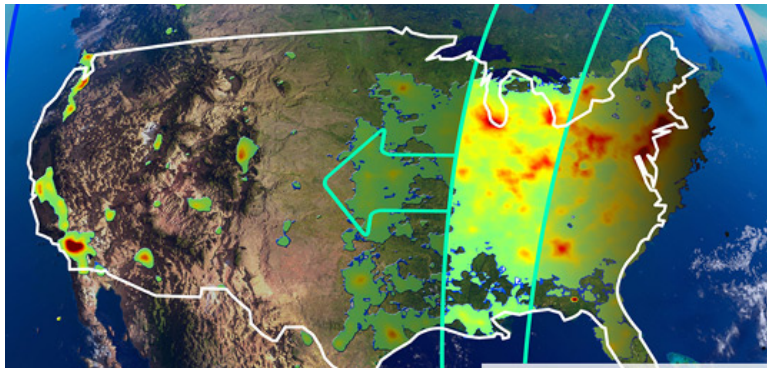


TEMPO: The future of space-based air pollution observations



Peter Zoogman

Harvard-Smithsonian Center for Astrophysics

Thanks to: D.J. Jacob, K. Chance, X. Liu, M. Lin, A.M. Fiore, K. Travis, L. Zhang, P. Le Sager, A. Eldering, V. Natraj, S.S. Kulawik

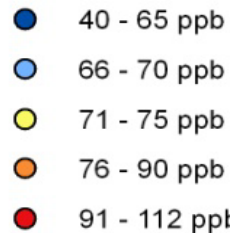
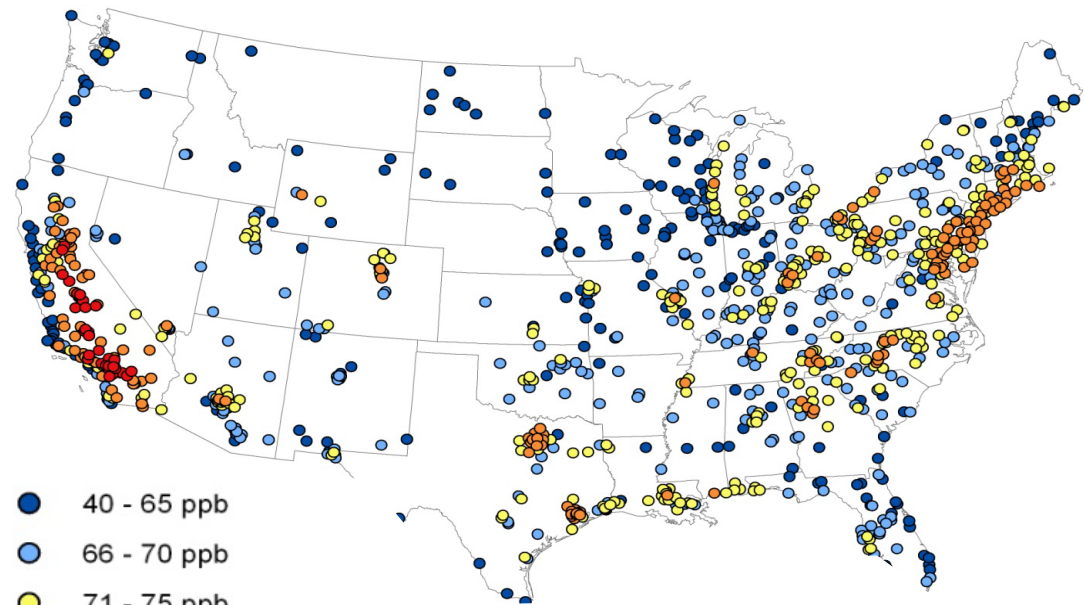
MIT MASS Seminar

September 15, 2014

Ozone pollution is a national problem

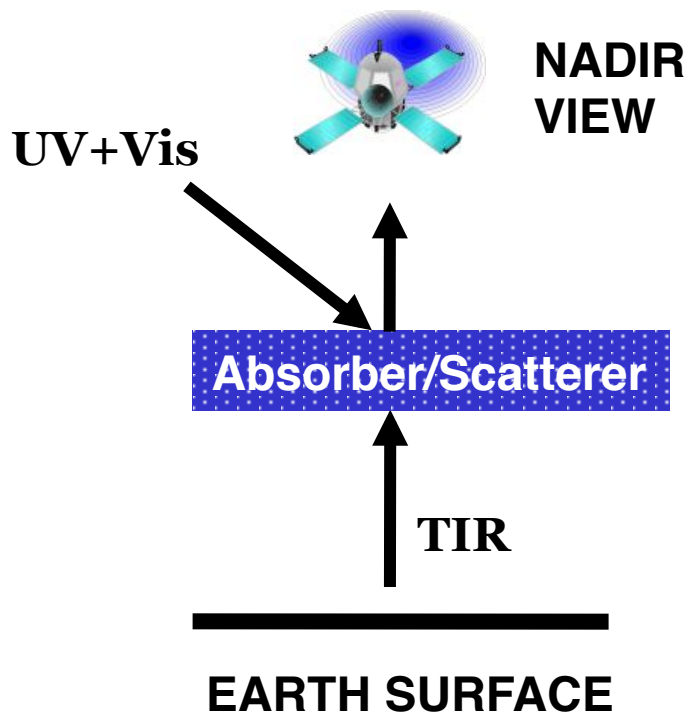
- Ozone in surface air is harmful to human health
- Surface ozone also causes crop damage
- MDA8 = maximum daily 8-hour average ozone

4th-highest annual maximum daily 8-hour ozone, 2008-2010



Current standard: 75 ppb
Proposed standard: 60-70 ppb

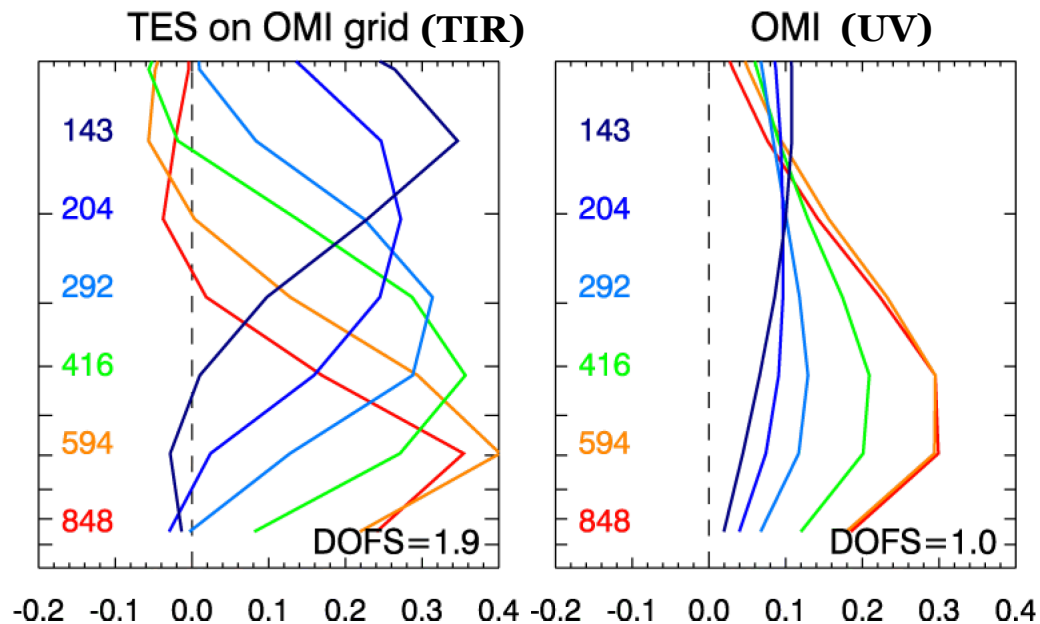
Satellite Observations of Ozone



Averaging Kernel matrix \mathbf{A} quantifies the vertical information provided by a satellite retrieval

$$\mathbf{x}' = \mathbf{x}_a + \mathbf{A}(\mathbf{x} - \mathbf{x}_a) + \varepsilon$$

