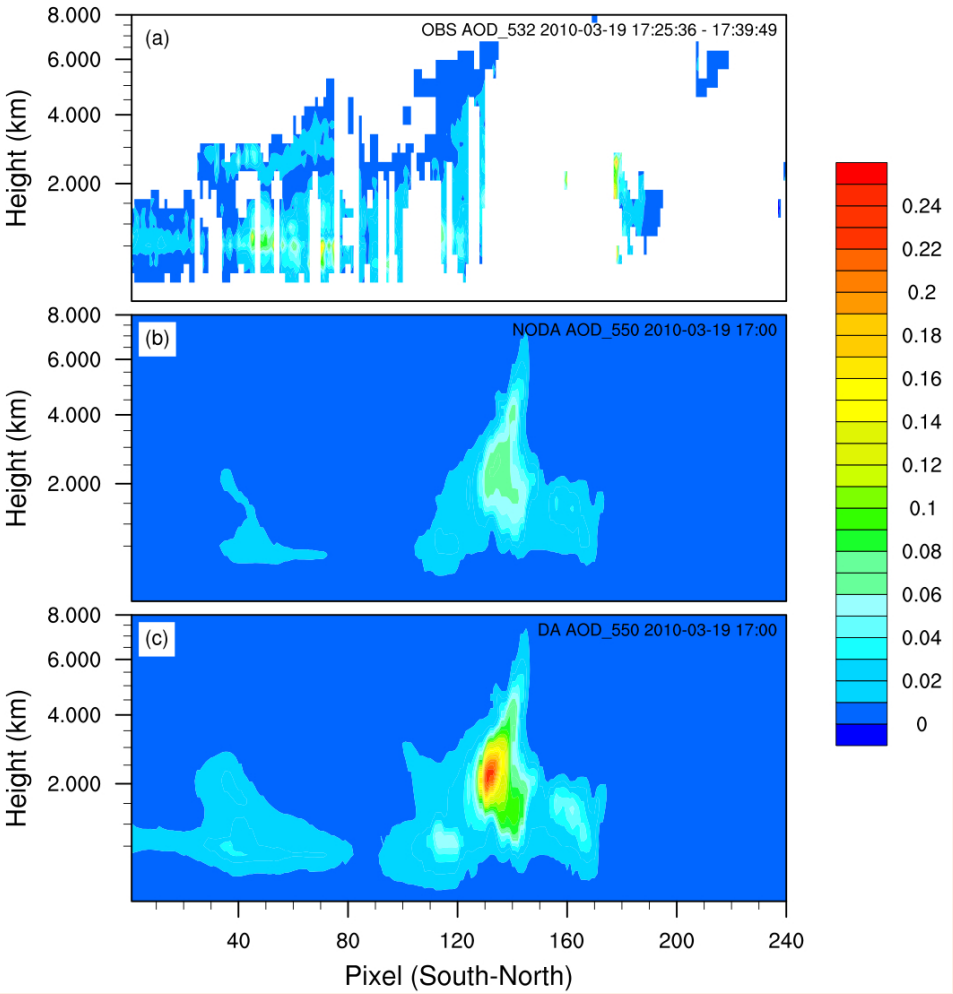
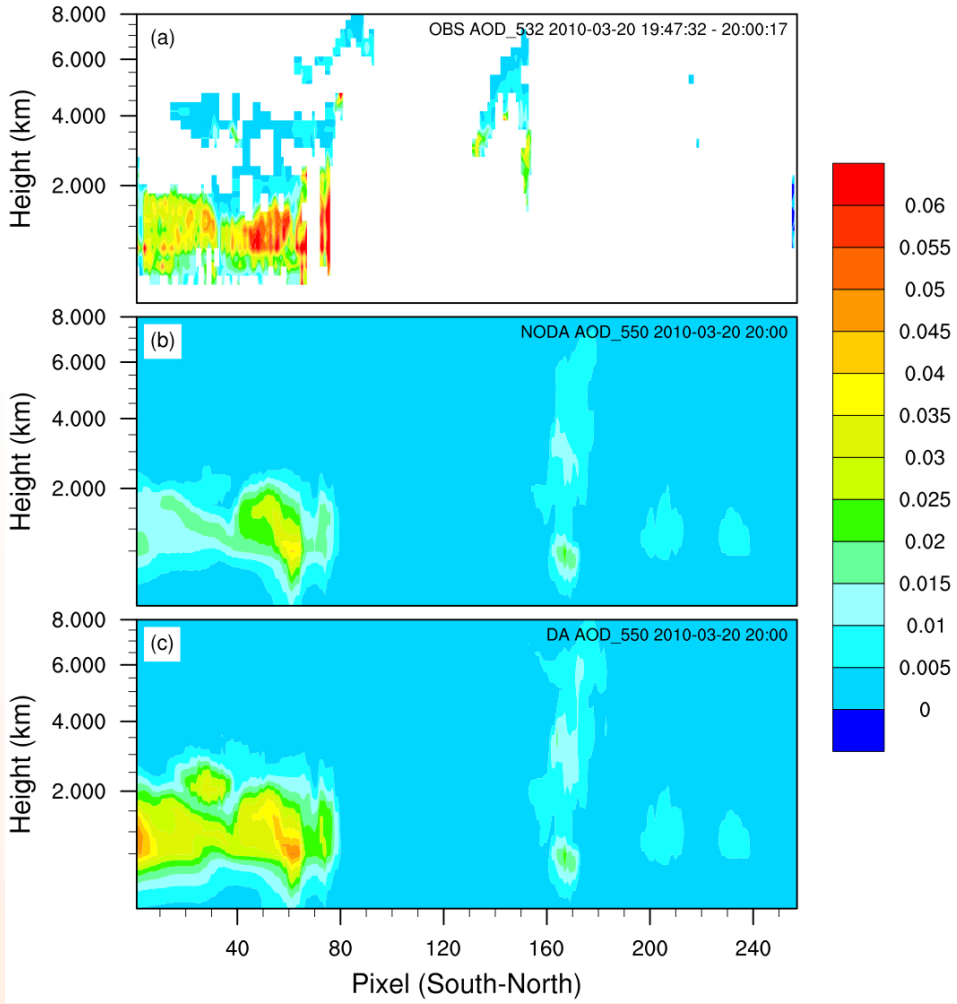
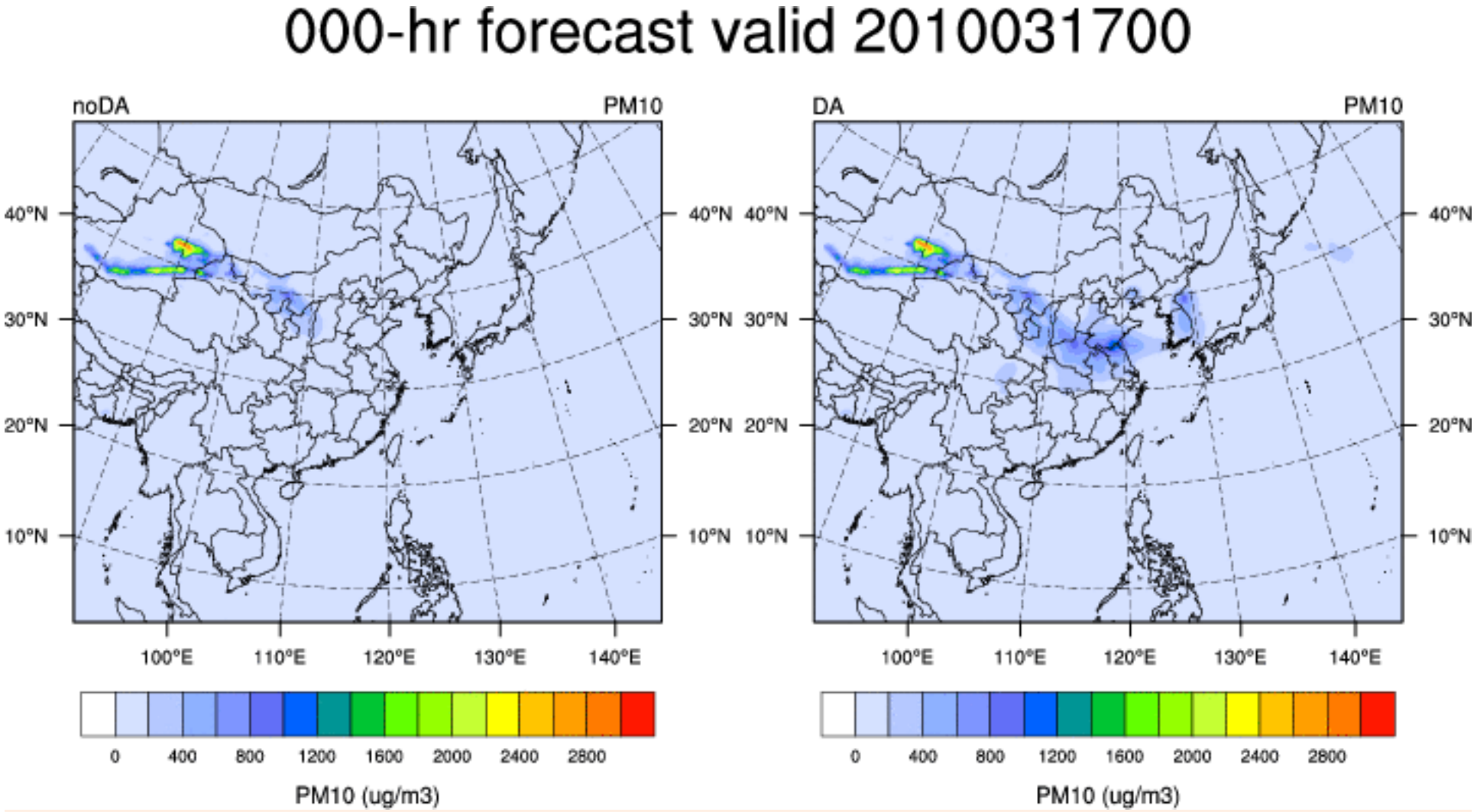


