Will ensemble approach improve surface PM2.5 estimate from space?

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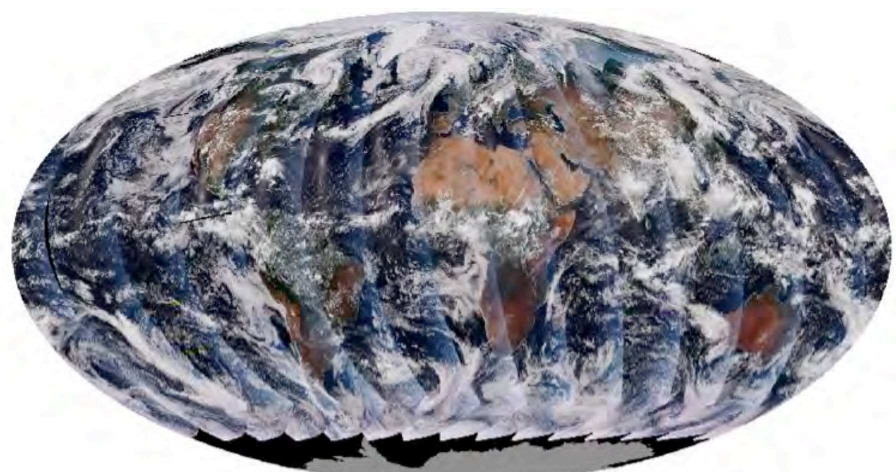
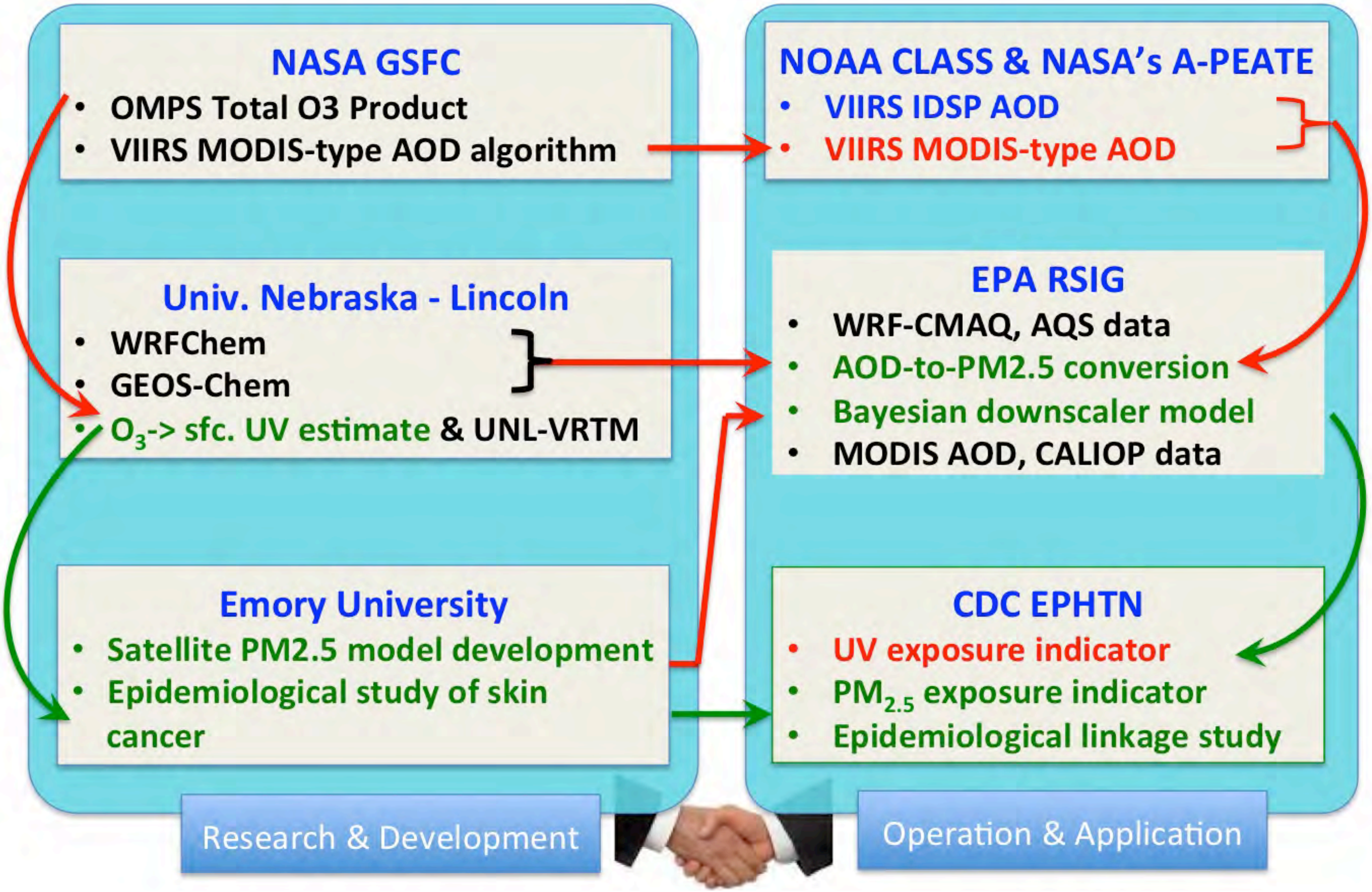


VIIRS,13:30 Local Time
14.1 revs/day

Work/Data Flow & Approaches



Black: datasets & model already in place; green: existing model capability and data flow that will be *improved*; red: the data and data flow will be created

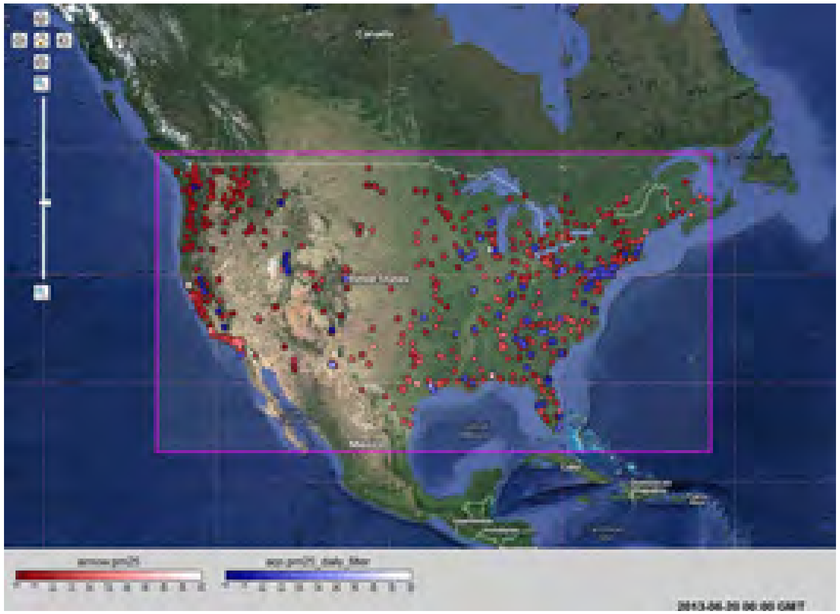
National Ambient Air Quality Standards
NAAQS as of Oct. 2011

Pollutant [final rule cite]		Primary/ Secondary	Averaging Time	Level
Carbon Monoxide [76 FR 54294, Aug 31, 2011]		primary	8-hour	9 ppm
			1-hour	35 ppm
Lead [73 FR 66964, Nov 12, 2008]		primary and secondary	Rolling 3 month average	0.15 μg/m^3 (1)
Nitrogen Dioxide [75 FR 6474, Feb 9, 2010] [61 FR 52852, Oct 8, 1996]		primary	1-hour	100 ppb
		primary and secondary	[illegible]	[illegible]b (2)
Ozone [73 FR 16436, Mar 27, 2008]		primary and secondary	8-hour	0.075 ppm (3)
Particle Pollution [71 FR 61144, Oct 17, 2006]	$PM_{2.5}$	primary and secondary	Annual	15 μg/m^3
			24-hour	35 μg/m^3
	PM_{10}	primary and secondary	24-hour	150 μg/m^3
Sulfur Dioxide [75 FR 35520, Jun 22, 2010] [38 FR 25678, Sept 14, 1973]		primary	1-hour	75 ppb (4)
		secondary	3-hour	0.5 ppm

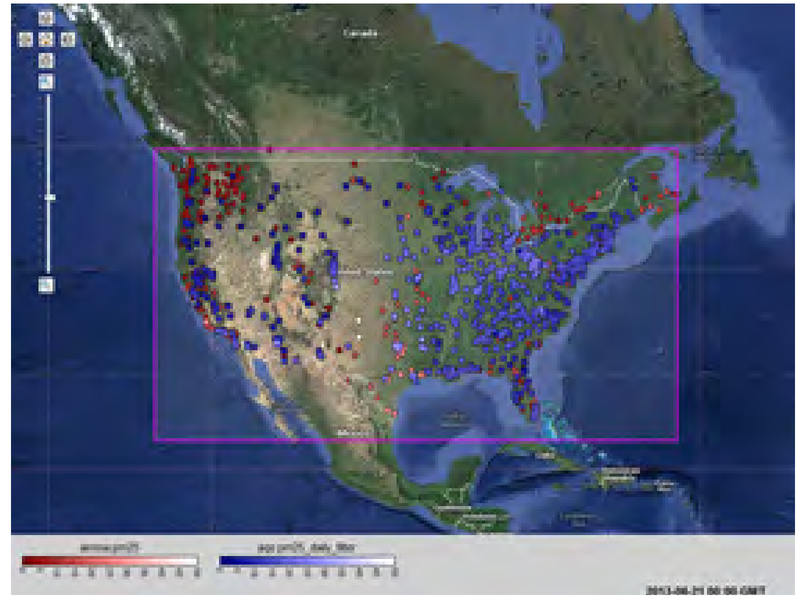
12 μg/m^3, FR, 15 Jan. 2013

Existing $PM_{2.5}$ ground monitoring in continental U.S.