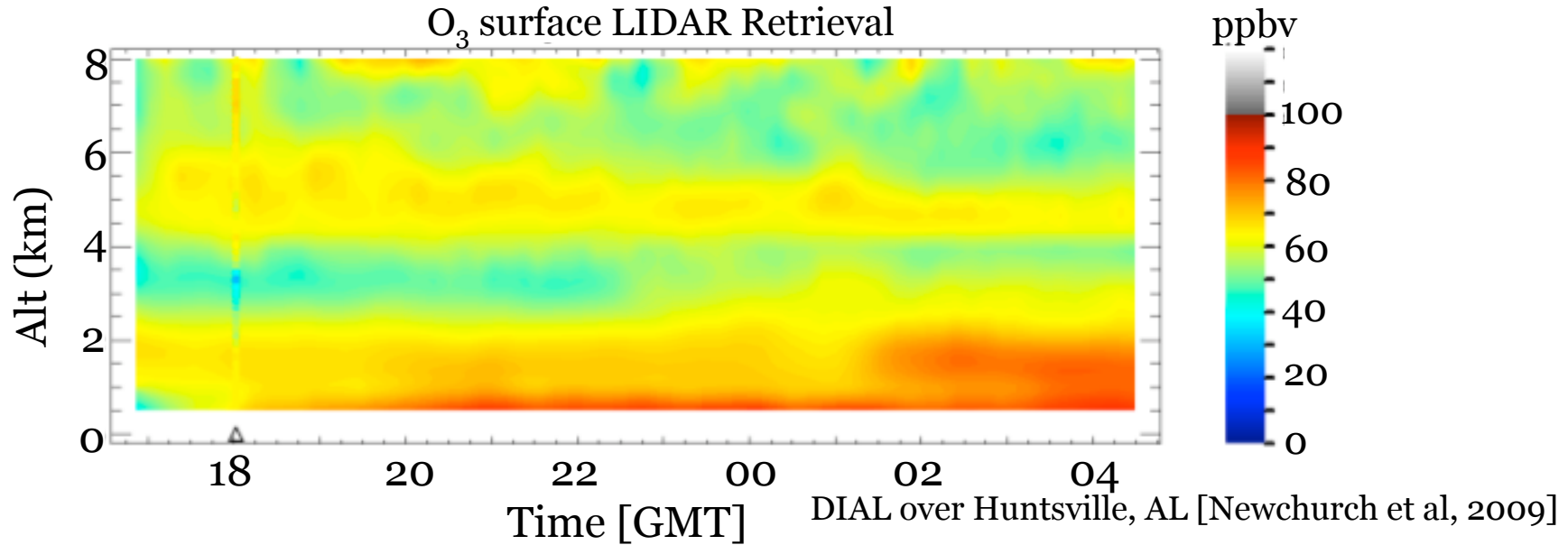
$$\mathbf{A} = \frac{\partial \mathbf{x}'}{\partial \mathbf{x}}$$



[Zhang et al. 2010]

The Difficulty of Ozone Air Quality from Space

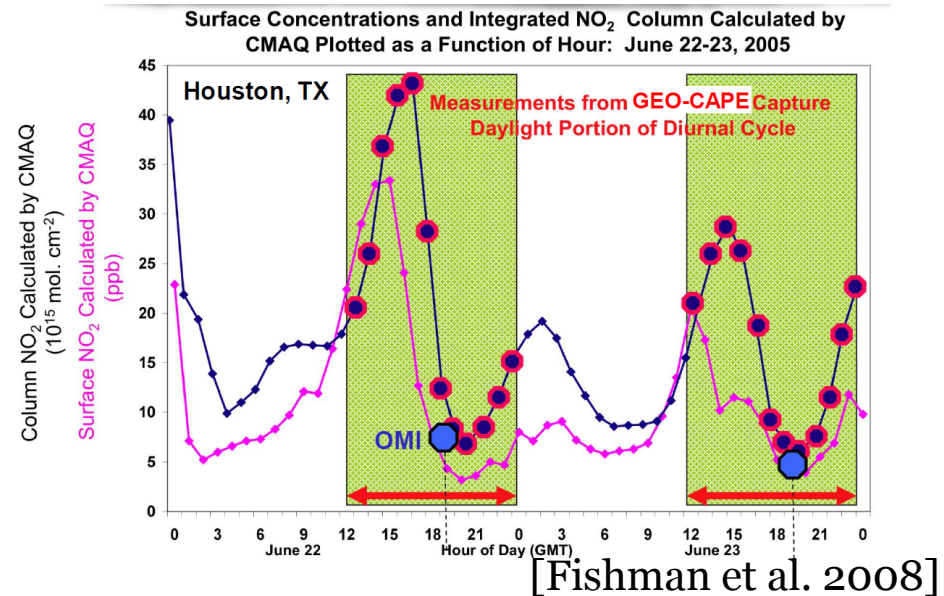
- Ozone concentrations very heterogeneous both spatially and temporally



Ozone chemistry complex and non-linear

Short timescales → large diurnal variation

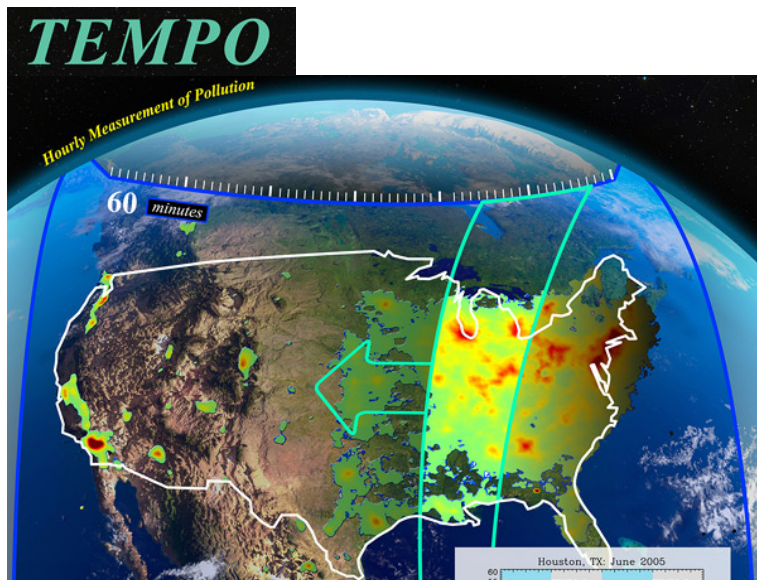
NAS/EPA: current ground/sonde network inadequate for air quality monitoring



Observations from TEMPO

Features:

- High temporal resolution
- Multispectral observations for increased vertical information
 - 290-490 nm (UV)
 - 540-740 nm (Vis)

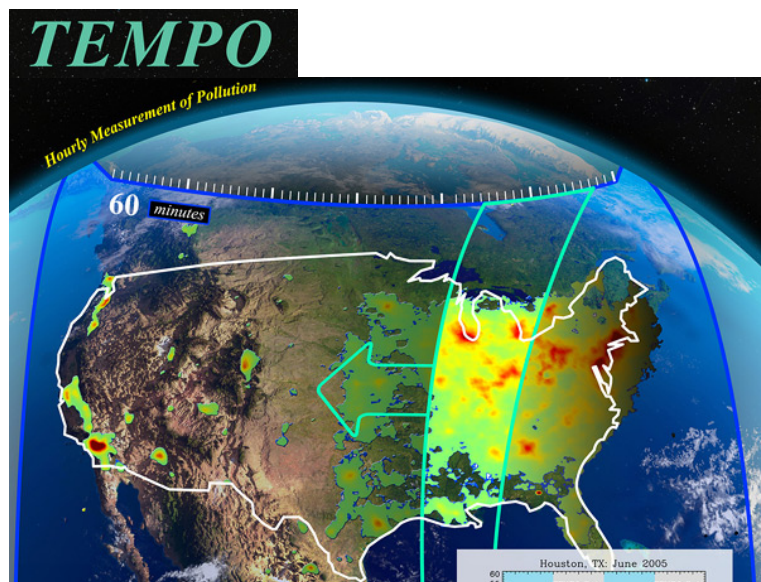


Species/Products	
O ₃ Profile	0-2 km (ppb)
	FT (ppb) ⁴
	SOC ⁴
Total O ₃	
NO ₂ *	
H ₂ CO* (3/day)	
SO ₂ * (3/day)	
C ₂ H ₂ O ₂ * (3/day)	
AOD	
AAOD	
Aerosol Index (AI)	
CF ⁴	
CTP (hPa) ⁴	