2010-03-20 20:00



Surface PM10



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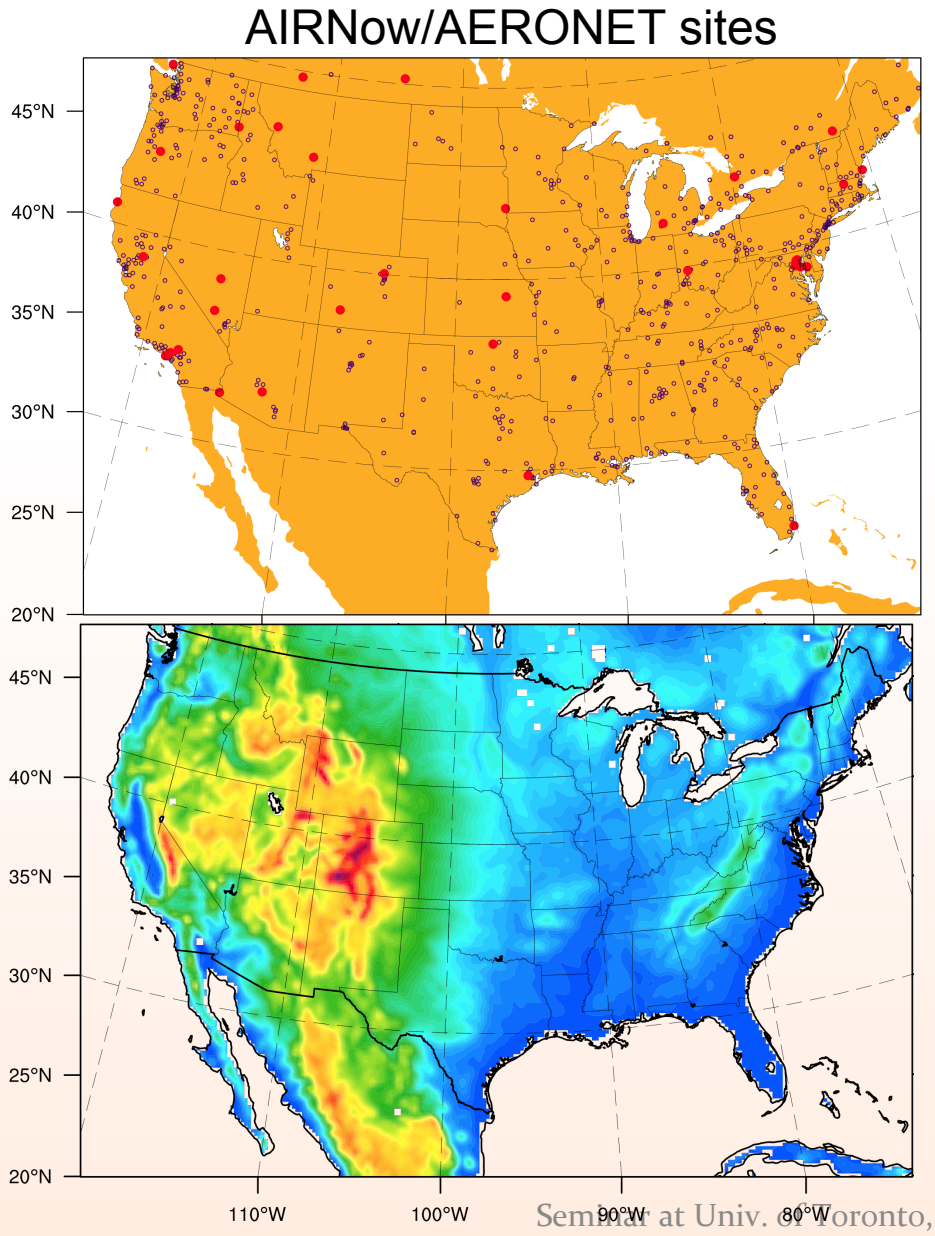
Schwartz C. et al., (2011): Synergic assimilation of MODIS aerosol optical depth and surface PM2.5 for air quality prediction. In preparation.

North America domain



246x164 @20 km
41L with top @50 hPa

Validation observations:

- AERONET sites
- AIRNow PM2.5 sites (also assimilated)

chem_opt=300:

