Aerosol Data Assimilation using GSI and WRF/Chem-GOCART

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NCAR/NESL/MMM

Outline

- Technical introduction
- Applications
- Future plan

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WRF/Chem and GOCART

- WRF/Chem is an online-coupled meteoroglogy-chemistry model
  - allow aerosol/chemistry feedback to meteorological fields.

- The GOCART aerosol module (originally developed by NASA) 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}]

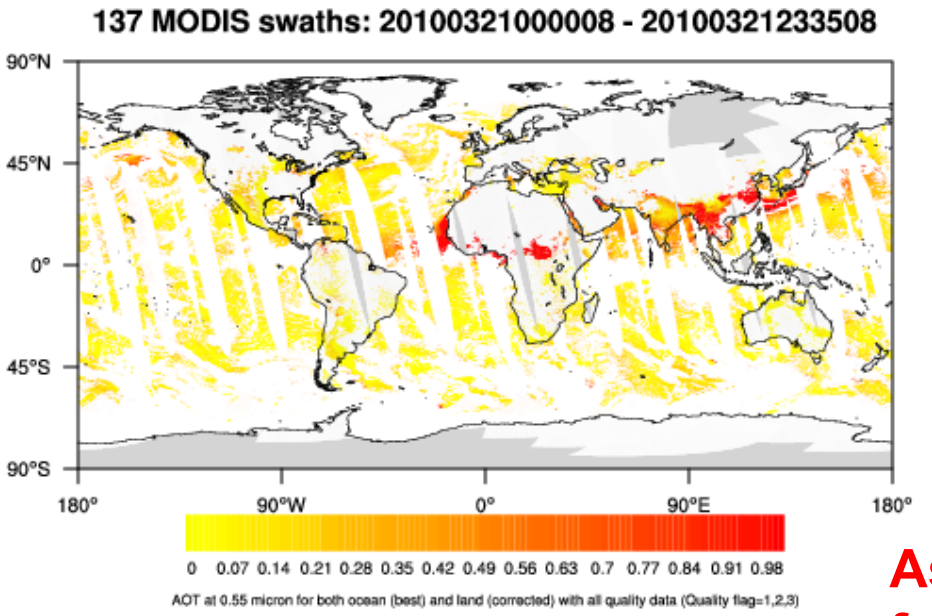
- WRF-Chem "P25" aerosol variable also an analysis variable
  - P25 is unspeciated aerosols contributing to $PM_{2.5}$

15 aerosol variables (mass concentration) to be analyzed

WRF/Chem-GOCART also includes a variable 'P10', unspeciated aerosols contributing to PM10. Only analysed when assimilating surface PM10 observations.

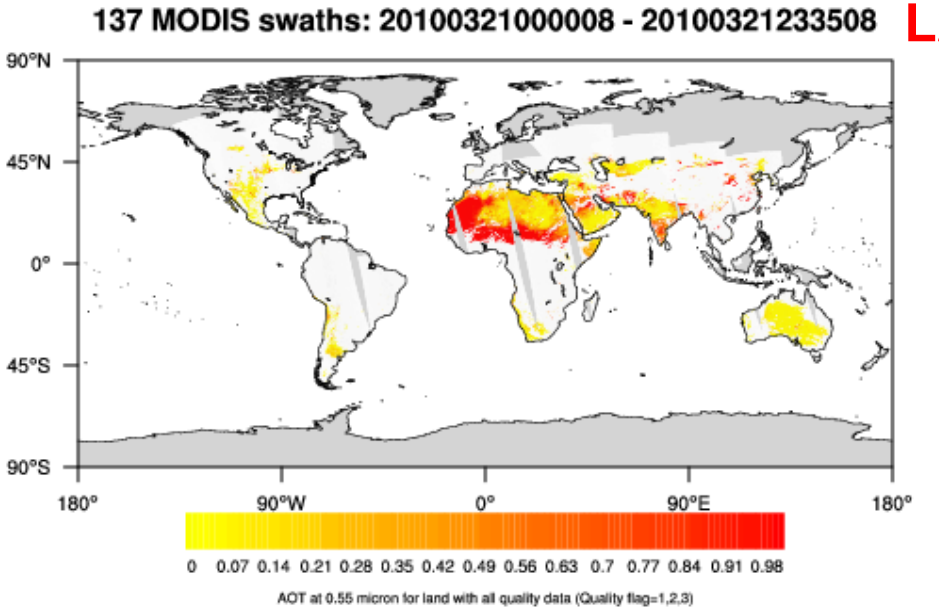
Implementation within GSI-3DVAR

- WRF/Chem-GOCART model interface in GSI, i.e., I/O for aerosol fields.
- Observation reading interface in GSI
  - MODIS AOD/Radiance, PM2.5, PM10, ……
  - Obs thinning for MODIS data is done in reading step
- Observation error covariances
  - Diagonal, i.e., only standard deviation of errors
- Background error covariances
  - Spatial correlation for each species, no multivariate correlation
  - Statistics from "NMC" method
- Observation operators, need both forward and Jacobian
- Quality control



Standard AOD (or AOT) (Aerosol Optical Depth/Thickness) product over ocean & land

Assimilate only 0.55 μm band from both Terra and Aqua. L2: 10km x 10km resolution.



"Deep Blue" AOD product over bright land surface

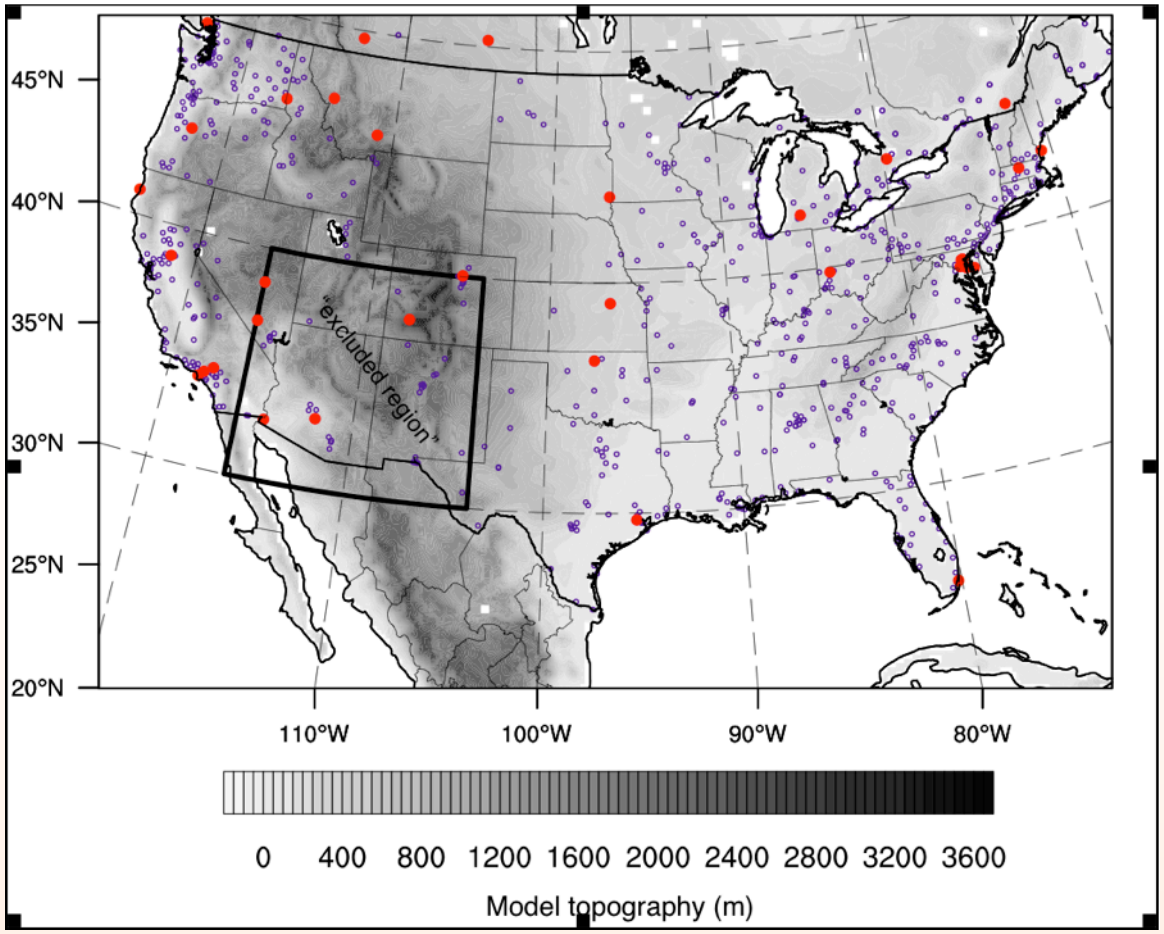
NASA HDF-format data converted to BUFR format to be used in GSI.

Primary Use	Band	Bandwidth (nm)
Land/Cloud/Aerosols Boundaries	1	620 - 670
	2	841 - 876
Land/Cloud/Aerosols Properties	3	459 - 479
	4	545 - 565
	5	1230 - 1250
	6	1628 - 1652
	7	2105 - 2155
Ocean Color/Phytoplankton Biogeochemitry	8	405 - 420
	9	438 - 448
	10	483 - 493
	11	526 - 536
	12	546 - 556
	13	662 - 672
	14	673 - 683
	15	743 - 753
	16	862 - 877
Atmospheric Water Vapor	17	890 - 920
	18	931 - 941
	19	915 - 965

Primary Use	Band	Bandwidth (μm)
Surface/Cloud Temperature	20	3.660 – 3.840
	21	3.929 – 3.989
	22	3.929 – 3.989
	23	4.020 – 4.080
Atmospheric Temperature	24	4.433 – 4.498
	25	4.482 – 4.549
Cirrus Clouds Water Vapor	26	1.360 – 1.390
	27	6.535 – 6.895
	28	7.175 – 7.475
Cloud Properties	29	8.400 – 8.700
Ozone	30	9.580 – 9.880
Surface/Cloud Temperature	31	10.780 – 11.280
	32	11.770 – 12.270
Cloud Top Altitude	33	13.185 – 13.485
	34	13.485 – 13.785
	35	13.785 – 14.085
	36	14.085 – 14.385