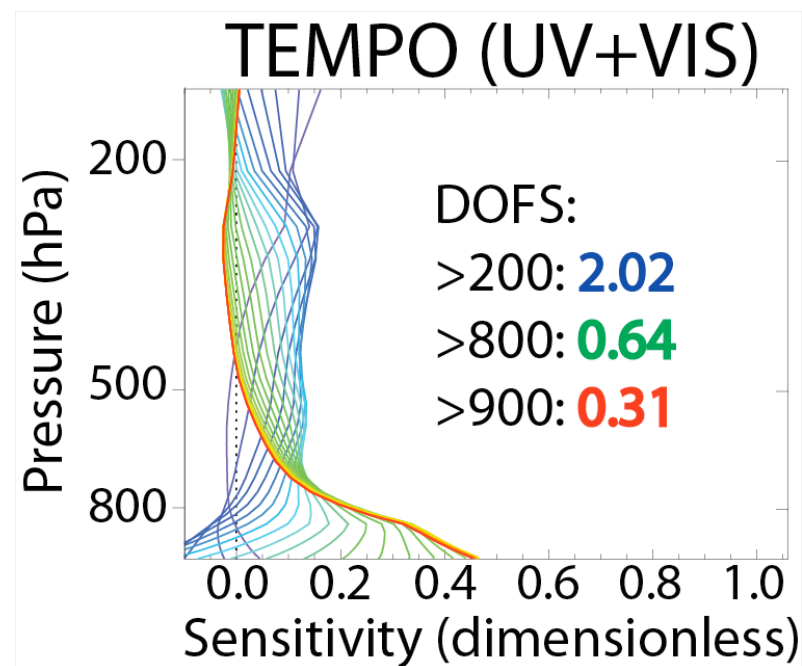
Observations from TEMPO

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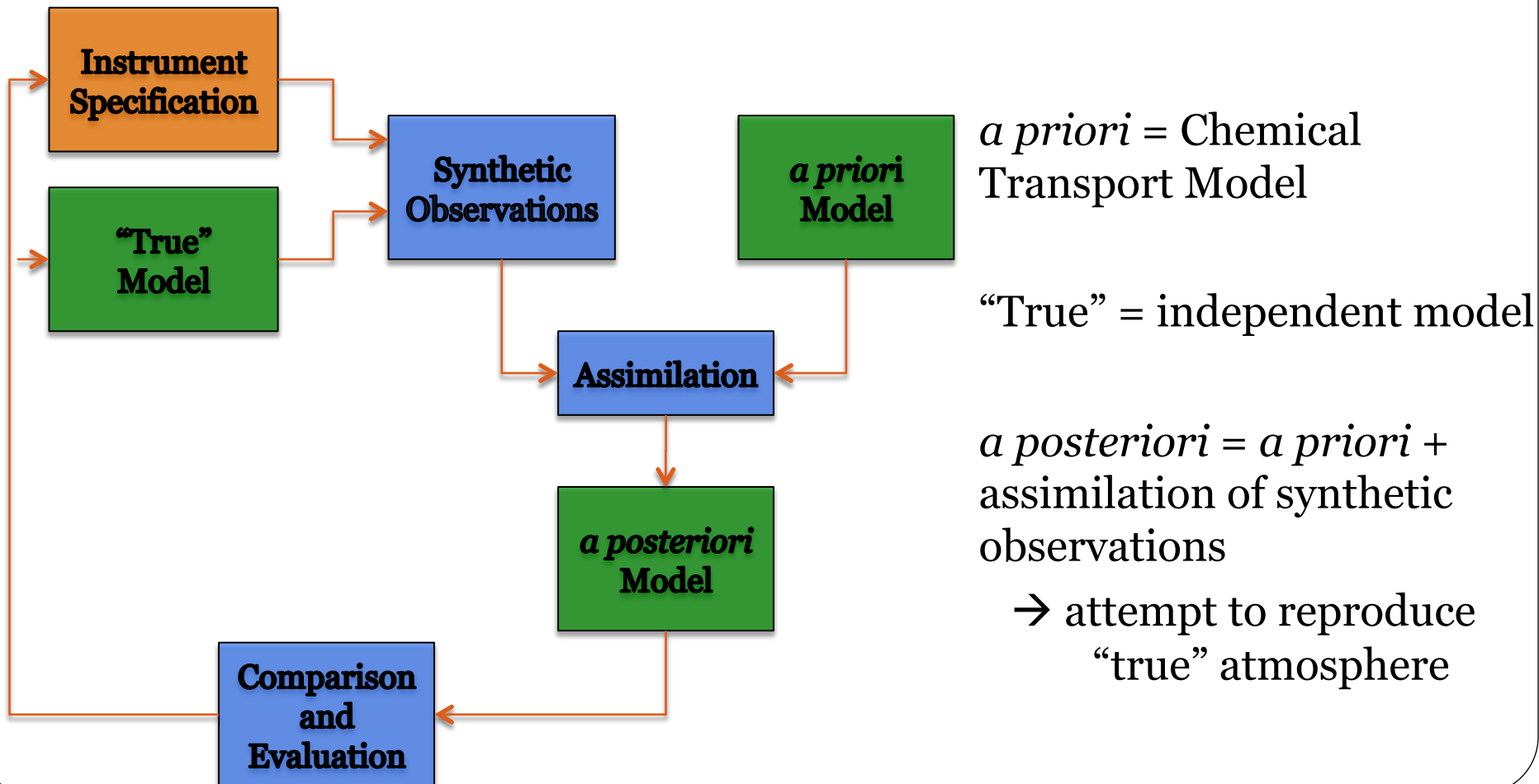
TEMPO Ozone Averaging Kernel Matrix



[Natraj et al, 2011]

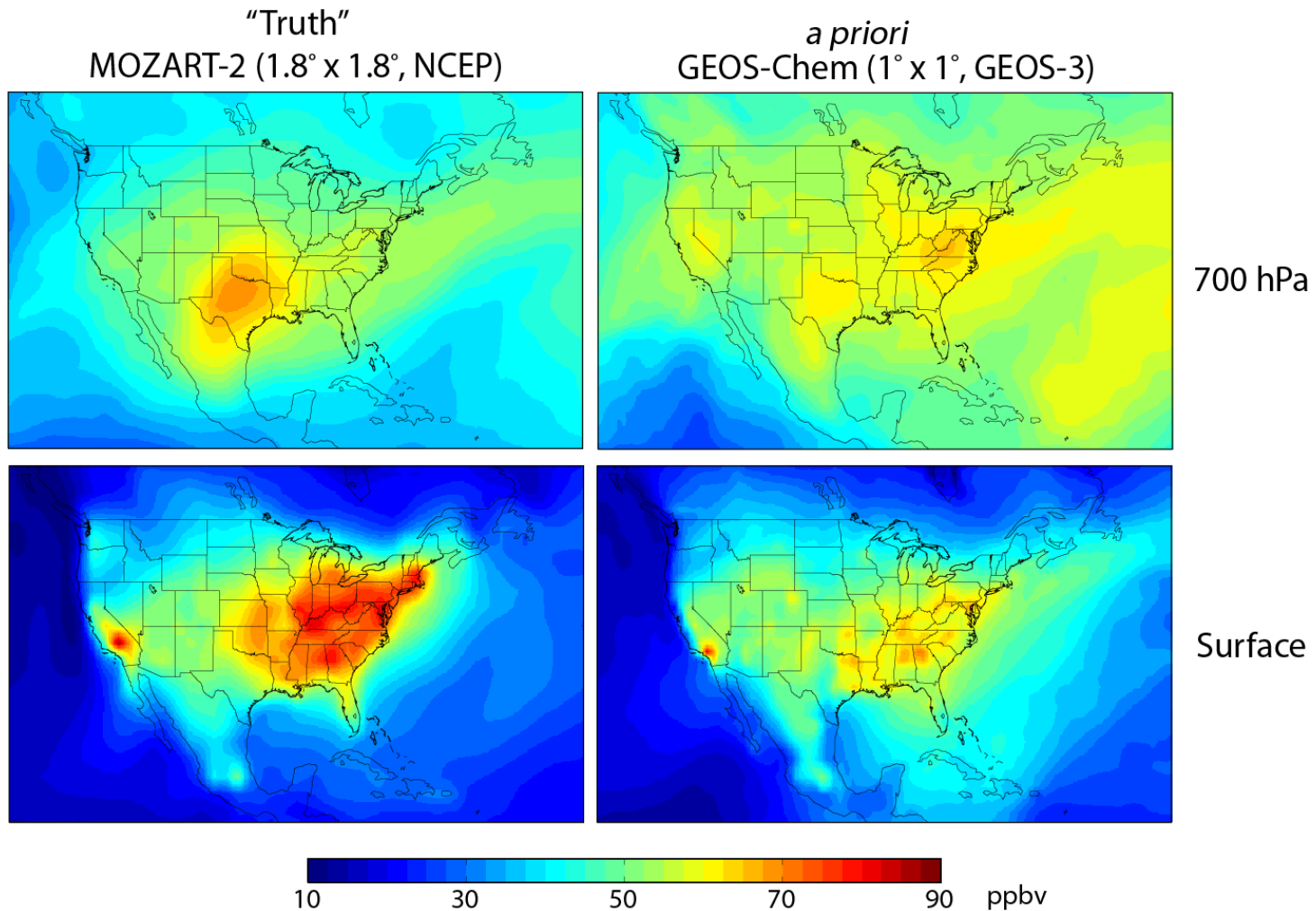
Observing System Simulation Experiment

- What additional information is provided by TEMPO on near-surface ozone?
- How will we be able to use this information for assessment and forecasting?