20 June 2013



21 June 2013



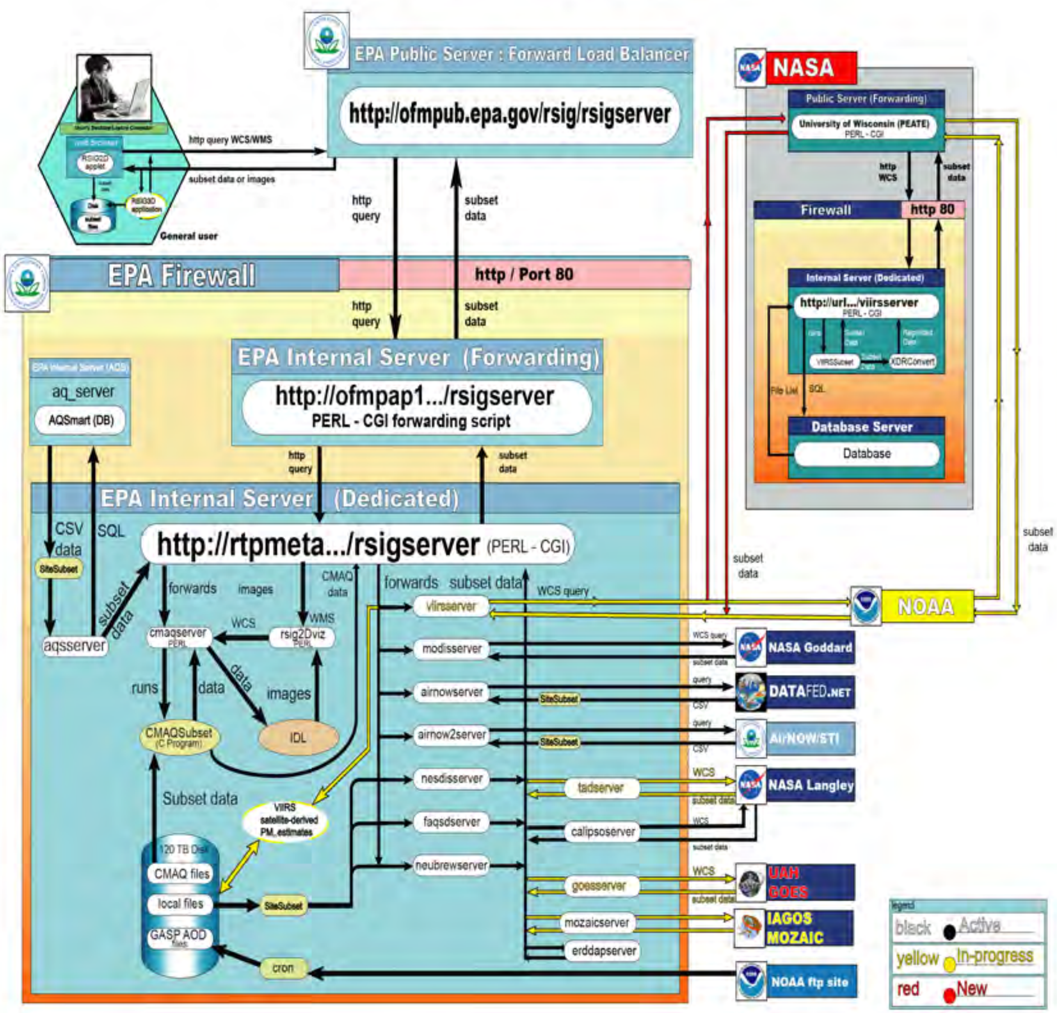
Blue: ~1000 stations using Federal Reference Method (FRM) as part of Air Quality System (AQS). Measure daily PM2.5 at daily, every 3rd or 6th day frequency.

Red: ~600 stations using a variety of techniques to provide continuous (hourly resolution) PM2.5 mass, in support of the AIRNow program.

Still, many areas remain unmonitored.

Use of EPA Remote Sensing Information Gateway to deliver VIIRS AOD/$PM_{2.5}$ data products

RSIG Data Flow Diagram



http://ofmpub.epa.gov/rsig/rsigserver?index.html

- **Current satellite WCS:**
  - ➢ **MODIS C6 (10 km, 3 km, DB)**
  - ➢ **CALIOP, GASP (GOES AOD)**
  - ➢ **Prototype NOAA-VIIRS**
- **Establish OGC compliant Web Coverage Service (WCS) between PEATE and RSIG to add NASA- VIIRS data (This project).**
- **GEOS-Chem scaling factors used to create a daily Look-Up-Table (LUT) of the spatial varying relation of AOD and $PM_{2.5}$ (van Donkelaar et. al., 2012, ES&T) .**
- **Prototype use of AOD-to-PM2.5 scaling factors via regional models (WRF-CMAQ & WRF-CHEM) and explore ensemble type approach (This project).**

SATELLITE MEASUREMENTS OF AEROSOL MASS AND TRANSPORT

Atmospheric Environment, 1984.

ROBERT S. FRASER

Laboratory for Atmospheric Sciences, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.

YORAM J. KAUFMAN

University of Maryland in collaboration with Goddard Laboratory for Atmospheric Sciences, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.

and

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Science Systems and Applications, Inc. 10210 Greenbelt Road, Seabrook, MD 20706, U.S.A.

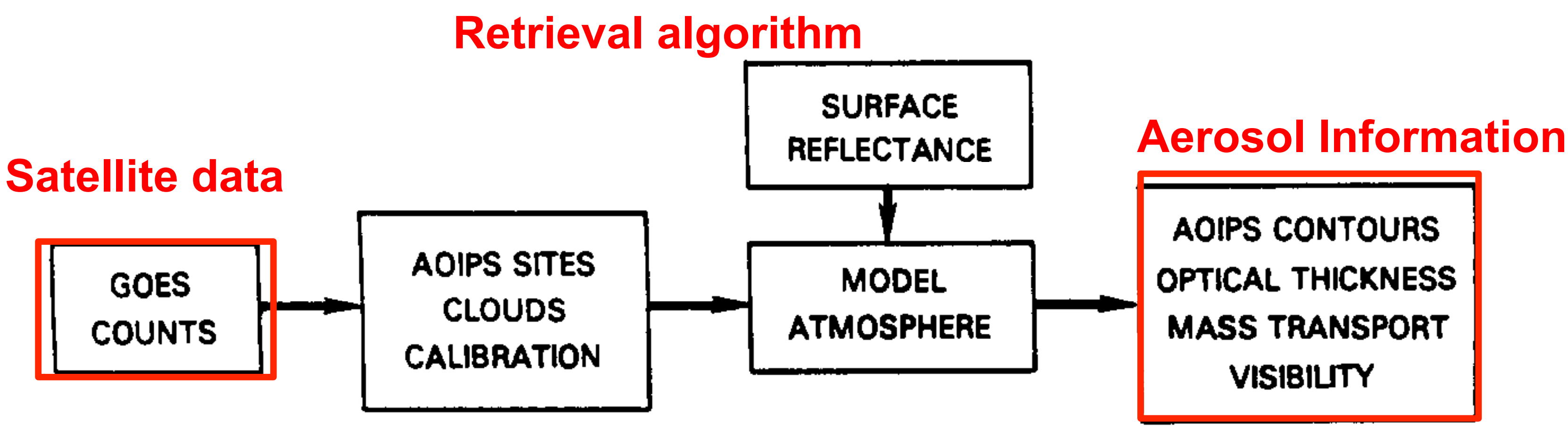
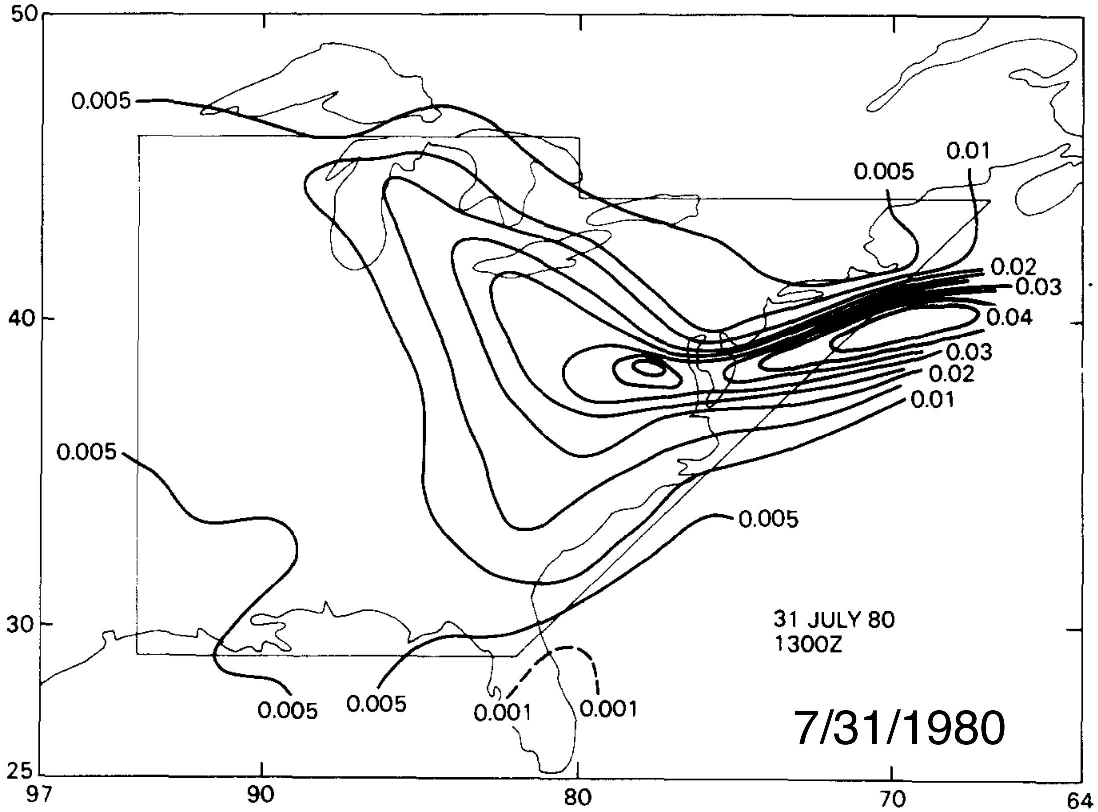


Fig. 3. Algorithm for deriving aerosol properties from satellite observations.



Atmospheric loading of particulate sulfur (gm^{-2}) on 31 July 1980.

Derived from GOES visible reflectance are

- **Aerosol optical thickness (AOT)/depth (AOD)**
- **Columnar amount of sulfur**

Table 1. Comparison of columnar masses of sulfur derived from ground-based and satellite observations. The satellite observations were made at 1300 GMT on 31 July 1980

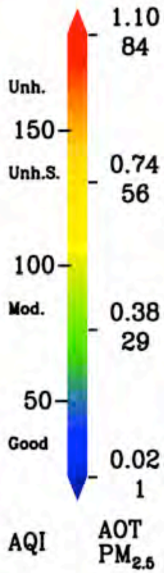
1 Place	2 Latitude (deg. N)	3 Longitude (deg. W)	4 Particulate sulfate mass ($\mu g\ m^{-3}$)	5 Columnar sulfur mass ($g\ m^{-2}$)	6 Reference	7 Satellite sulfur mass ($g\ m^{-2}$)	8 Ratio columns 7 and 5
Virginia	38.7	78.3	38	0.018	Ferman *et al.* (1981)	0.040	2.3
Virginia	38.7	78.3	38	0.018	Stevens *et al.* (1984)	0.040	2.3
Near Baltimore	39.3	76.4	24	0.014	Tichler *et al.* (1981)	0.017	1.2

NASA Earth Observation System

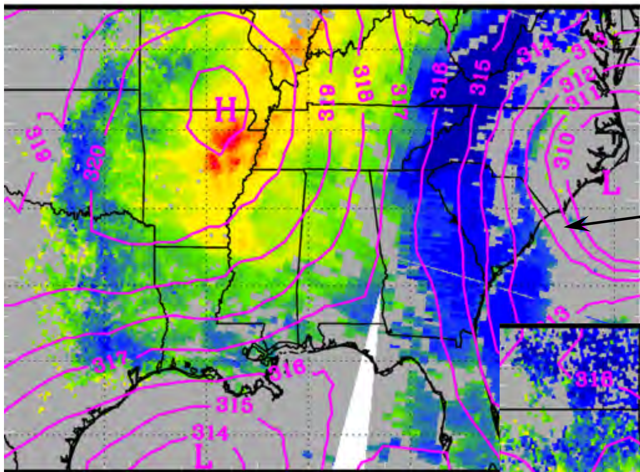
18 Dec. 1999

Updated Jan. 2015

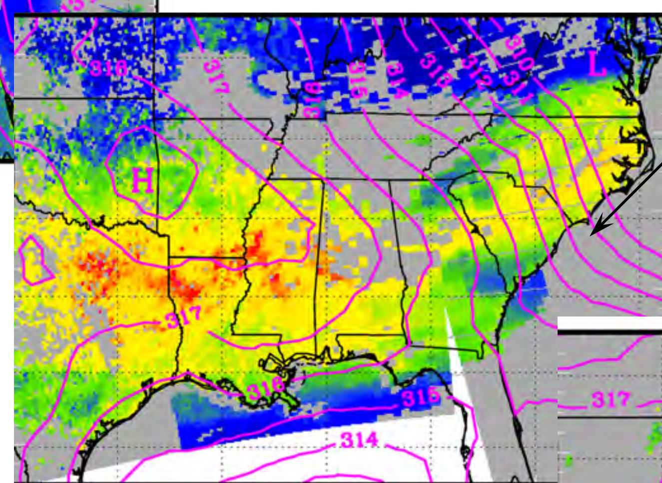
Satellite Remote Sensing of Aerosol Transport