Channels 1~7 used for AOD retrieval

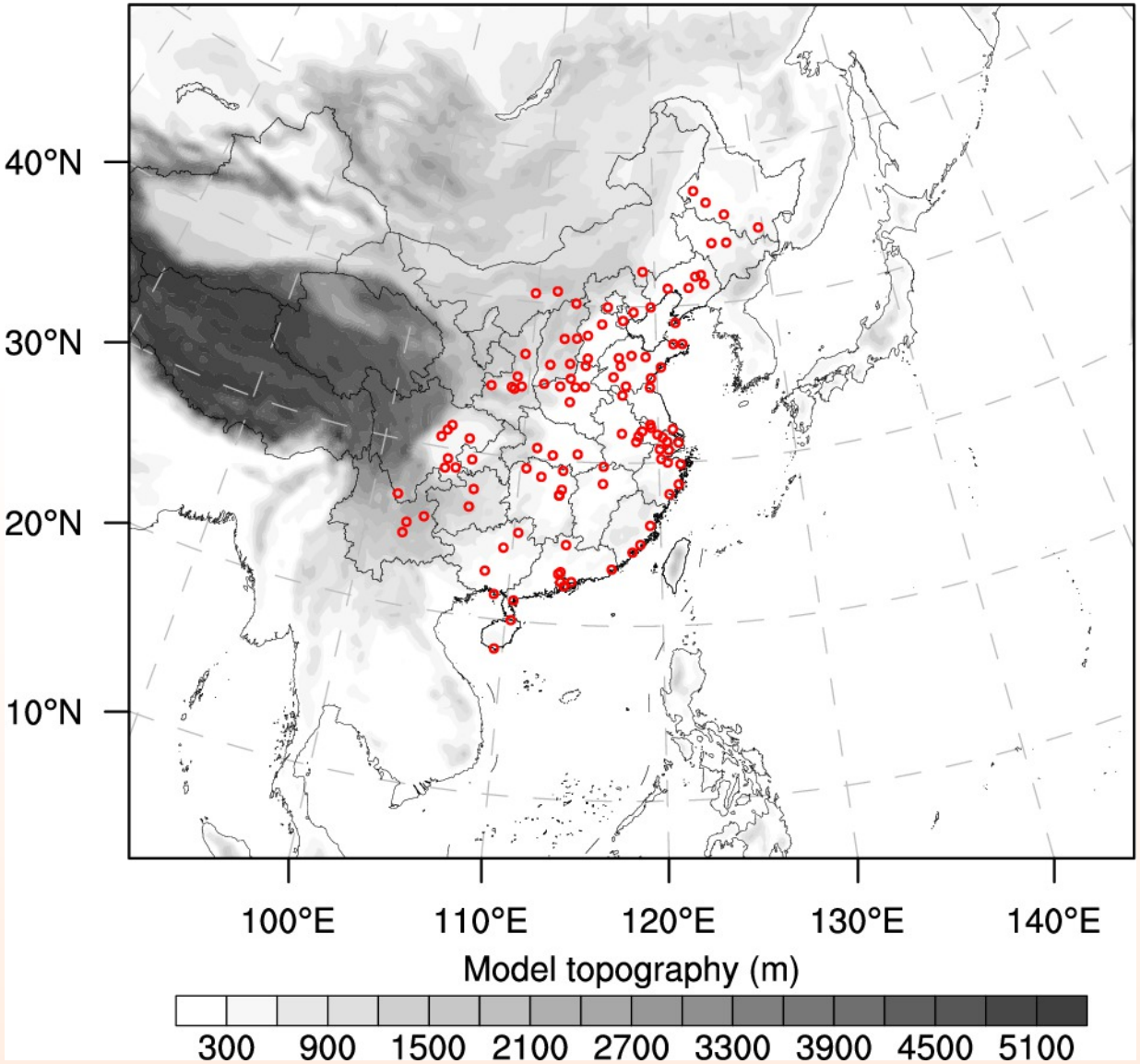
US AIRNow network for PM2.5 obs (particulate matter with diameter < 2.5 µm)



AERONET sites

AIRNow PM2.5 sites

China PM10 network



Observation Operators

- MODIS AOD:
  - Use Community Radiative Transfer Model (CRTM) (from V2.1) of Joint Center for Satellite Data Assimilation (JCSDA) as the observation operator, including both forward and Jacobian models to calculate the gradient of cost function.

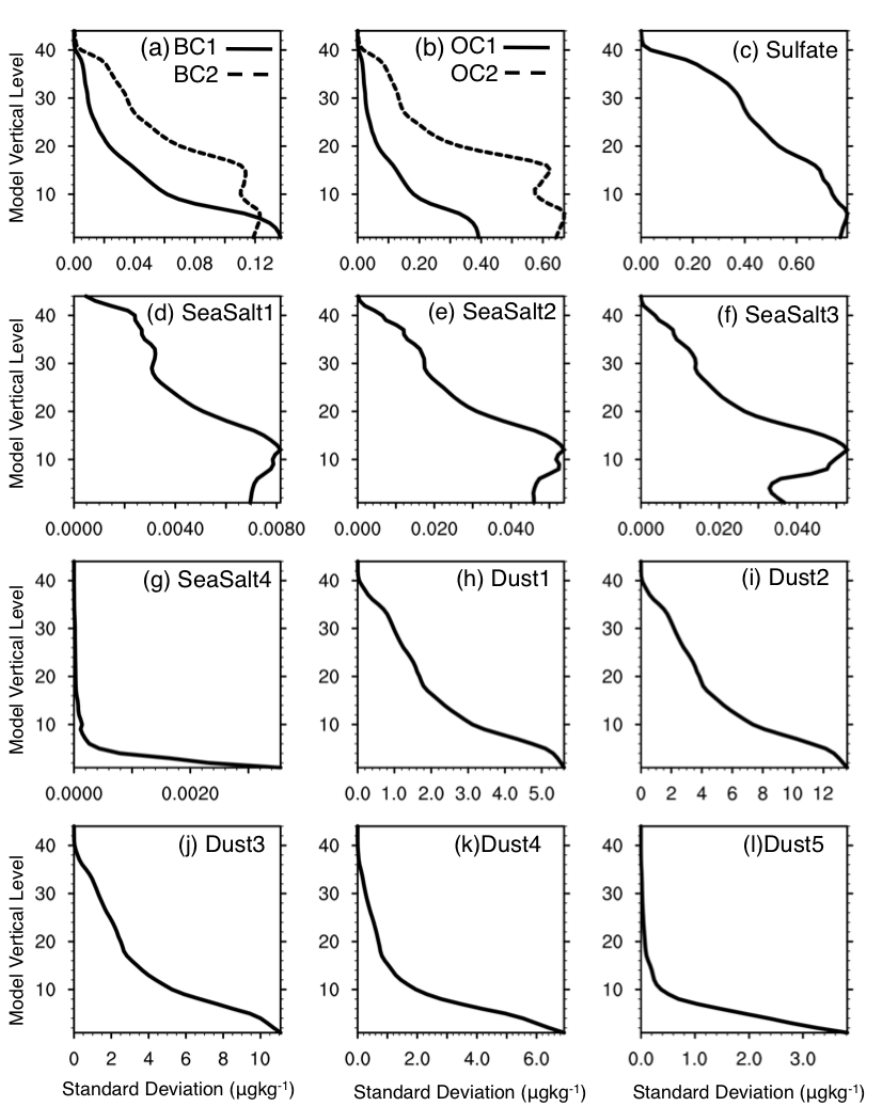
- MODIS radiance (visible/near-infrared band)
  - More complicated, need to consider sunlight scattering and surface reflectance.
  - Latest CRTM includes initial capability for visible radiance.

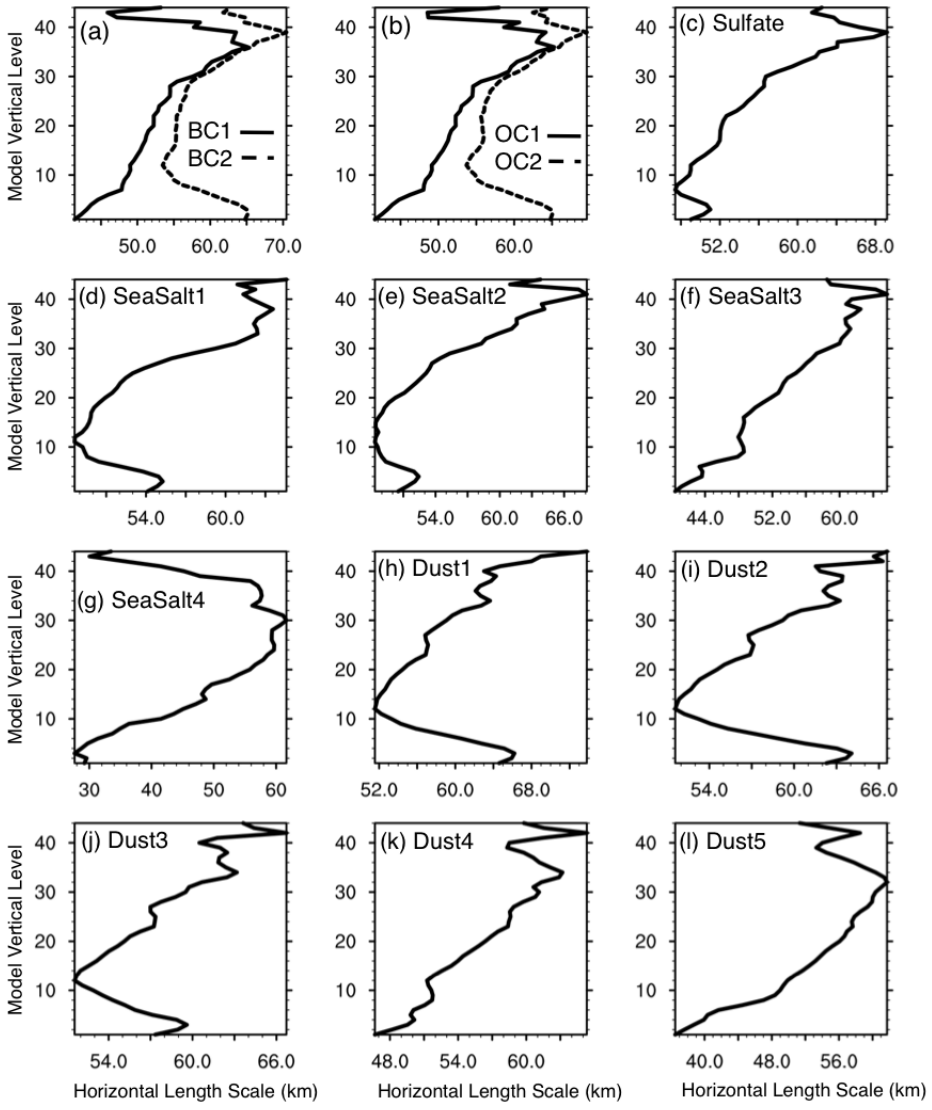
- Linear formula for model-simulated $PM_{2.5}$ (from WRF-Chem)
  - $PM_{2.5} = \rho[p25 + bc1 + bc2 + 1.8(oc1 + oc2) + dust1 + 0.286*dust2 + seas1 + 0.942*seas2 + 1.375*sulf]$

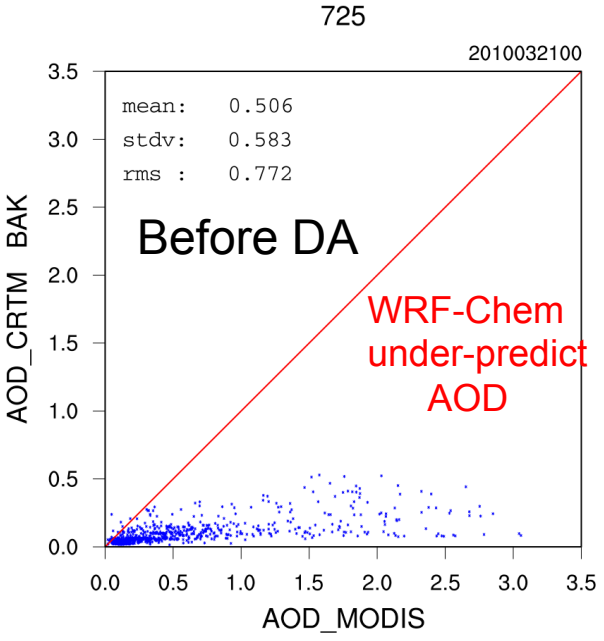
Estimate B for Aerosol Species (WRFDA GEN_BE tool)