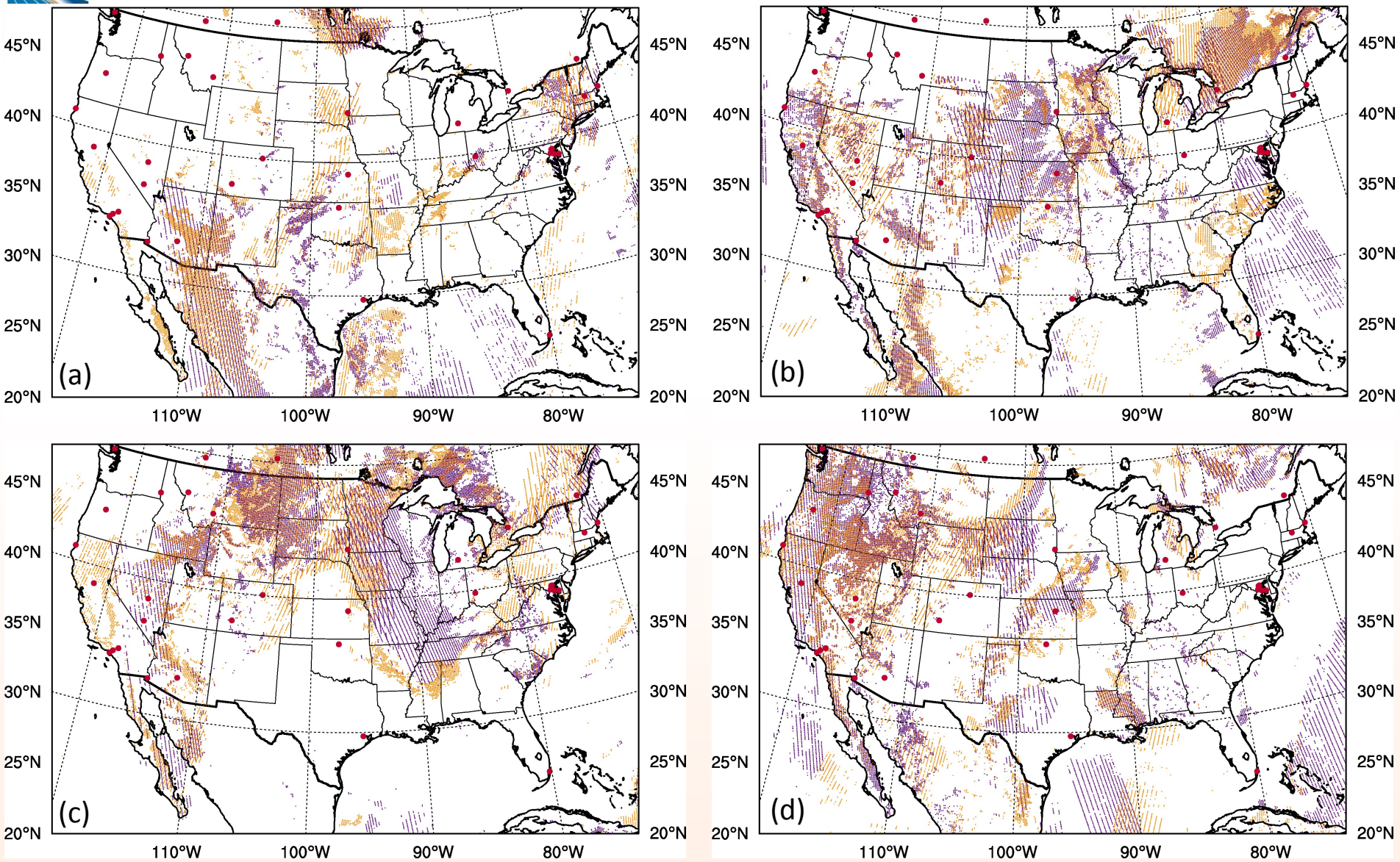
- GOCART w/o chemistry

Experimental design

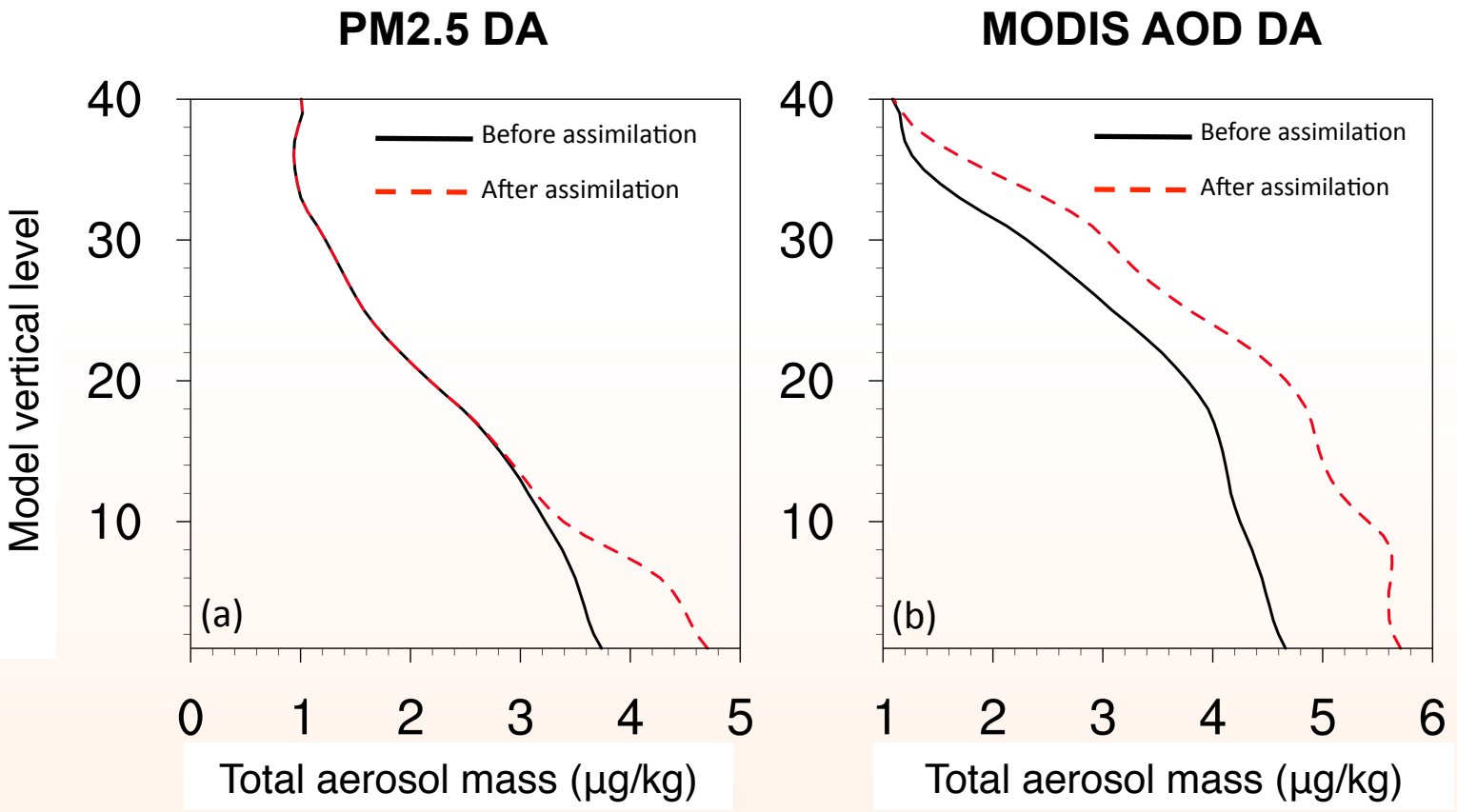
- 4 experiments
  1) No data assimilation (continuous WRF-Chem forecast)
  2) $PM_{2.5}$ DA
  3) AOD DA
  4) AOD+$PM_{2.5}$ DA

- Cyclic data assimilation with 6-hr cycles beginning 0000 UTC 01 June, ending 1800 UTC 14 July, 2010. (~45 days)
  - $PM_{2.5}$ observations assimilated each cycle, but AOD observations primarily available only at 1800 UTC
  - All 1800 UTC analyses initialized 48-hr forecasts

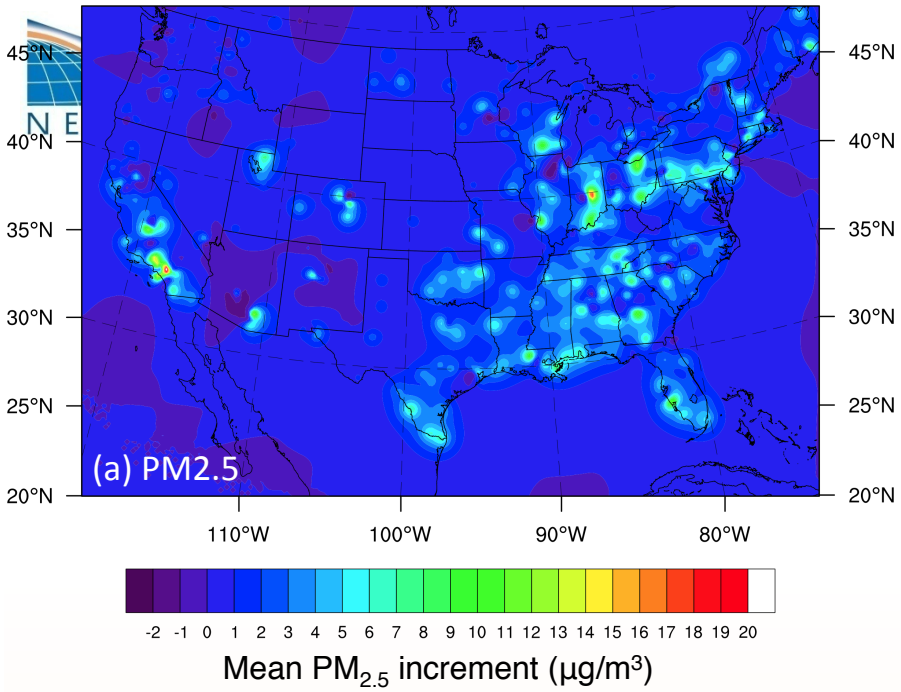
- Meteorological fields updated every 6-hrs from 20-km NAM grids

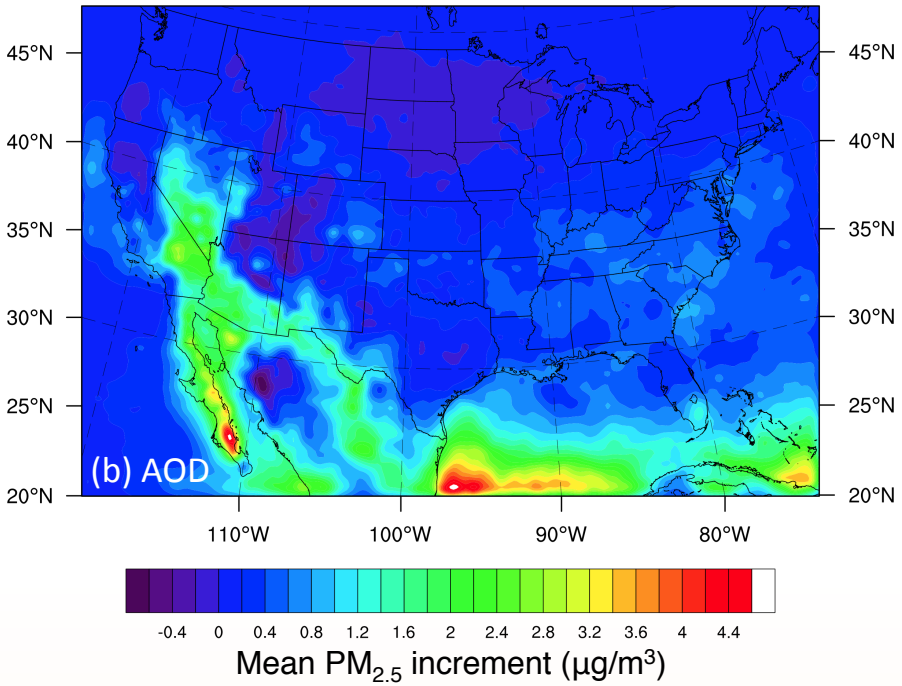


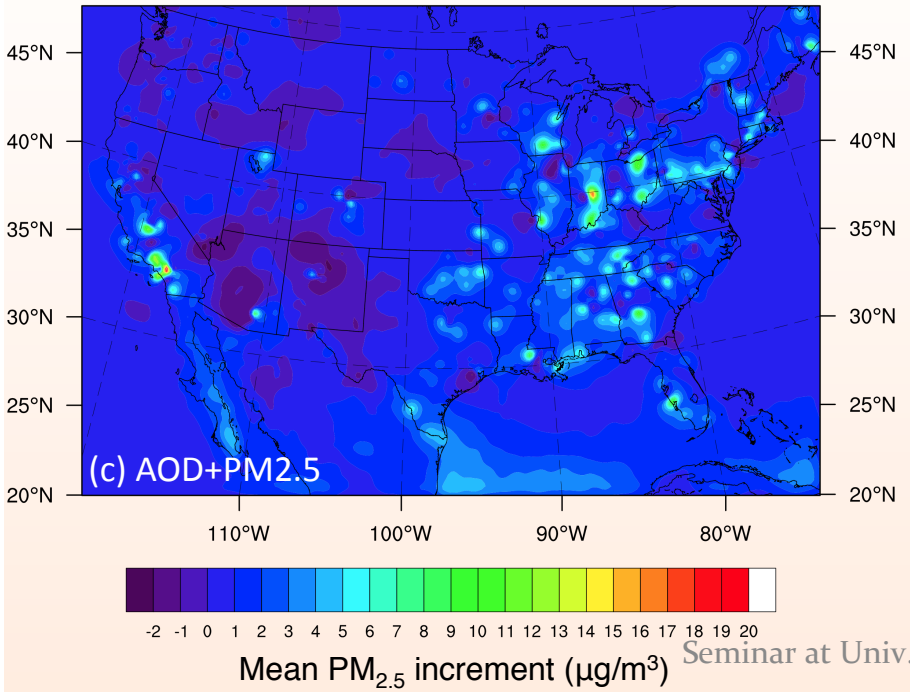
MODIS coverage at 1800 UTC (June 2/17, July 2/14; no deep-blue used)