Simulation Models are Different

MDA8 Ozone averaged for July 2001

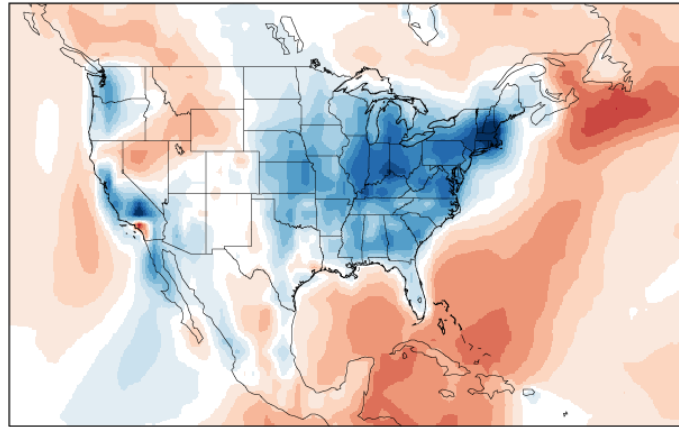


- “Truth” and GEOS-Chem have different:
Meteorology, Chemistry, Emissions

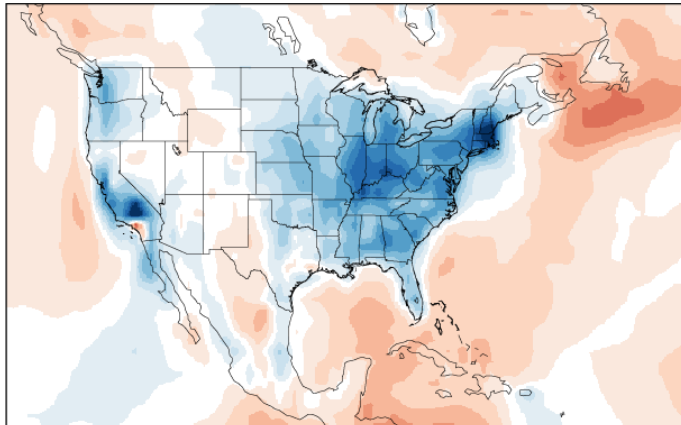
Air Quality Information from GEO

Error in Surface MDA8 Ozone averaged for July 2001

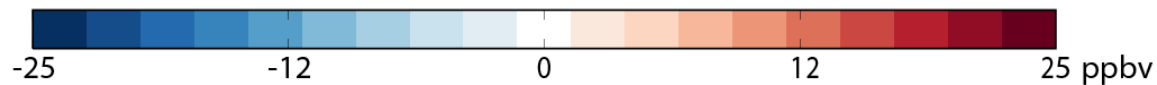
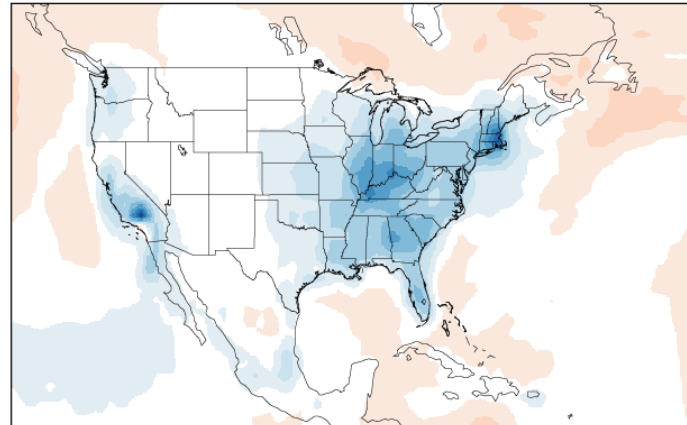
a priori RMSE: 8.0 ppbv



LEO UV+Vis+TIR RMSE: 6.5 ppbv



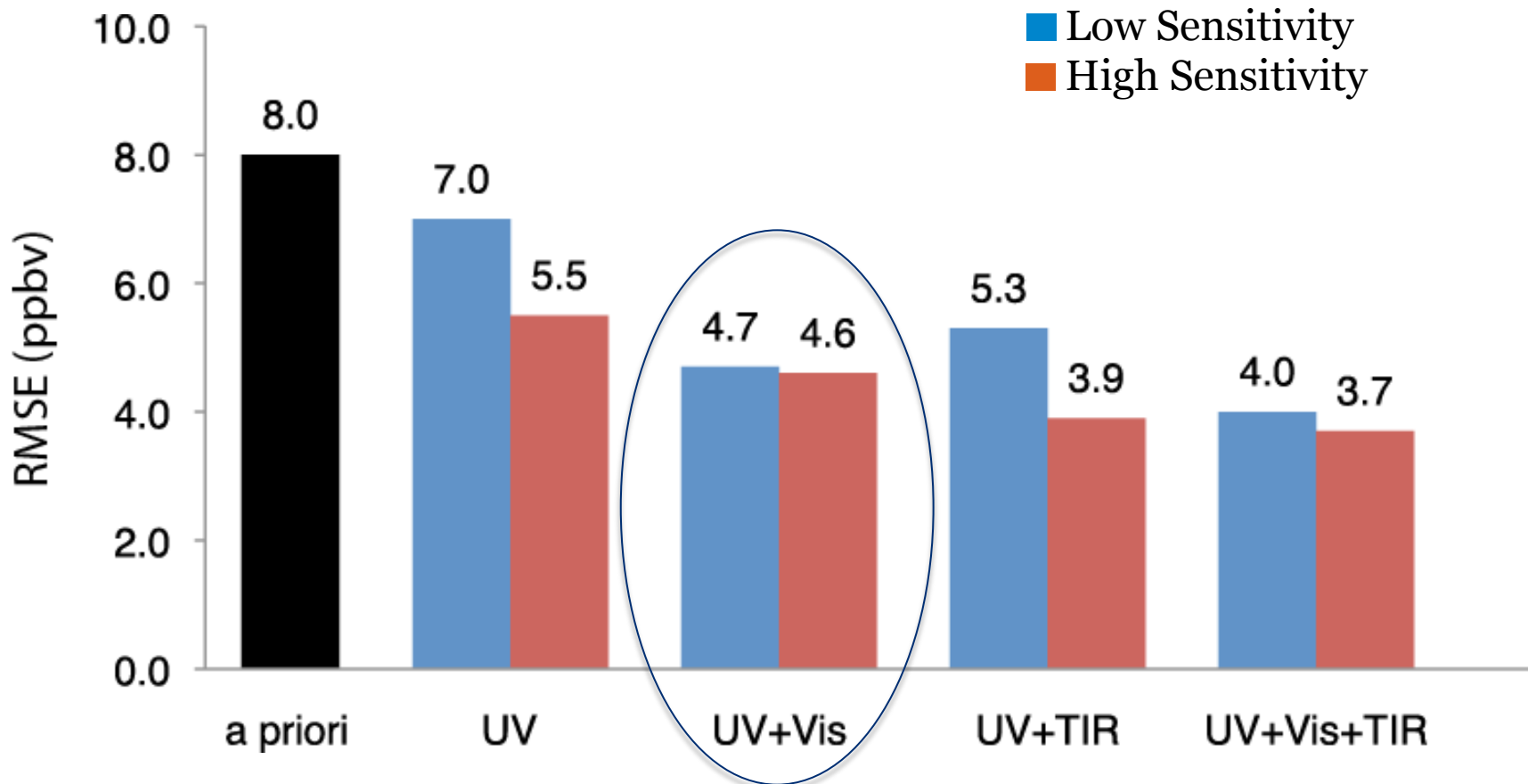
Geo UV+Vis+TIR RMSE: 3.7 ppbv



Need to combine observations in multiple spectral regions at high temporal resolution to constrain ozone air quality

Comparison of Spectral Combinations

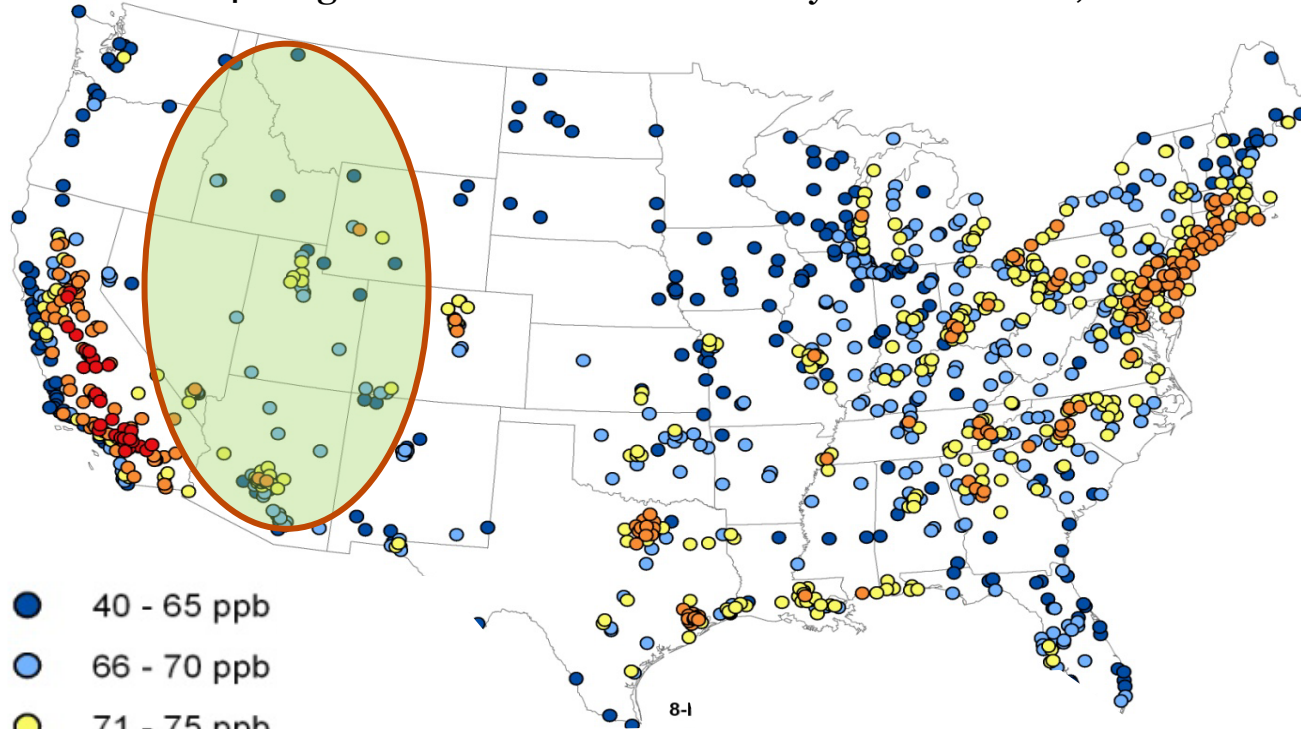
Error in ozone surface air concentration over the US after assimilation of observations in different spectral combinations



UV+Vis, UV+TIR, and UV+Vis+TIR combinations all improve greatly relative to UV alone