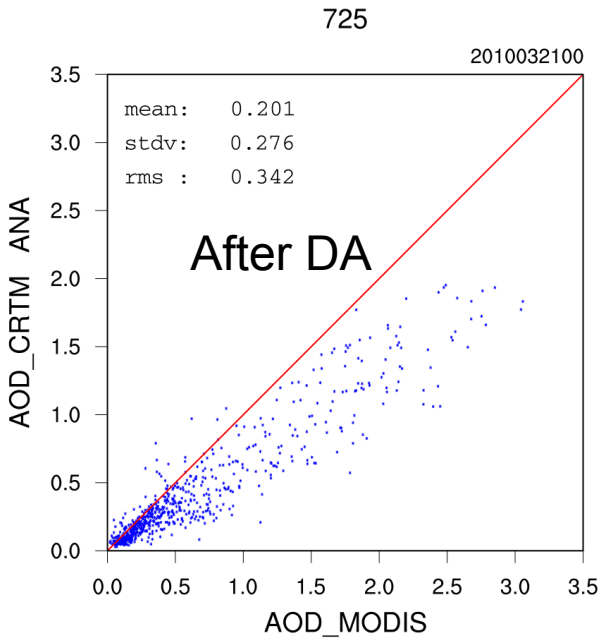
- "NMC" method is used to compute aerosol background error covariance (B) statistics using WRF-Chem model forecasts (at 00Z and 12Z).
  - Uses differences between 24- and 12-hr forecasts valid at the same time
  - Compute standard deviation, vertical and horizontal length-scale for GOCART aerosol variables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

Matrix B: Standard deviation & horizontal length-scale statistics obtained over a dust-storm period in China

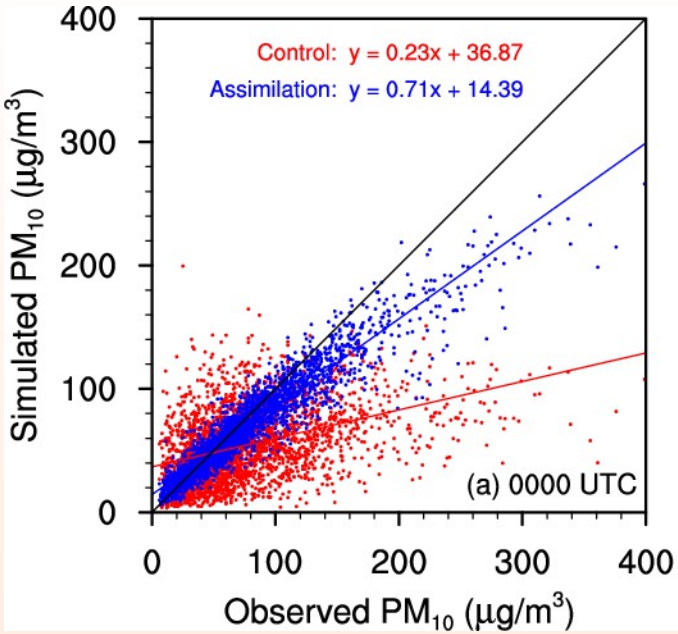


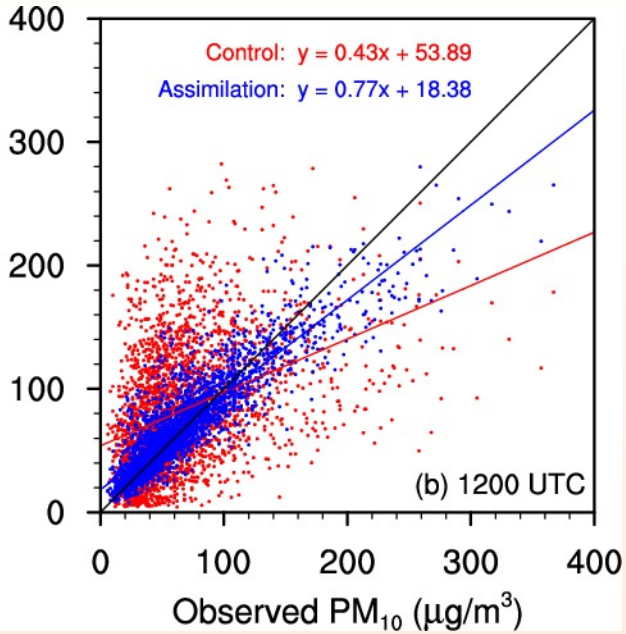






AOD DA over US





PM10 DA over China

How it works?

Three files to configure

- aeroinfo
  - MODIS channel selection
- anavinfo
  - Specify control variables and background error tuning
- gsiparm.anl
  - GSI namelist

aeroinfo

! sens/instr/sat	chan	use	pressure error	gross error	obs variational qc	b_aero	pg_aero
v.modis_aqua	1	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	2	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	3	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	4	1	0.000	0.100	0.050	1.000	0.000
v.modis_aqua	5	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	6	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	7	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	8	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	9	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	10	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	11	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	12	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	13	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	14	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	15	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	16	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	17	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	18	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	19	-1	0.000	0.500	0.350	1.000	0.000
v.modis_aqua	19	-1	0.000	0.500	0.350	1.000	0.000
v.modis_terra	1	-1	0.000	0.500	0.340	1.000	0.000
v.modis_terra	2	-1	0.000	0.500	0.340	1.000	0.000
v.modis_terra	3	-1	0.000	0.500	0.340	1.000	0.000
v.modis_terra	4	1	0.000	0.100	0.050	1.000	0.000
v.modis_terra	5	-1	0.000	0.500	0.340	1.000	0.000
……							
……							

Only channel-4 (0.55 μm) used

anavinfo

```
state_vector::
!var     level  itracer amedge  source      funcof
 u       40     0       no      met_guess    u
 v       40     0       no      met_guess    v
 tv      40     0       no      met_guess    tv
 tsen    40     0       no      met_guess    tv,q
 q       40     1       no      met_guess    q
 oz      40     1       no      met_guess    oz
# cw      40     1       no      met_guess    cw
 p3d     41     0       yes     met_guess    p3d
 ps      1      0       no      met_guess    p3d
 sst     1      0       no      met_guess    sst
 sulf    40     1       no      chem_guess   sulf
 bc1     40     1       no      chem_guess   BC1
 bc2     40     1       no      chem_guess   BC2
 oc1     40     1       no      chem_guess   OC1
 oc2     40     1       no      chem_guess   OC2
 dust1   40     1       no      chem_guess   DUST1
 dust2   40     1       no      chem_guess   DUST2
 dust3   40     1       no      chem_guess   DUST3
 dust4   40     1       no      chem_guess   DUST4
 dust5   40     1       no      chem_guess   DUST5
 seas1   40     1       no      chem_guess   SEAS1
 seas2   40     1       no      chem_guess   SEAS2
 seas3   40     1       no      chem_guess   SEAS3
 seas4   40     1       no      chem_guess   SEAS4
 p25     40     1       no      chem_guess   p25
::
```

```
control_vector::
!var     level  itracer as/tsfc_sdv  an_amp0   source  funcof
 sf      40     0       1.00         -1.0      state   u,v
 vp      40     0       1.00         -1.0      state   u,v
 ps      1      0       0.50         -1.0      state   p3d
 t       40     0       0.70         -1.0      state   tv
 q       40     1       0.70         -1.0      state   q
 oz      40     1       0.50         -1.0      state   oz
 sst     1      0       1.00         -1.0      state   sst
# cw      40     1       1.00         -1.0      state   cw
 sulf    40     1       1.00         -1.0      state   sulf
 bc1     40     1       1.00         -1.0      state   BC1
 bc2     40     1       1.00         -1.0      state   BC2
 oc1     40     1       1.00         -1.0      state   OC1
 oc2     40     1       1.00         -1.0      state   OC2
 dust1   40     1       1.00         -1.0      state   DUST1
 dust2   40     1       1.00         -1.0      state   DUST2
 dust3   40     1       1.00         -1.0      state   DUST3
 dust4   40     1       1.00         -1.0      state   DUST4
 dust5   40     1       1.00         -1.0      state   DUST5
 seas1   40     1       1.00         -1.0      state   SEAS1
 seas2   40     1       1.00         -1.0      state   SEAS2
 seas3   40     1       1.00         -1.0      state   SEAS3
 seas4   40     1       1.00         -1.0      state   SEAS4
 p25     40     1       1.00         -1.0      state   p25
 stl     1      0       1.00         -1.0      motley  sst
 sti     1      0       1.00         -1.0      motley  sst
::
```

```
chem_guess::
!var     level  itracer crtm_use  type     orig_name
 sulf    40     1       12        sulf     sulf
 bc1     40     1       12        BC1      BC1
 bc2     40     1       12        BC2      BC2
 oc1     40     1       12        OC1      OC1
 oc2     40     1       12        OC2      OC2
 dust1   40     1       12        DUST1    DUST_1
 dust2   40     1       12        DUST2    DUST_2
 dust3   40     1       12        DUST3    DUST_3
 dust4   40     1       12        DUST4    DUST_4
 dust5   40     1       12        DUST5    DUST_5
 seas1   40     1       12        SEAS1    SEAS_1
 seas2   40     1       12        SEAS2    SEAS_2
 seas3   40     1       12        SEAS3    SEAS_3
 seas4   40     1       12        SEAS4    SEAS_4
 p25     40     1       10        p25      P25
::
```

gsiparm.anl

```
&OBS_INPUT
 dmesh(1)=20.0,dmesh(2)=20.0,dmesh(3)=60.0,dmesh(4)=240.0,dmesh(5)=120.0,time_window_max=6.0,
 dfile(01)='modisbufr', dtype(01)='modis_aod', dplat(01)='terra',  dsis(01)='v.modis_terra',   dval(01)=1.0,  dthin(01)=2, dsfcalc(01)=0,
 dfile(02)='modisbufr', dtype(02)='modis_aod', dplat(02)='aqua',  dsis(02)='v.modis_aqua',  dval(02)=1.0,  dthin(02)=2, dsfcalc(02)=0,
/
```

```
&CHEM
laeroana_gocart = .true.
luse_deepblue = .false.
aod_max_val = 2
luse_desert = .true.
luse_coastal = .true.
luse_land = .true.
luse_water = .true.
/
```