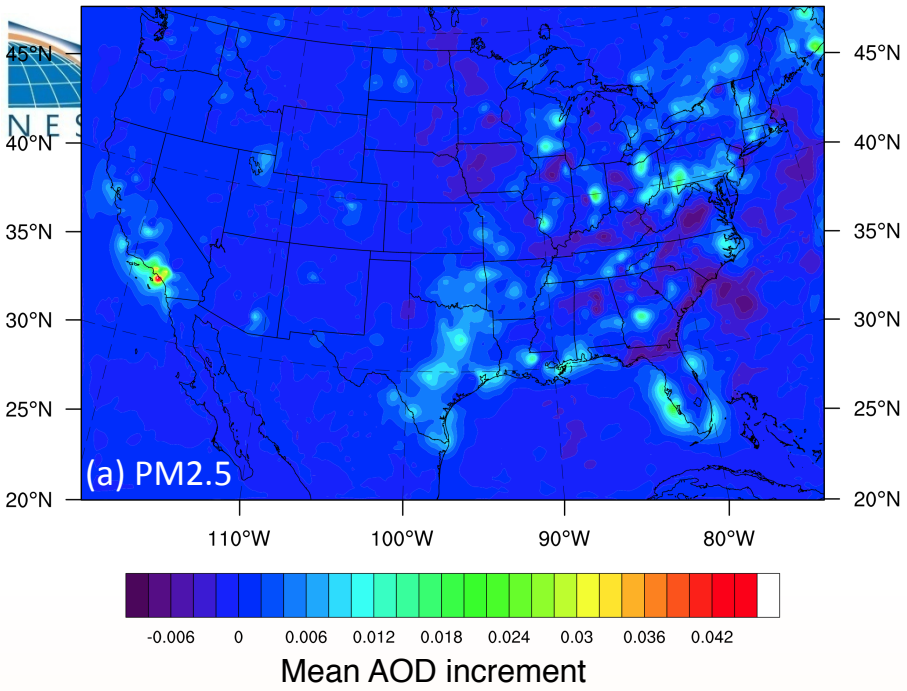
Aggregated over all 1800 UTC analyses

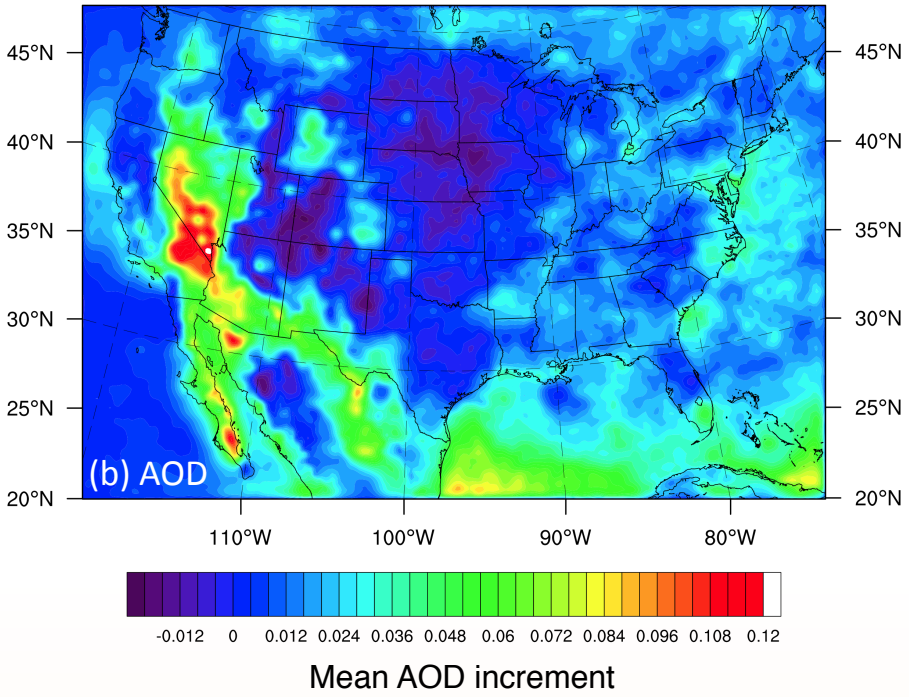


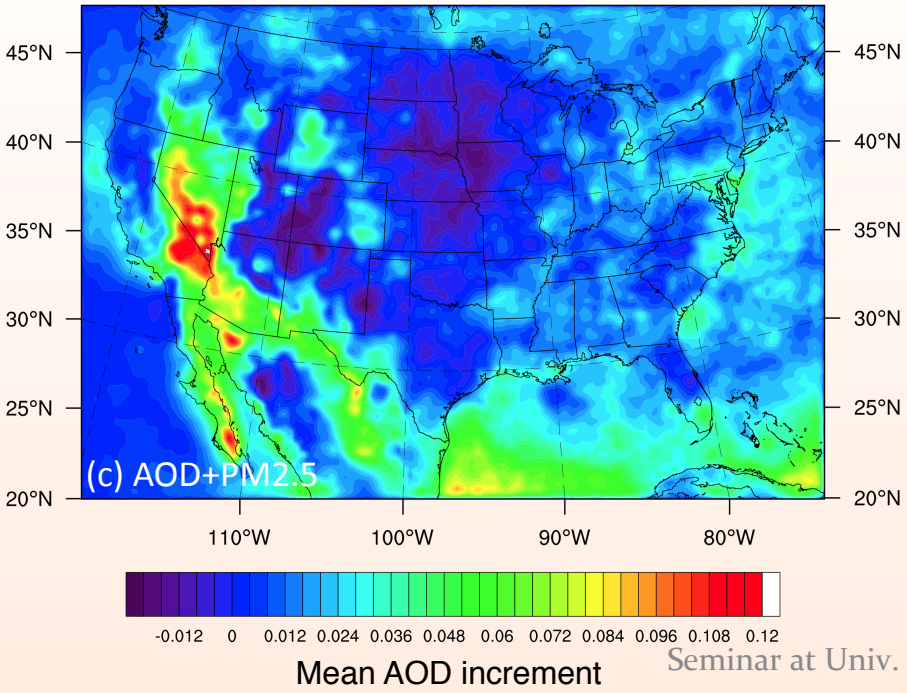




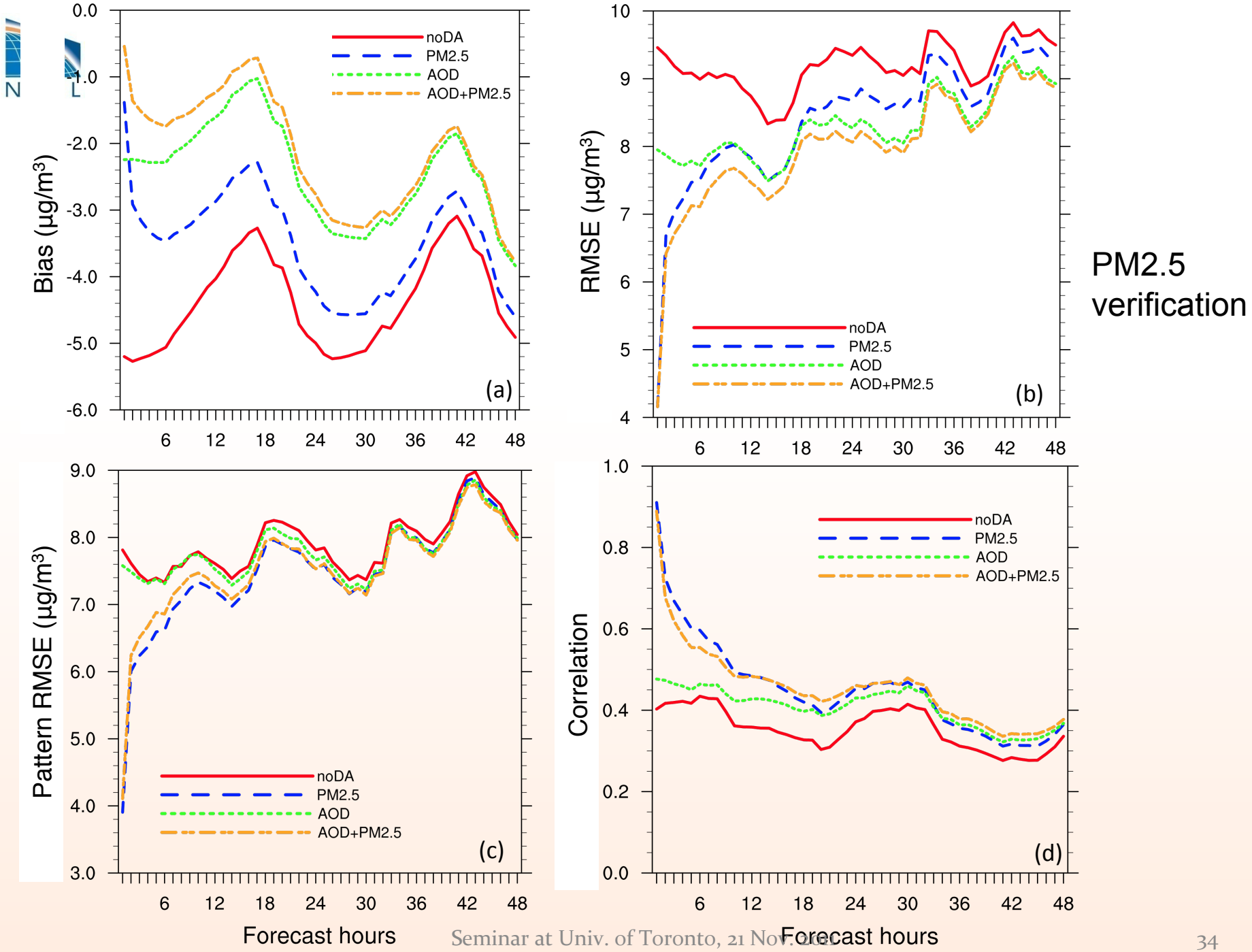
