# PM2.5 vs AOD on Fine Time Scale

Qian Tan[1], Mian Chin[2], Hongbin Yu[2]
[1]Bay Area Environmental Research Institute
[2]NASA GSFC

# PM2.5 vs AOD

❖ **From satellite observable to air quality application**

**Global monitoring of air pollution over land from the Earth Observing System-Terra Moderate Resolution Imaging**

**Global Estimates of Ambient Fine Particulate Matter Concentrations from Satellite-Based Aerosol Optical Depth: Development and Application**

*Aaron van Donkelaar,[1] Randall V. Martin,[1,2]*
*and Paul J. Villeneuve[5,6]*

[1]Department of Physics and Atmospheric Science, Da ... nter
for Astrophysics, Cambridge, Massachusetts, USA; [3]S ... mbia,
Canada; [4]NASA Goddard Space Flight Center, Greenl ... nto,
Toronto, Ontario, Canada; [6]Population Studies Divisi

**and $PM_{2.5}$ mass: Implica**

Jun Wang and Sundar A. Christop
Department of Atmospheric Sciences, Universi

## IMPROVING NATIONAL AIR QUALITY FORECASTS WITH SATELLITE AEROSOL OBSERVATIONS

BY JASSIM AL-SAADI, JAMES SZYKMAN,* R. BRADLEY PIERCE, CHIEKO KITTAKA, DOREEN NEIL, D. ALLEN CHU, LORRAINE REMER, LIAM GUMLEY, ELAINE PRINS,+ LEWIS WEINSTOCK, AND JACK FISHMAN

## Remote Sensing of Particulate Pollution from Space: Have We Reached the Promised Land?

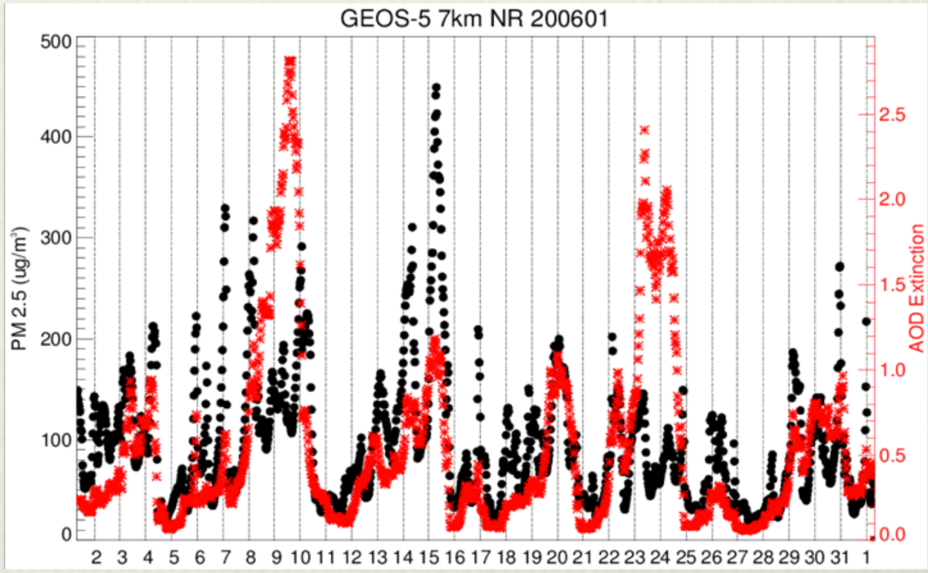
Raymond M. Hoff & Sundar A. Christopher

air

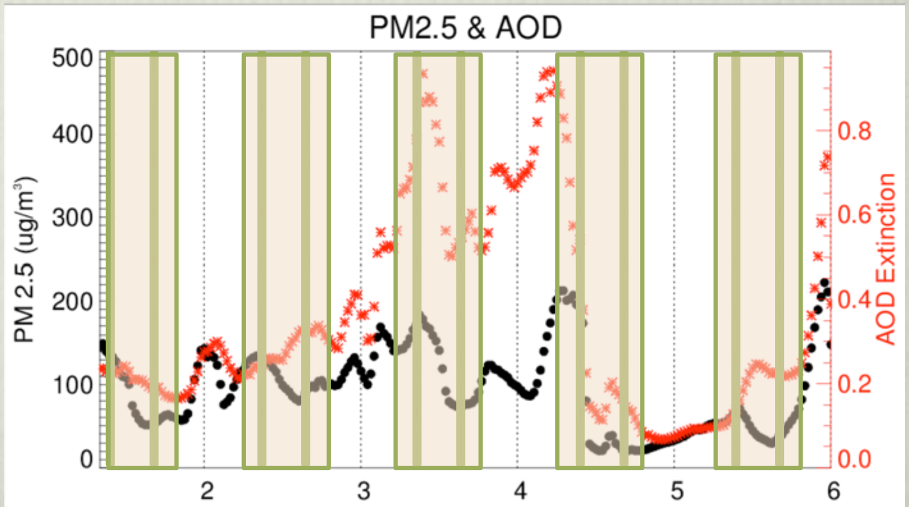
Hoff c

# Variation of PM2.5 & AOD

- Common factors
  - Synoptic systems
- Diurnal variation
  - Surface PM2.5
    - Emissions
    - Photochemical reactions
    - Boundary layer mixing
  - AOD
    - Mass loading of aerosols
    - Aerosol vertical distribution
    - $H_2O$/RH diurnal cycle



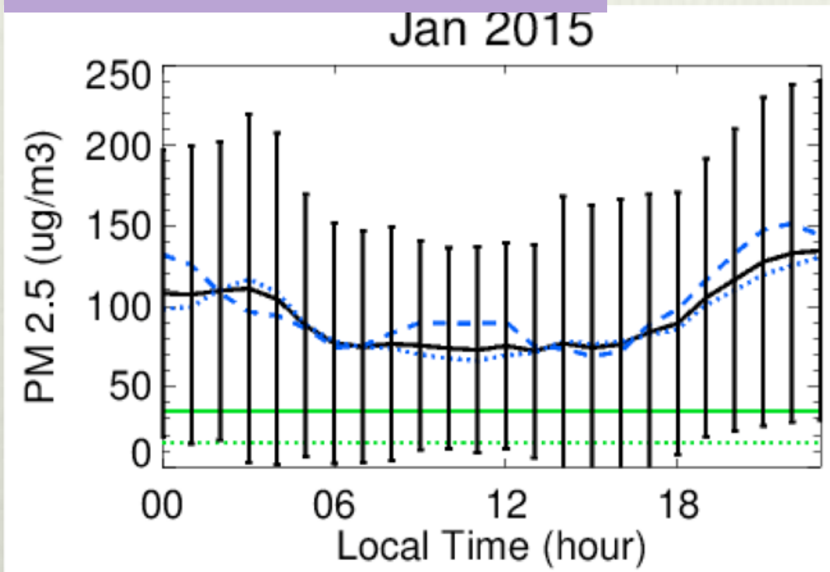

LEO vs GEO sampling

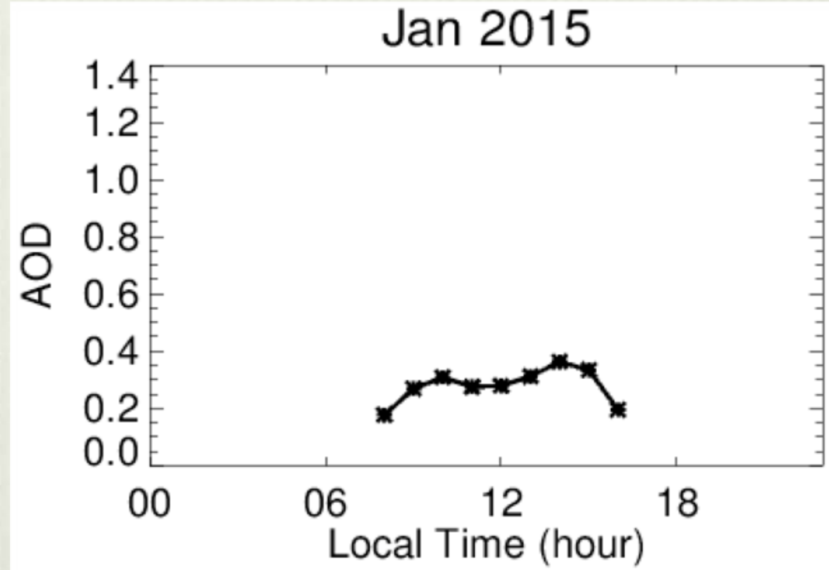


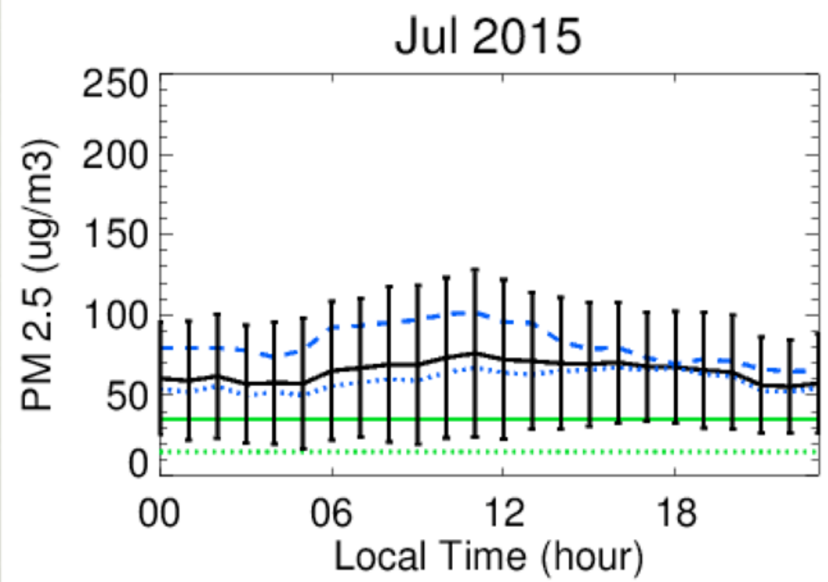
# Diurnal variations: Observed PM2.5 & AOD

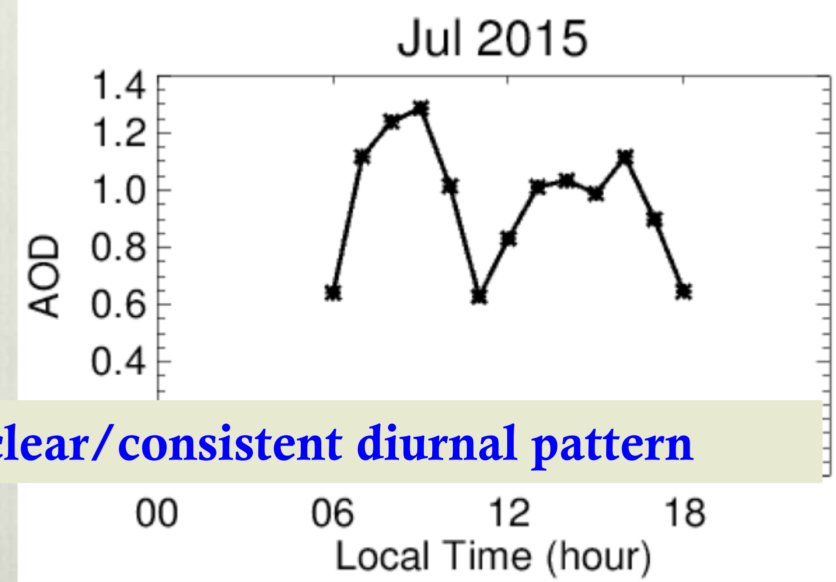
Result of PBL change?