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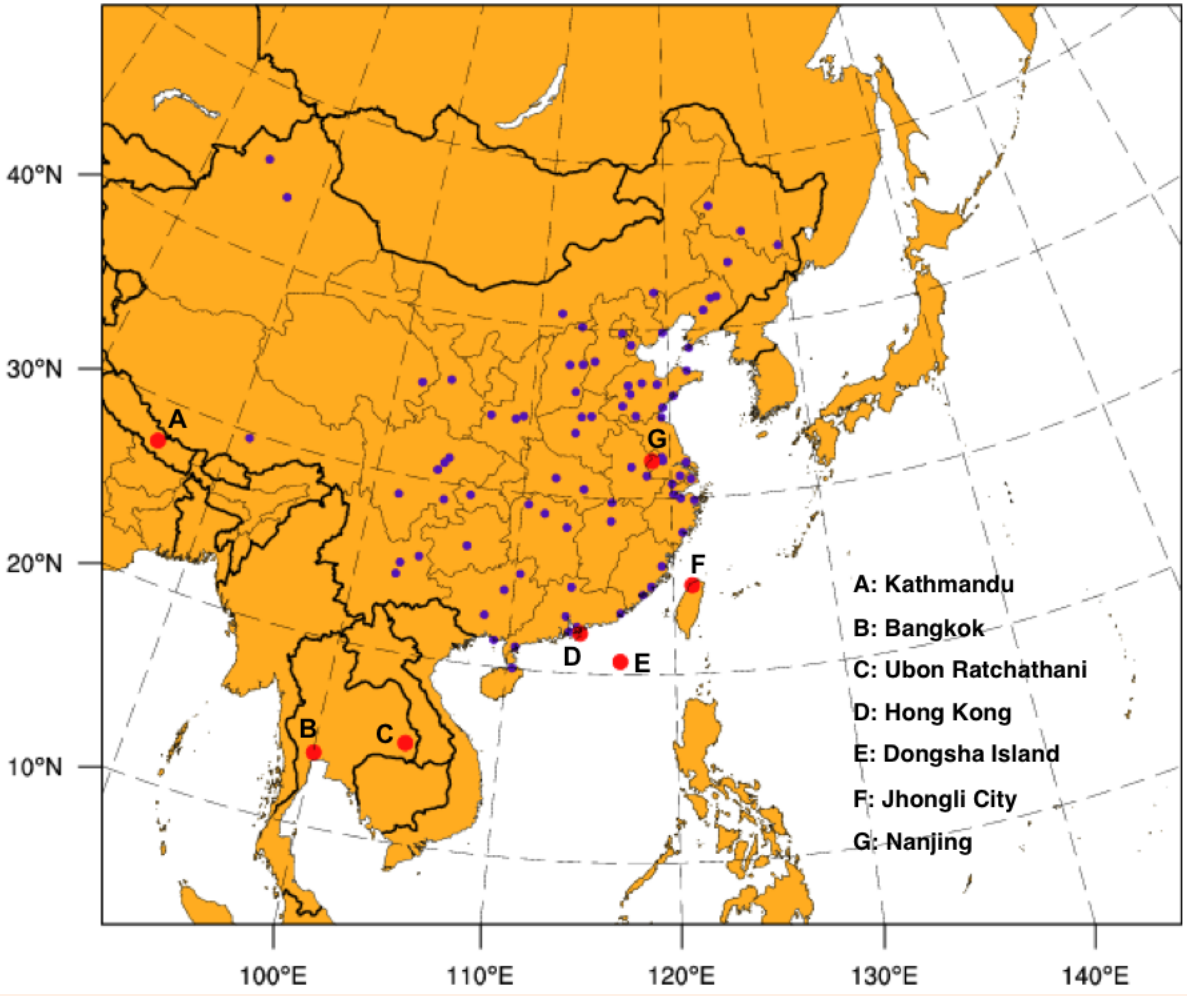
Dust storm affected Nanjing on Mar. 21, 2010

昨天北方沙尘来到南京，使南京蒙上灰蒙蒙的"沙帐"。张鸽 摄

East Asia domain (AOD DA)