09/10/02



09/11/02



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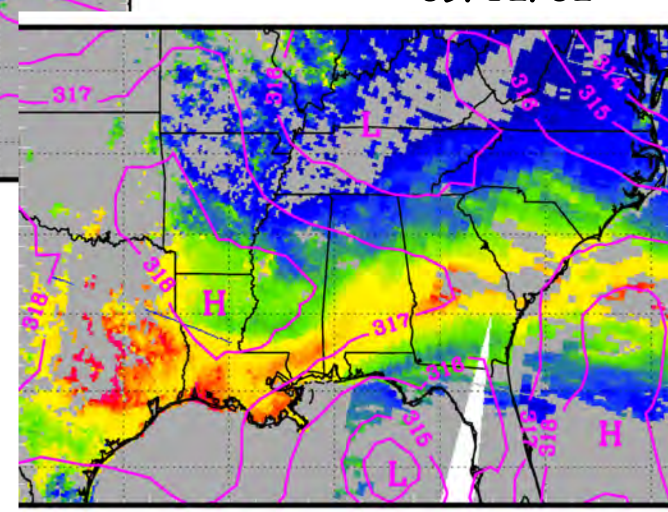


MODIS Aerosol Optical Thickness & 700mb Geopotential Height

PM2.5 = A*AOD + B

Wang & Christopher, 2003;

Past studies on AOD vs. surface PM concentration

(from Hoff and Christopher, 2009, JAWMA)

2003

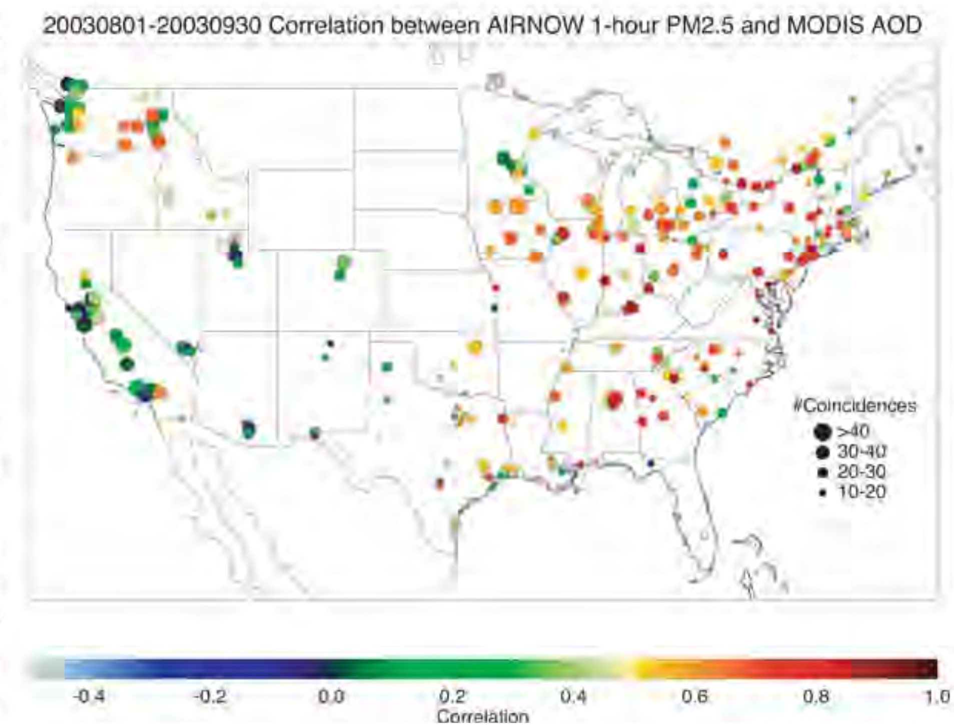
Author	Sensor	Date	Region	Number of Ground Monitors	$PM_{2.5}/PM_{10}$	Linear Regression	R
Wang[154]	MODIS (Terra)	2002	Alabama	7	$PM_{2.5}$ (24 hr)[a]	$77.0\tau - 0.23$	0.67
	MODIS (Aqua)	2002	Alabama	7	$PM_{2.5}$ (24 hr)[a]	$68.6\tau + 1.93$	0.76
	Average	2002	Alabama	7	$PM_{2.5}$ (24 hr)[a]	$72.3\tau + 0.85$	0.98
Chu[153]	MODIS	August–October 2000	Italy	1	PM_{10}	$54.7\tau + 8.0$	0.82
Engel-Cox[161]	MODIS	April–September 2002	United States	1338	$PM_{2.5}$	$22.6\tau + 6.4$	0.4
					$PM_{2.5}$ (24 hr)	$18.7\tau + 7.5$	0.43
Liu[208]	MISR	2003	St. Louis	22	$PM_{2.5}$	NA	0.8
Engel-Cox[163]	MODIS	July 1 to August 30, 2004	Baltimore	4	$PM_{2.5}$	$31.1\tau + 5.2$	0.65
					$PM_{2.5}$ (<PBL)	$48.5\tau + 6.2$	0.65
					$PM_{2.5}$ (24 hr)	$25.3\tau + 11.1$	0.57
					$PM_{2.5}$ (24 hr < PBL)	$64.8\tau + 1.76$	0.76
Liu[169]	MISR	2001	Eastern United States	346	$PM_{2.5}$		–
Al-Saadi[164]	MODIS	Review	United States		$PM_{2.5}$	62.0τ	NA
Gupta[171]	MODIS	2002 and July–November 2003	Global cities	26	PM_{10}[a]	$141.0\ \tau$	0.96
Koelemeijer[152]	MODIS	2003	Europe	88 ($PM_{2.5}$)	$PM_{2.5}$[a]	NA	0.63
					PM_{10}[a]	$214.0\tau - 42.3$	0.58
Kacenelenbogen[118]	POLDER	April–October 2003	France	28	$PM_{2.5}$	$26.6\tau + 13.2$	0.7
Gupta[173]	MODIS	February 2000 to December 2005	Southeastern United States	38	$PM_{2.5}$	$29.4\tau + 8.8$	0.62
					$PM_{2.5}$ (24 hr)	$27.5\tau + 15.8$	0.52
Hutchison[158]	MODIS	August–November 2003 and 2004	Texas	28	$PM_{2.5}$ (August)[a]	$68.8\tau - 39.9$	0.47
					$PM_{2.5}$ (September)[a]	$59.7\tau - 17.2$	0.98
Paciorek[177]	GOES-12	2004	United States	Not given	$PM_{2.5}$ (24 hr)	NA	0.5
					$PM_{2.5}$ (yearly)	NA	0.75
An[179]	MODIS	April 3–7, 2005	Beijing	6	PM_{10}[a]	$21.7\tau + 6.1$	0.92
					$PM_{2.5}$[a]	$31.1\tau + 5.1$	0.92
					$PM_{2.5}$	$120\tau + 5.1$	0.72

2009

multivariate regression, Kriging, neutral network, etc…

AOD vs. surface PM is non-linear

~200 sites over continental U.S.



PM vs AOT linear correlation coefficient

$$\tau = f(rh) \times Q_{dext}(0) \times m_{daer}(0) \times H_{eff} \quad (1)$$

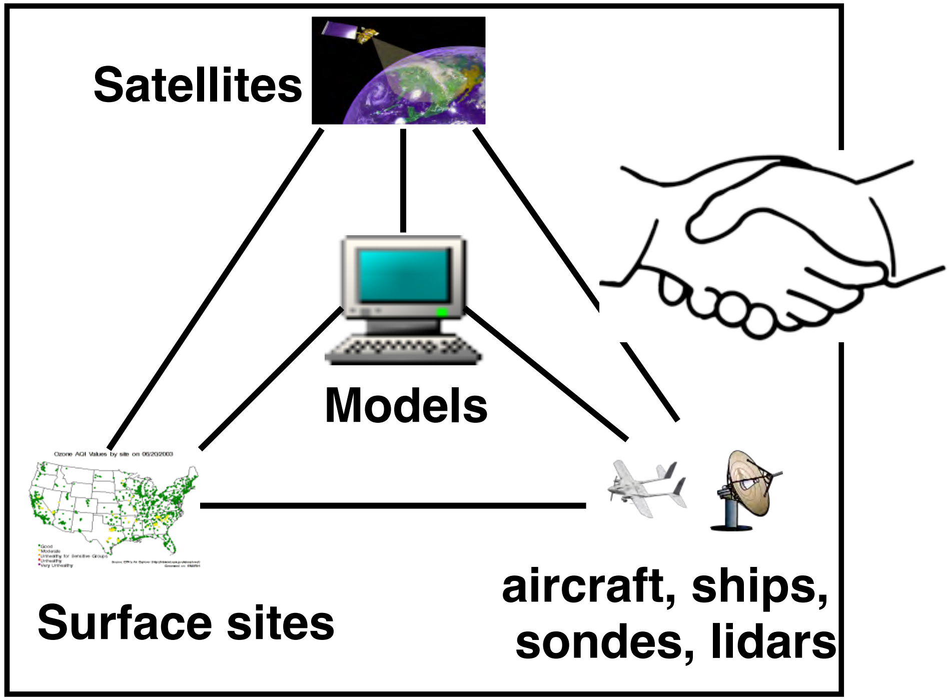
$$H_{eff} = \int_0^{TOA} \beta_{ext}(z)\, dz \Big/ \beta_{ext}(0) \quad (2)$$

CTM has been used to provide ancillary information needed to derive surface $PM_{2.5}$ from AOD.
(Liu et al., 2004; Wang et al., 2010; van Donkelaar et al., 2010).