$$AOD = \int_{surface}^{TOA} extinction(z)\, dz$$



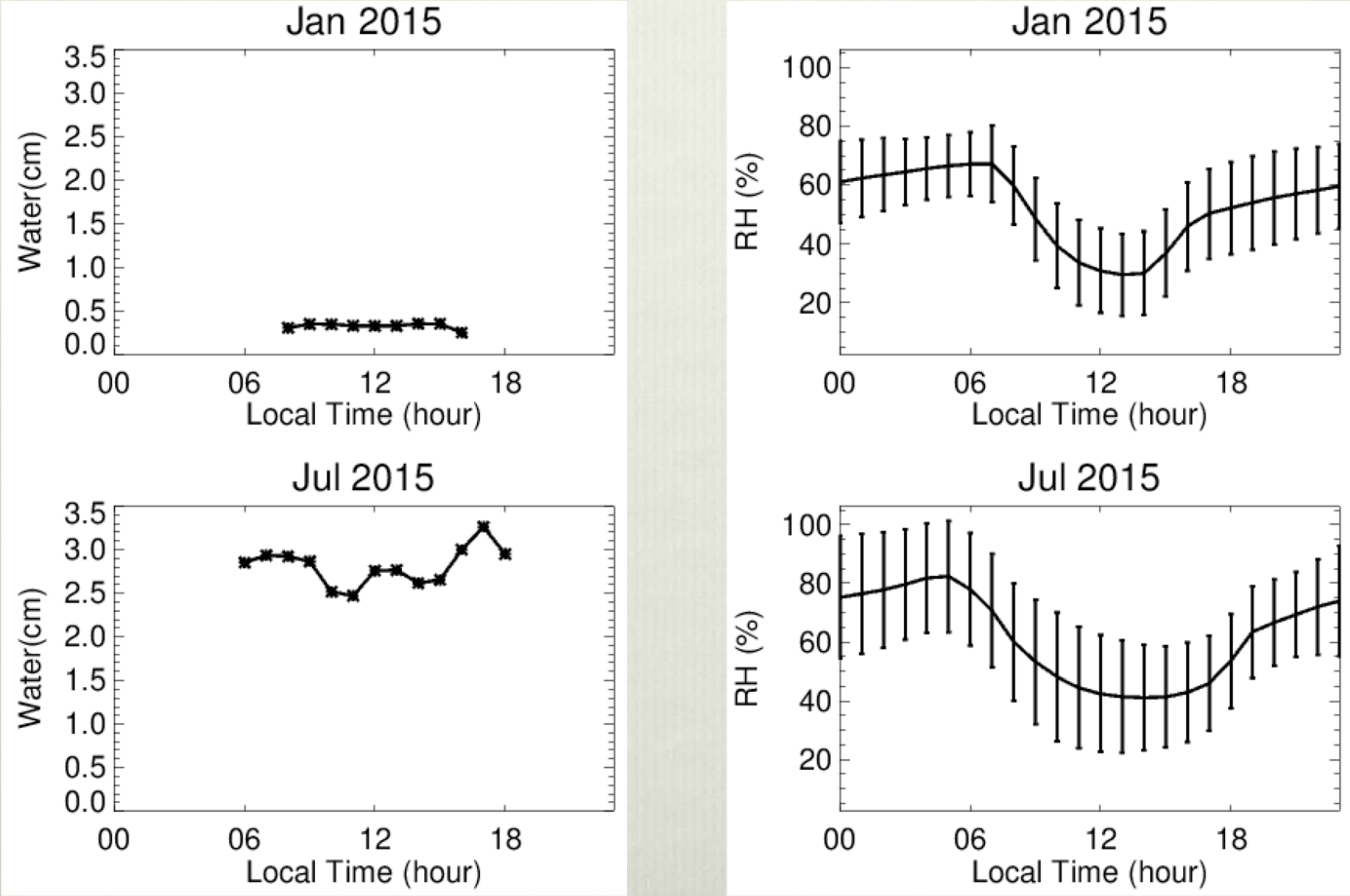




**No clear/consistent diurnal pattern**

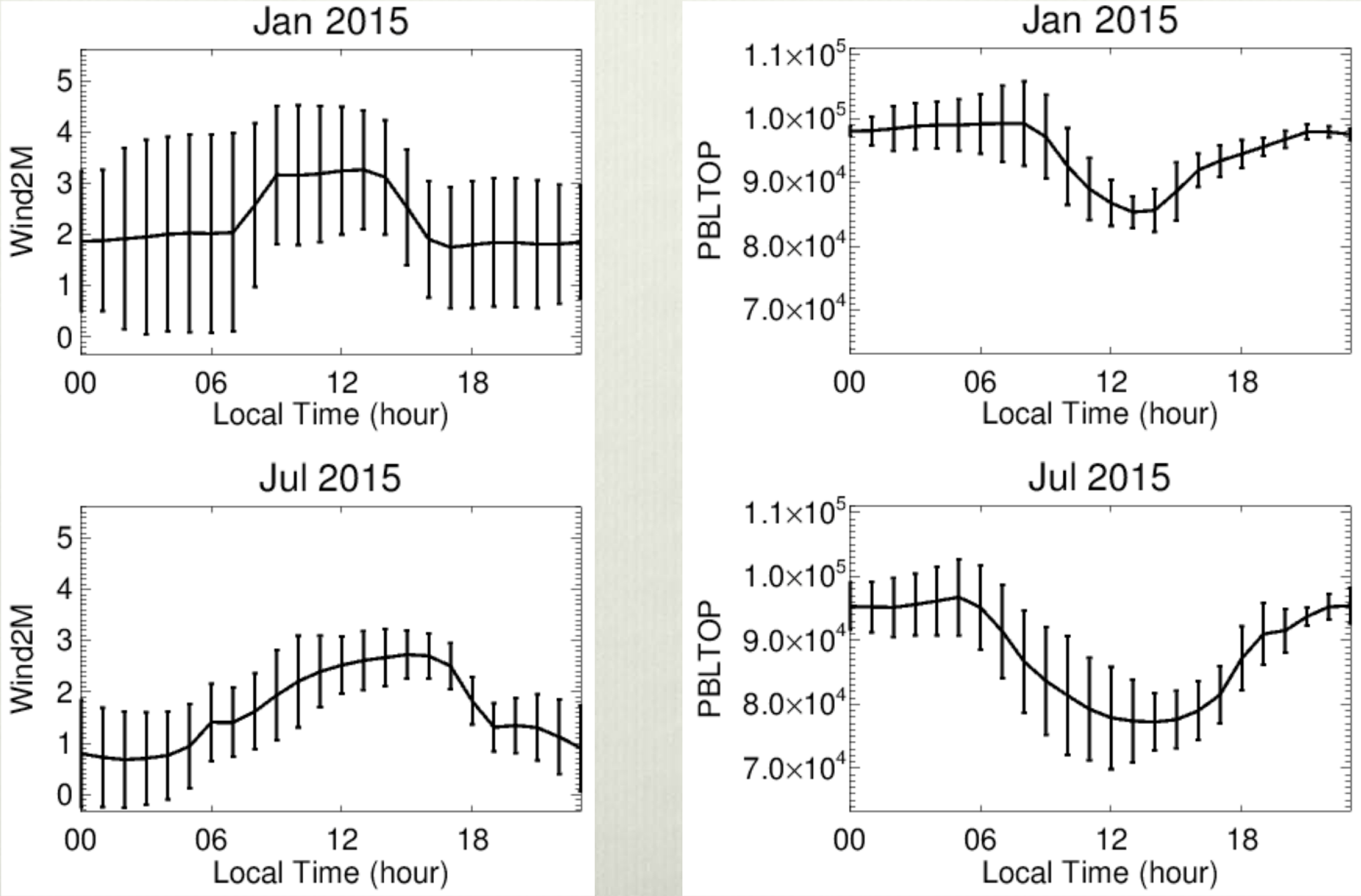
$$AOD \cong F(PM2.5_{surface}, PM_{3D}, Optical, RH_{surface}, H_2O_{column}, PBL, rain, cloud\ fraction, wind, etc.)$$

# Diurnal cycle: water column & surface RH



$$AOD \cong F(PM2.5_{surface}, PM_{3D}, Optical, RH_{surface}, H_2O_{column}, PBL, rain,\ cloud\ \ fraction, wind, etc.)$$

# Diurnal cycle: wind & PBL



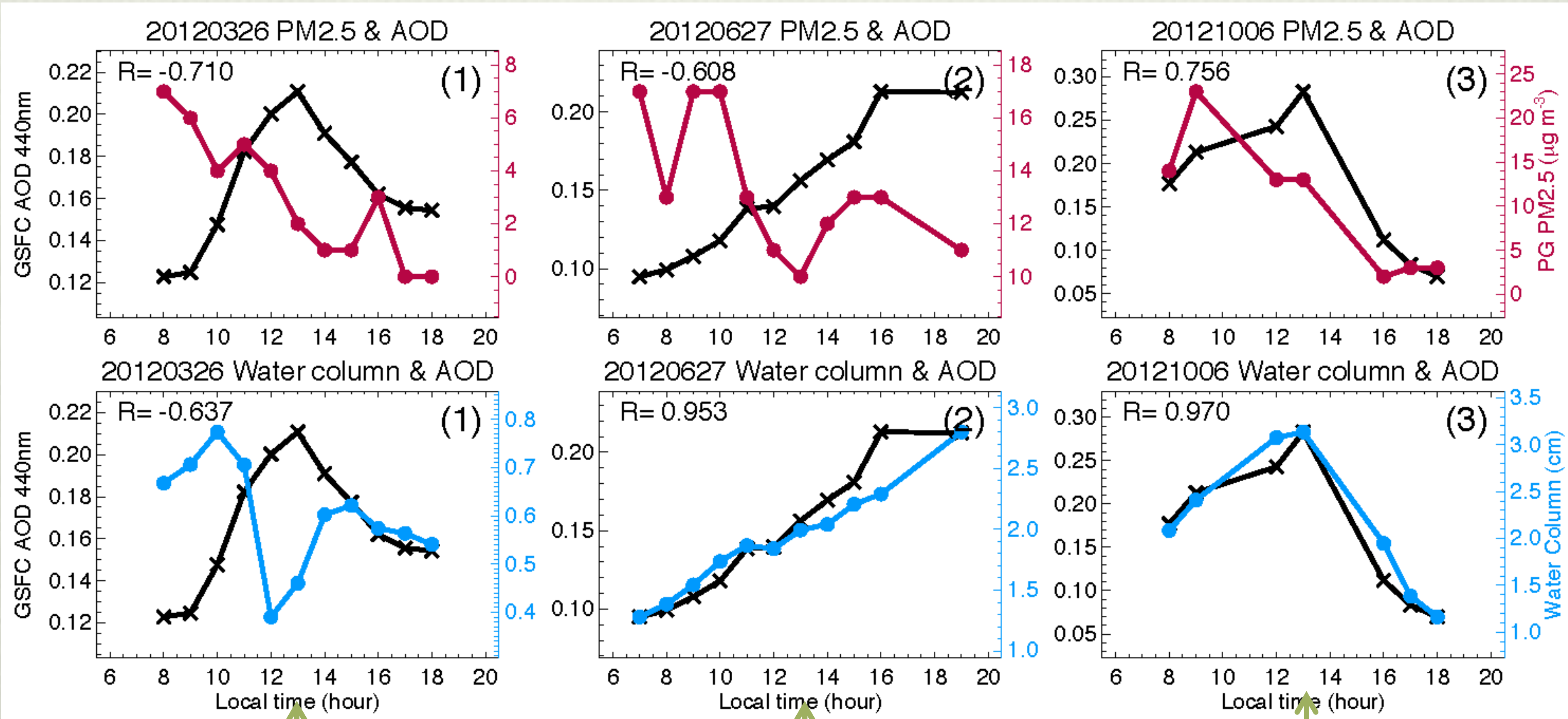
# PM2.5 vs AOD on higher temporal resolution


- **Observations**
  - PM2.5 hourly observations
  - AOT hourly observations
  - Paired Sites: USA: GSFC, St. Louis, Fresno, Houston; Beijing (China)


- **Model**
  - MERRA-2
  - GEOS-5 7km
- **Diurnal cycle**
  - PM2.5, AOD, meteorological fields.