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

Validation observations:
7 AERONET sites

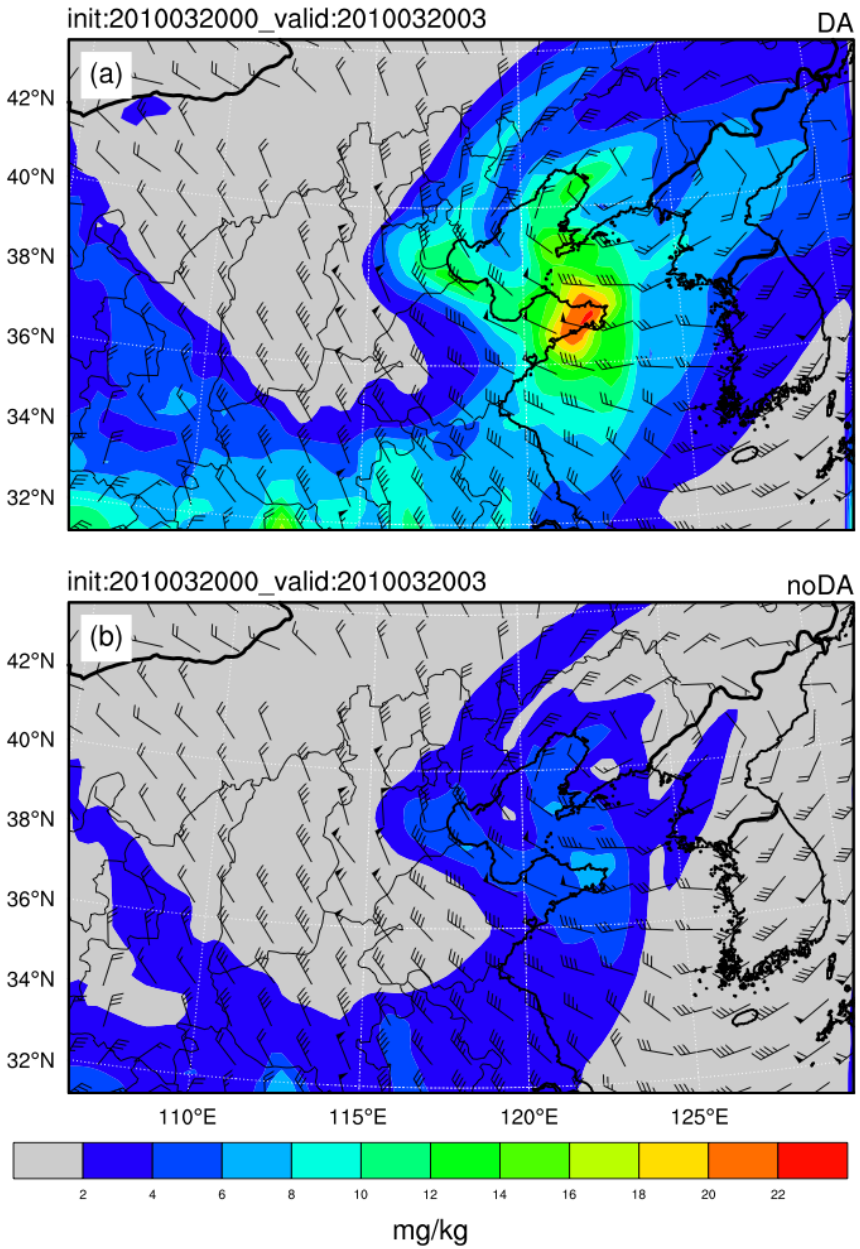
chem_opt=301:
GOCART+RACM

Emissions:
Online biogenic
RETRO+"Streets" anthropogenic

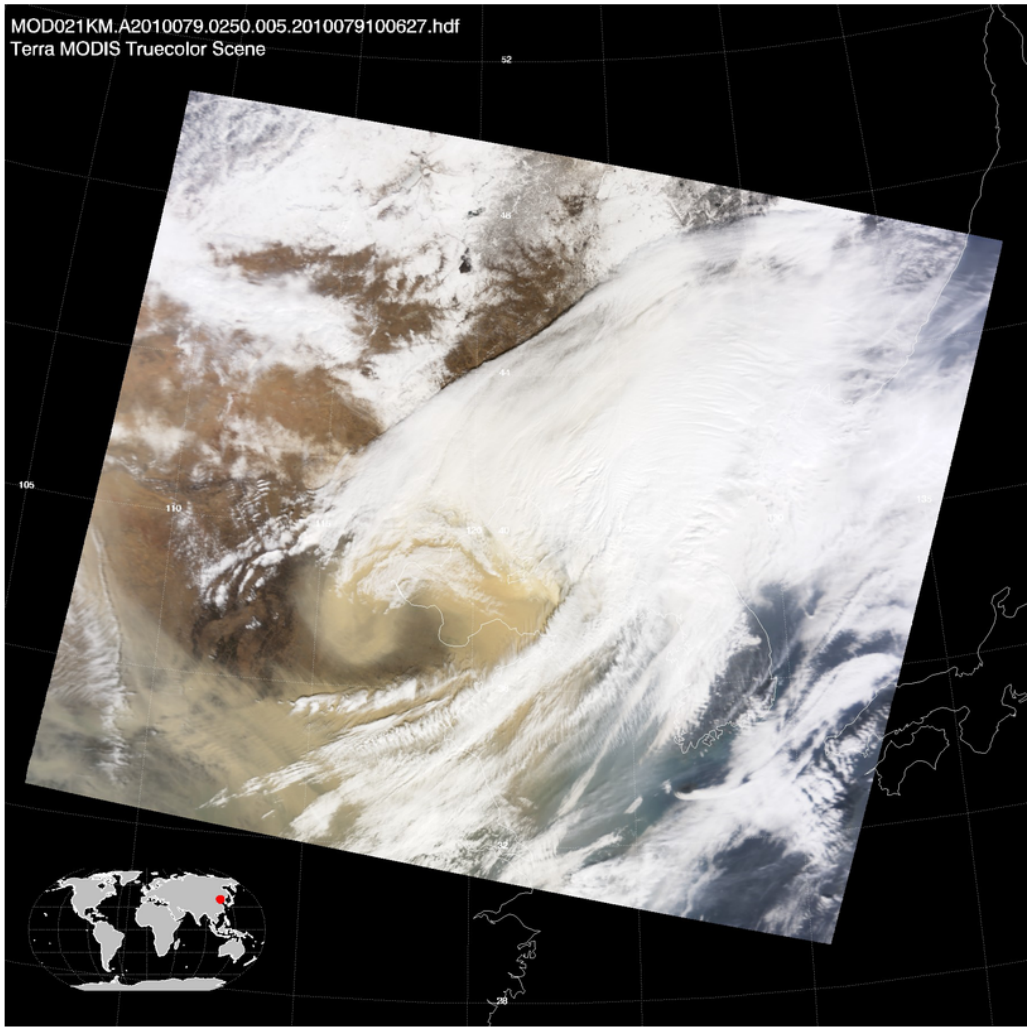
LBC: NCAR CAM-Chem

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

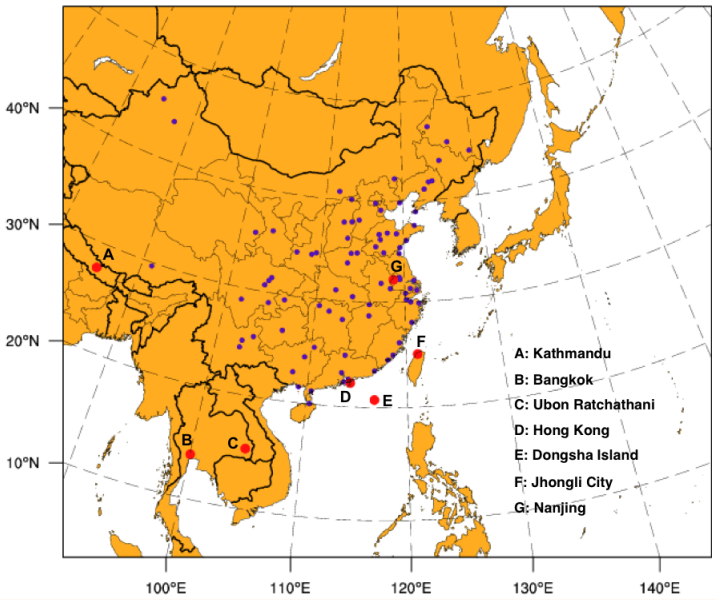
DUST

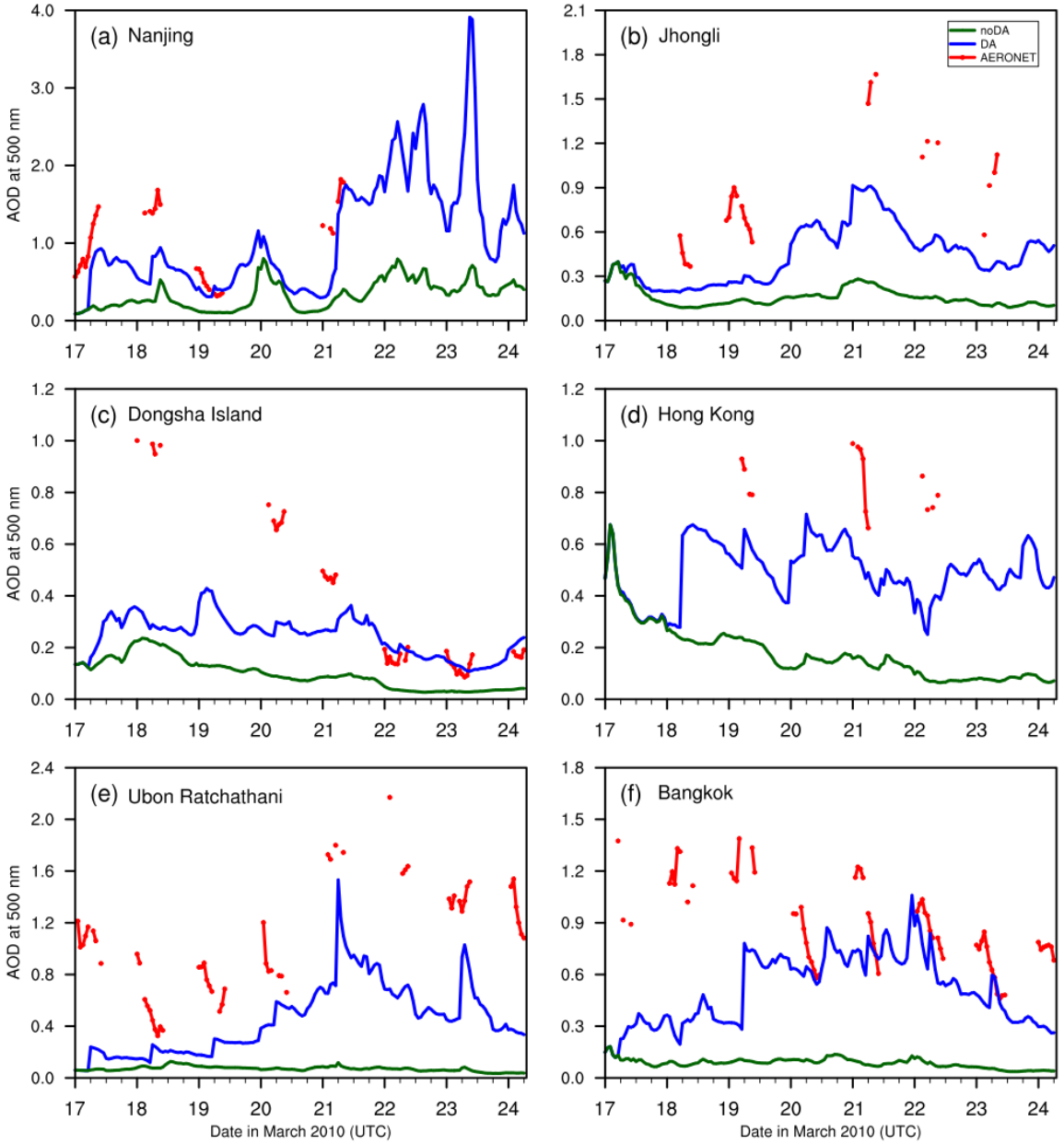


Column dust vs. MODIS true color image. 2010032003

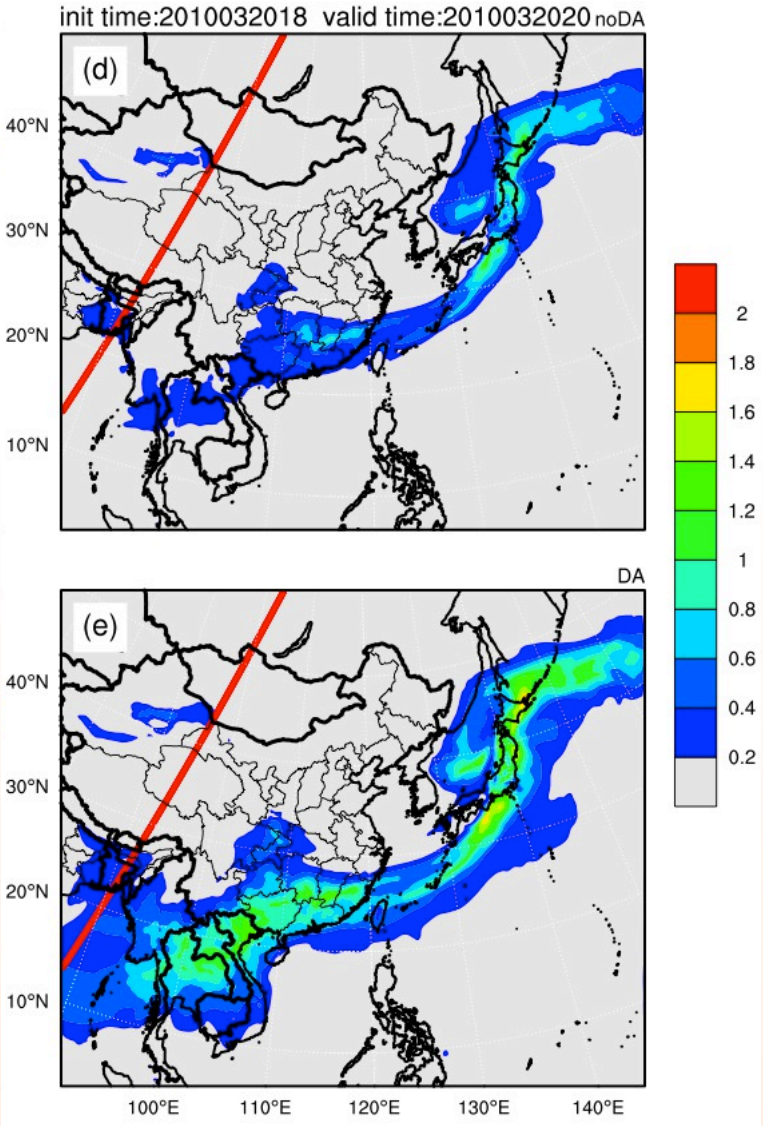


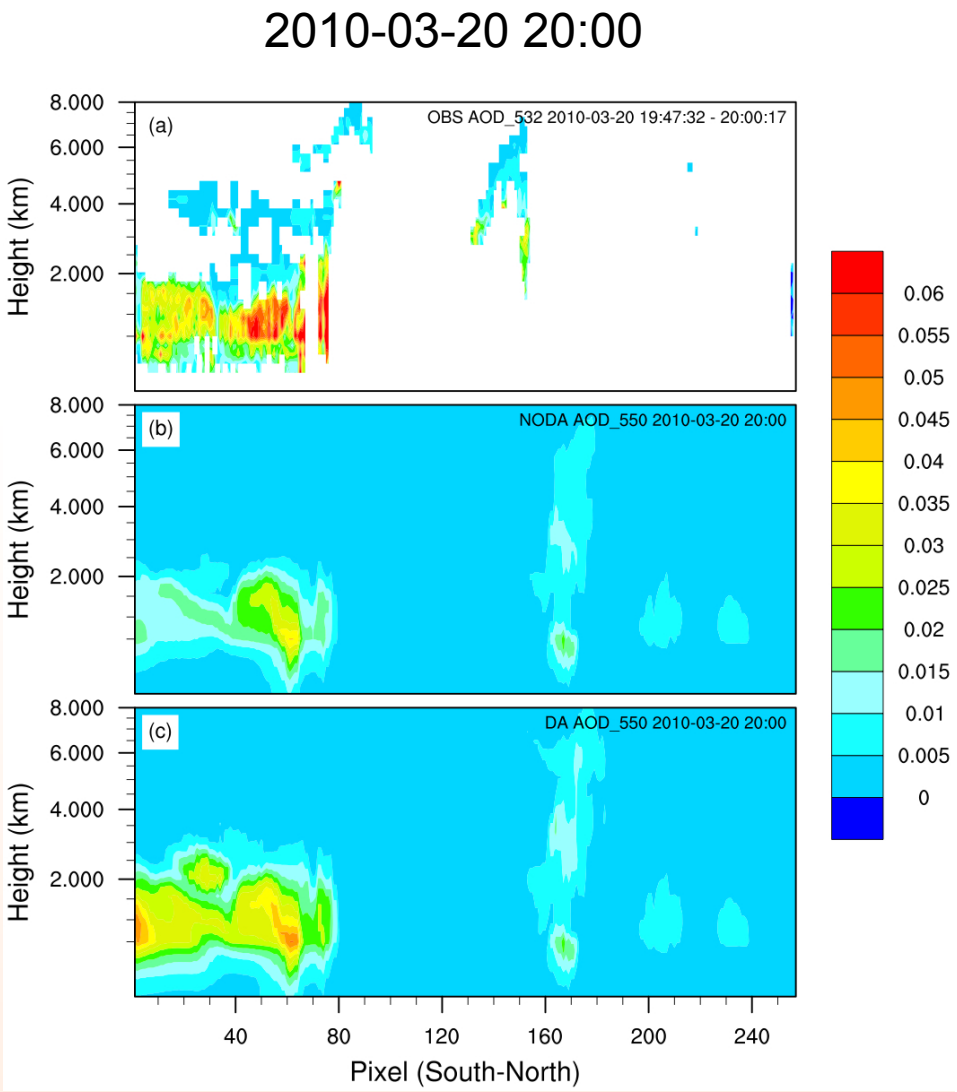
Verify @500nm at other 6 AERONET sites



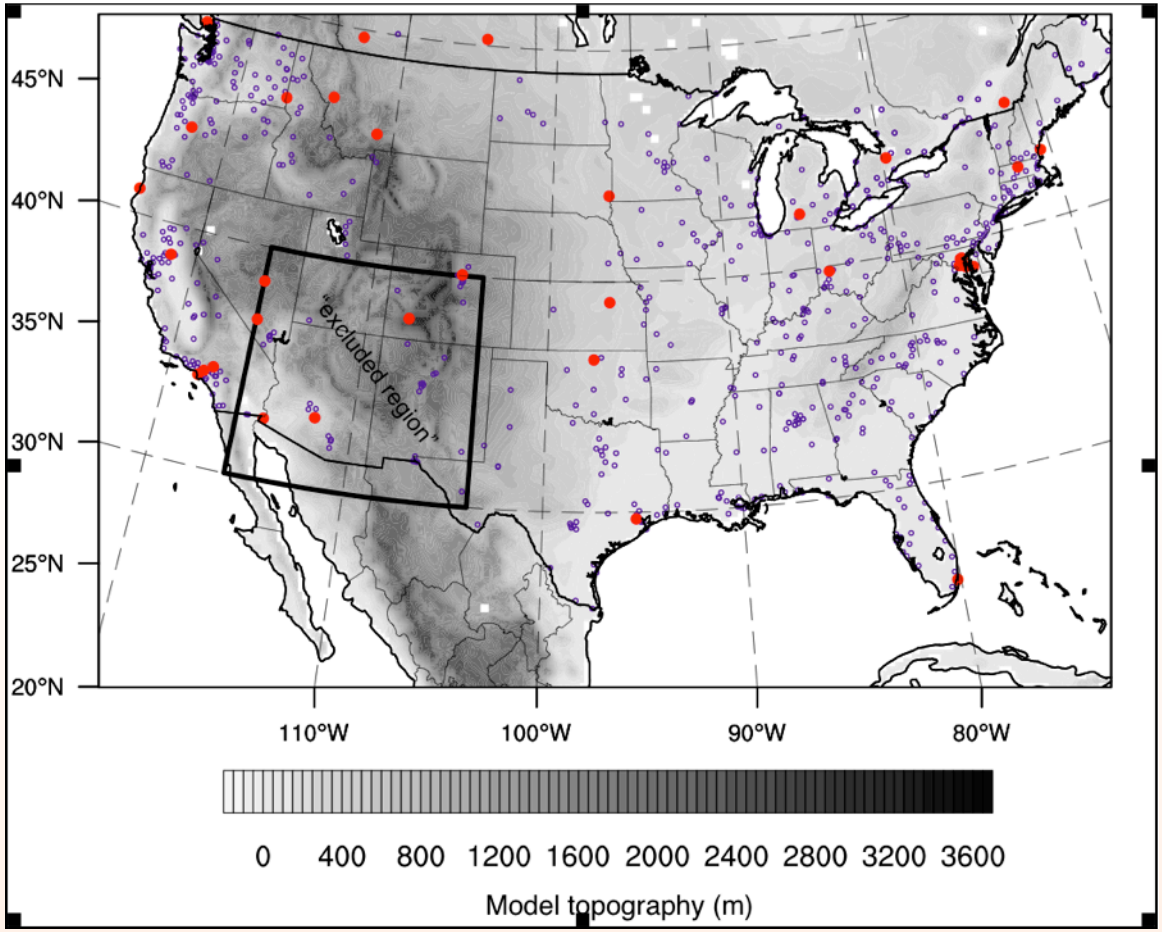


AOD vertical distribution vs. CALIOP