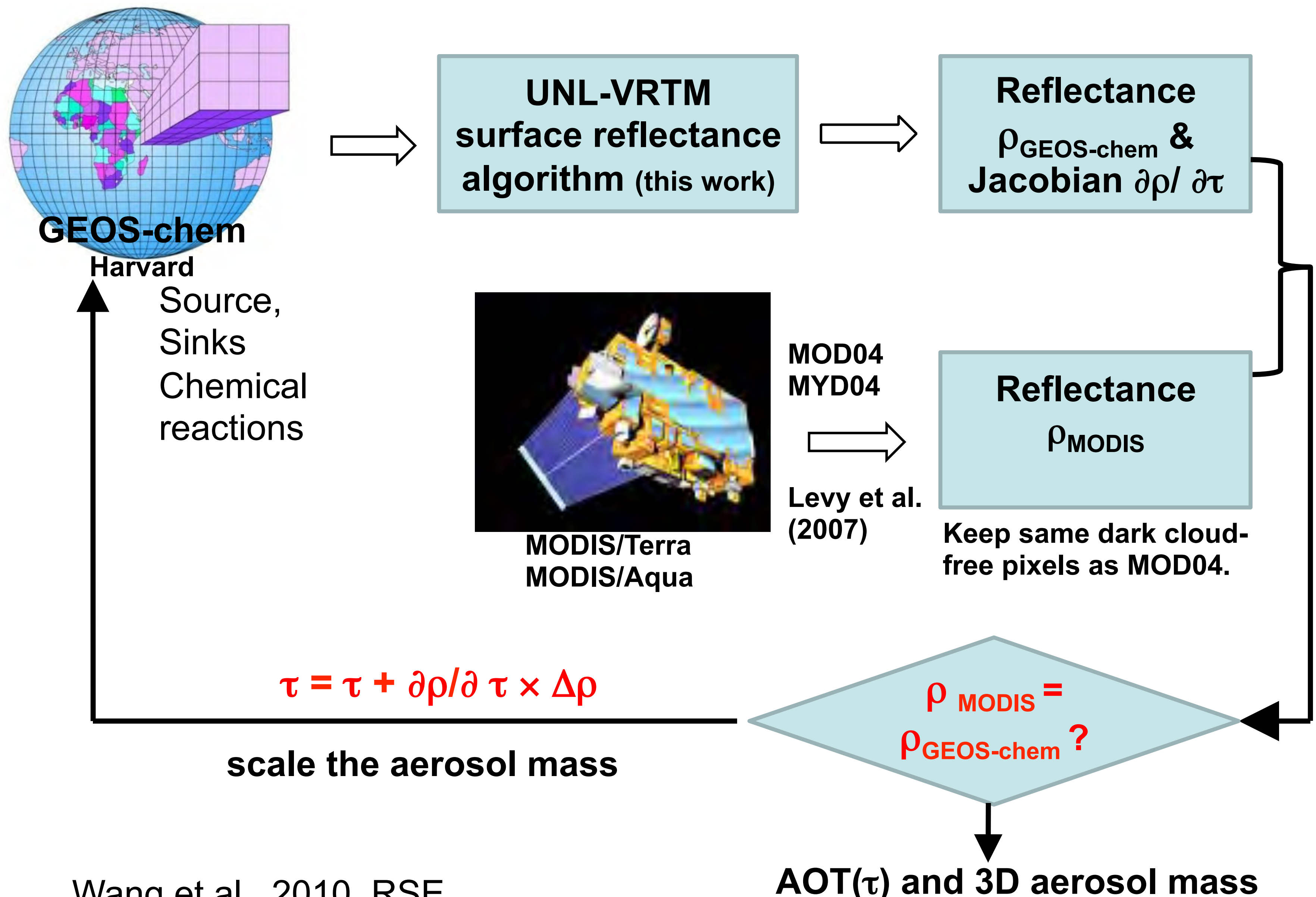
Engel-Cox et al., 2004, JAWMA.

Challenges & Strategies

- **Challenges:**
  - Vertical distribution, particle size distribution, aerosol composition, sampling bias
  - Cloudy conditions
- **Strategies:**
  - Ensemble modeling using WRF-Chem, WRF-CMAQ, and GEOS-Chem
  - Spatial & statistical modeling



Direct Use of Reflectance to constrain CTM Model

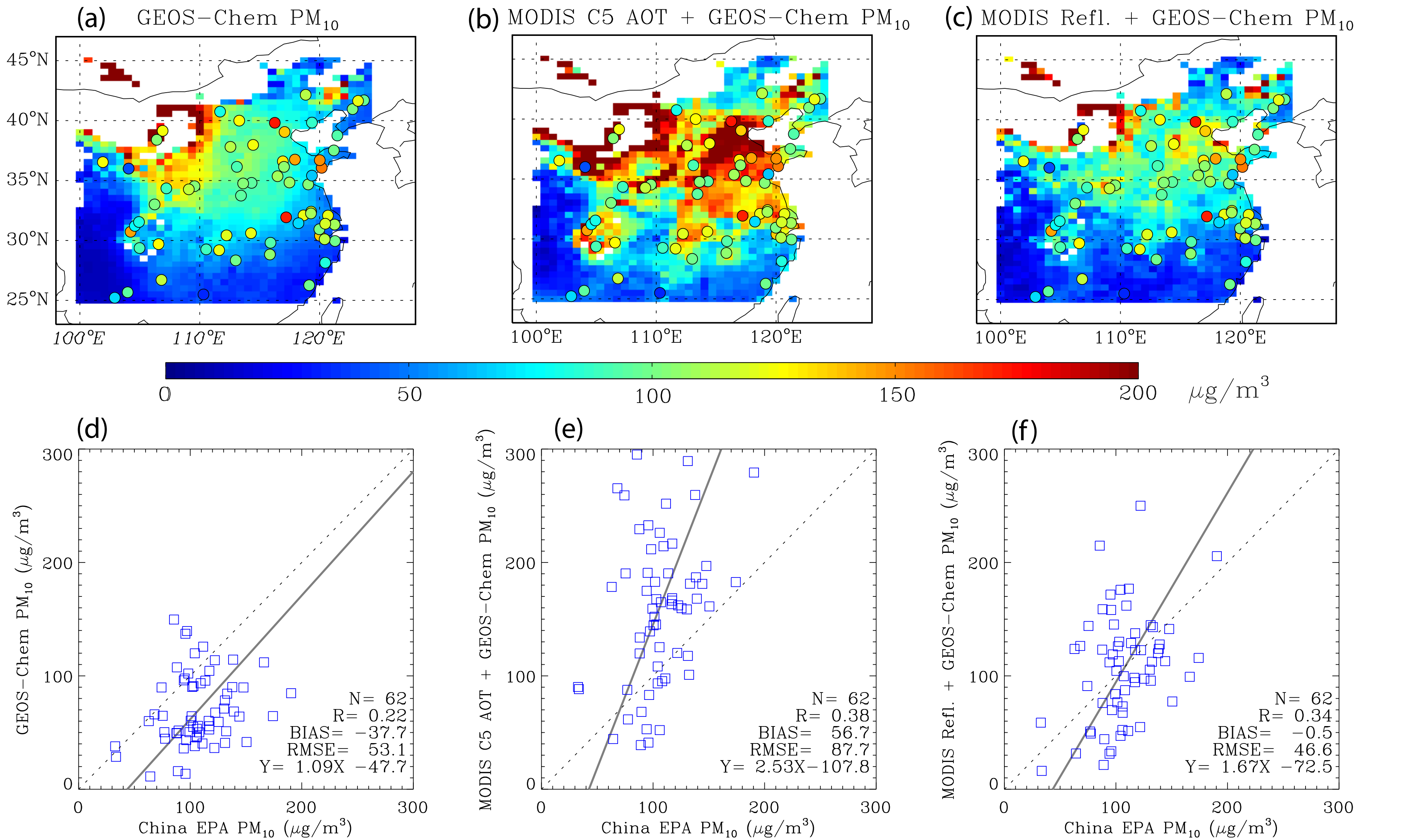


Wang et al., 2010, RSE.

Results for April 2008 over China

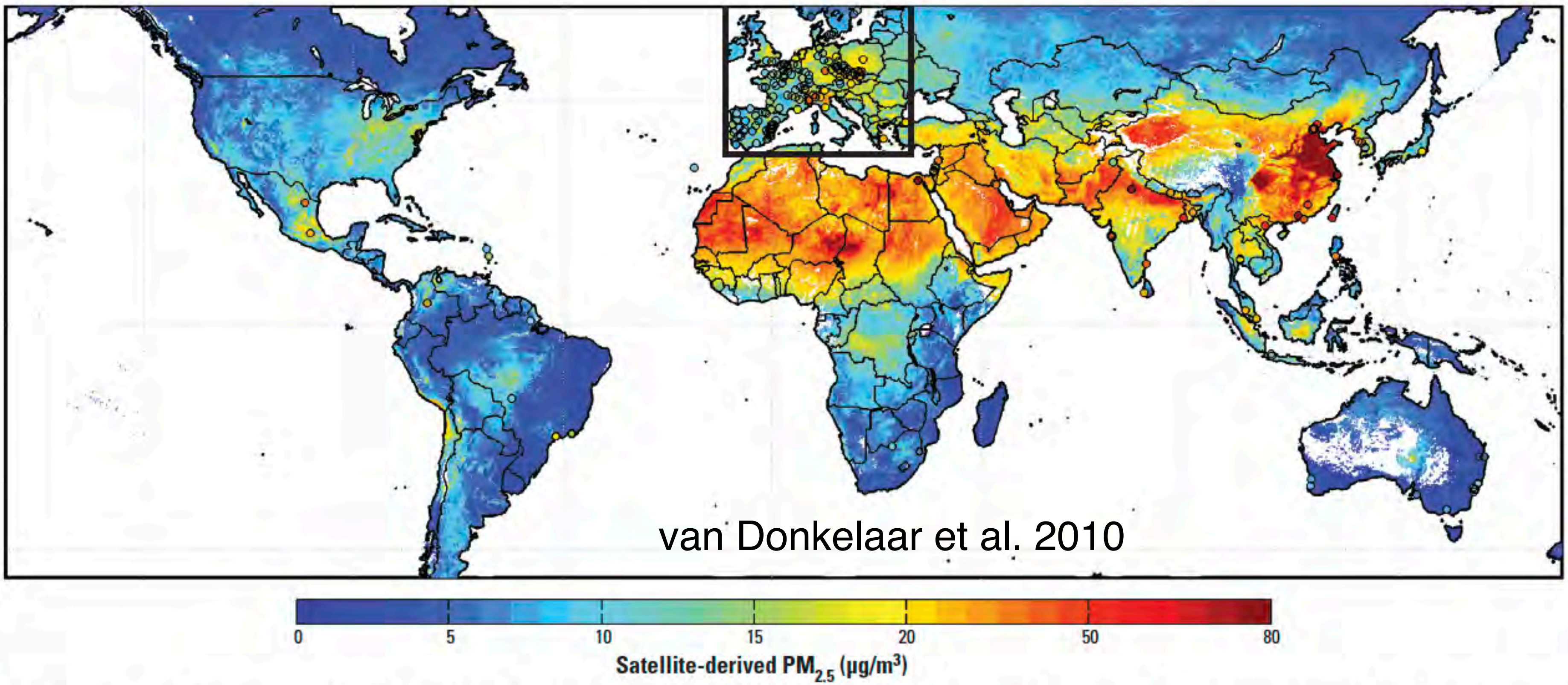
Wang et al., 2010

Model only | **Model + MODIS product** | **This work Model + MODIS Ref.**



Surface $PM_{2.5}$ climatology

$PM_{2.5}$ averaged during 1/1/2001 – 12/31/2006, 10x10 km^2
MODIS & MISR AOD + a CTM (GEOS-Chem)