# How are AOD and PM2.5 correlated within a day?

- ❖ Example of daytime AERONET AOD and EPA PM2.5 near GSFC

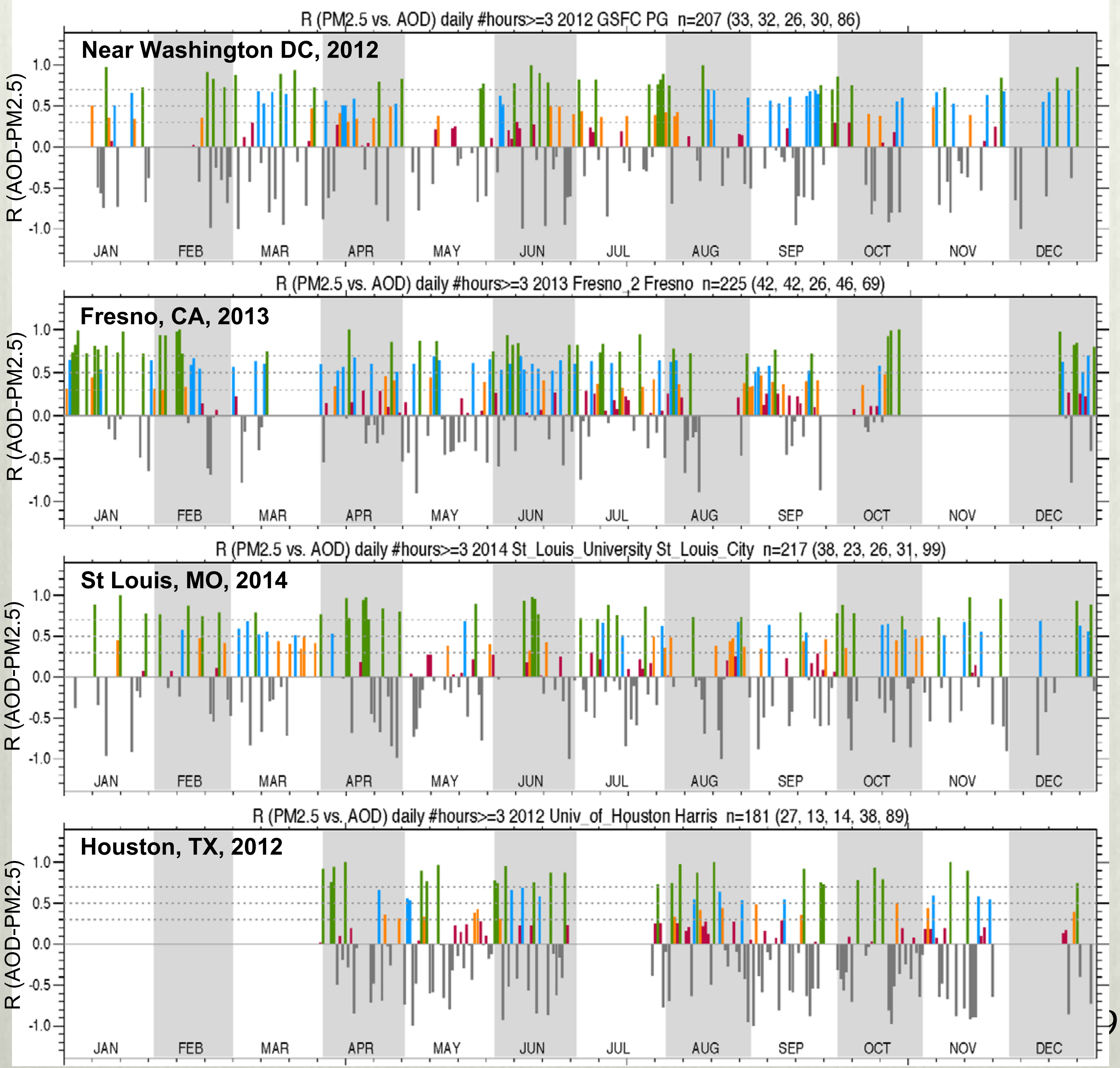



**AOD** negatively correlated with both **PM2.5** and **$H_2O$(g)**

**AOD** negatively correlated with **PM2.5** but positively with **$H_2O$(g)**

**AOD** positively correlated with both **PM2.5** and **$H_2O$(g)**

# Daily AOD-PM2.5 correlation coefficients in the four locations




**Near Washington DC, 2012:**
**Total available days: 207**
- 16% ( 33): R ≥ 0.7
- 15% ( 32): 0.5 ≤ R < 0.7
- 13% ( 26): 0.3 ≤ R < 0.5
- 14% ( 30): 0.0 ≤ R < 0.3
- 42% ( 86): R < 0.0

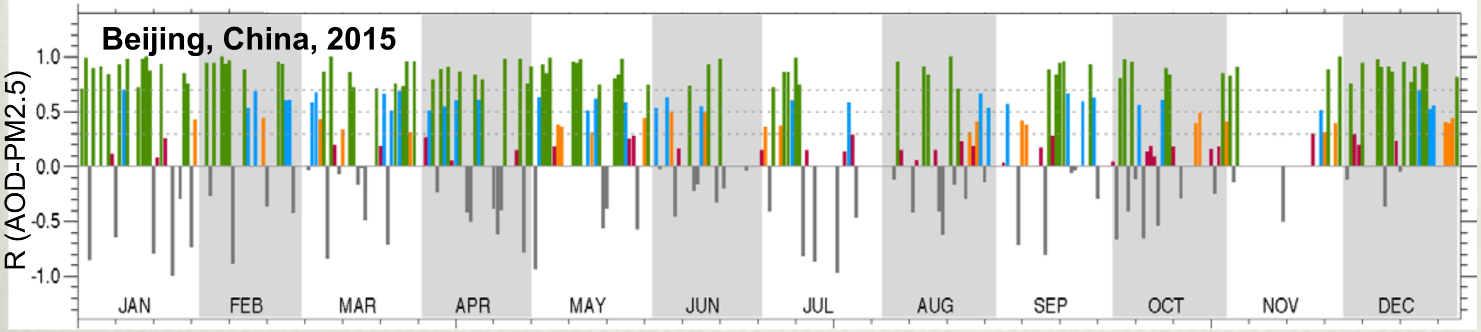
**Fresno, 2013:**
**Total available days: 225**
- 19% ( 42): R ≥ 0.7
- 19% ( 42): 0.5 ≤ R < 0.7
- 11% ( 26): 0.3 ≤ R < 0.5
- 20% ( 46): 0.0 ≤ R < 0.3
- 31% ( 69): R < 0.0

**St. Louis, 2014:**
**Total available days: 217**
- 17% ( 38): R ≥ 0.7
- 11% ( 23): 0.5 ≤ R < 0.7
- 12% ( 26): 0.3 ≤ R < 0.5
- 14% ( 31): 0.0 ≤ R < 0.3
- 46% ( 99): R < 0.0

**Houston, 2012:**
**Total available days: 181**
- 15% ( 27): R ≥ 0.7
- 7% ( 13): 0.5 ≤ R < 0.7
- 8% ( 14): 0.3 ≤ R < 0.5
- 21% ( 38): 0.0 ≤ R < 0.3
- 49% ( 89): R < 0.0

# Daily correlation coefficients in Beijing, China, 2015

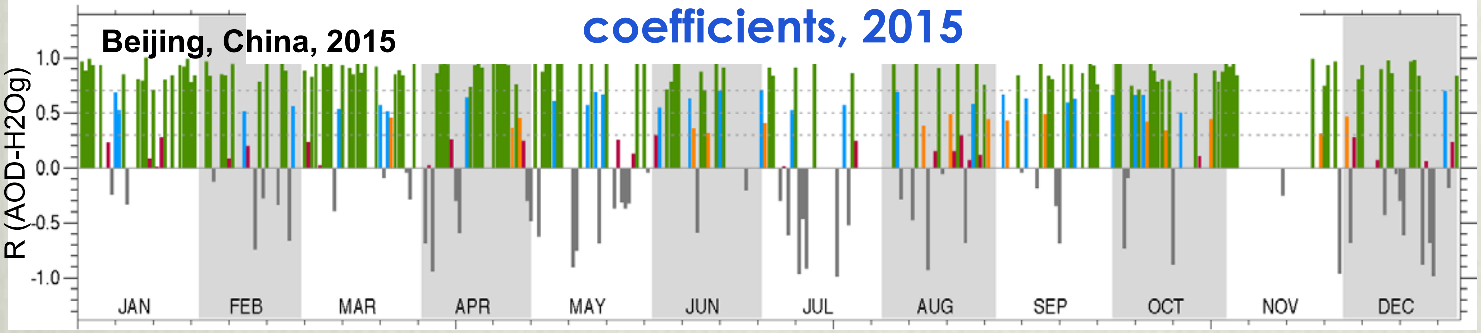
## Daily AOD-PM2.5 vapor correlation coefficients, 2015




**Beijing, AOD-PM2.5, 2015:**
**Total available days: 212**

- 36% ( 92): R ≥ 0.7
- 14% ( 35): 0.5 ≤ R < 0.7
- 10% ( 25): 0.3 ≤ R < 0.5
- 15% ( 38): 0.0 ≤ R < 0.3
- 25% ( 64): R < 0.0

## Daily AOD-water vapor correlation coefficients, 2015




**Beijing, AOD-water, 2015:**
**Total available days: 256**

- 50% (127): R ≥ 0.7
- 11% ( 29): 0.5 ≤ R < 0.7
- 6% ( 16): 0.3 ≤ R < 0.5
- 10% ( 26): 0.0 ≤ R < 0.3
- 22% ( 58): R < 0.0

- For all three years (2014-2016) and two pairs of Beijing sites, 30-40% days AOD and PM2.5 are correlated with R ≥ 0.7 and 25-33% days R < 0 – better correlations than sites in the US
- For AOD-water vapor, 40-60% days they are correlated with R ≥ 0.7 and 20-25% days R < 0 – Comparable the sites in the US

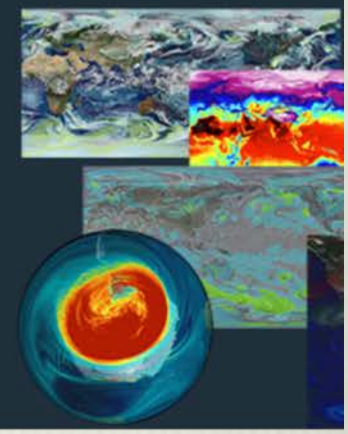
**Closer to the large sources, PM2.5 plays more role in AOD changes**