North America domain (AOD+PM2.5 DA)



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

Observation coverage:

AERONET sites (not assimilated)

AIRNow PM2.5 sites (assimilated)

chem_opt=300 (AFWA's config):

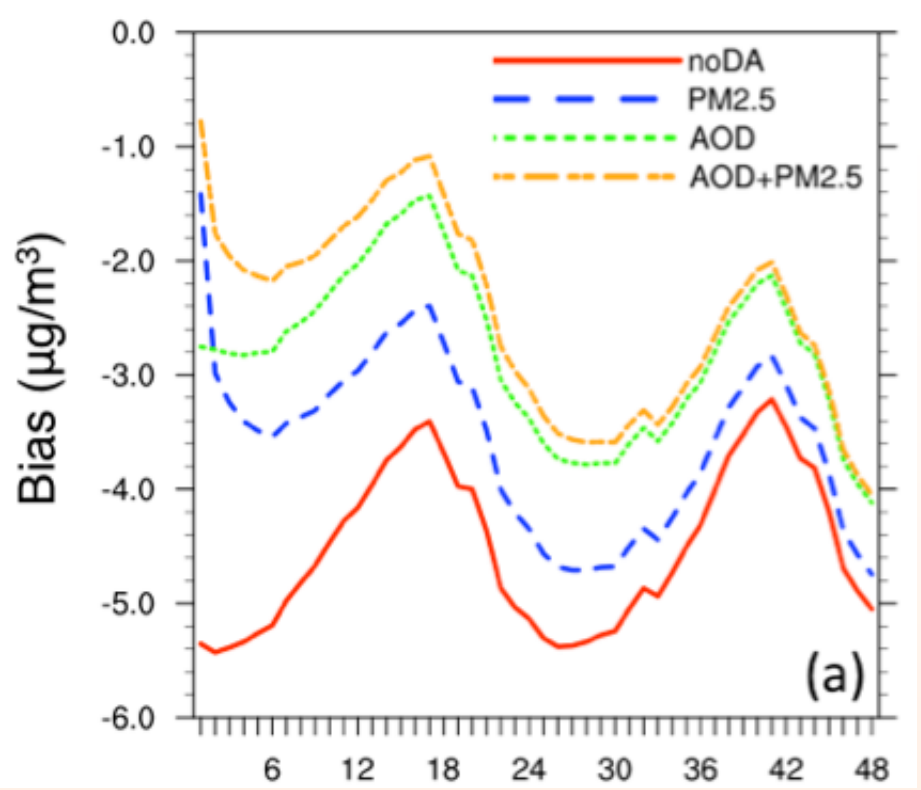
GOCART w/o chemistry

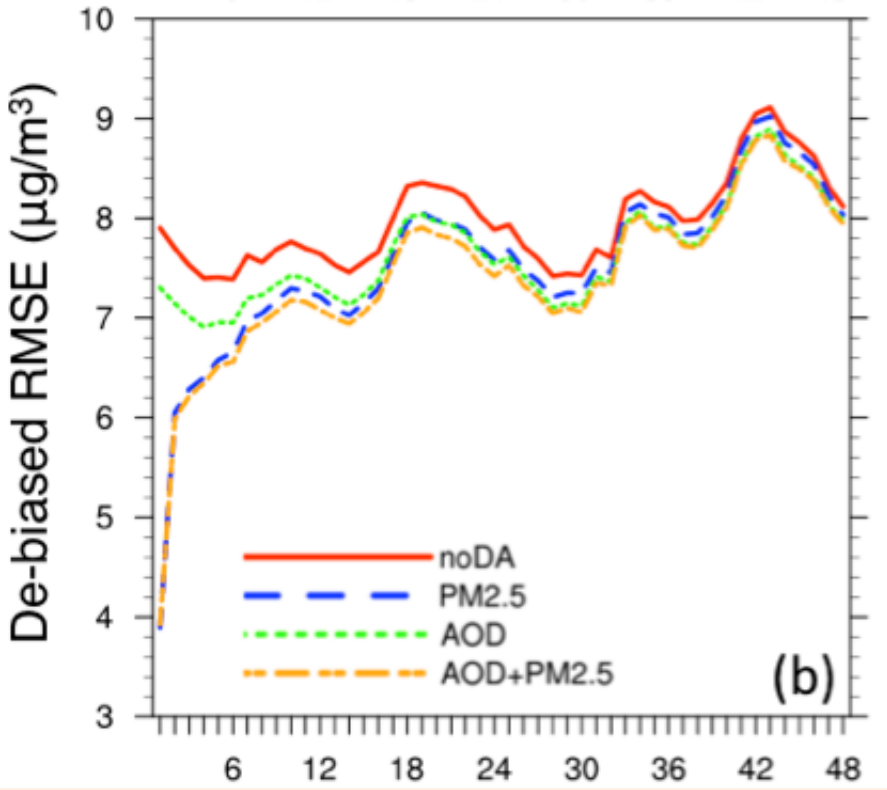
Area within the box excluded for PM2.5 verification score calculation: desert area, inaccurate MODIS AOD

June 1 ~ July 14, 2010

$PM_{2.5}$ 48-h forecast verification

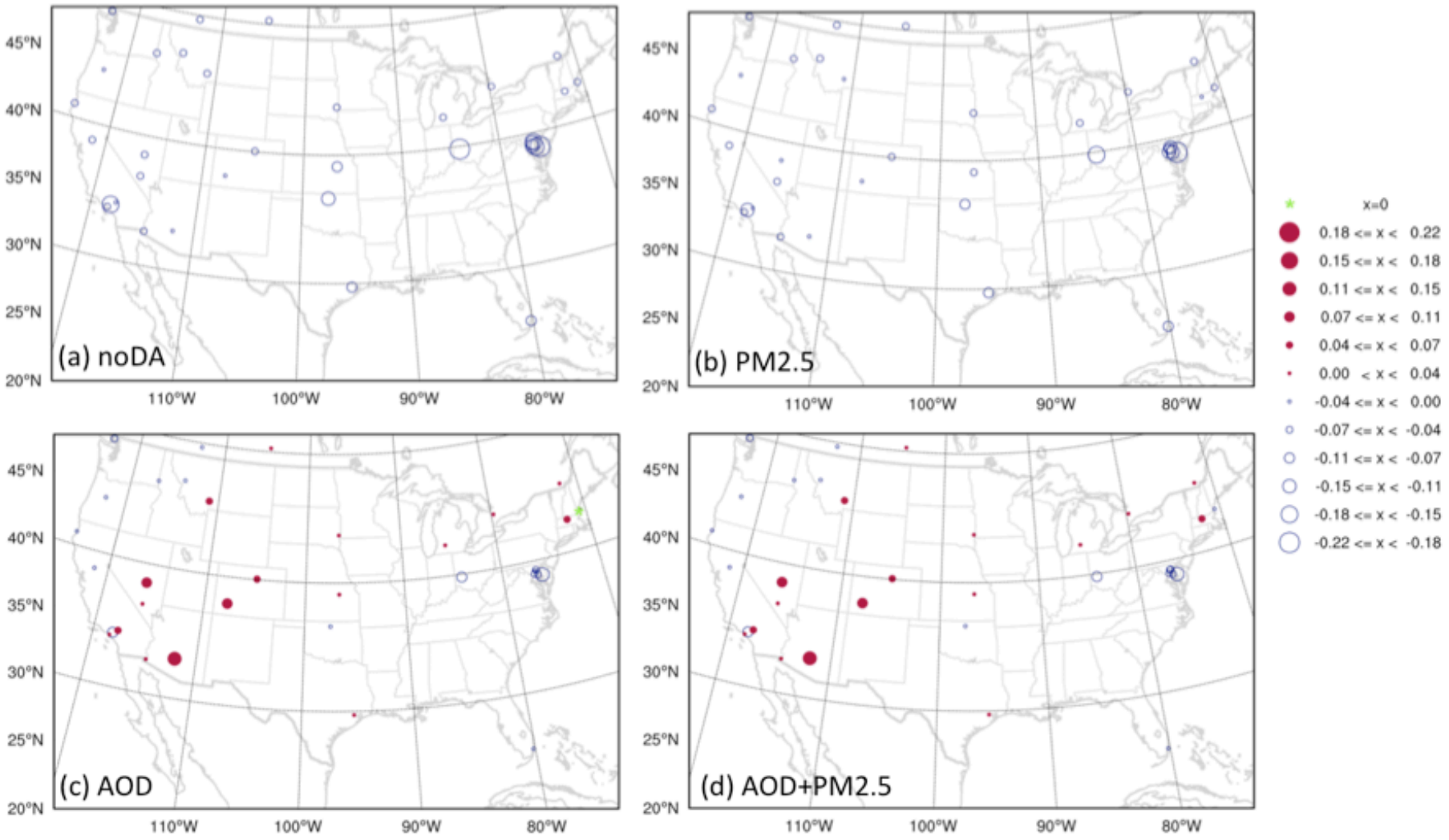
- PM2.5 obs impact quickly decreased in the first 1-hour.
- MODIS AOD is more efficient than PM2.5 data to correct low model bias.