An ensemble approach
multiple AOD products + multiple models

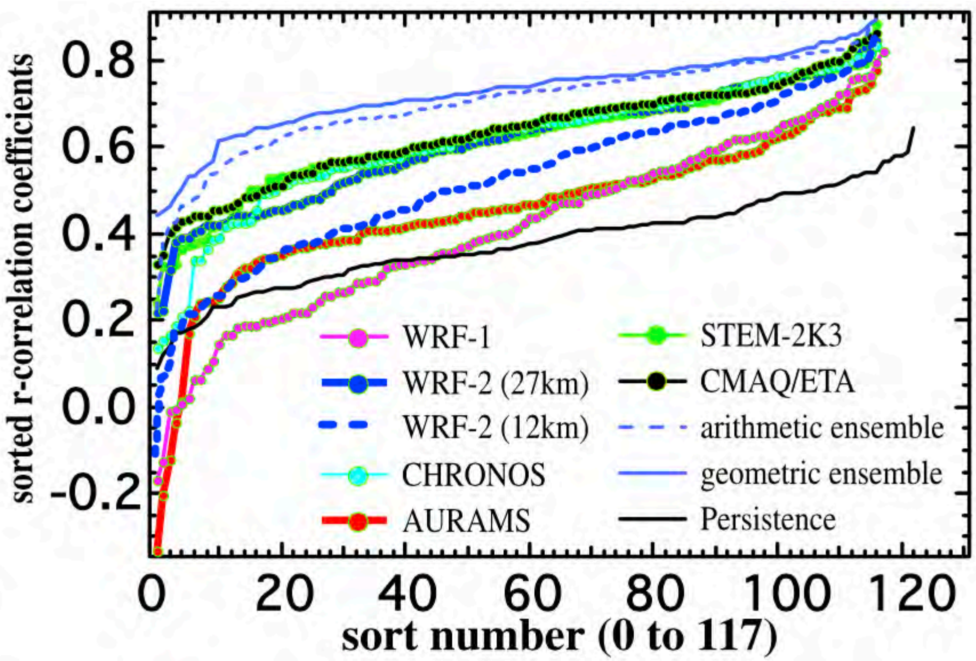
- **Hypothesis:**
  - **each satellite AOD product has its unique strengths and weaknesses, and a combination of them can yield a better AOD product than any individual product**
- **Questions:**
  - **if the climatology of $PM_{2.5}$-AOD ratio can be better represented by the ensemble mean of multi-models (instead of one model, GEOS-Chem, that is currently used);**
  - **if the combination of AOD from different sensors and algorithms together with $PM_{2.5}$-AOD ratio from (a) can yield the best estimate of $PM_{2.5}$ than from each individual source of AOD, and**
  - **the cost-and-benefits of using hindcast to estimate surface $PM_{2.5}$ from AOD.**

Evaluation of several $PM_{2.5}$ forecast models using data collected during the ICARTT/NEAQS 2004 field study

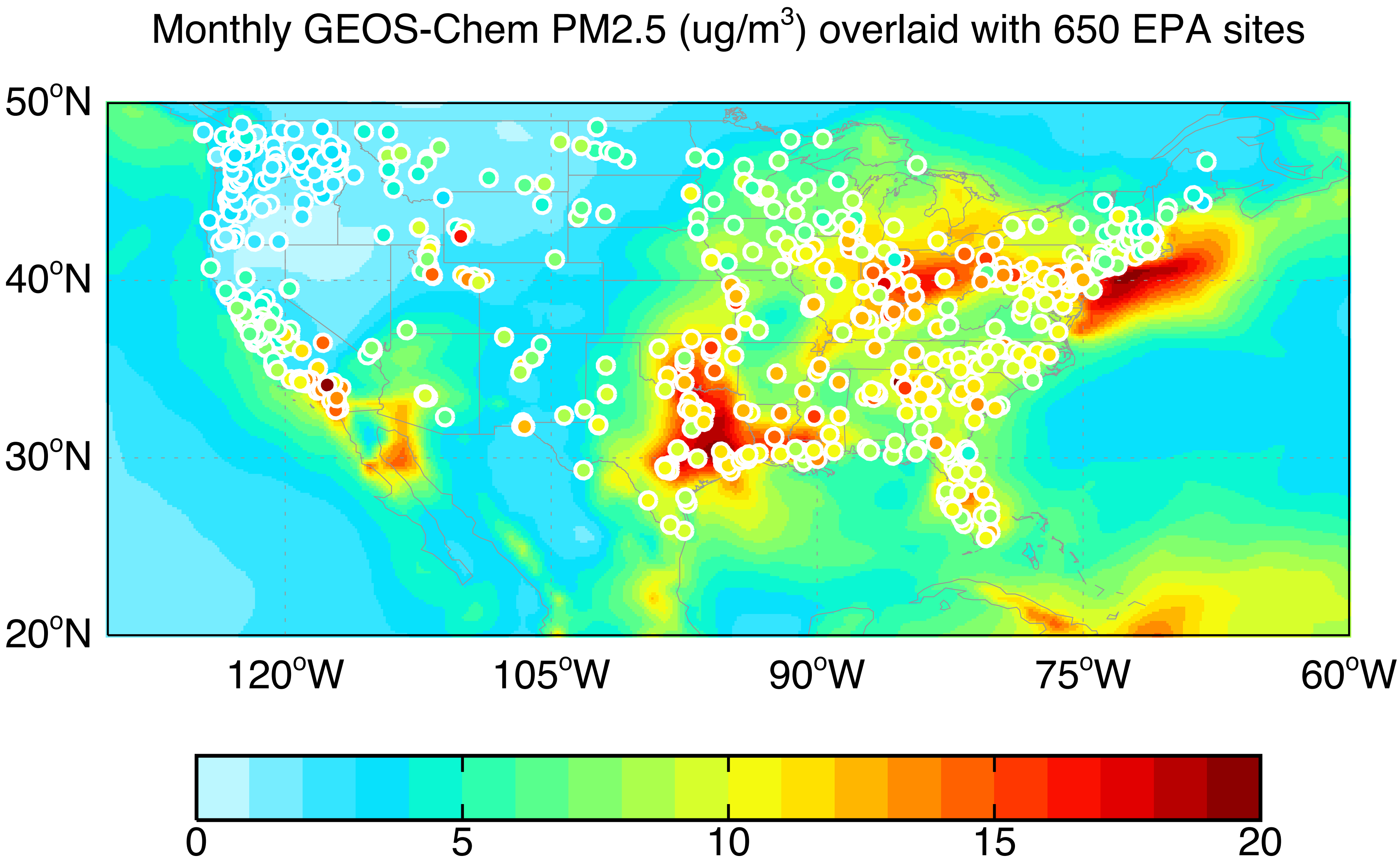
S. McKeen,[1,2] S. H. Chung,[1,2] J. Wilczak,[3] G. Grell,[2,4] I. Djalalova,[2,3] S. Peckham,[2,4] W. Gong,[5] V. Bouchet,[6] R. Moffet,[6] Y. Tang,[7] G. R. Carmichael,[7] R. Mathur,[8,9] and S. Yu[9,10]

JGR, 2007.

The ensemble $PM_{2.5}$ forecast, created by combining six separate forecasts with equal weighting, is also evaluated and shown to yield the best possible forecast in terms of the statistical measures considered.