# What does model say?

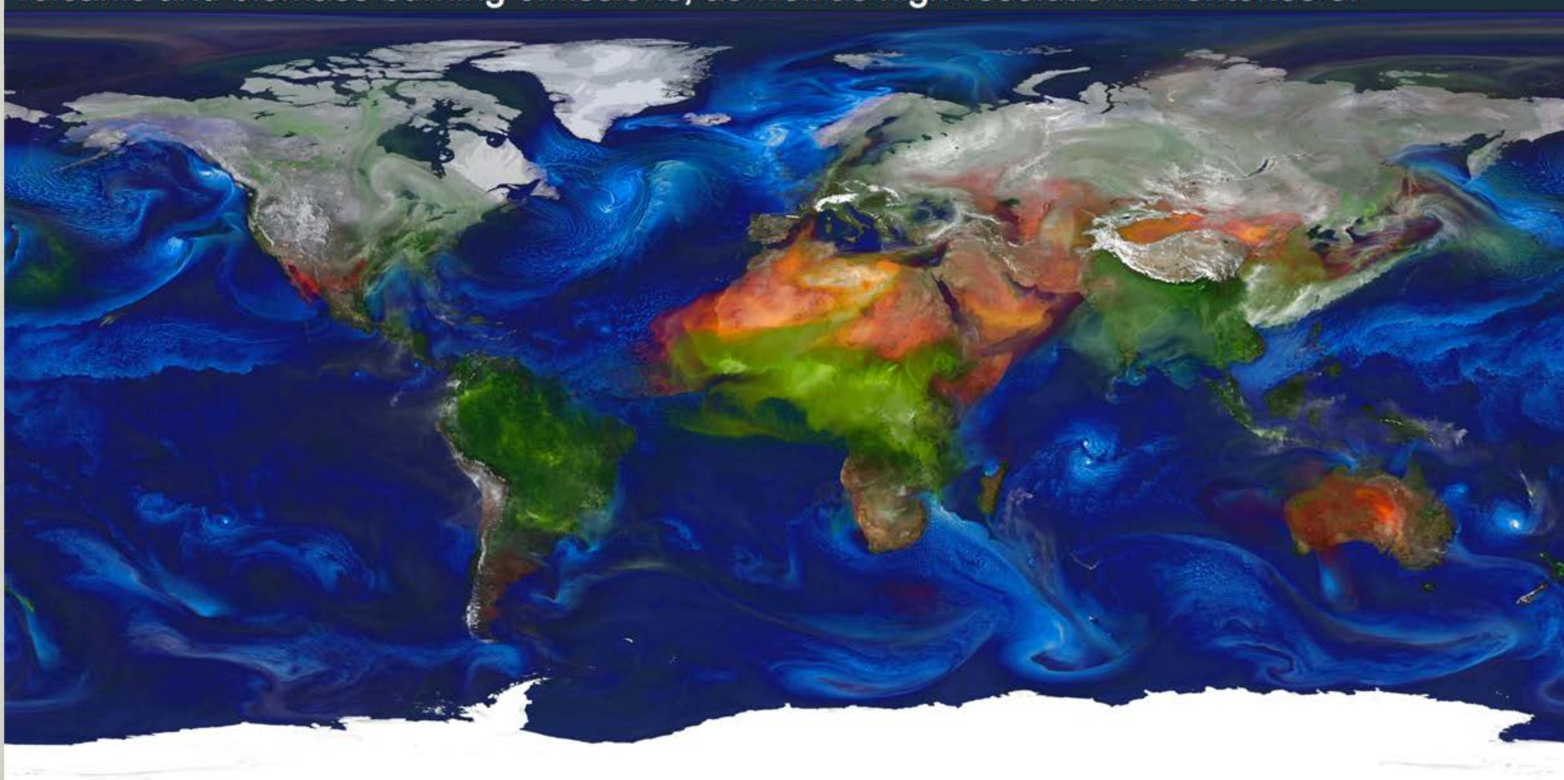
## GEOS-5 Nature Run, Ganymed Release

### Non-hydrostatic 7 km Global Mesoscale Simulation

The GEOS-5 Nature Run (Ganymed Release) is a 2-year global, non-hydrostatic mesoscale simulation for the period June 2005 through May 2007 with a 7 km horizontal resolution. In addition to standard meteorological parameters (wind, temperature, moisture, surface pressure), this simulation includes 15 aerosol tracers (dust, seasalt, sulfate, black and organic carbon), $O_3$, CO and $CO_2$.

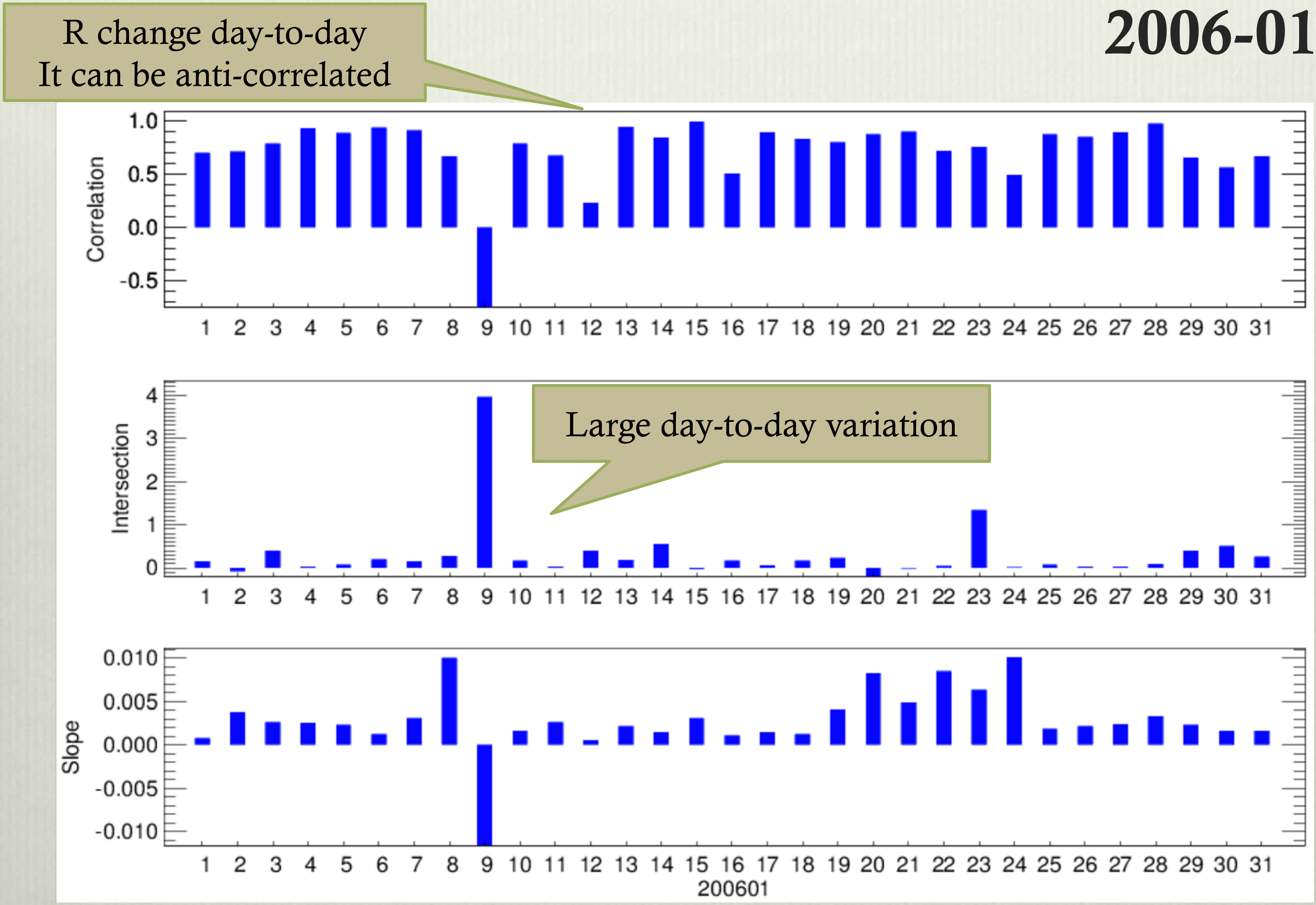


This model simulation is driven by prescribed sea-surface temperature and sea-ice, daily volcanic and biomass burning emissions, as well as high-resolution inventories of



7km, 0.0625$^{o}$
2005/05-2007/06
30 min
Natural run, no assimilation

# R/intersection/slope of daily PM2.5 vs AOD 2006-01

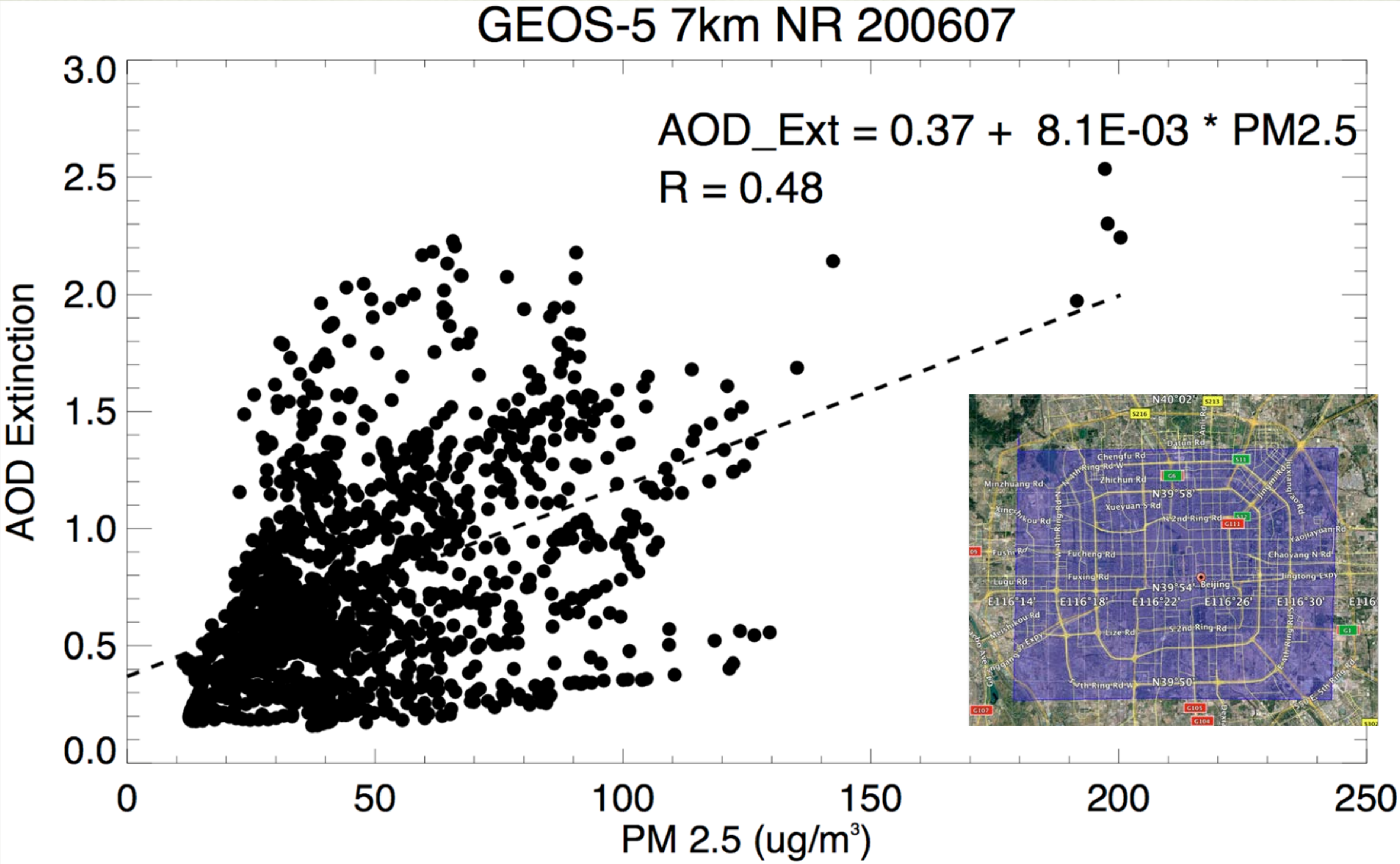


$$AOD \cong F(PM2.5_{surface}, PM_{3D}, Optical, RH_{surface}, H_2O_{column}, PBL, rain, cloud\ fraction, wind, etc.)$$