North American Background Ozone

4th-highest annual maximum daily 8-hour ozone, 2008-2010

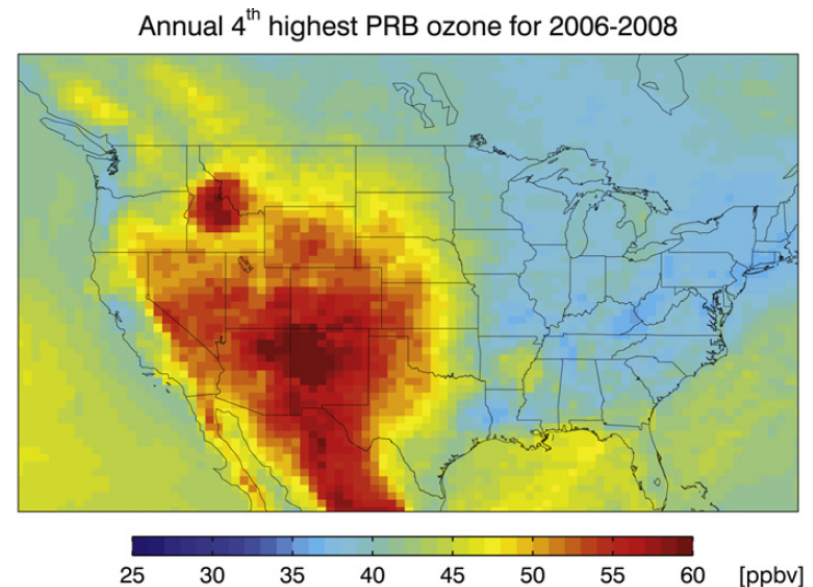
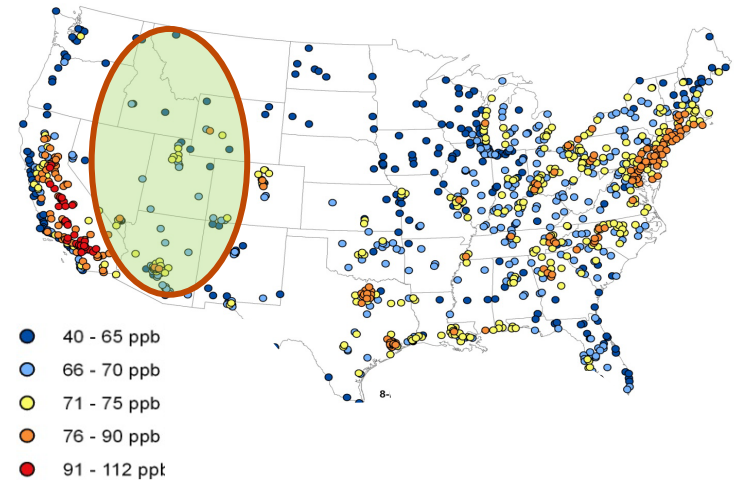


- 40 - 65 ppb
- 66 - 70 ppb
- 71 - 75 ppb
- 76 - 90 ppb
- 91 - 112 ppb

Current standard: 75 ppb
Proposed standard: 60-70 ppb

North American Background Ozone

- O₃ that would occur in the absence of anthropogenic emissions in the U.S., Canada, and Mexico.
- Sets limit on levels achievable through domestic controls
- Highest in the Intermountain West

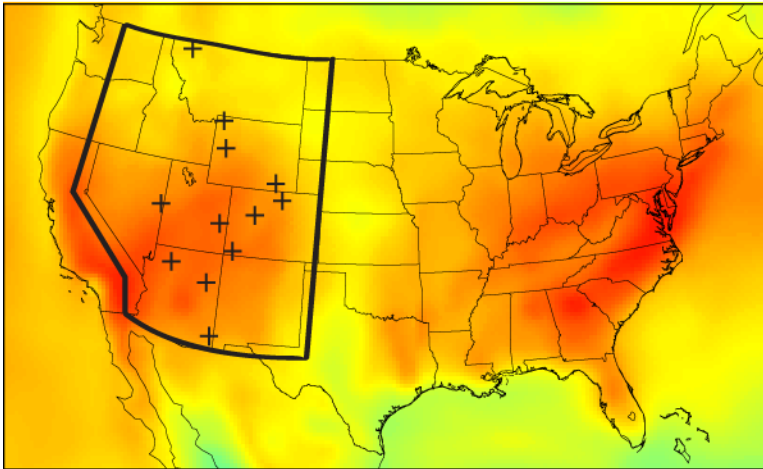


[Zhang et al. 2011]

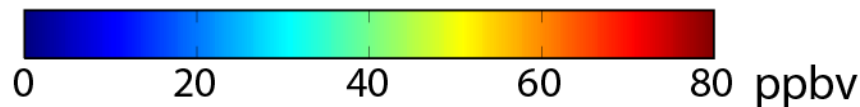
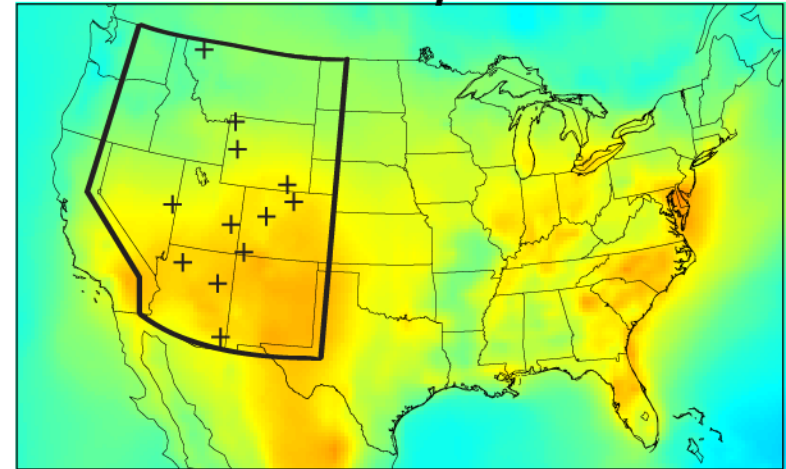
Simulation Models