mean PM2.5 increments for 1800 UTC analyses



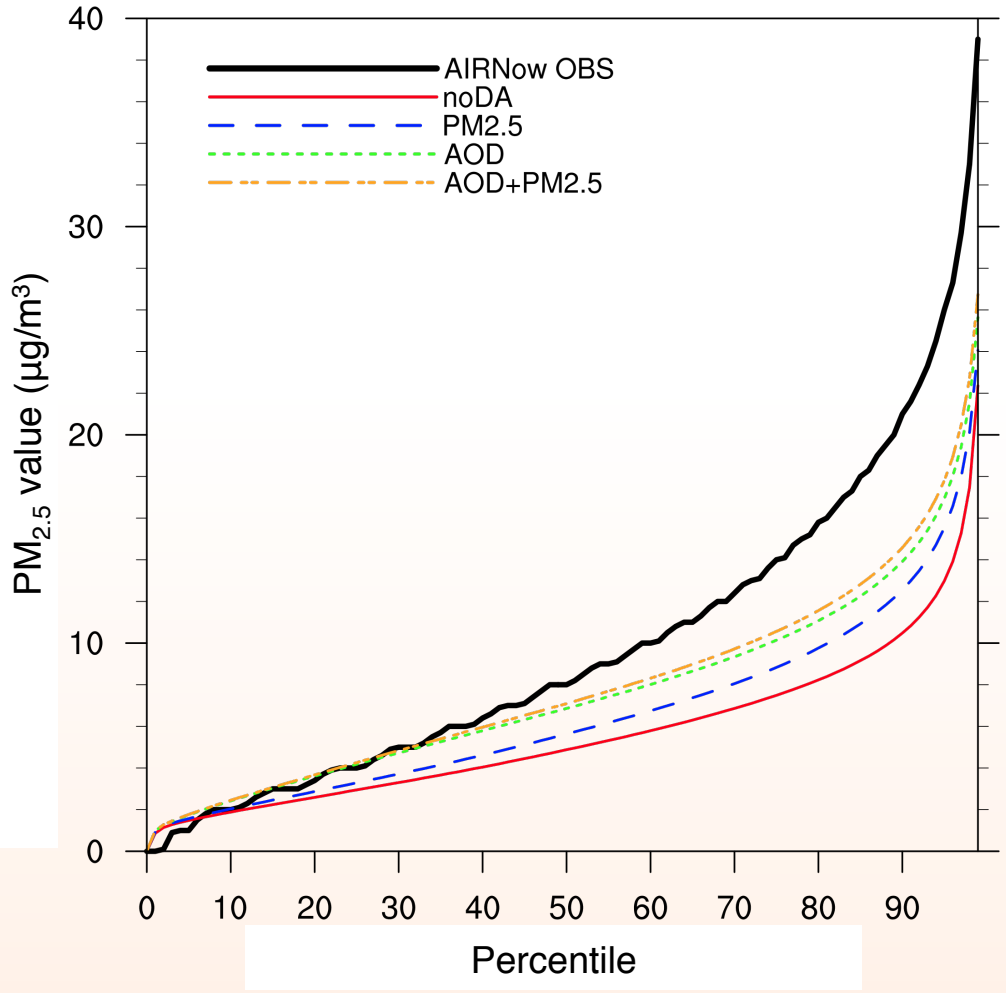


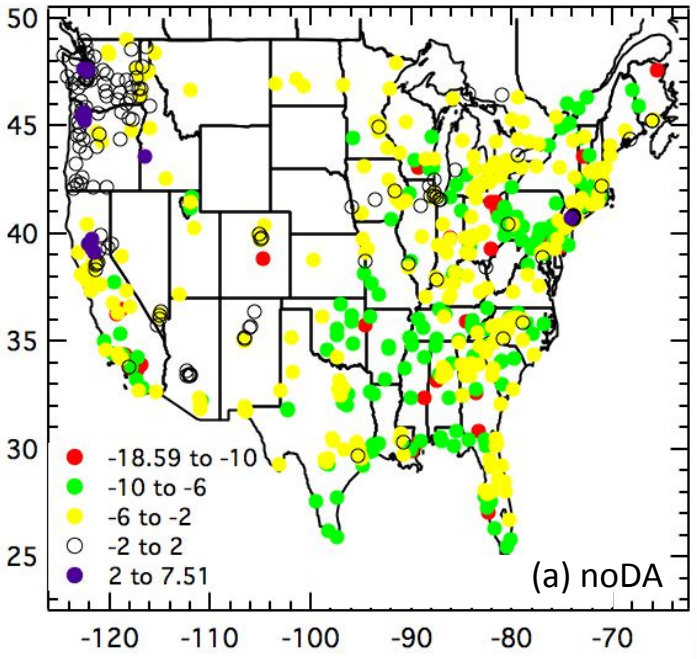


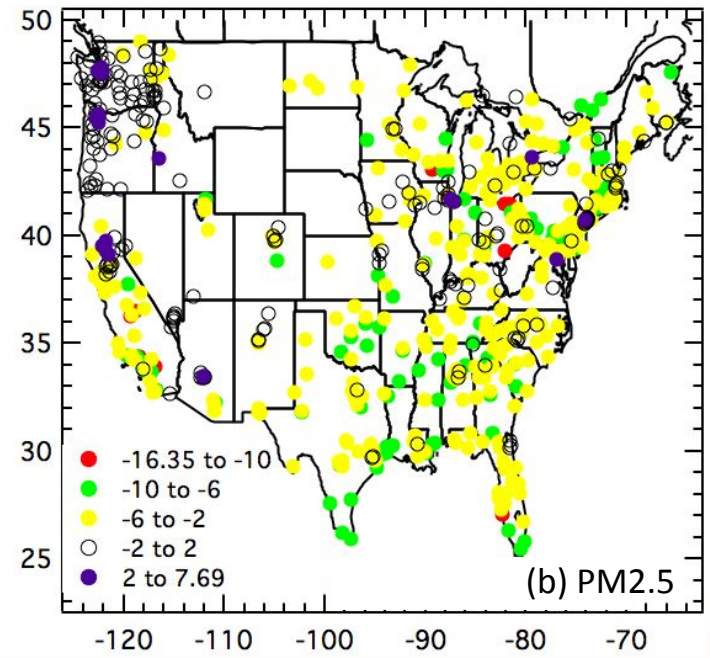
mean AOD increments at 550 nm for 1800 UTC analyses