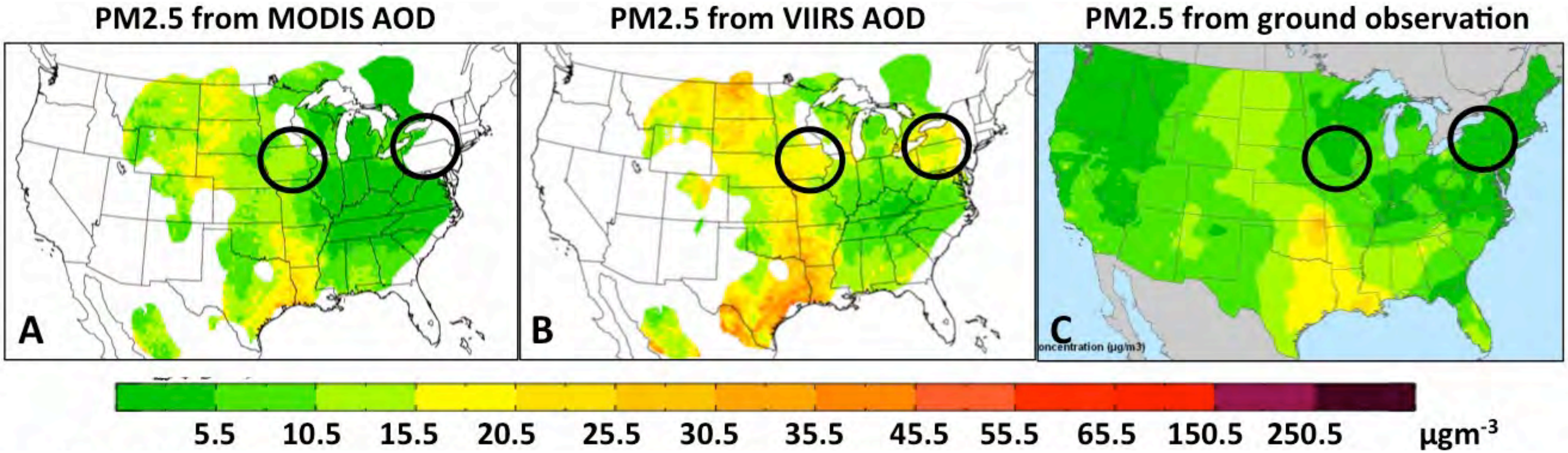


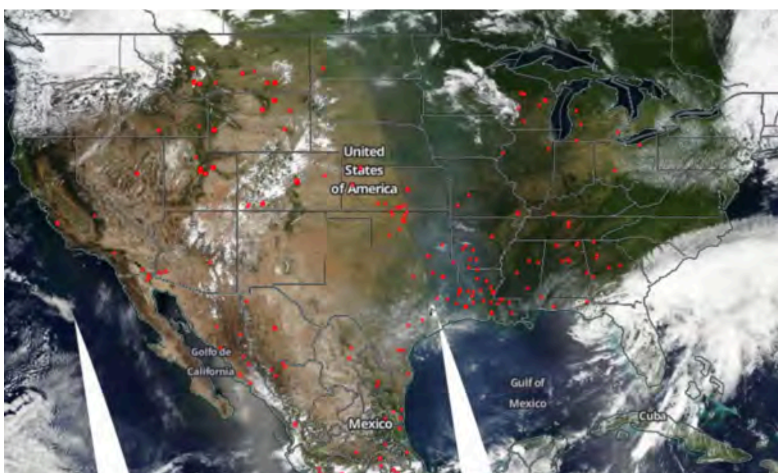
Focusing on June 2012

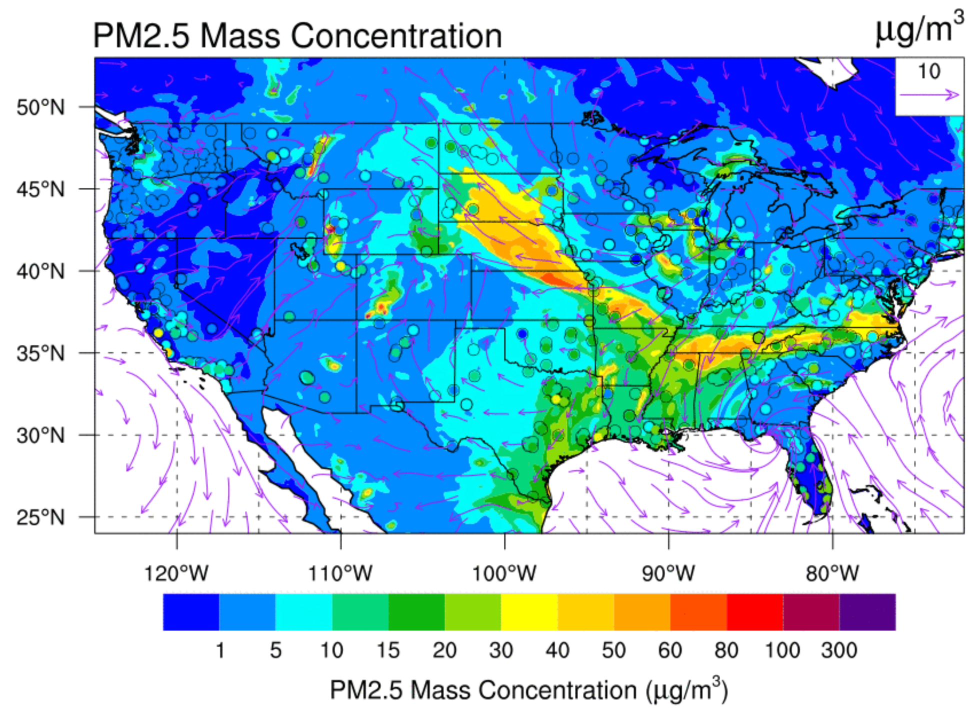


6/26/2012

A case study

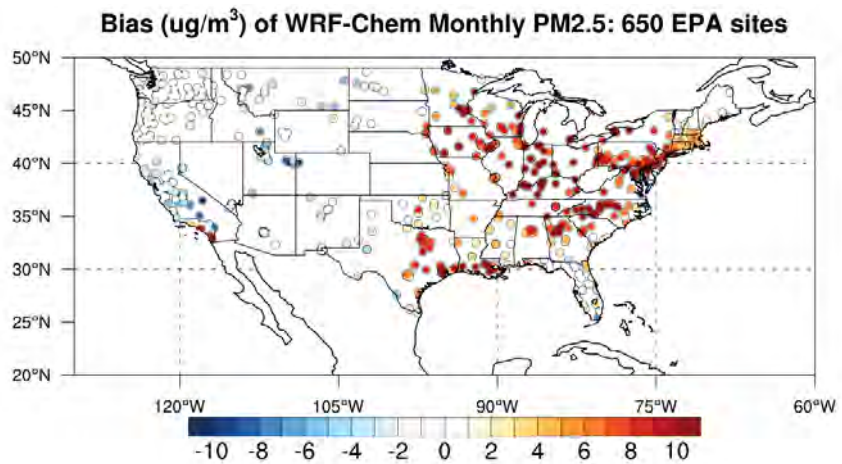


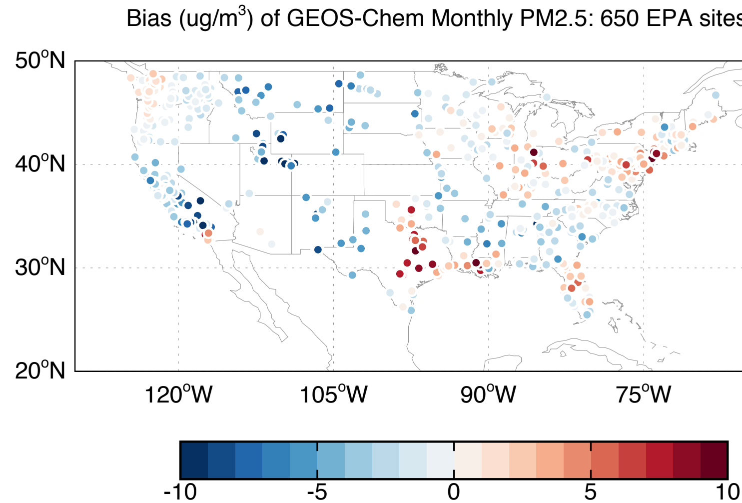




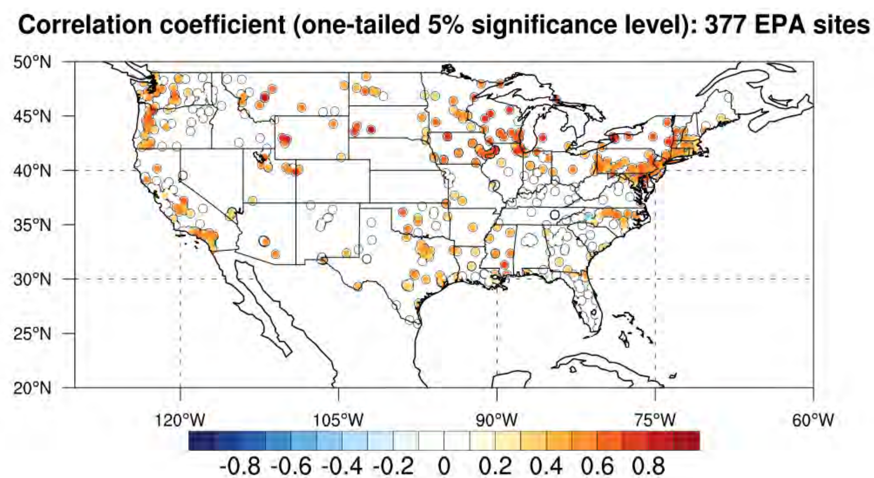
WRF-Chem

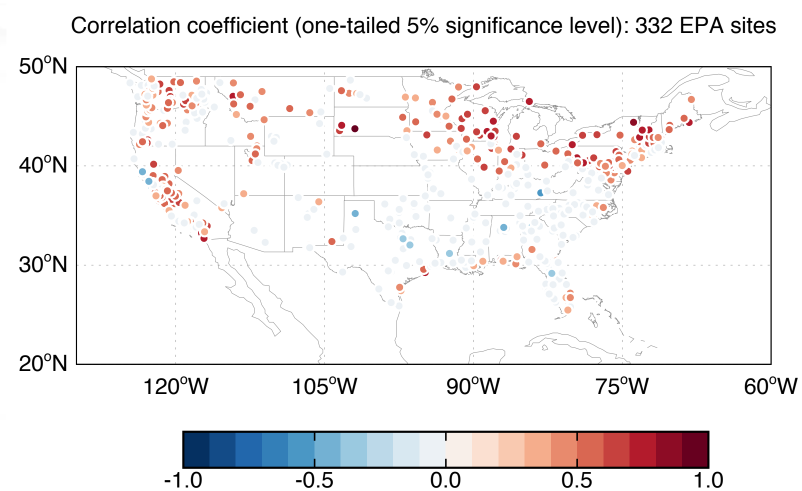
GEOS-Chem





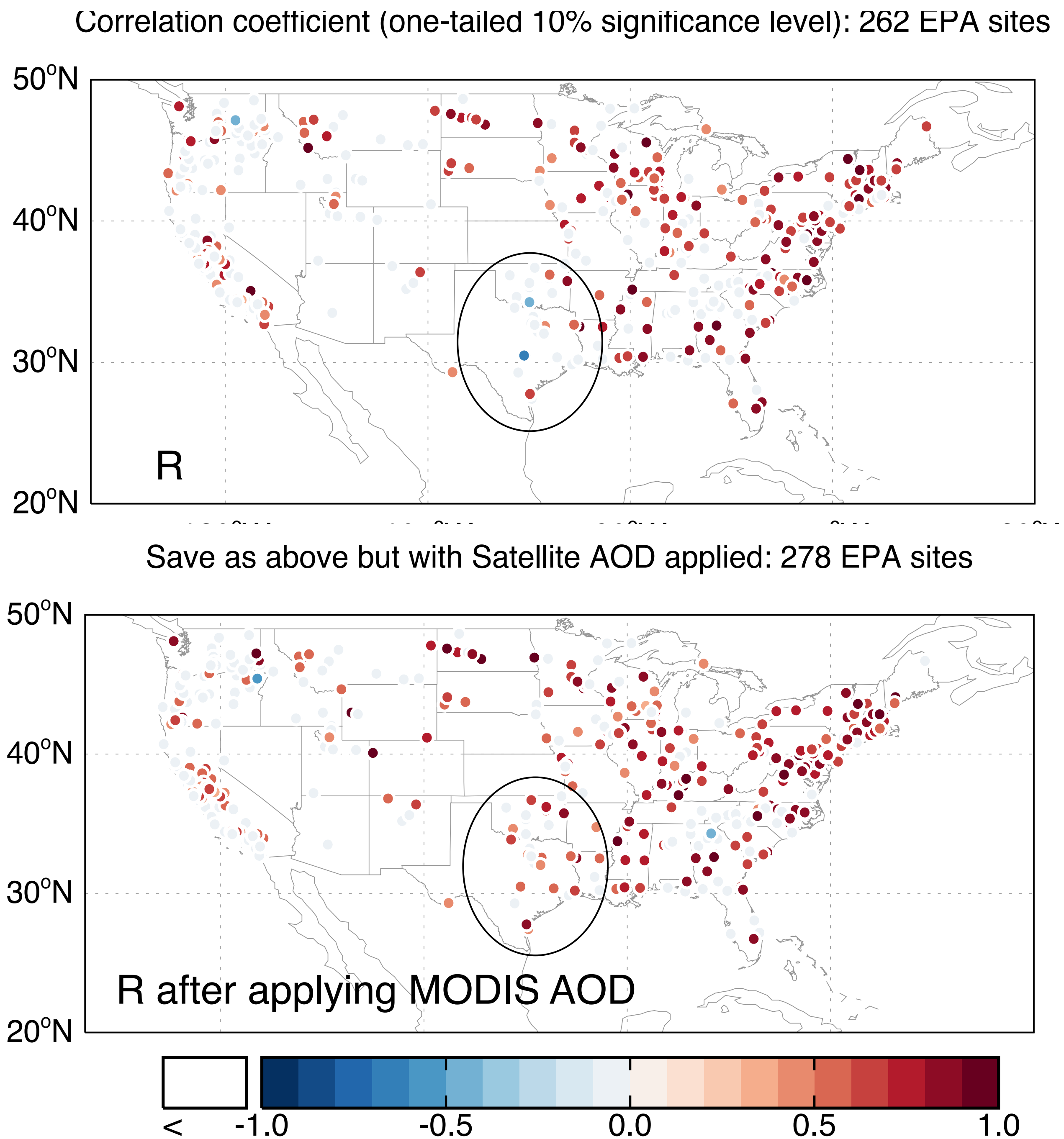
bias



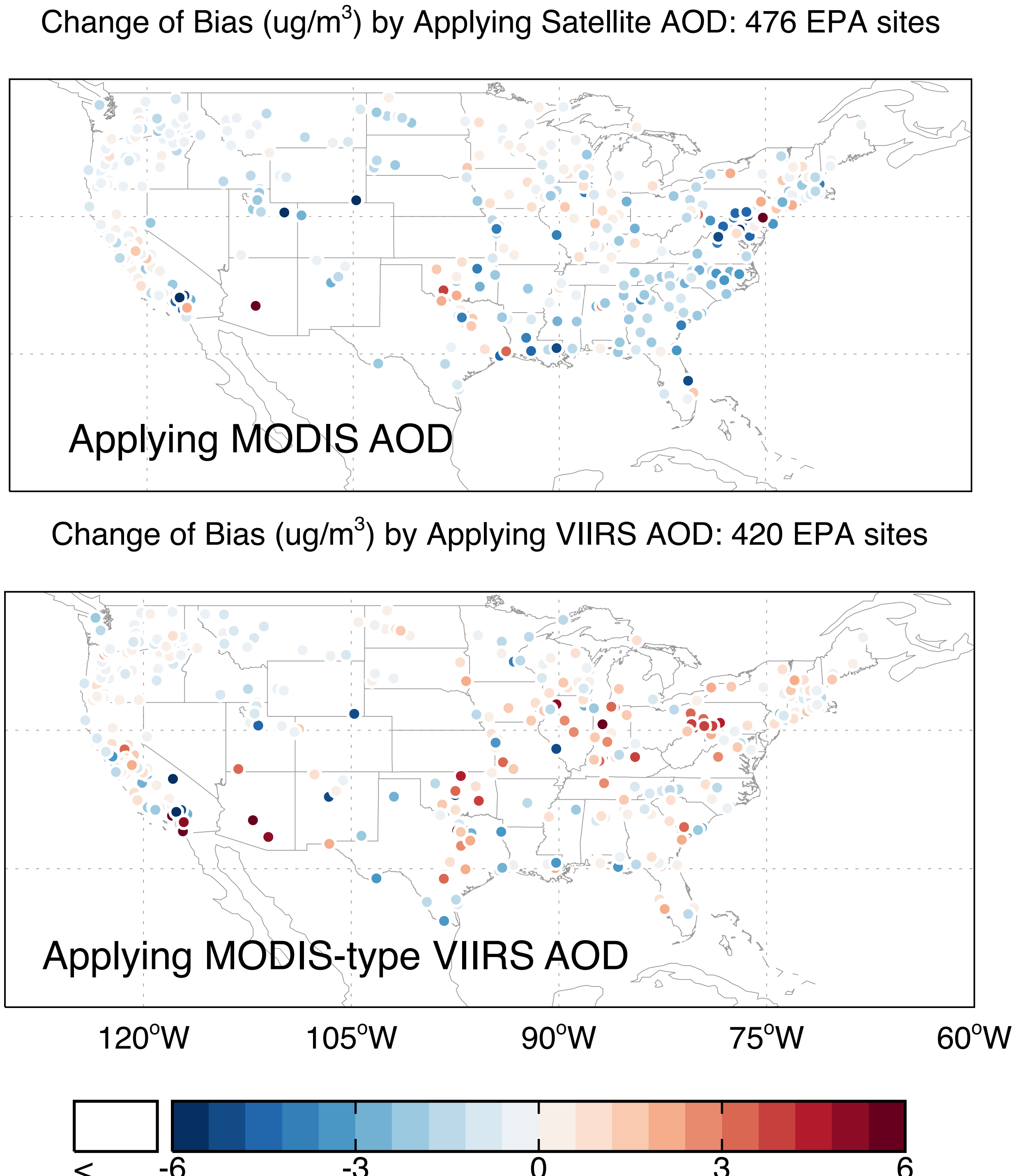


R

It appears that WRF-Chem does a better job in simulating surface PM2.5 over Texas, albeit its large positive bias over eastern part of U.S.