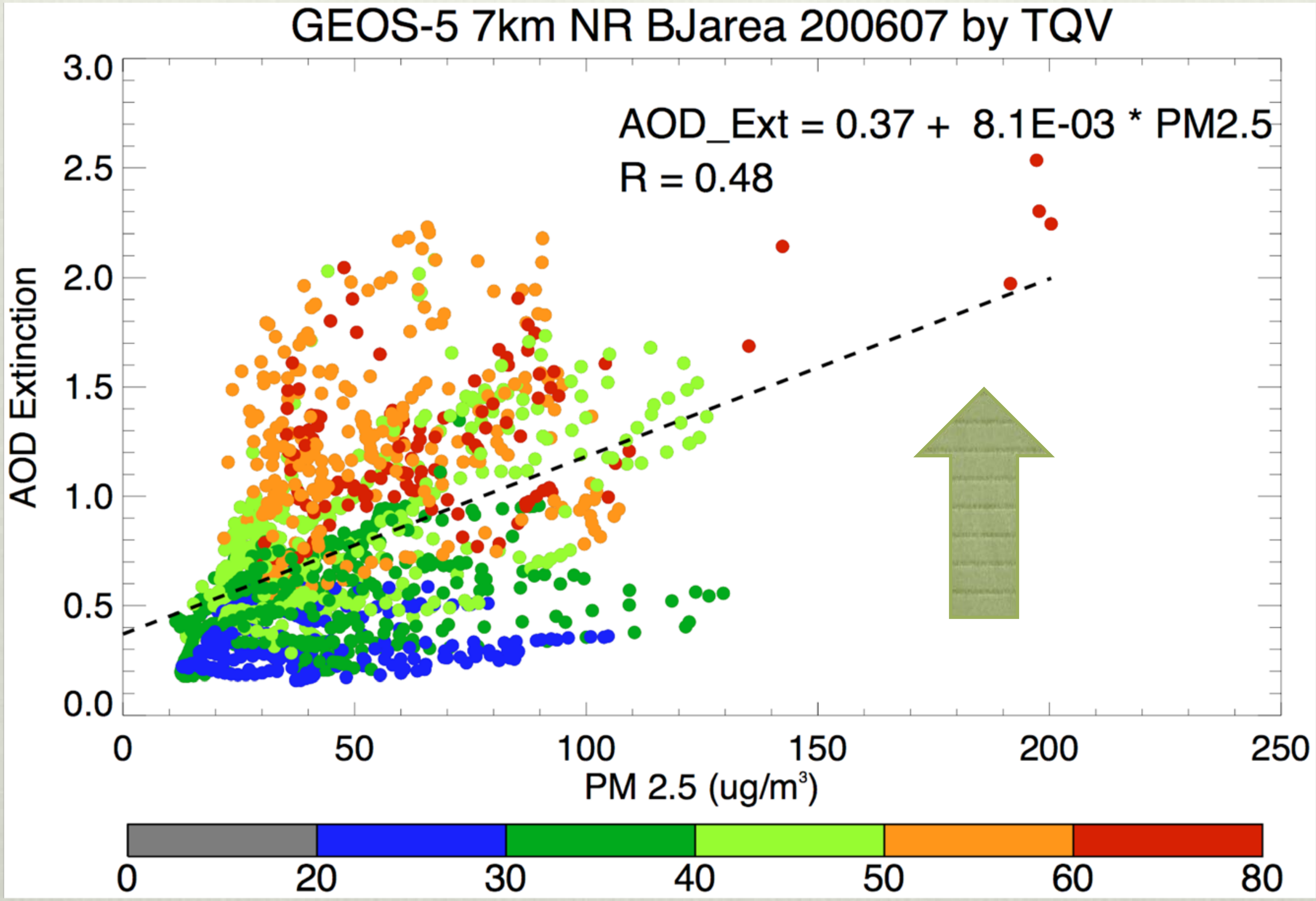
# Variables checked

| | | | | | |
|---|---|---|---|---|---|
| **CAPE** | **CLDTOT** | **CWP** | **IWP** | **LWP** | **PBLH** |
| convective available potential energy | cloud fraction | condensed water path | ice water path | liquid water path | PBL height |
| **PRECTOT** | **PS** | **QLML** | **QV10M** | **RH** | **SLP** |
| total precipitation | surface pressure | surface specific humidity | 10 m specific humidity | relative humidity | sea level pressure |
| **T10M** | **TAUTOT** | **TQI** | **TQL** | **TQV** | **U10M** |
| 10 meter temperature | total cloud optical depth | total precipitable ice water | total precipitable liquid water | total precipitable water vapor | 10 meter wind |
| **U50M** | **V10M** | **V50M** | **W850** | **Wind10M** | **Wind50M** |
| 50 meter wind | 10 meter wind | 50 m wind | Wind @ 850mb | 10 meter wind speed | 50 meter wind speed |