Surface MDA8 Ozone averaged for April-June 2010

AM3-Chem "true" ozone



GEOS-Chem *a priori* ozone

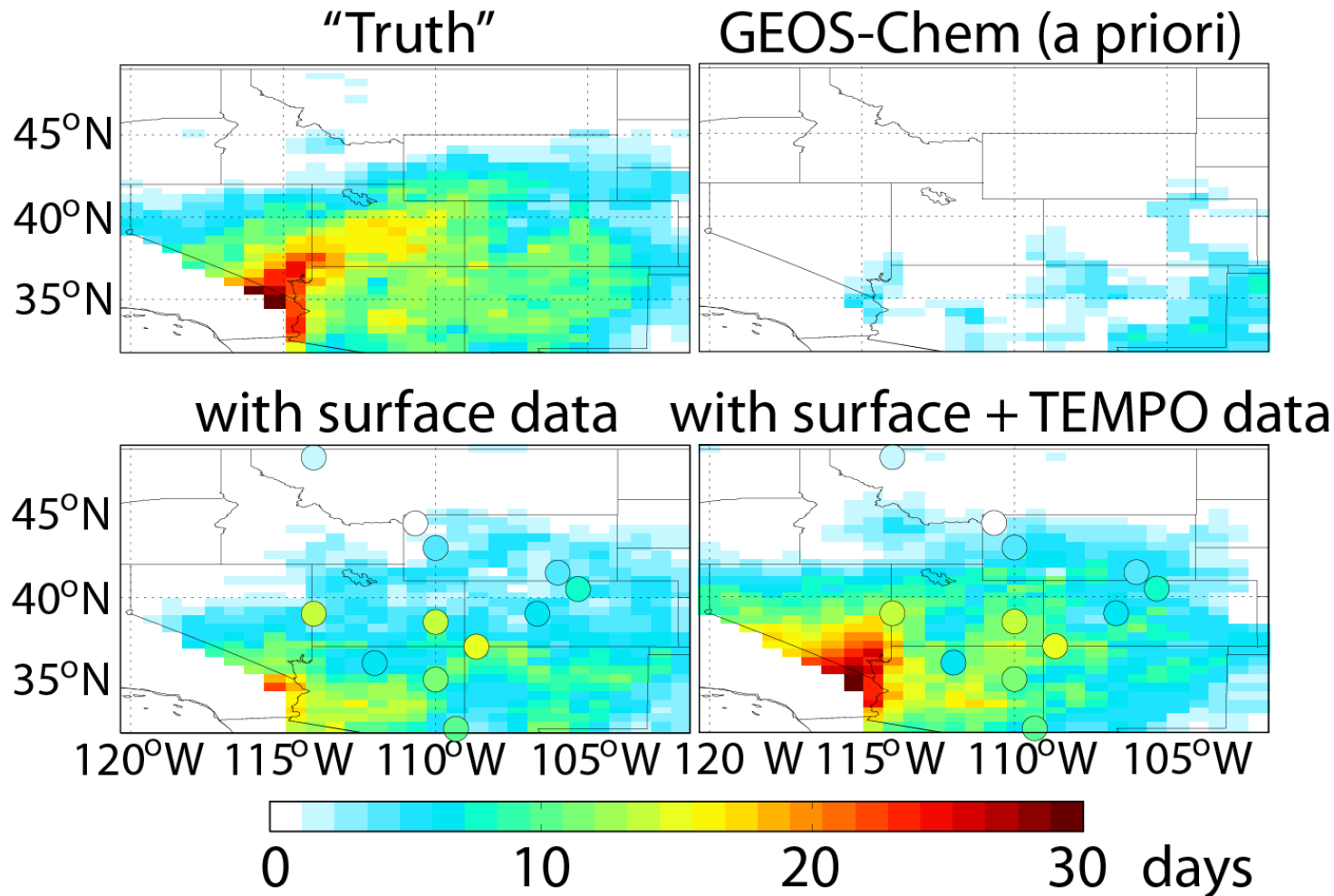


GEOS-Chem does well below 70 ppbv but cannot reproduce high-ozone events

AM3-Chem is biased high but can simulate high-ozone events

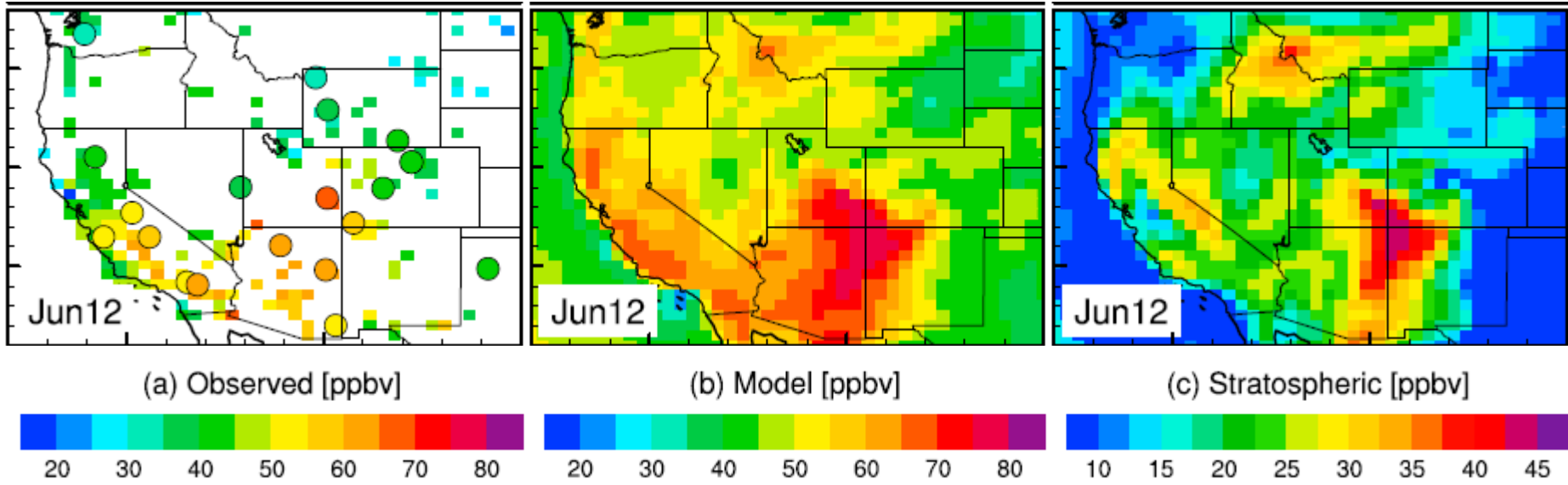
Observing high-ozone days

Number of days MDA8 ozone > 70 ppbv



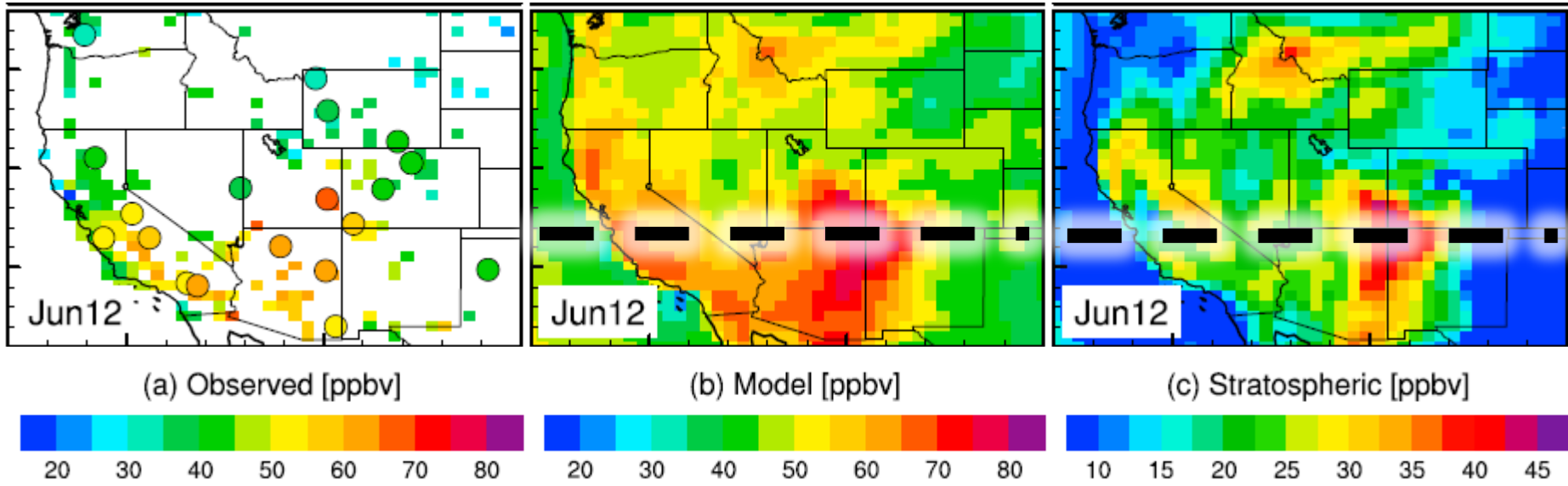
Assimilation of surface measurements does not fully correct bias or spatial pattern
Adding TEMPO observations fully corrects bias and captures most of the distribution

Seeing a Stratospheric Intrusion



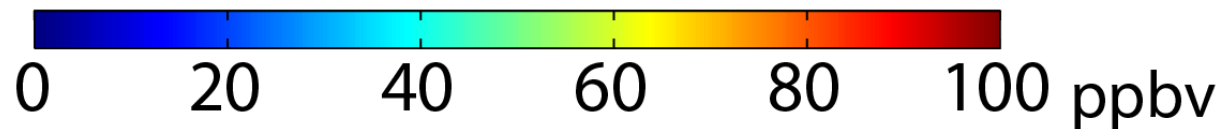
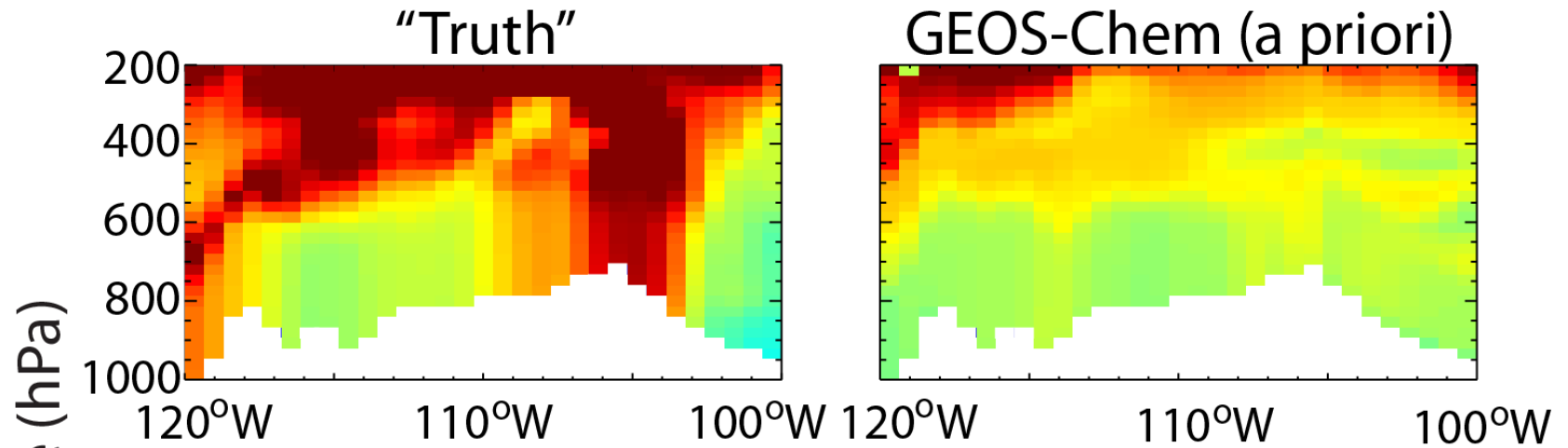
[Lin et al. 2012]