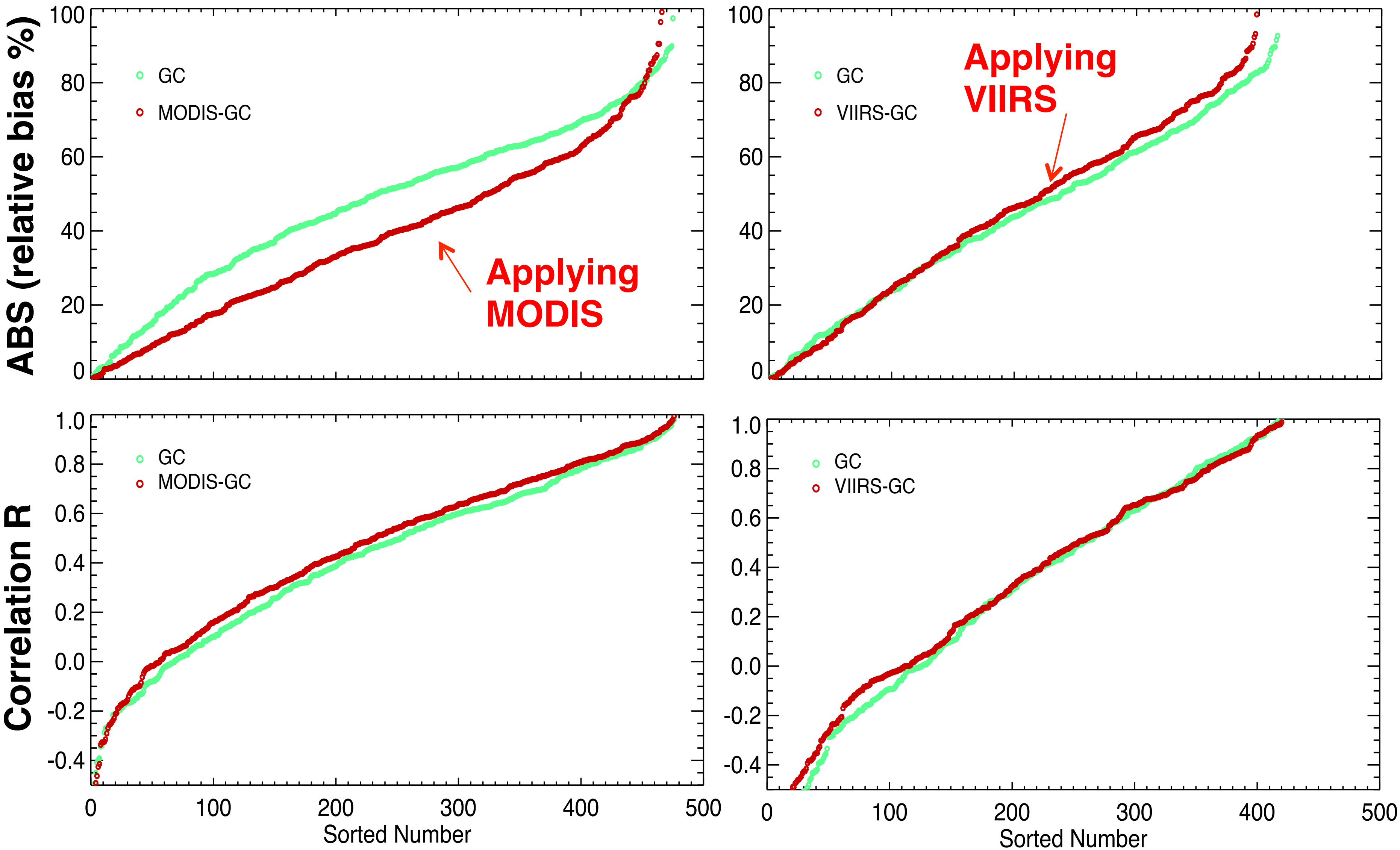
Correlation coefficient (one-tailed 10% significance level): 262 EPA sites
50°N
40°N
30°N
20°N
R
Save as above but with Satellite AOD applied: 278 EPA sites
50°N
40°N
30°N
20°N
R after applying MODIS AOD
< -1.0
-0.5
0.0
0.5
1.0



|b2| - |b1|

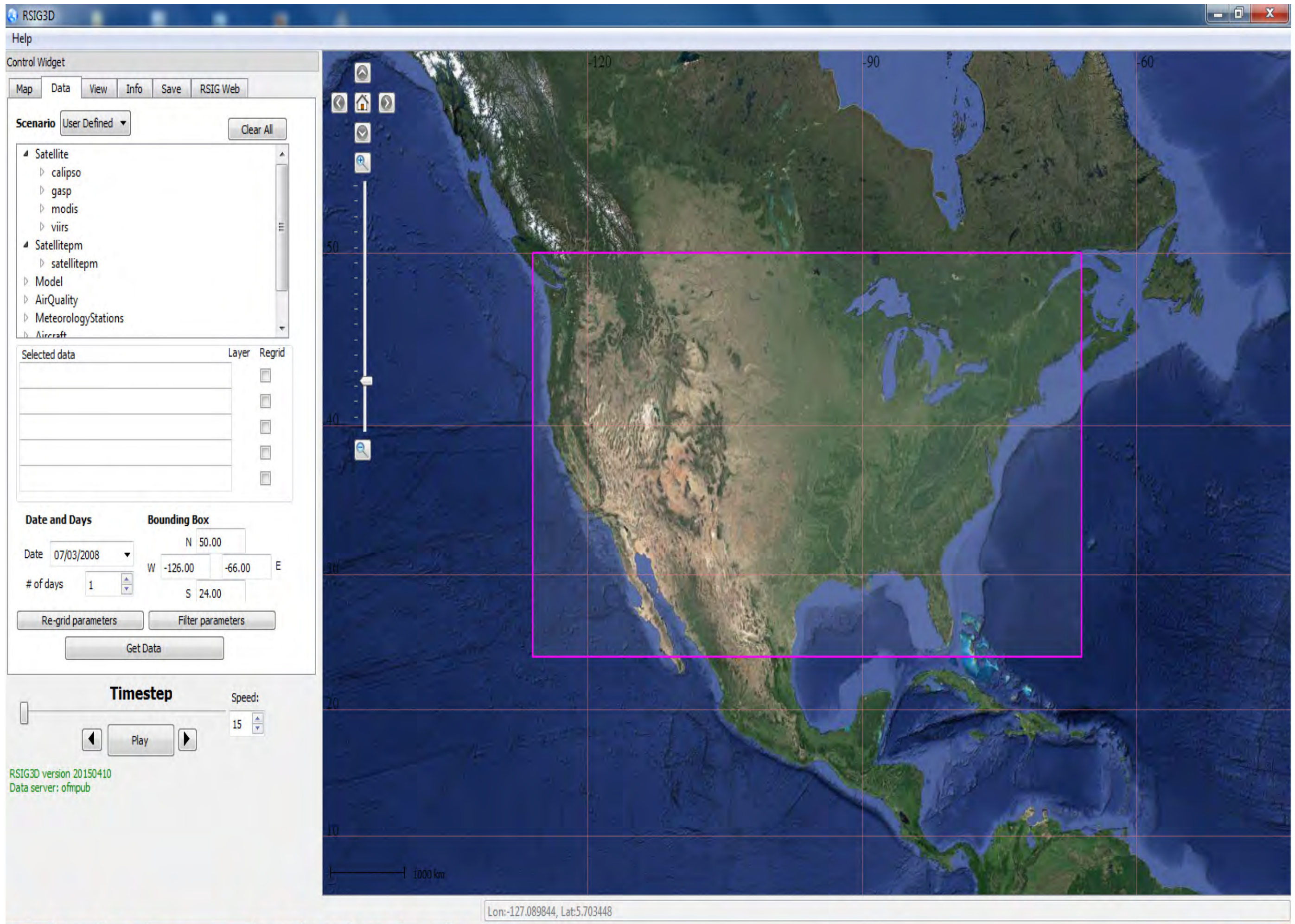
MODIS-type VIIRS AOD leads to significant overestimation