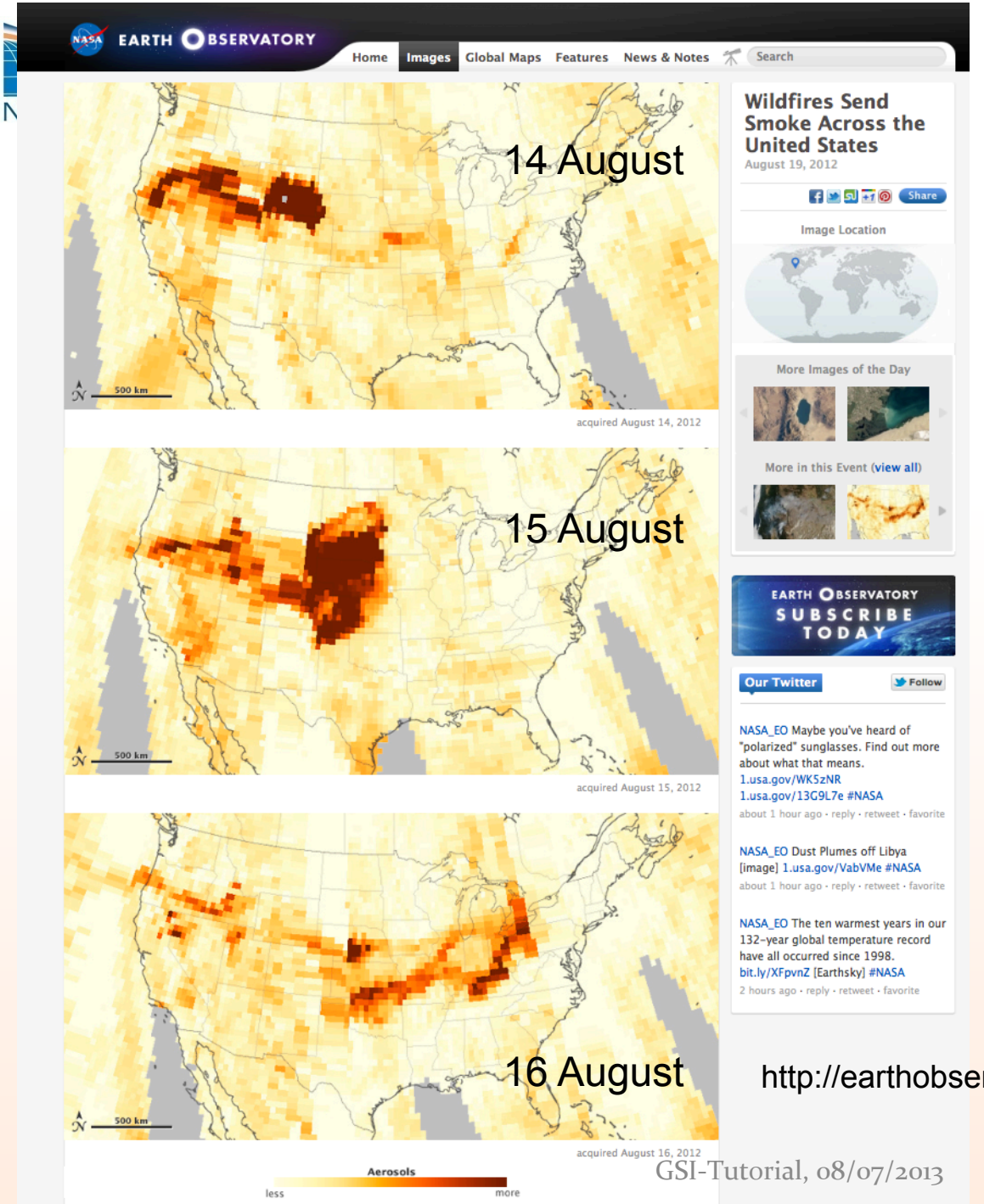




Forecast Range (hours)

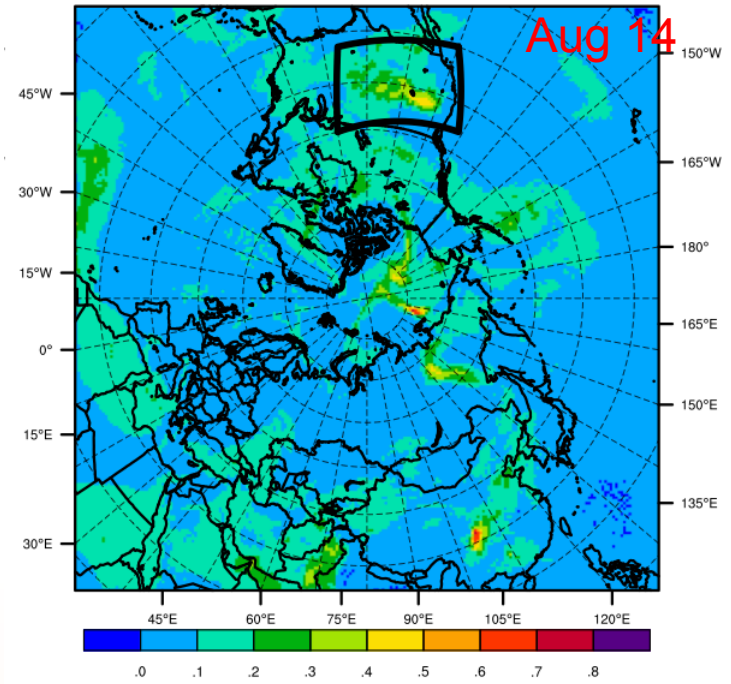
Mean AOD bias vs. AERONET

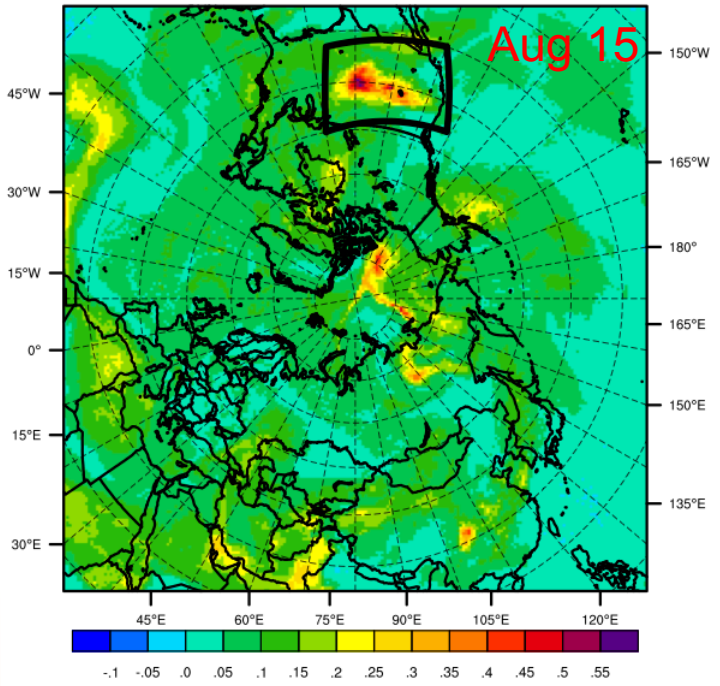


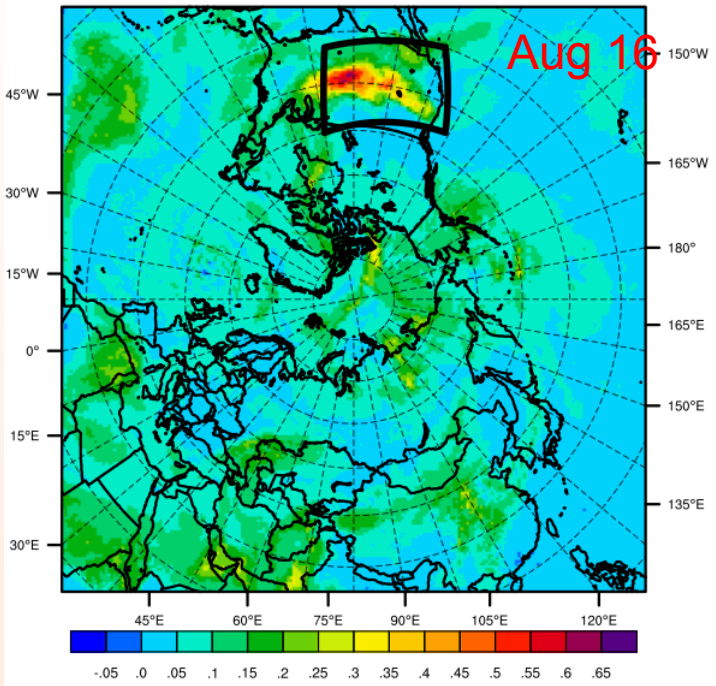


Intense wildfires in California and Idaho sent smoke eastward across the United States in mid-August 2012. Smoke affected air quality as far away as the Great Lakes Region, and some of the thickest smoke stretched from the Dakotas to Texas.