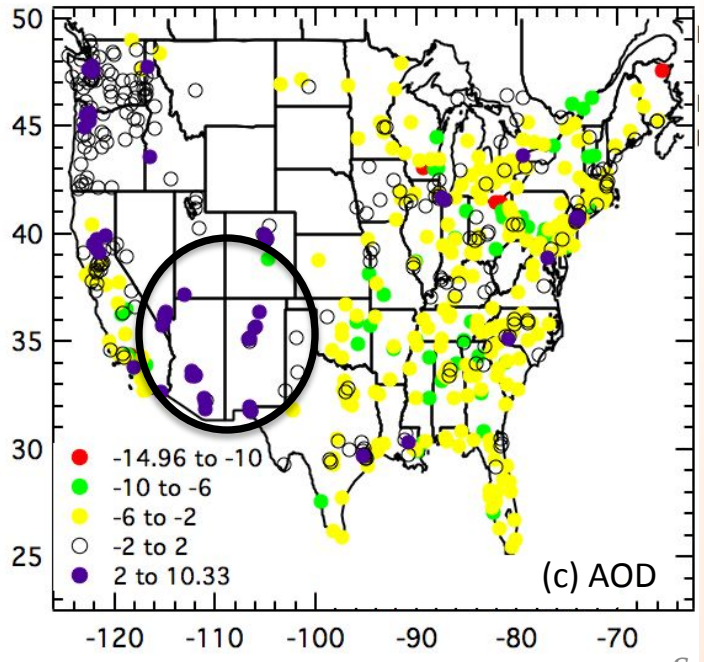
PM2.5 verification

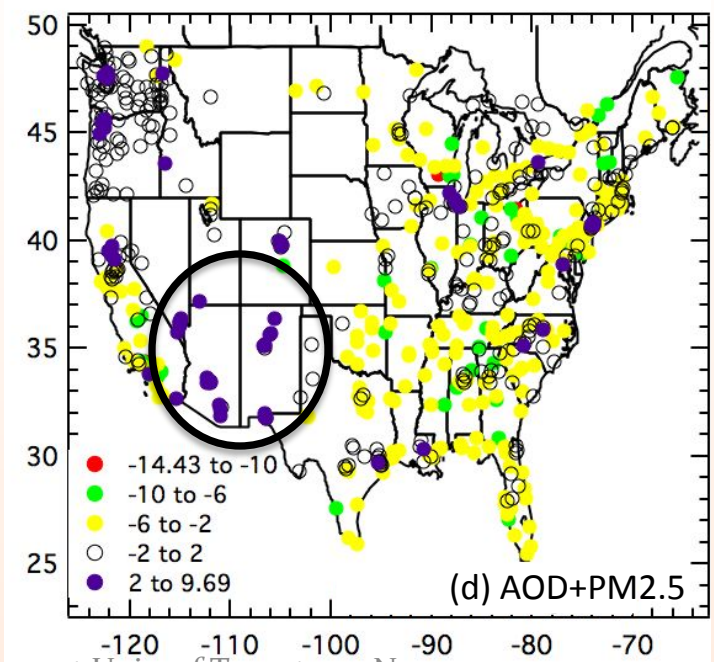

AIRNow OBS
noDA
PM2.5
AOD
AOD+PM2.5
PM2.5 value (µg/m3)
Percentile
0
10
20
30
40
50
60
70
80
90
0
10
20
30
40