Seeing a Stratospheric Intrusion

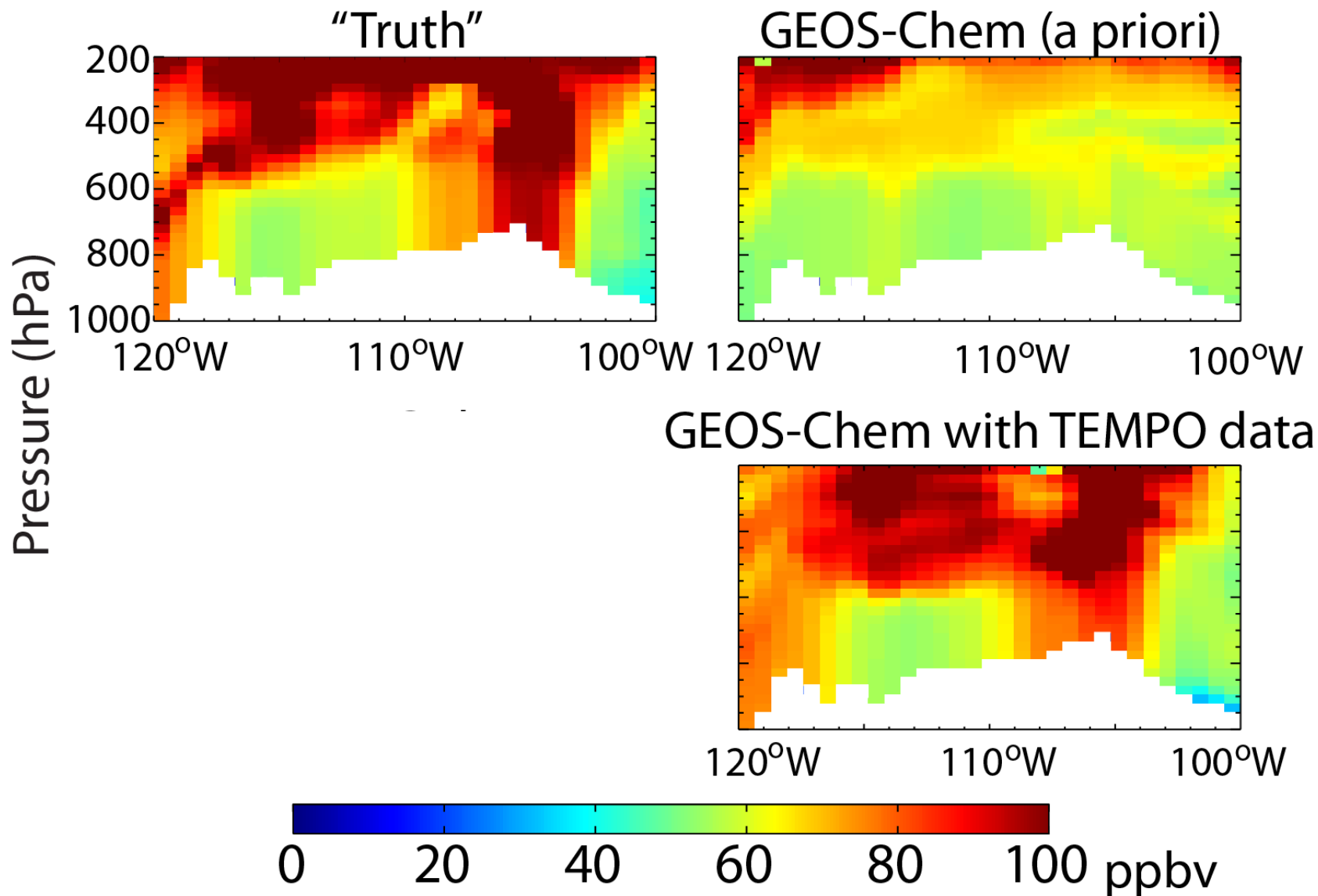


[Lin et al. 2012]

Seeing a Stratospheric Intrusion

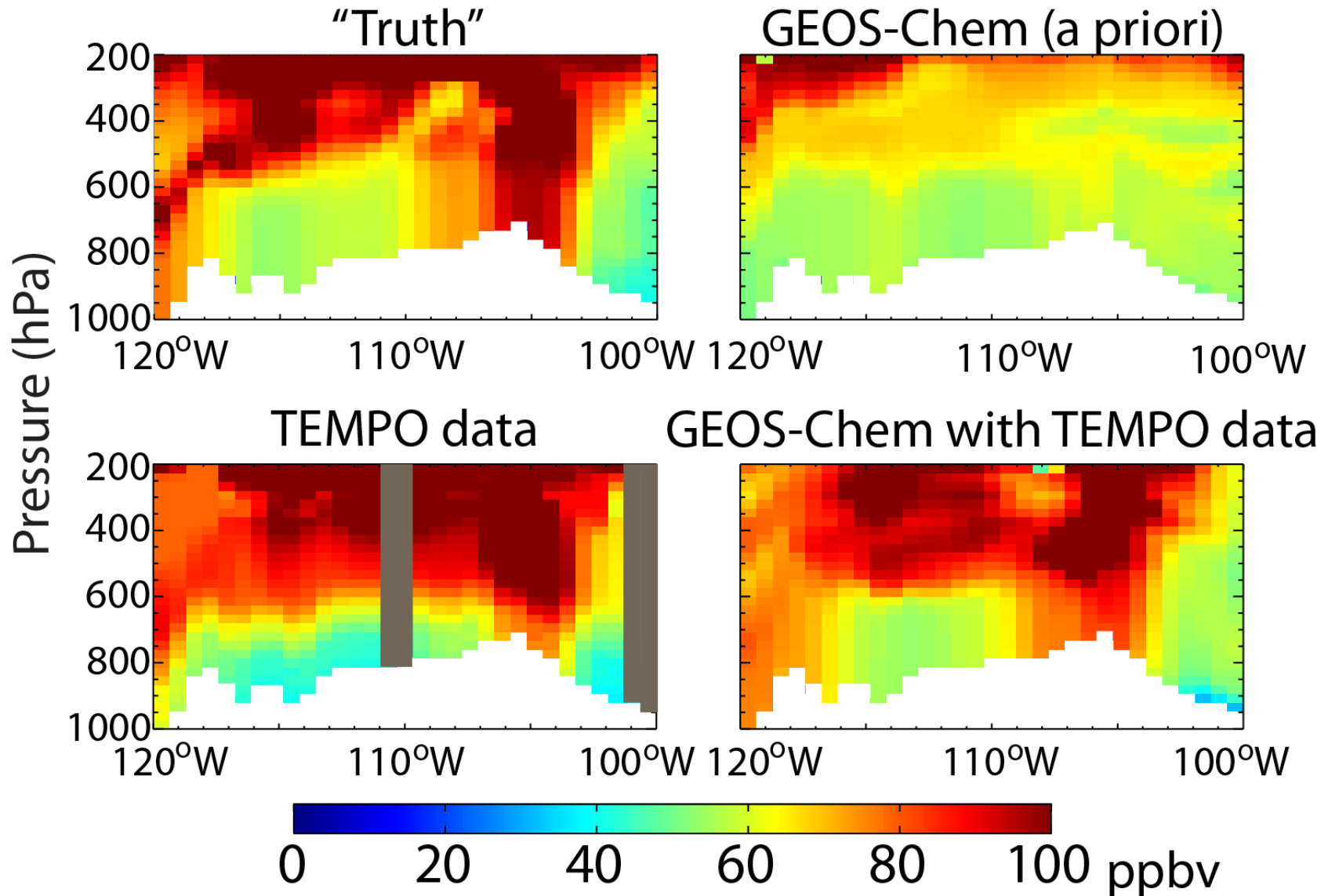


Seeing a Stratospheric Intrusion



Assimilation of TEMPO observations into GEOS-Chem recaptures structure of intrusion