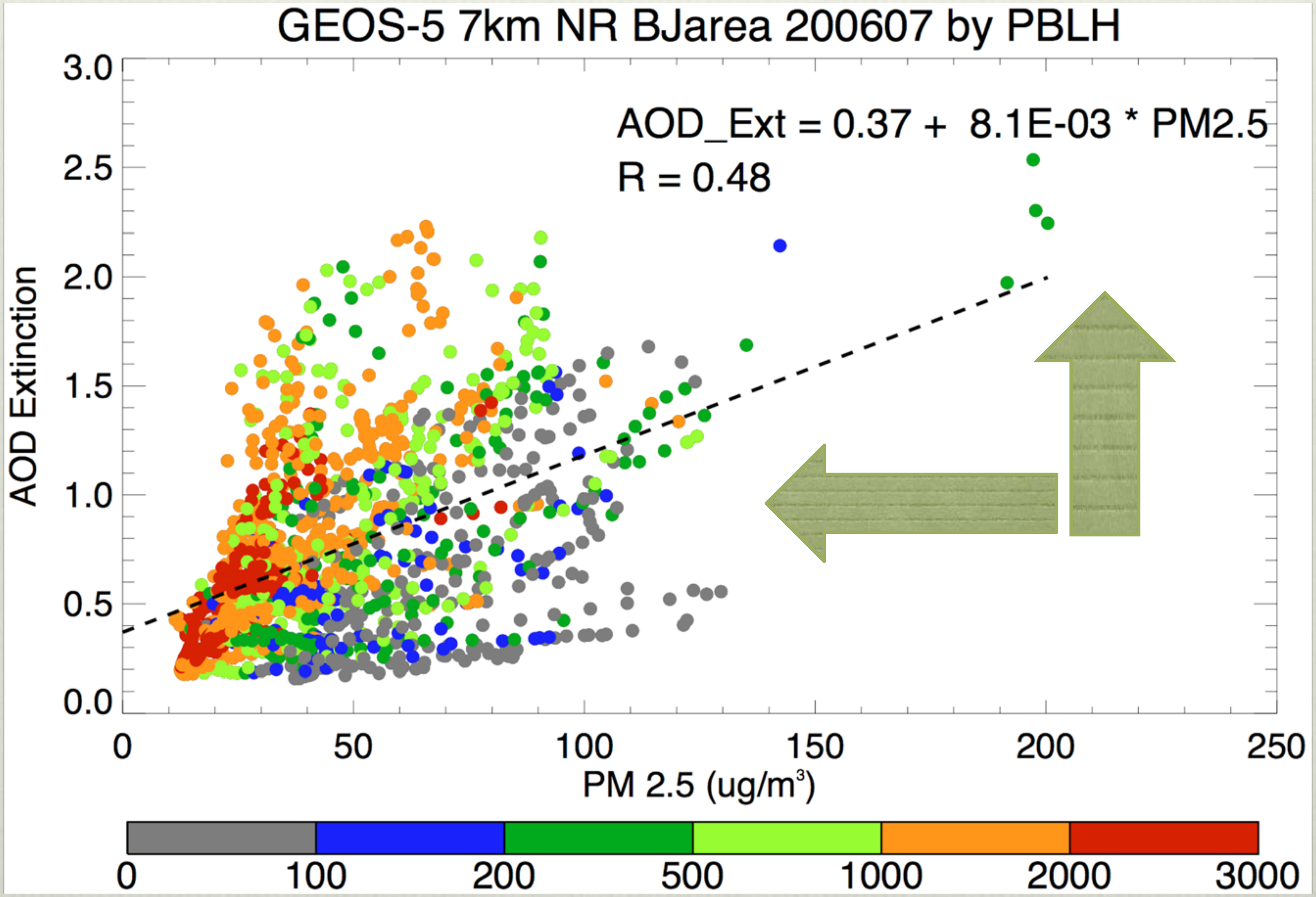
# Regional average around Beijing



# Same PM2.5, more total column $H_2O$ vapor, higher AOD

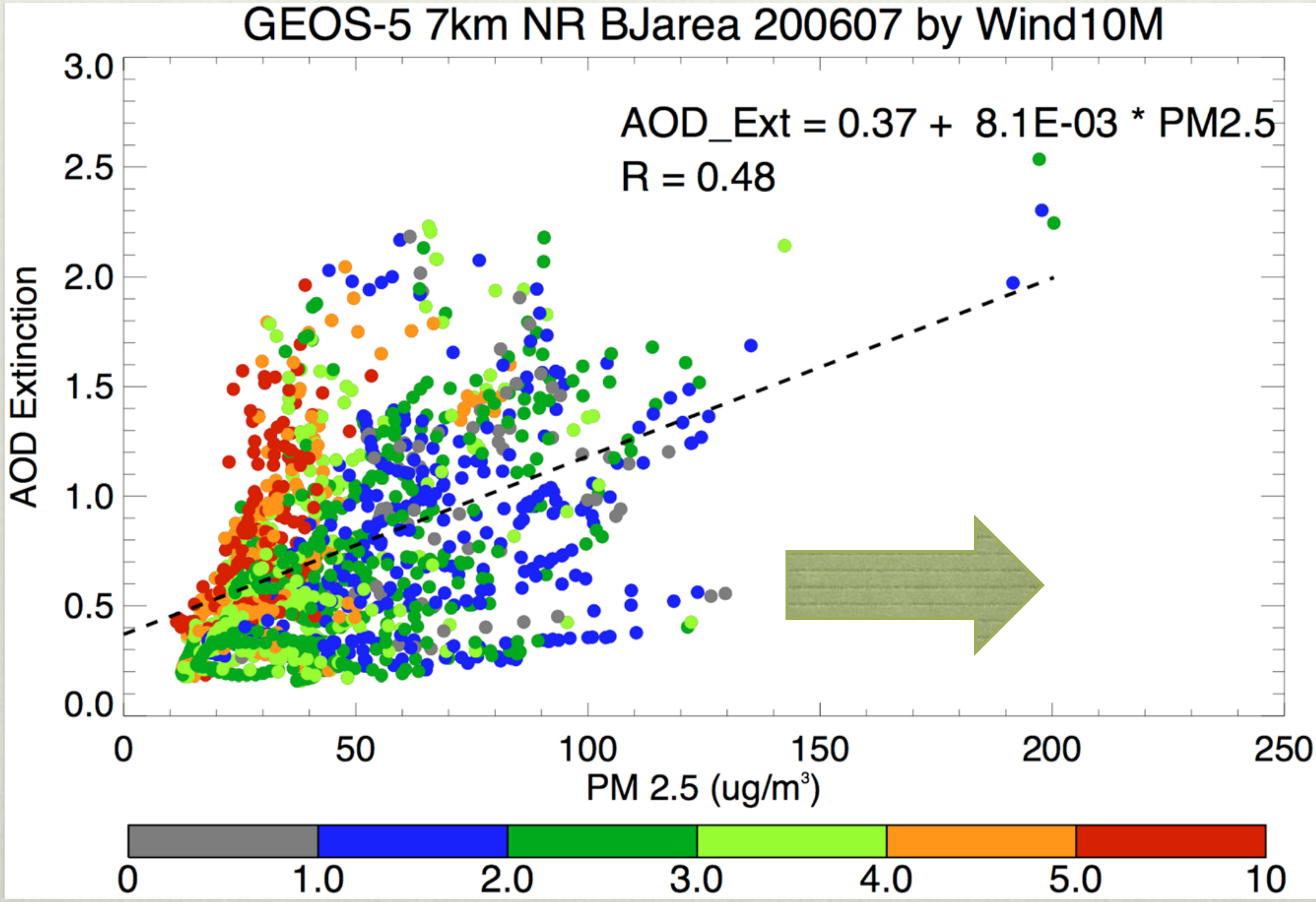


# Same AOD: higher PBL →less PM2.5
# Same PM2.5: higher PBL →higher AOD

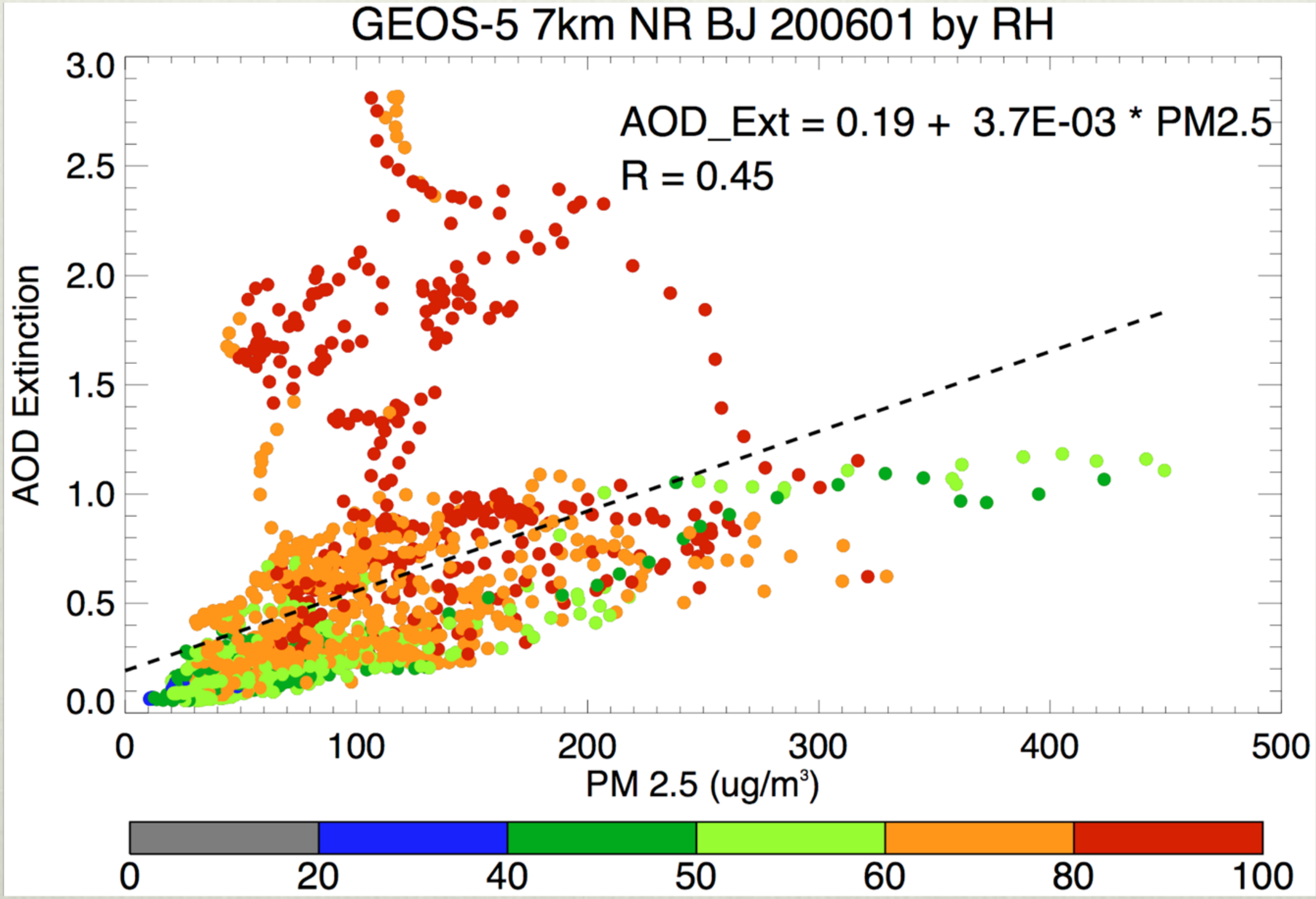


# More stagnation → more PM2.5

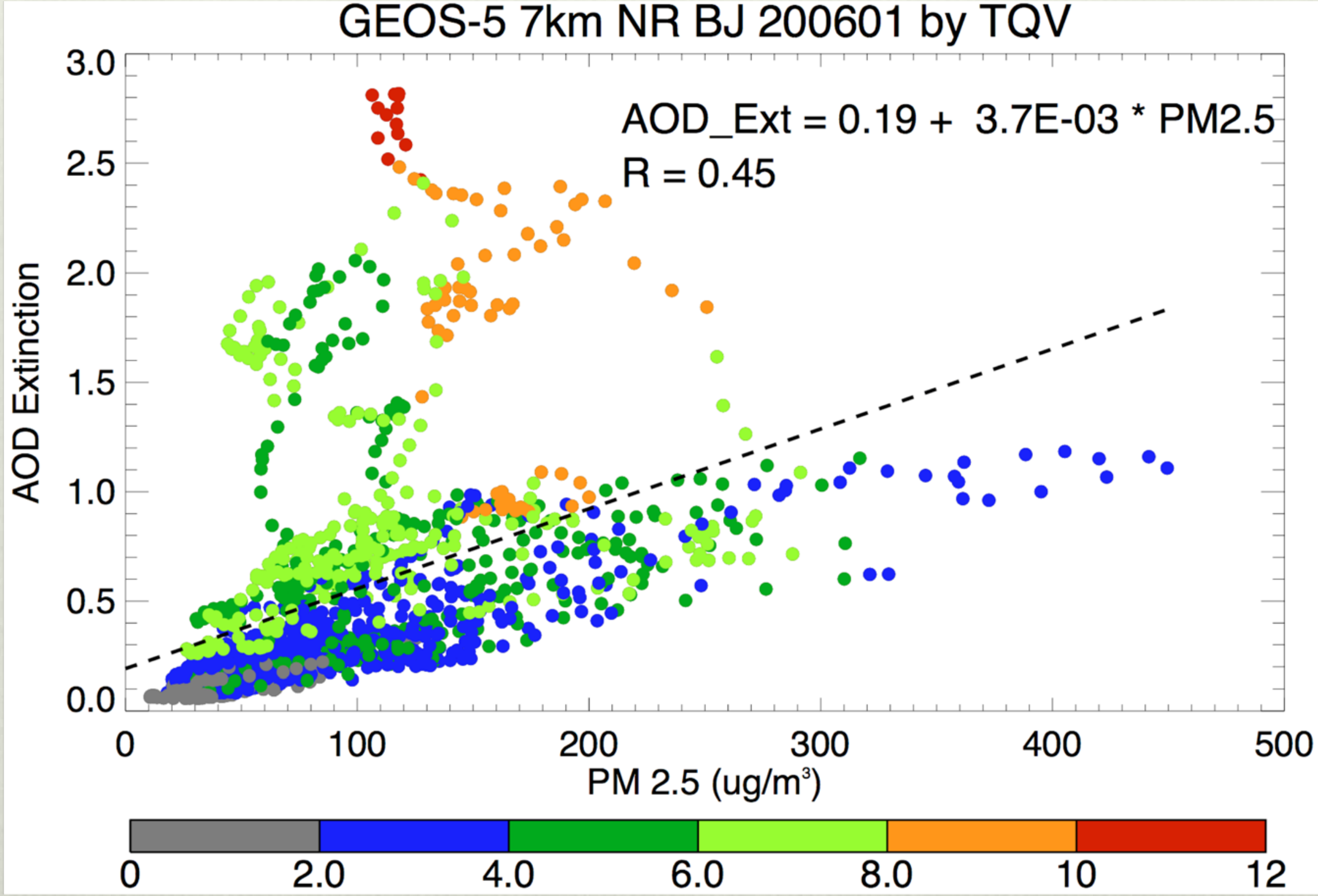
**Wind speed is correlated to RH & TQv**