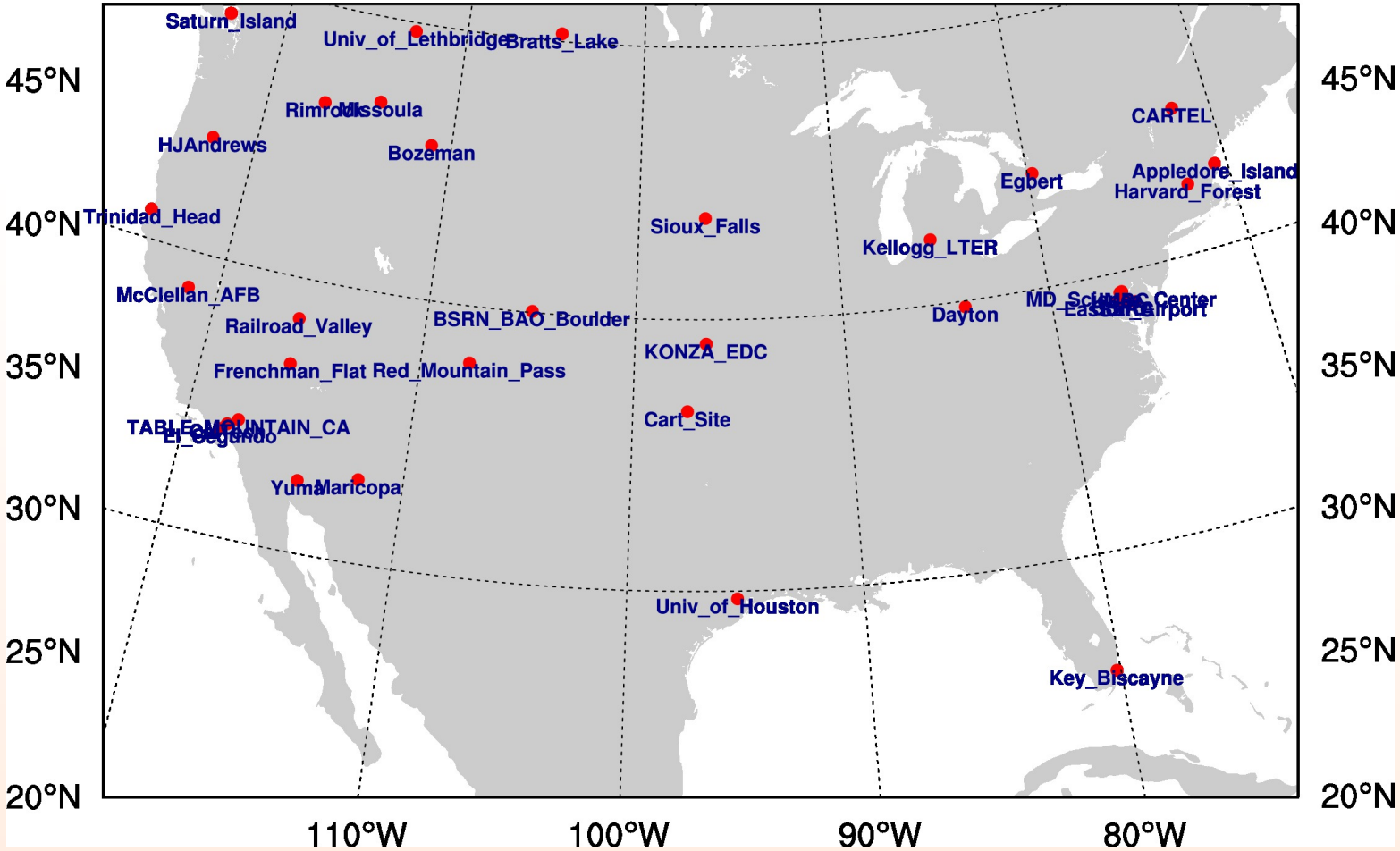
PM2.5
Mean Bias





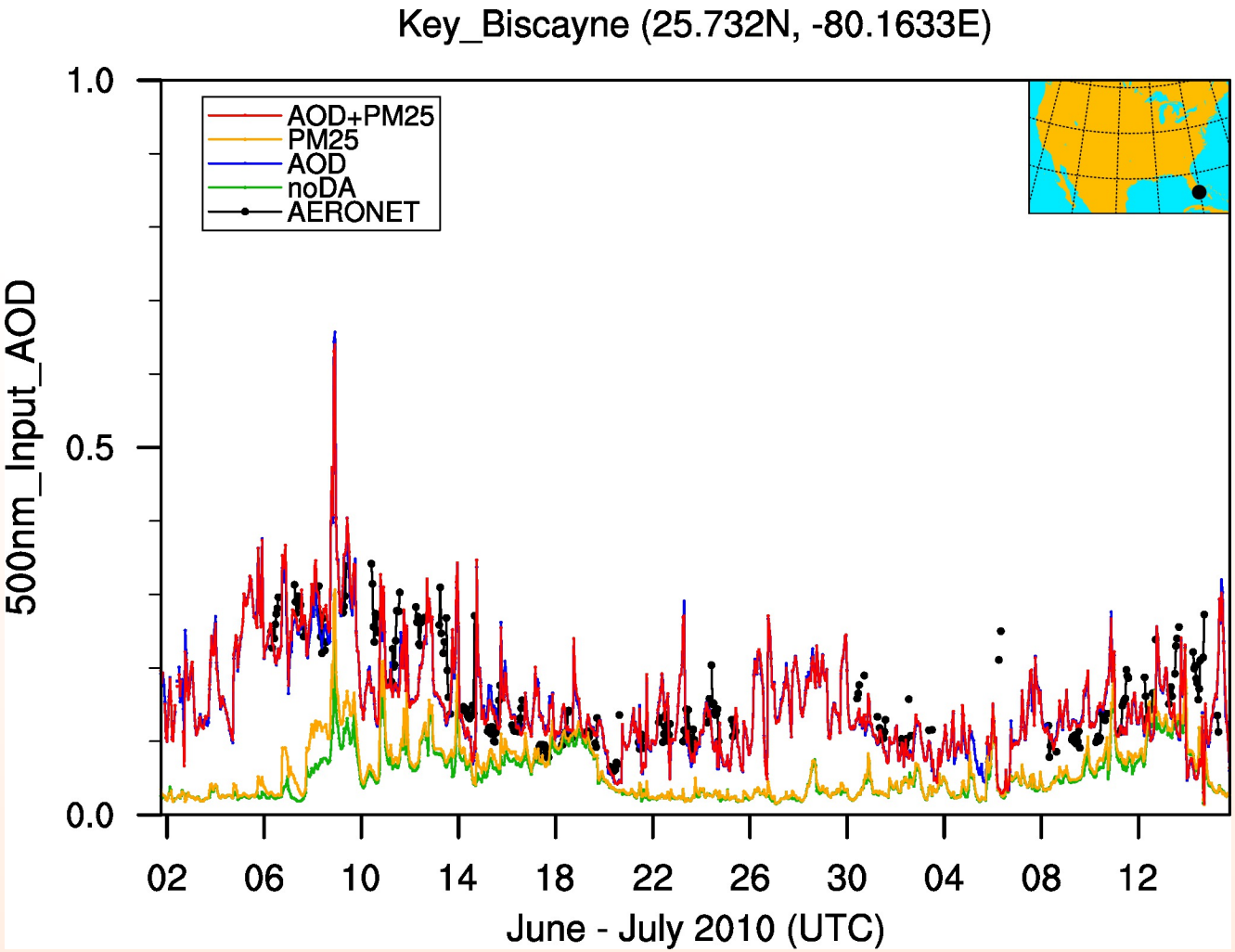
AERONET verification

- AERONET sites within the domain (n=34)

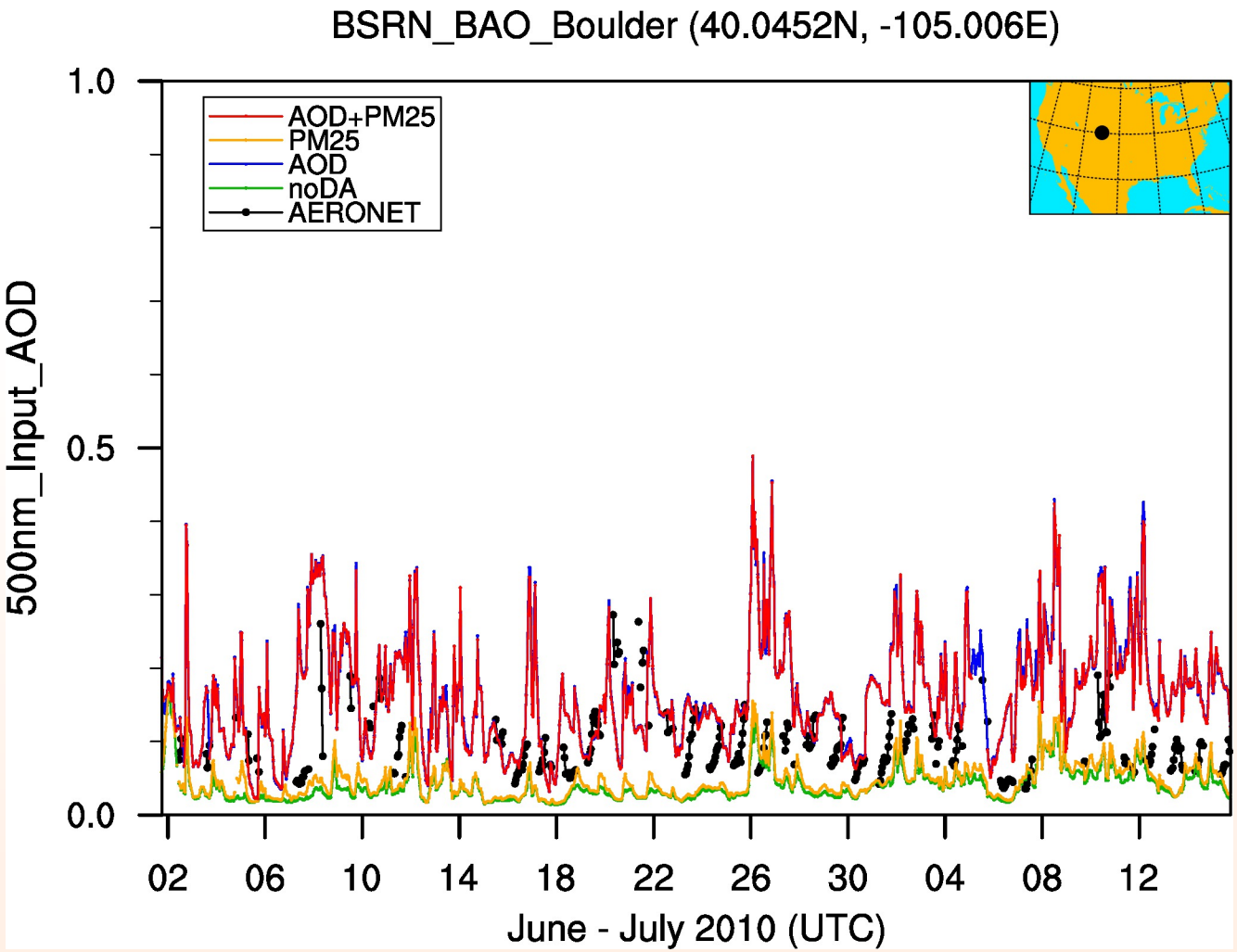


AERONET time-series (500 nm)

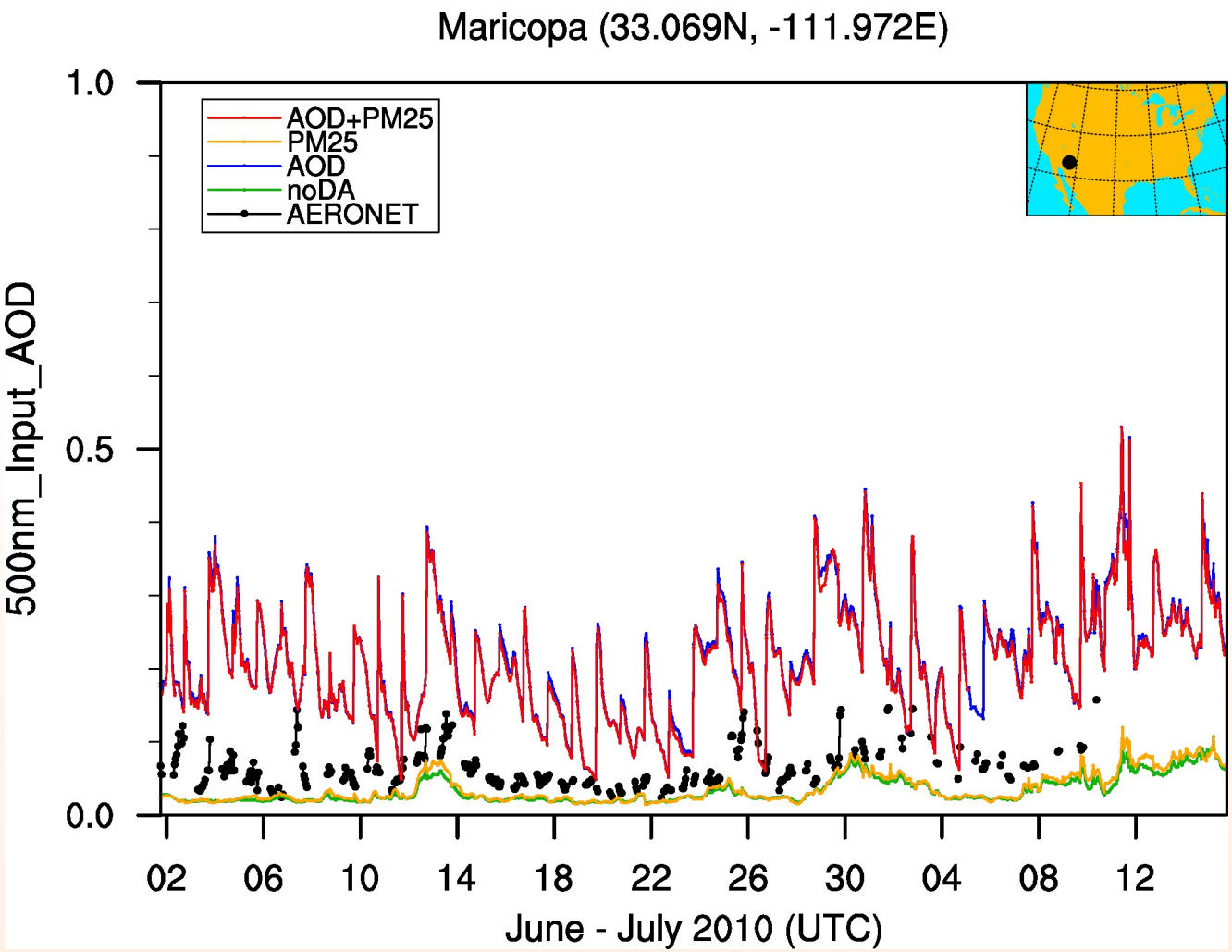
- Model curves: 0-23 hr forecasts each 1800 UTC initialization