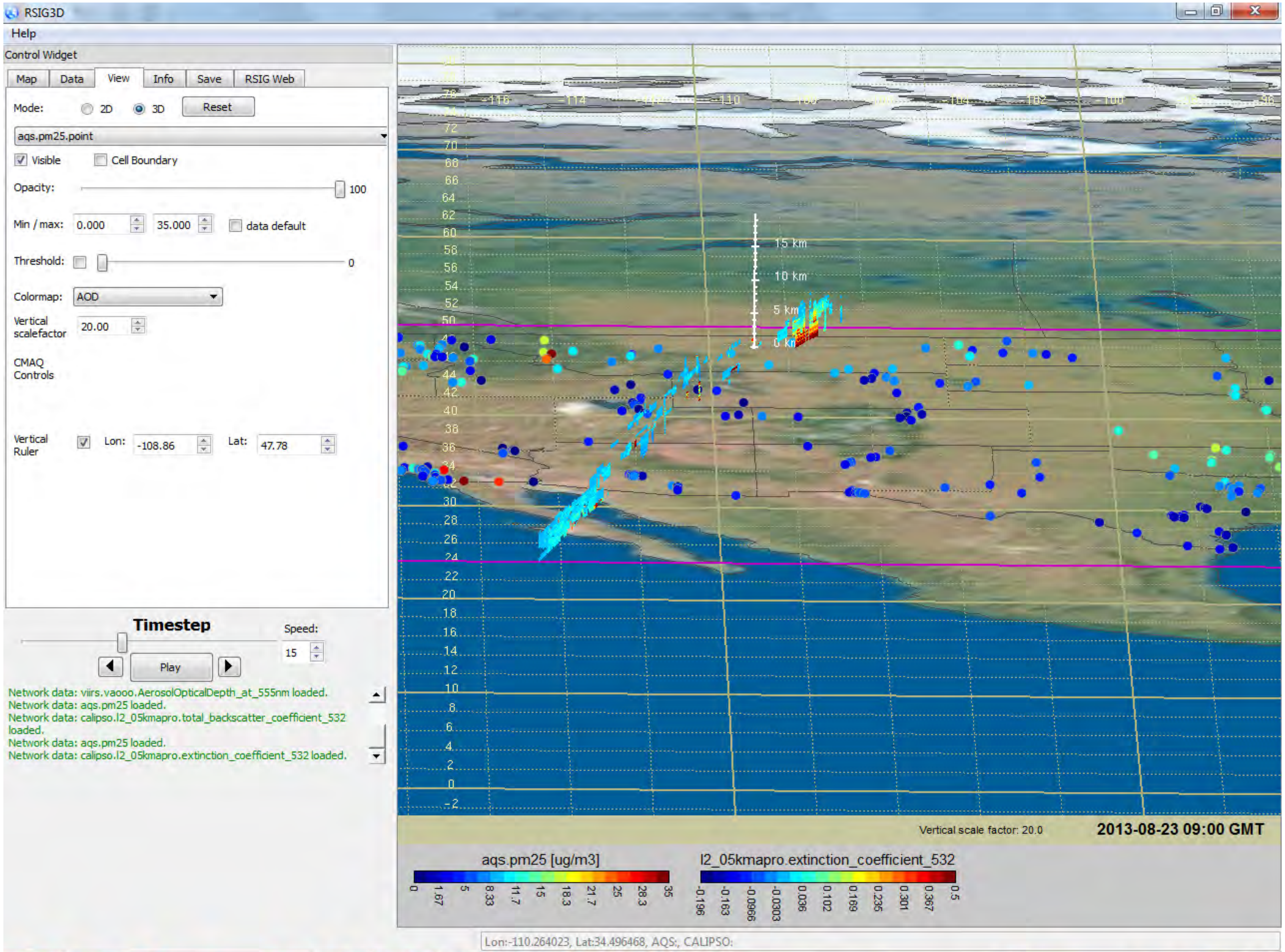
Distribution of sorted relative bias and correlation coefficient for each station



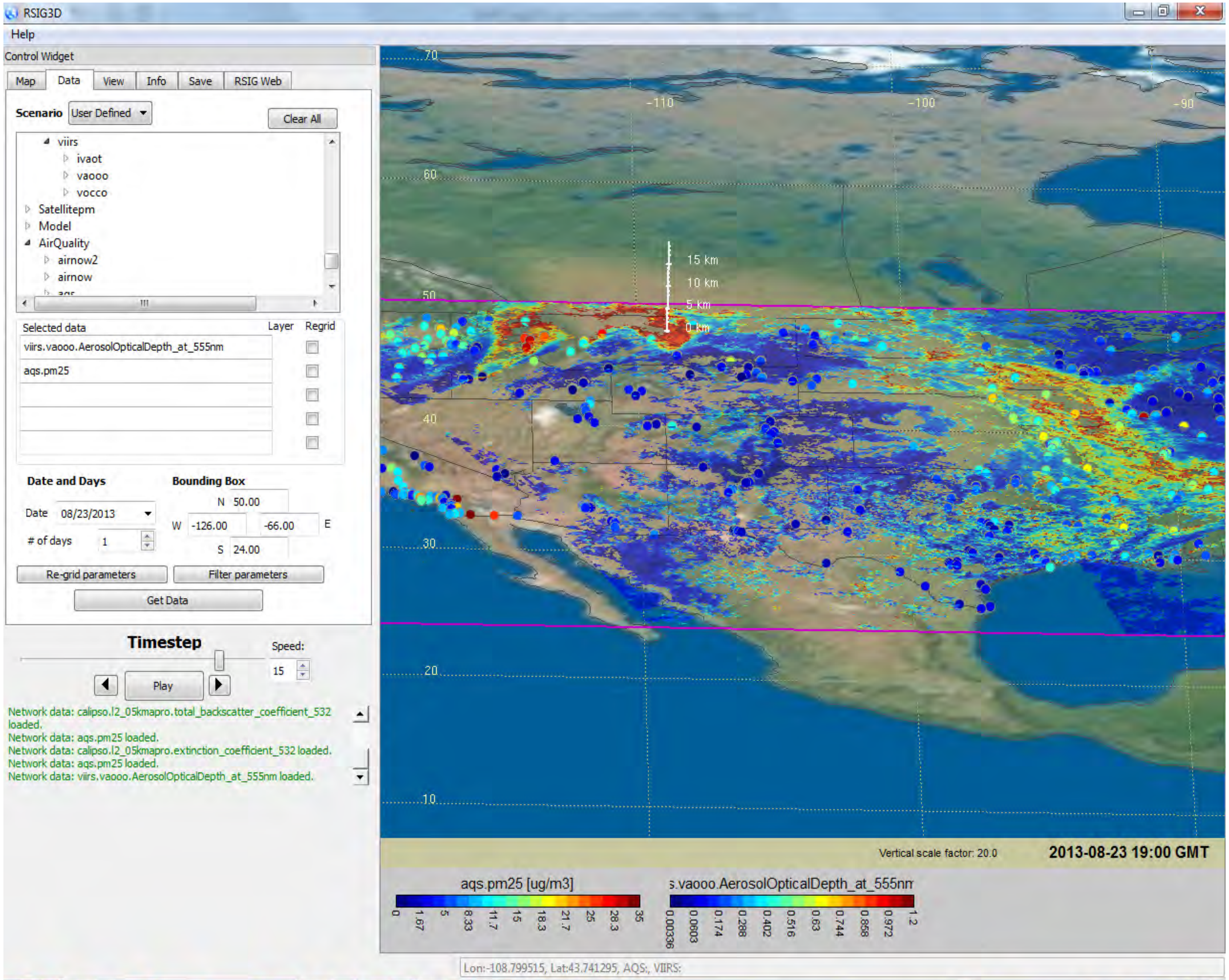
Use of EPA Remote Sensing Information Gateway to delivery NASA-VIIRS AOD/$PM_{2.5}$ data products

- **User Interface for New RSIG 3-Dimensional application.**
- **Delivers data/ products to user via web coverage services.**
- **Beta testing to begin summer 2015.**





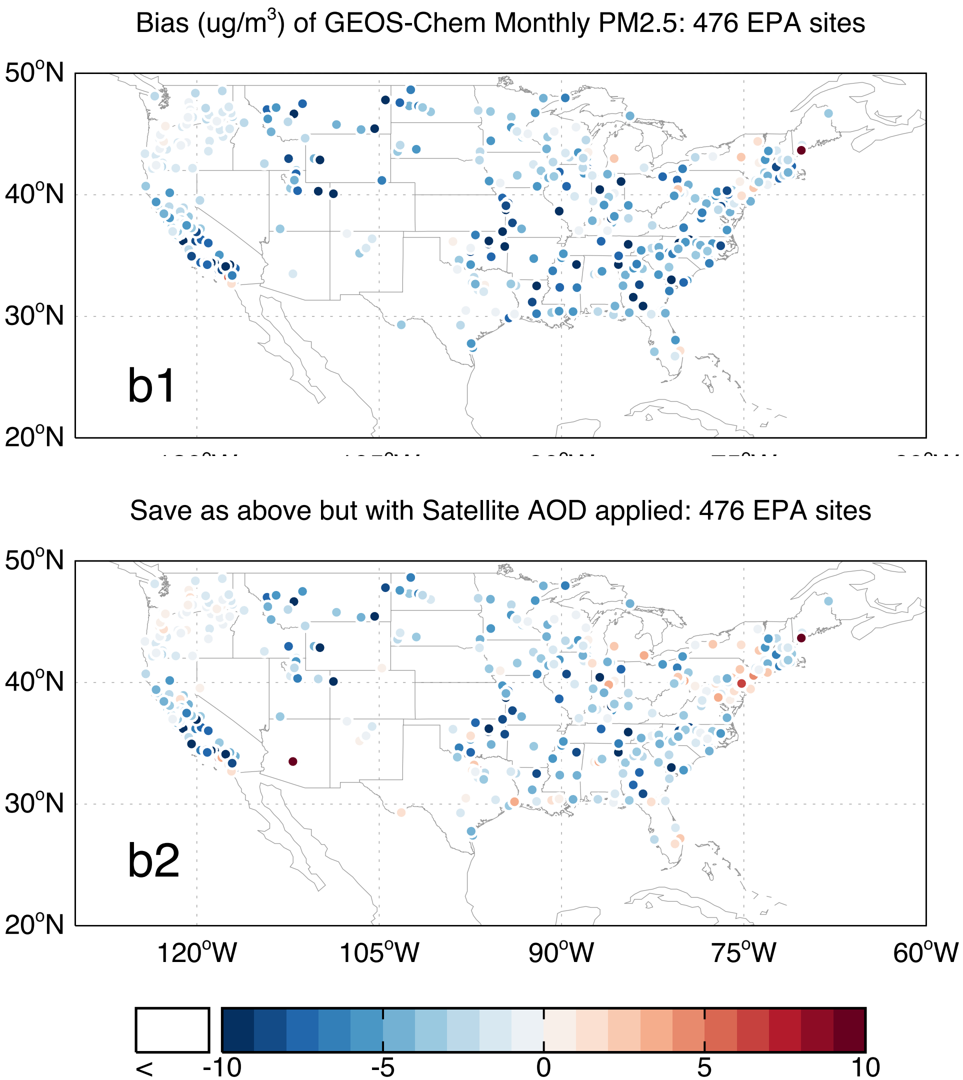
- **Early morning CALIOP overpass shows extremely high extinction (532 nm) in the lowest 2 km associated with smoke from the RIM fire (Aug 2013).**

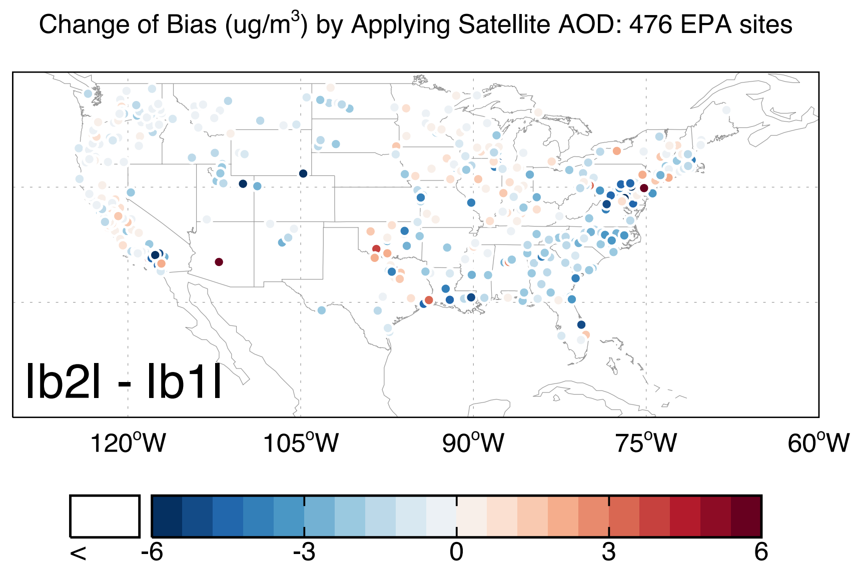


- **VIIRS AOD (NOAA-EDR) captures high AOT covering most of MT and moving into the Dakotas, both areas associated with sparse surface $PM_{2.5}$ monitoring coverage.**

Thank you !

Applying MODIS AOD reduces biases in GEOS-Chem $PM_{2.5}$





Change of Daily Absolute-Bias (ug/m^3) by Applying Satellite AOD: 476 EPA sites