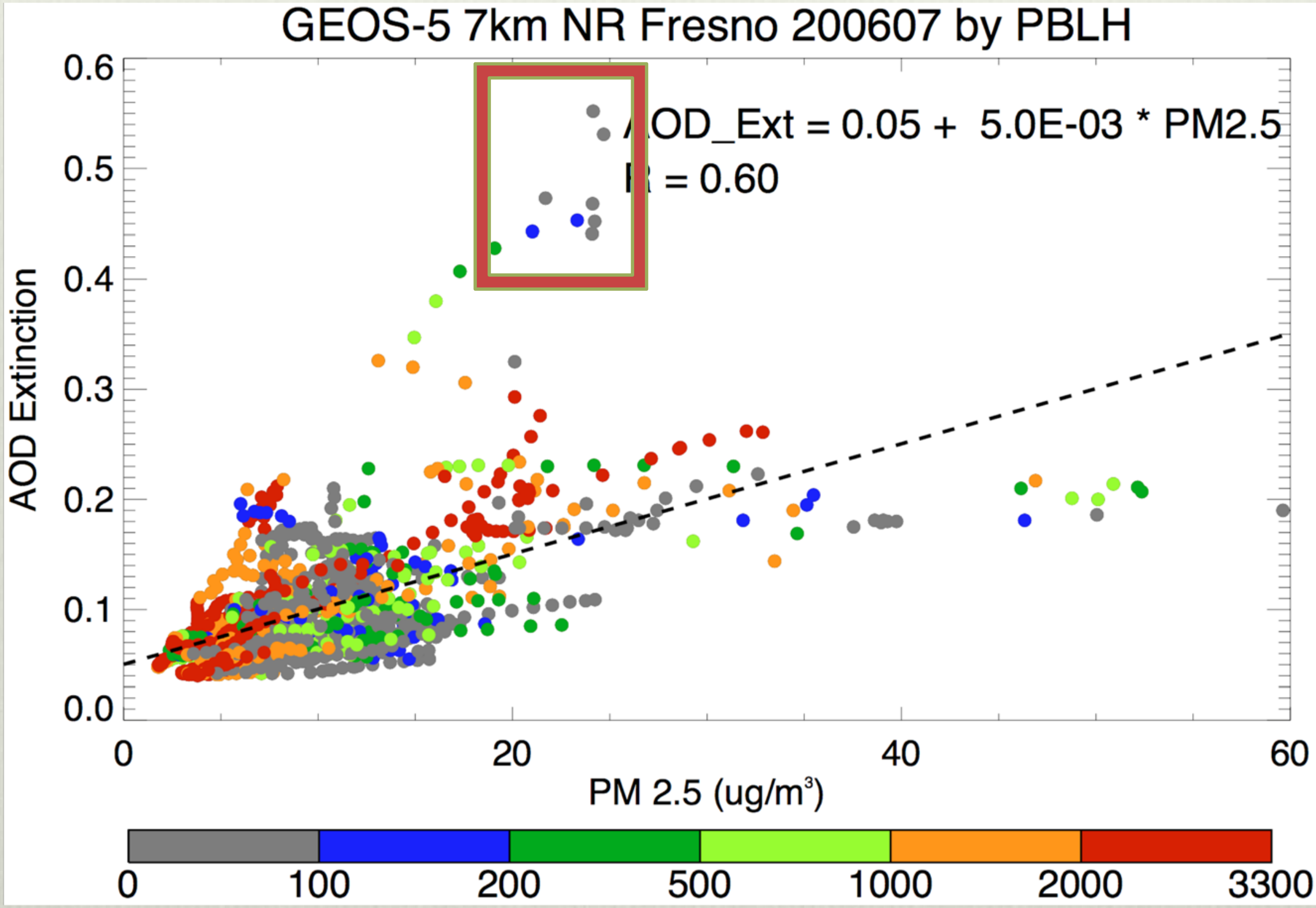
# Total column Qv vs Surface RH



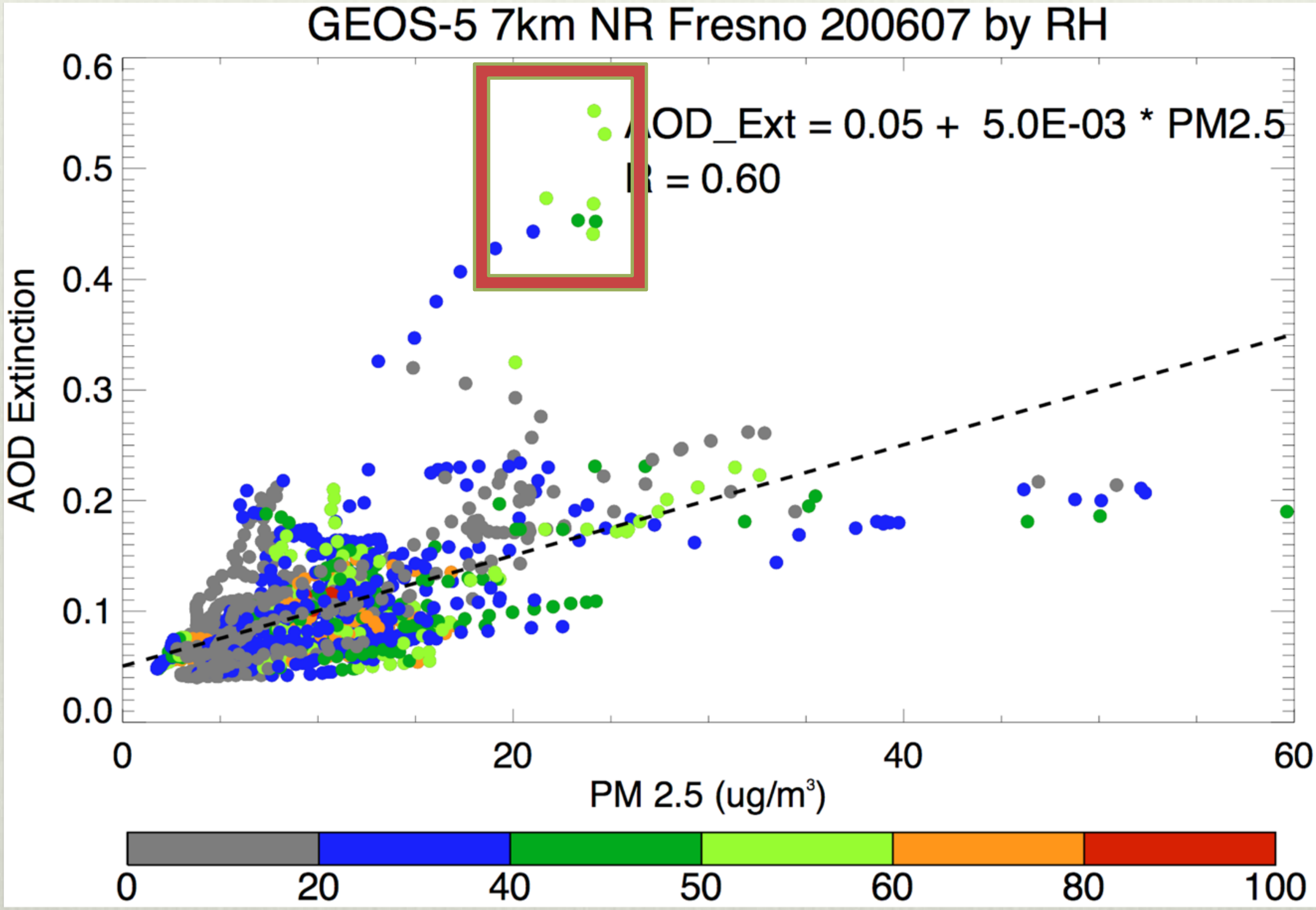
# Total column Qv vs Surface RH



# Fresno, summer (dry)
# Same PM2.5, lower PBL, higher AOD (?)



# Fresno, summer (dry)
# RH plays bigger role in AOD for this case



# Conclusion

- **AOD is affected by aerosol loading and multiple meteorological conditions**
- **Within a day, AOD vs PM2.5 correlation change with time and location.**
- **Near major source regions, relative humidity + $H_2O$ column, PBL height, wind speed,  are needed to estimate PM2.5 from AOD.**
- **In other regions, information on aerosol composition, vertical distribution etc, are required.**

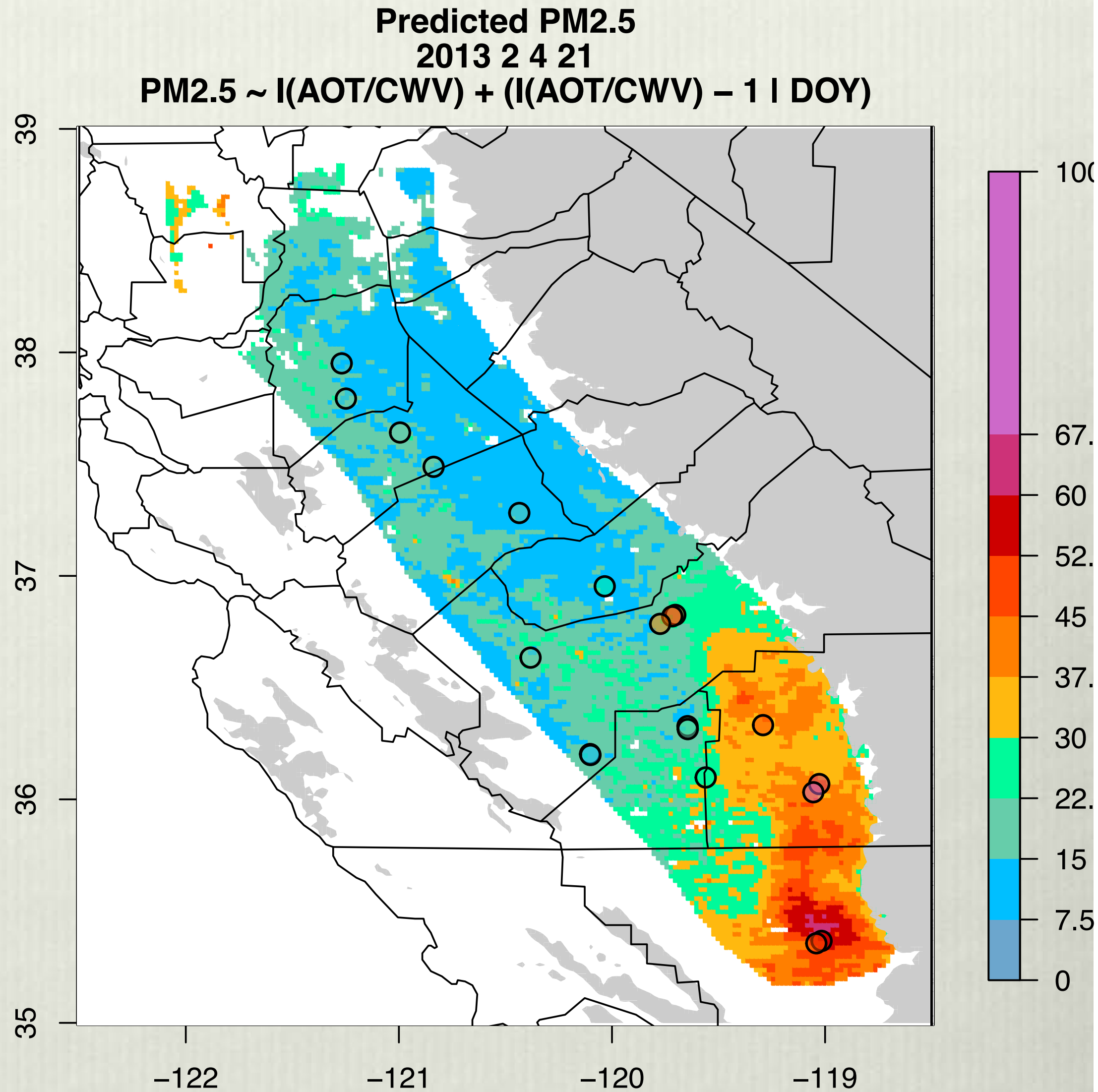
# *Estimate PM2.5 Using Mixed Effects Models*

**Robert Chatfield[1], Meytar H. Sorek[1]**
**[1]NASA Ames Research Center**

Using MAIAC Aerosol Optical Thickness and Water Vapor

Shown is a map of a major smog-aerosol episode in the San Joaquin Valley.

*Colors inside the circles show that $PM_{2.5}$ stations are generally close to the mapped values, within rms error.*




For the winter, 11/2012–03/2013
Area-wide estimation of $PM_{2.5}$, in μg m$^{-3}$
at 1 km resolution, has …

*rms residual error* = 7.3 μg m$^{-3}$ *and*
$R^2$ = 0.73

**Limitations**:
*accuracy of satellite AOT, CWV,*
*also very local effects*
*and peculuarities of the reference method (e.g. response to volatiles)*

*Mixed effects constrained by **many stations***

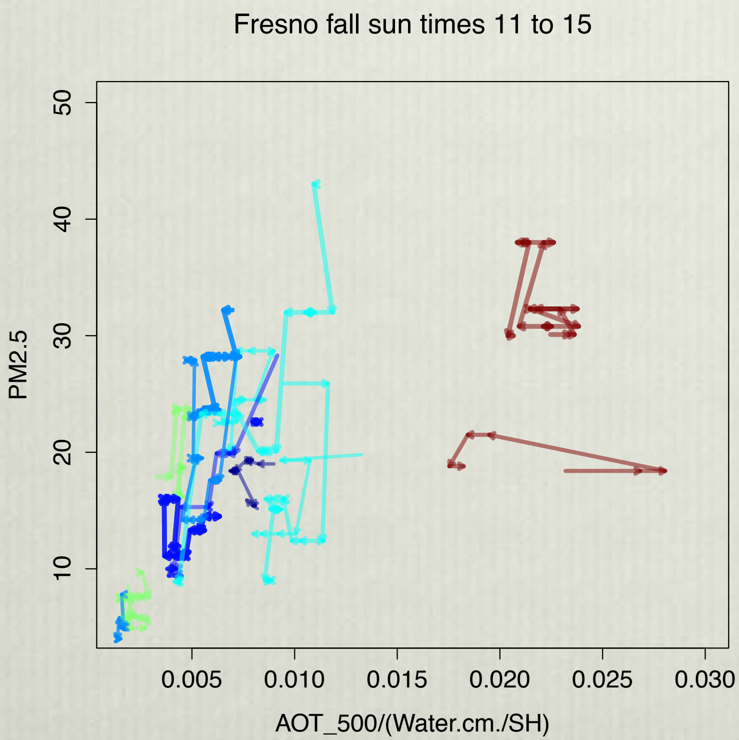
***Chatfield and Sorek-Hamer, AWMA 2018 submitted***

*GEO instruments allow Mixed Effects Models to beconstrained by **observations many times of day***
*(multiple observations help distinguish "signal" from "noise")*

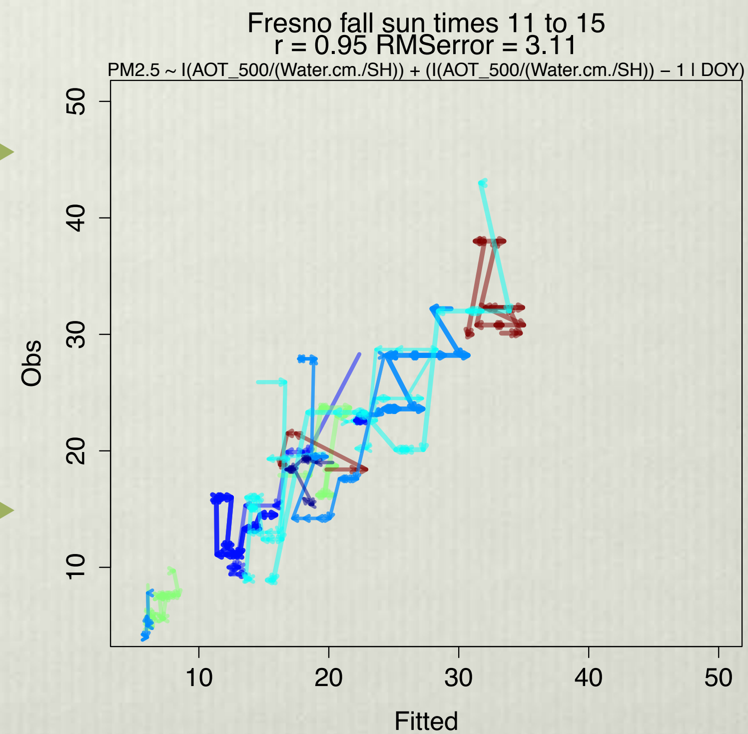
Arrows showing time variation of the predictor and PM2.5
By making a separate calibration each day, the accuracy improves (bottom right)
*Why one day?* Meteorology (subsidence, winds, mixing) is often correlated over a day's period, and composition is too.

**AERONET** estimates of AOT and CWV do have better precision than current MAIAC.

These ***Fresno, CA, 2007–2016*** estimates have *rms residual error of* ~3 μg $m^{-3}$ over many years and seasons rather than ~7 seen for MODIS MAIAC for this and (likely) other reasons.