http://earthobservatory.nasa.gov/IOTD/view.php?id=78881



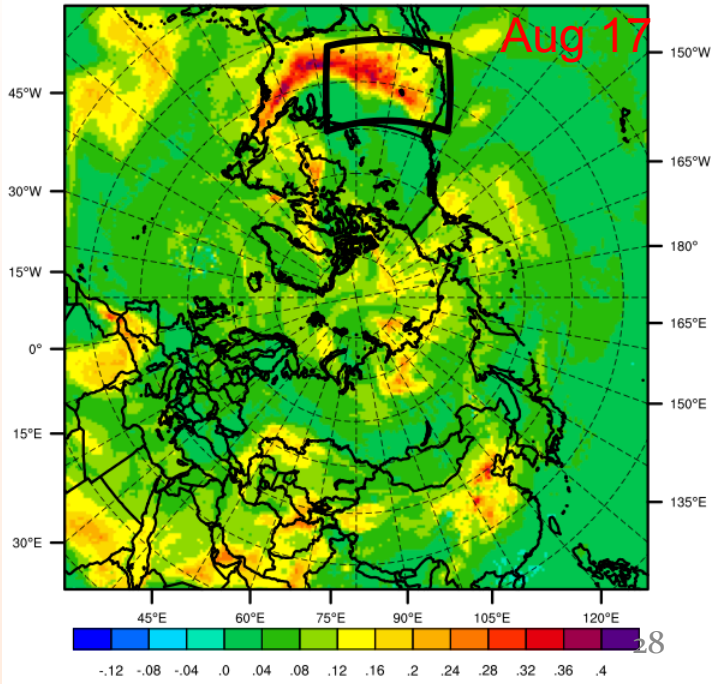




AOD difference

MetAOD_DA - MET_DA

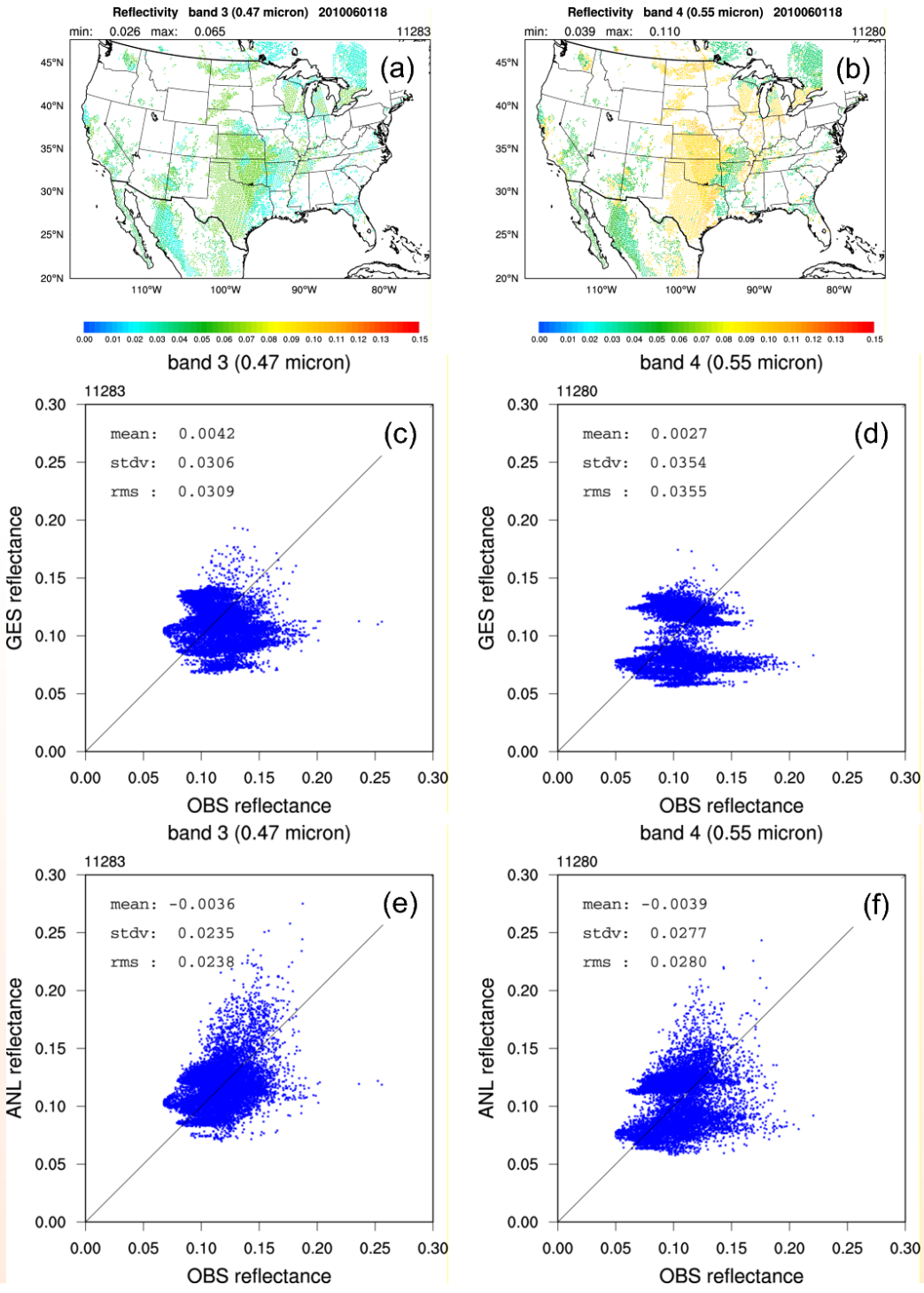
Shows the Aerosol transport by fire



Future Plan

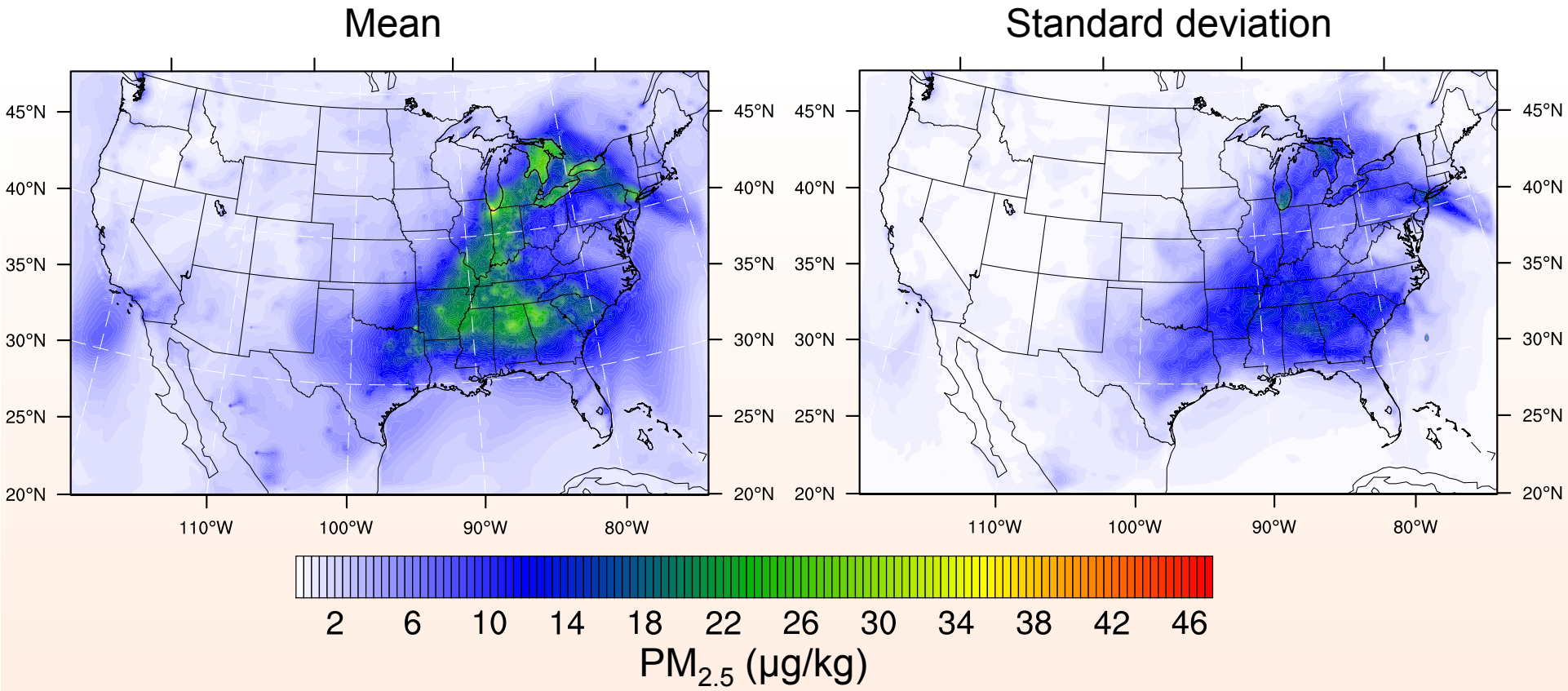
- Assimilate aerosol observations from multiple sources
  - Improve QC and observation error modeling
  - GOES, AVHRR, SeaWiFS, MISR, future GOES-R/VIIRS, CALIOP …
- Explore direct radiance DA for aerosol analysis
- Use Ensemble- and hybrid-based data assimilation techniques
- Coupled meteorological and aerosol DA

Initial work of MODIS radiance DA



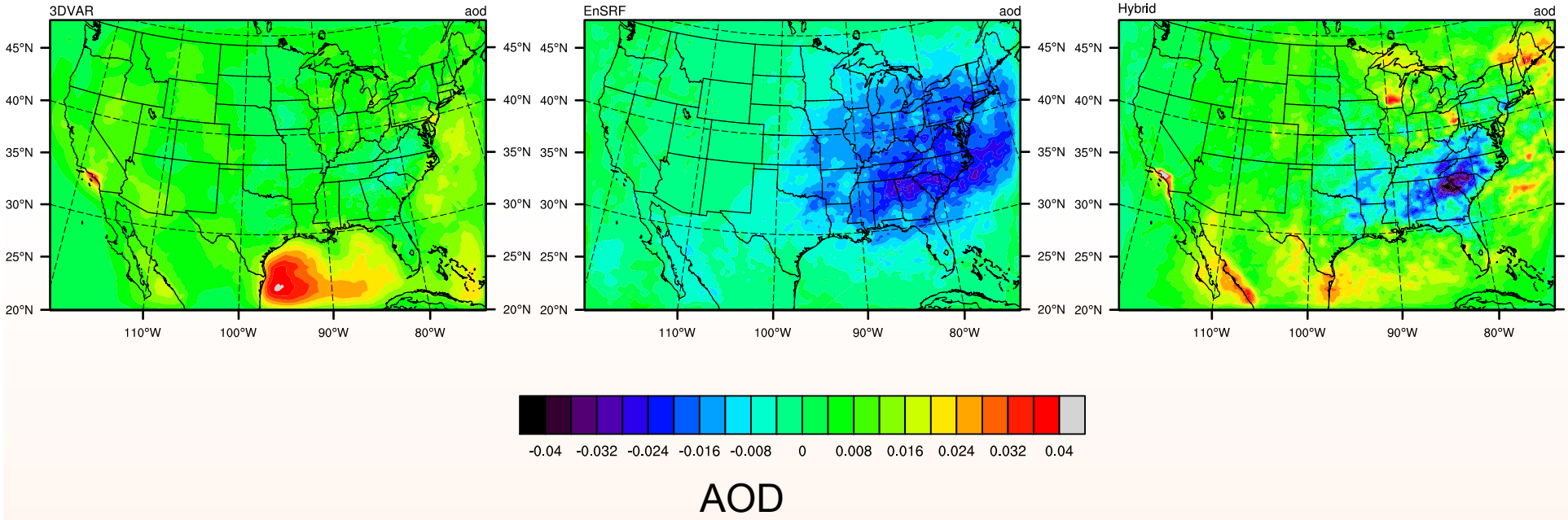
"Spun-up" $PM_{2.5}$ mean and spread (50 members)

- Ensemble mean and standard deviation after 5 days spin-up
- $PM_{2.5}$ at the lowest model level (@00UTC June 1)



Mean AOD analysis increments

- Average 1800 UTC AOD increments



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