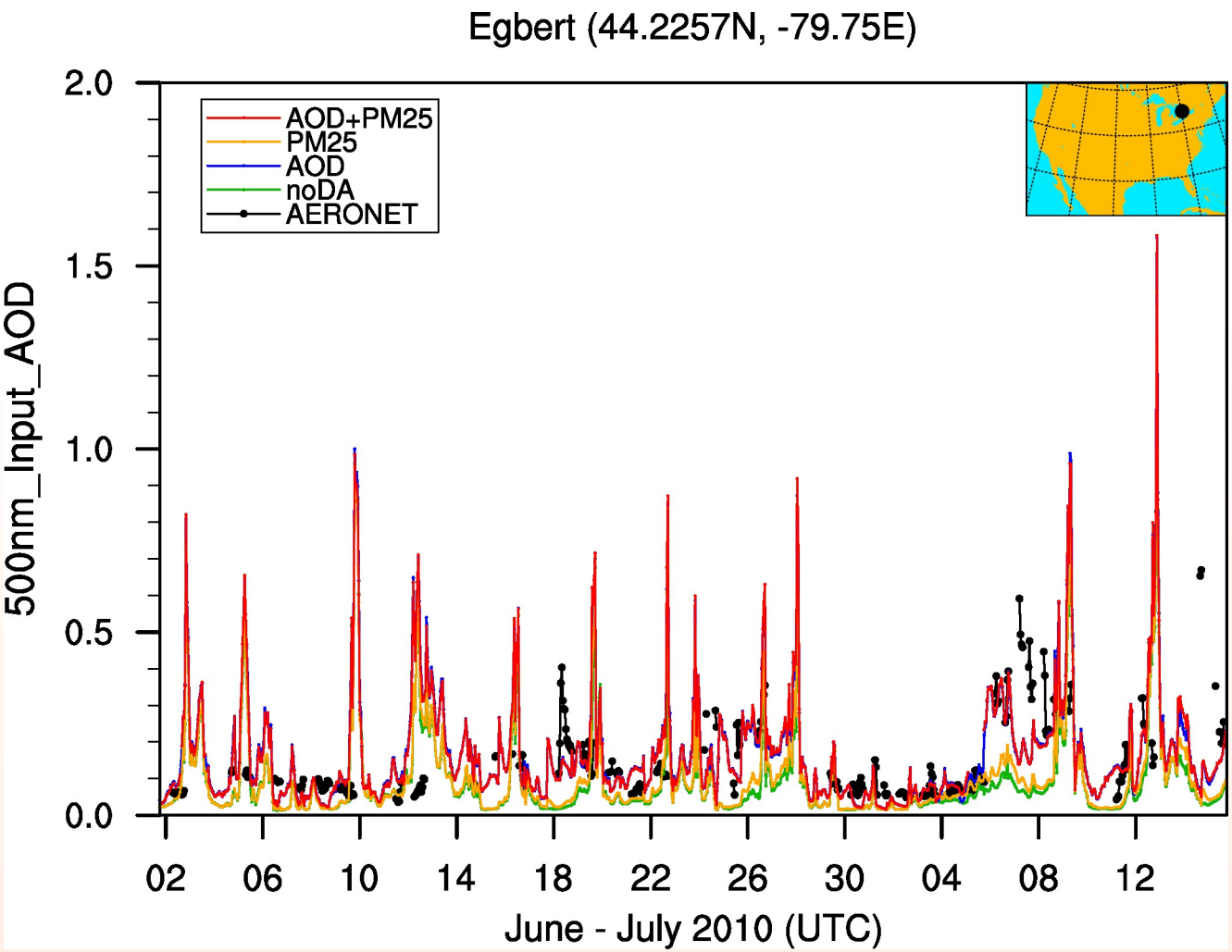
AERONET time-series (500 nm)



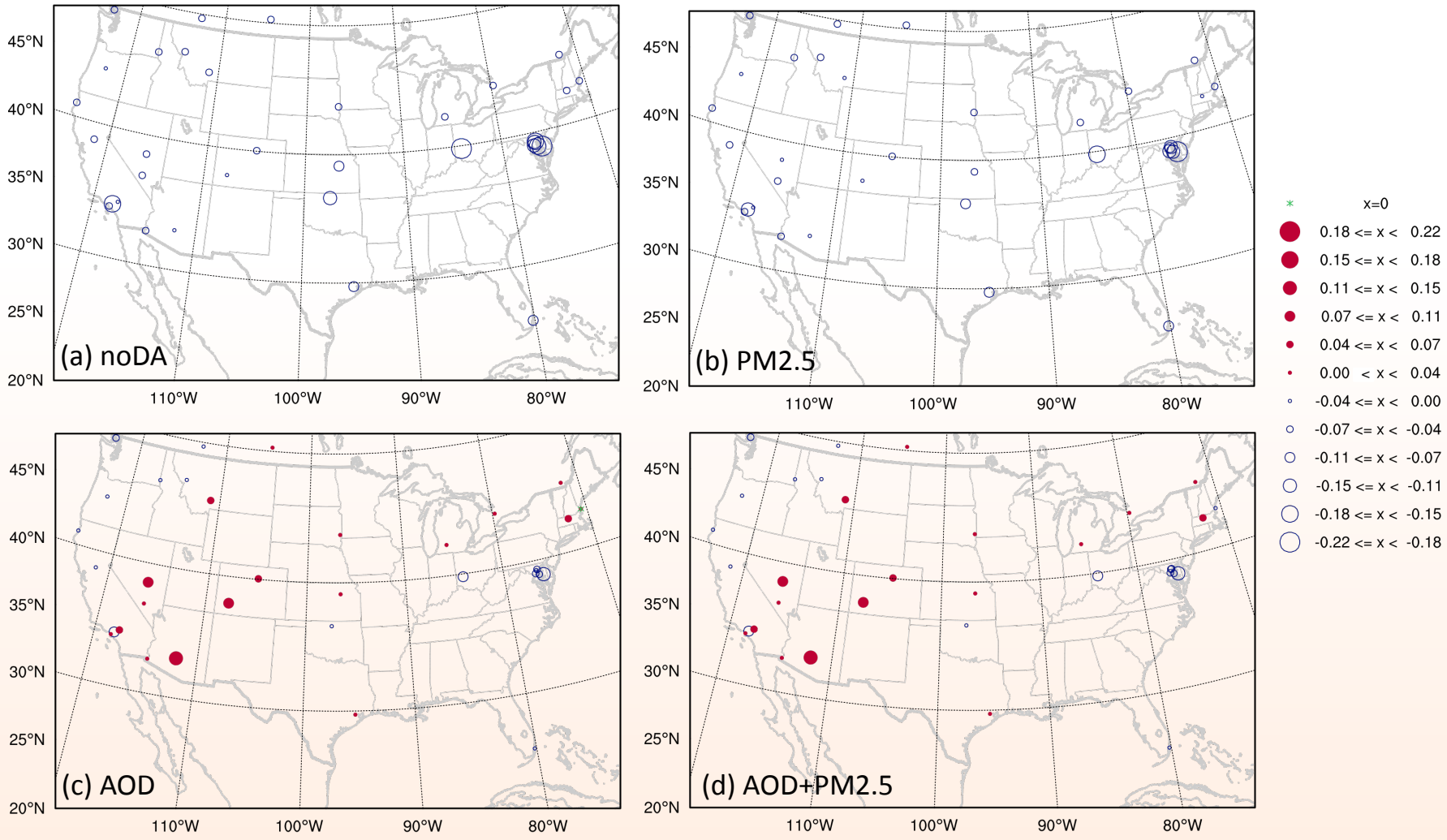
AERONET time-series (500 nm)



AERONET time-series (500 nm)



Mean Bias


45°N
40°N
35°N
30°N
25°N
20°N
110°W
100°W
90°W
80°W
(a) noDA
(b) PM2.5
(c) AOD
(d) AOD+PM2.5
x=0
0.18 <= x < 0.22
0.15 <= x < 0.18
0.11 <= x < 0.15
0.07 <= x < 0.11
0.04 <= x < 0.07
0.00 < x < 0.04
-0.04 <= x < 0.00
-0.07 <= x < -0.04
-0.11 <= x < -0.07
-0.15 <= x < -0.11
-0.18 <= x < -0.15
-0.22 <= x < -0.18

Summary

- WRF/Chem model generally underestimates aerosol concentration
- 3DVAR method developed here is general, easy to extend for assimilating any kind of aerosol observations as long as corresponding observation operator (as well as TL/AD or Jacobian) available
- Promising results for applications over East Asia and North America
- AOD observations apparently more useful than surface PM data even for surface PM forecast
- Need more careful quality control and data selection/improvement
  - e.g., MODIS AOD over western US desert area

Future work

- Assimilate more AOD products and other aerosol observations
  - GOES, AVHRR, SeaWiFS, MISR, future GOES-R/VIIRS …
  - PM10, Visibility, Lidar ext. coeffs. profiles (both ground- and satellite-based)
- Improve aerosol background error modeling
- Explore direct radiance DA for aerosol analysis
- Develop 4DVAR and EnDA approaches for aerosol analysis
- Extend to general chemical DA
- More applications
  - air-quality, biomass burning, volcanic ash, source inversion, weather-aerosol interaction …