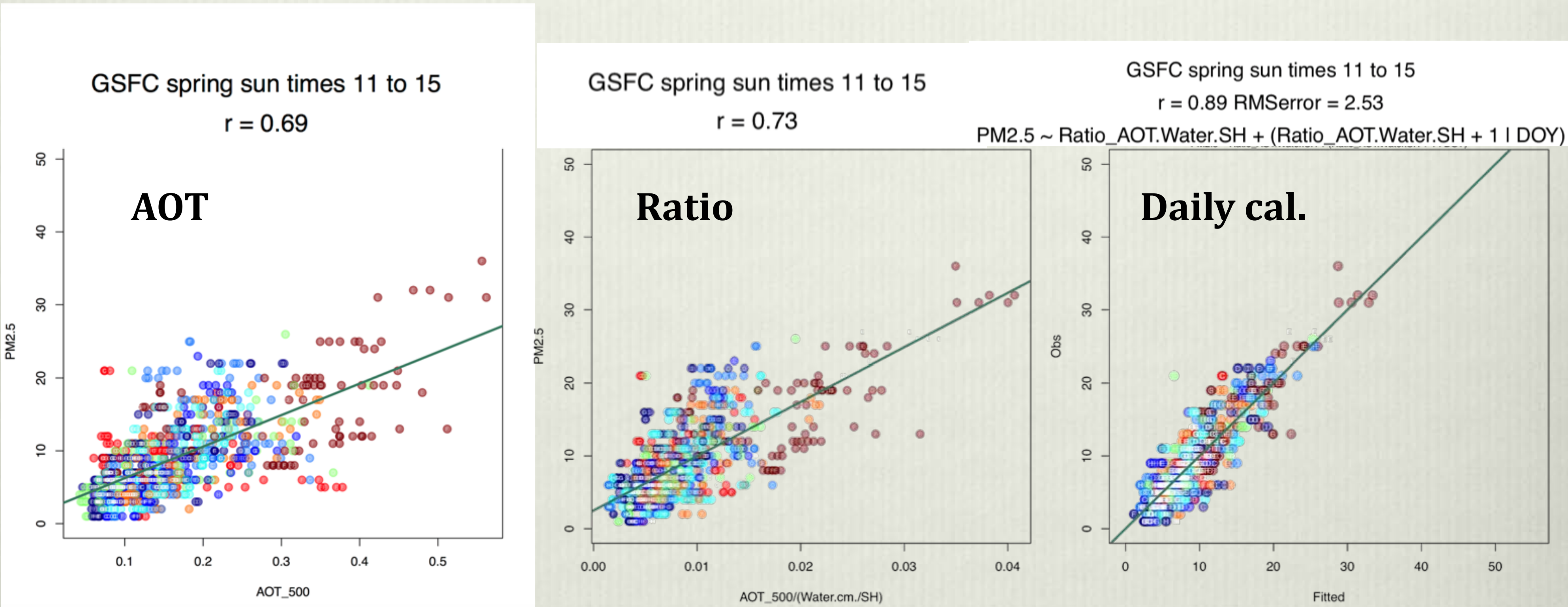



Calibrate sensitivity every day (mixed effects model)



*Note the progressive improvement as we estimate mixed depth using CWV, then use daily calibration of sensitivity*

*Comparing one AERONET at GSFC to one monitor at Beltsville, MD.*




*Moving from afternoon hours comparison shown (fully mixed PBL) to **all** hours of observation, ... still remarkably good results.*

**i.e, 0.63 (AOT) -> 0.69 (Ratio) -> 0.82 (fitted)**

*(Why? There should be layers not mixing to surface.)*

***Limitations of multiple observations per day***

As we have seen, there is variation during the day, especially RH and very local processes adding new particles to several-day loadings.

A definition of "homogenous region" is needed to make maps for each part of the country.

***Benefits***:

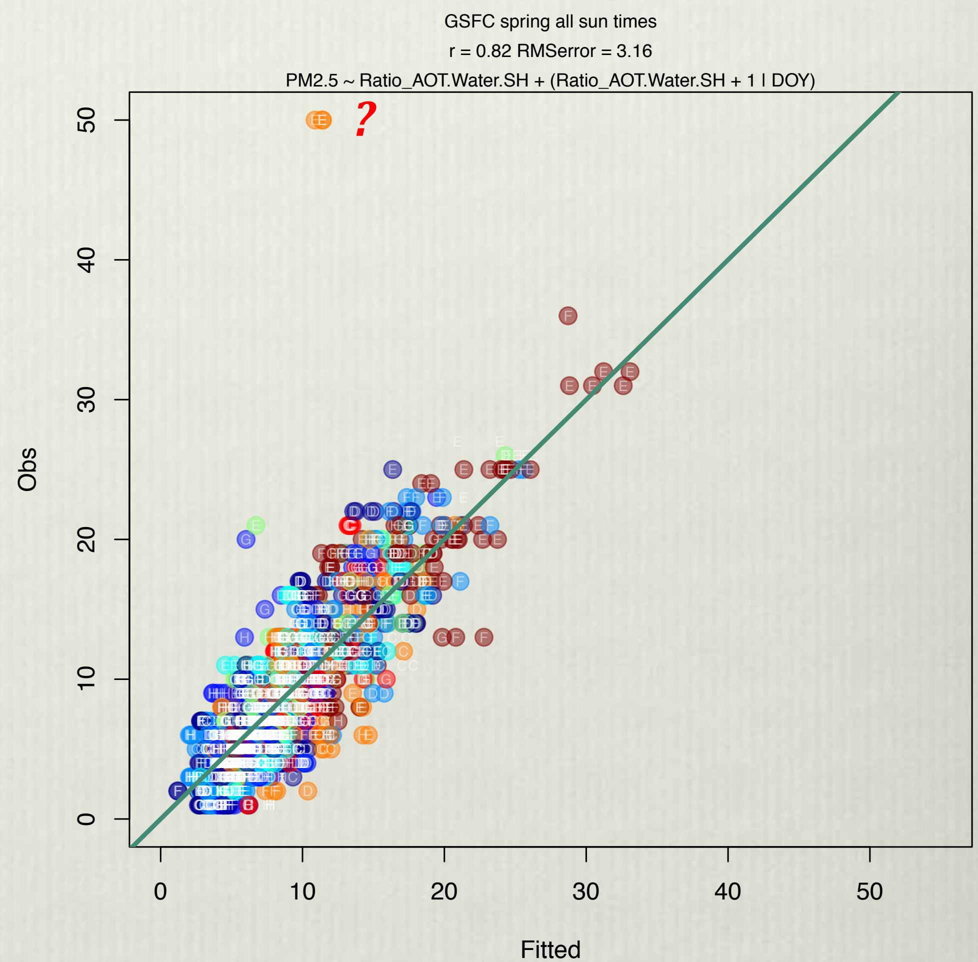
Although detailed GEO imagery *may* ***not*** *(yet!)* ***improve*** *our desired within-day estimation* of $PM_{2.5}$ variation,
the additional observations ***may still help*** *distinguish signal from noise day to day*.

***TEMPO CWV*** will aid in these regions;

For *these* regions, there is a ***correlated history*** of water input and then particle (precursor) input, with correlated mixing patterns.
***Not always true:*** in those cases, use whole meteorological PBL cycle carefully.

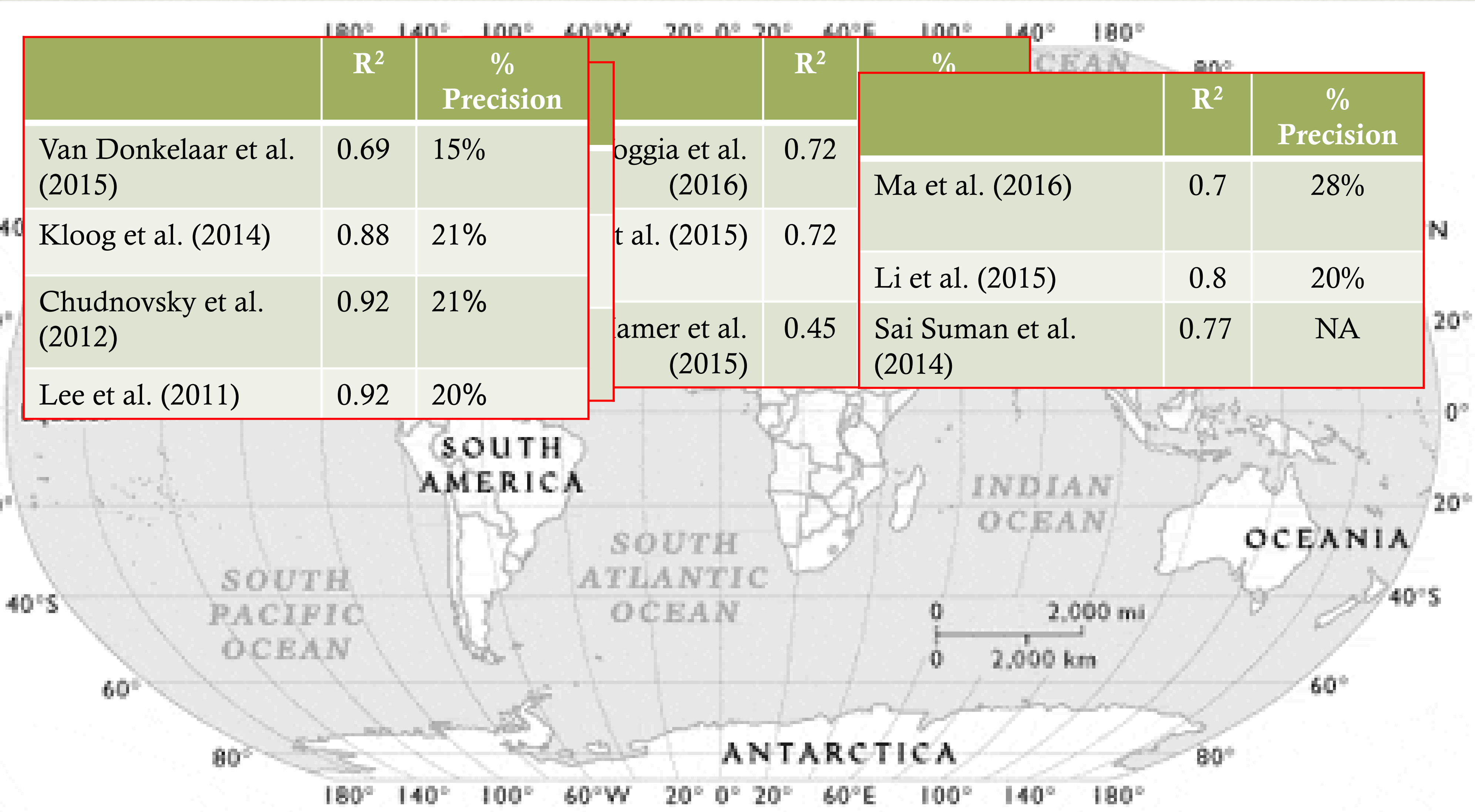
***GSFC / Beltsville, MD, 2007–2016***

also provides good relationships, although we know not all aerosol layers mix to the surface. (Need to understand theory.)




(Colors of points help allow us to identify the year and date of observation.)
Changes during one day are not obvious.

# Sample of Current Research Around the World




| | $R^2$ | % Precision |
|---|---|---|
| Van Donkelaar et al. (2015) | 0.69 | 15% |
| Kloog et al. (2014) | 0.88 | 21% |
| Chudnovsky et al. (2012) | 0.92 | 21% |
| Lee et al. (2011) | 0.92 | 20% |

| | $R^2$ | % |
|---|---|---|
| oggia et al. (2016) | 0.72 | |
| t al. (2015) | 0.72 | |
| amer et al. (2015) | 0.45 | |

| | $R^2$ | % Precision |
|---|---|---|
| Ma et al. (2016) | 0.7 | 28% |
| Li et al. (2015) | 0.8 | 20% |
| Sai Suman et al. (2014) | 0.77 | NA |

*Sorek-Hamer, HAQAST 2018*