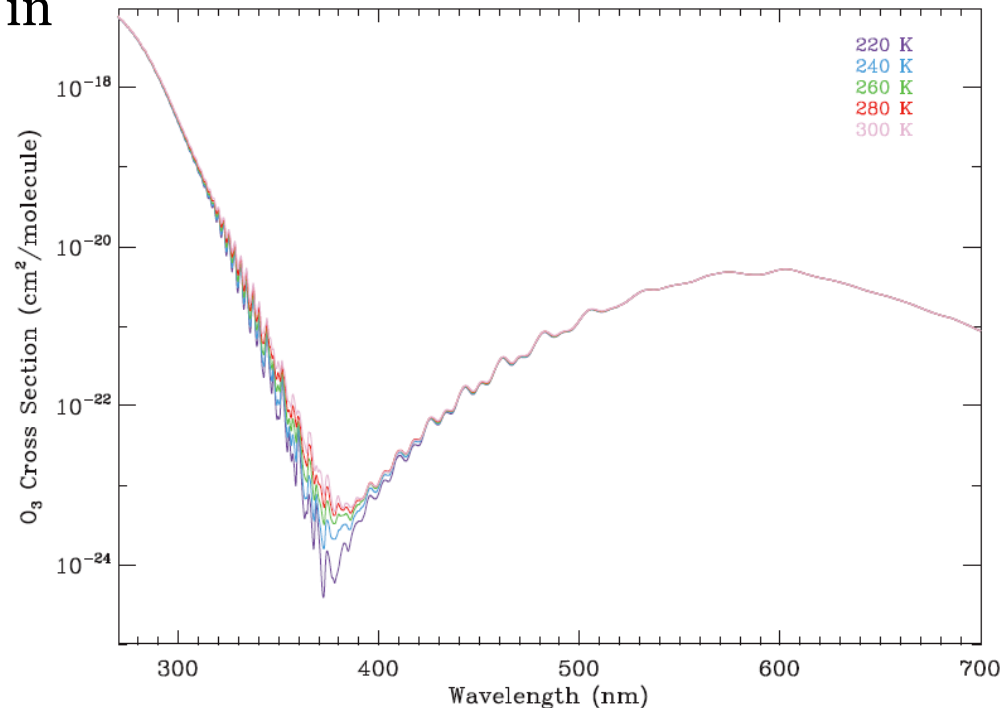
Seeing a Stratospheric Intrusion



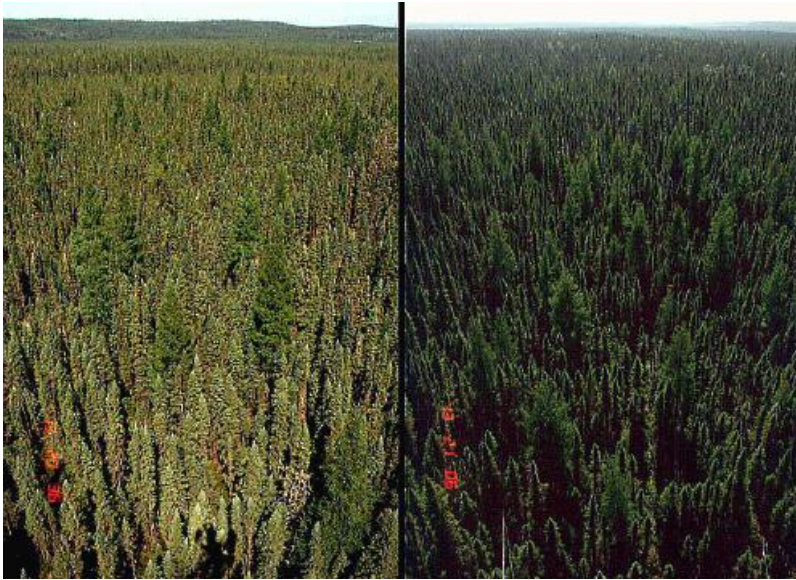
Assimilation of TEMPO observations into GEOS-Chem recaptures structure of intrusion

Ozone absorption in the Visible

- Ozone has weak spectral features in the Chappuis band (~500 – 700 nm)
- Since the atmosphere is optically thin in the visible, can get information near the surface
- But retrieval is more sensitive to errors in radiative transfer model
 - Example → **surface reflectance**



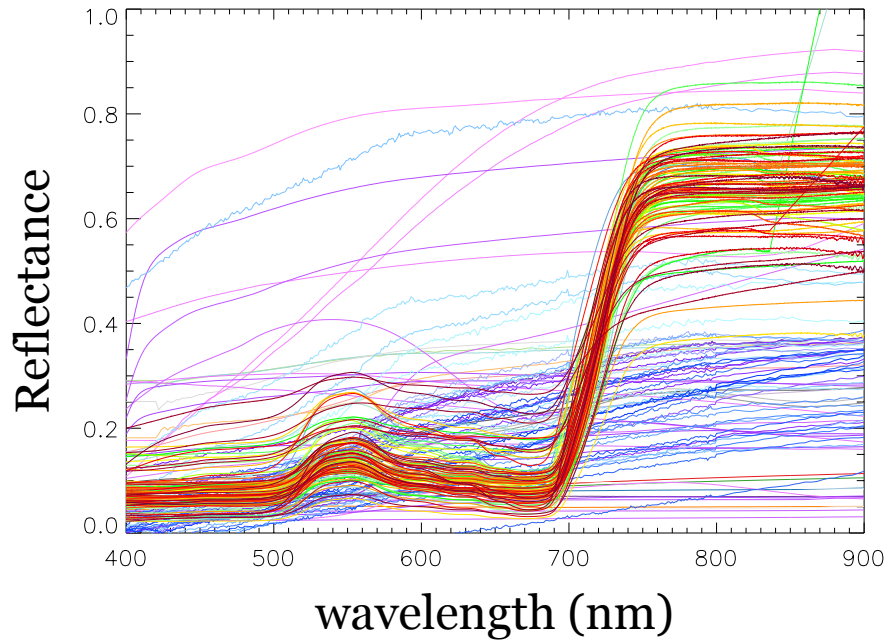
Surface Reflectance in the Visible



Pictures by Don Deering

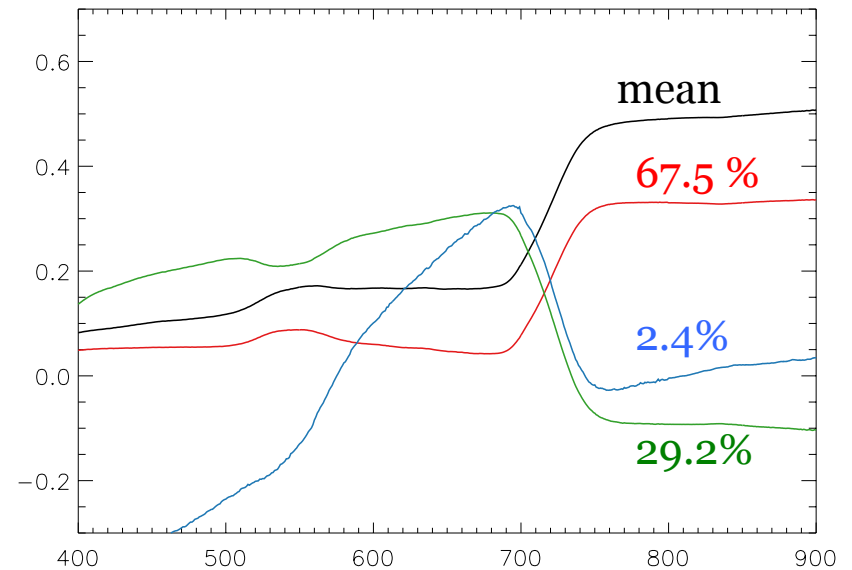
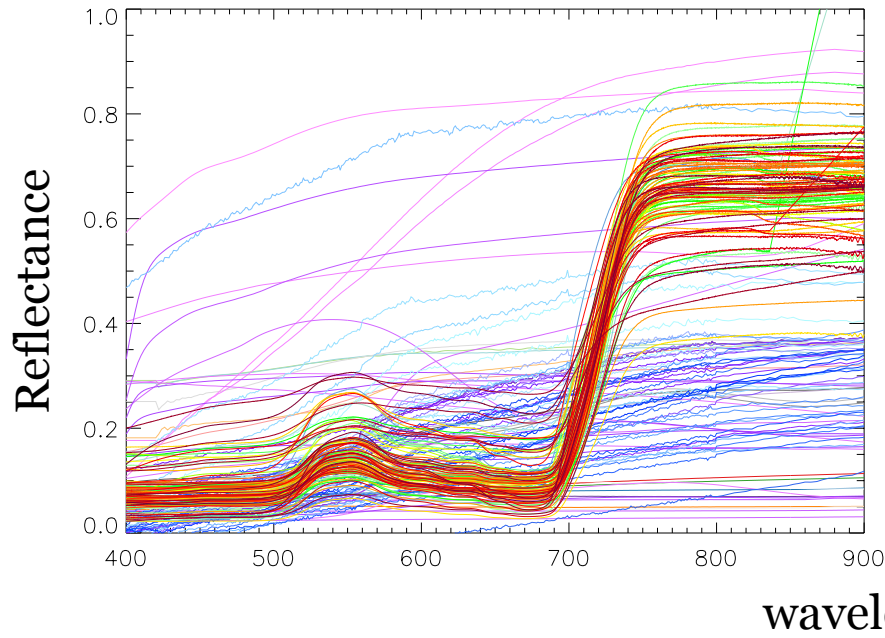
- Spectral variation
- Dependence on land cover
- Changes with viewing geometry

Reflectance Spectra by Surface Type



- Obtained lab spectra of possible ground cover
 - Includes vegetation, soils, rocks, manmade materials

Reflectance Spectra by Surface Type

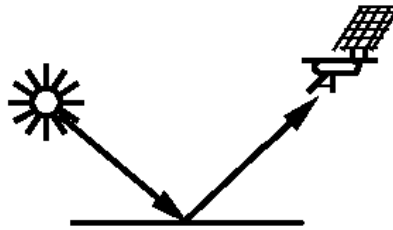


- Obtained lab spectra of possible ground cover
 - Includes vegetation, soils, rocks, manmade materials

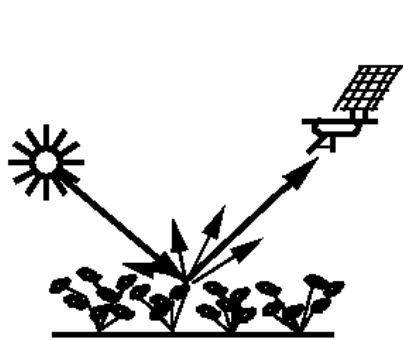
- Found 1st 3 EOFs capture >99% of the spectral variation

Effect of Viewing Geometry

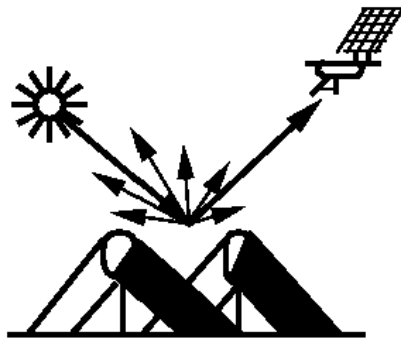
Bidirectional Reflectance Distribution Functions: Causes



Mirror BRDF:
specular reflectance



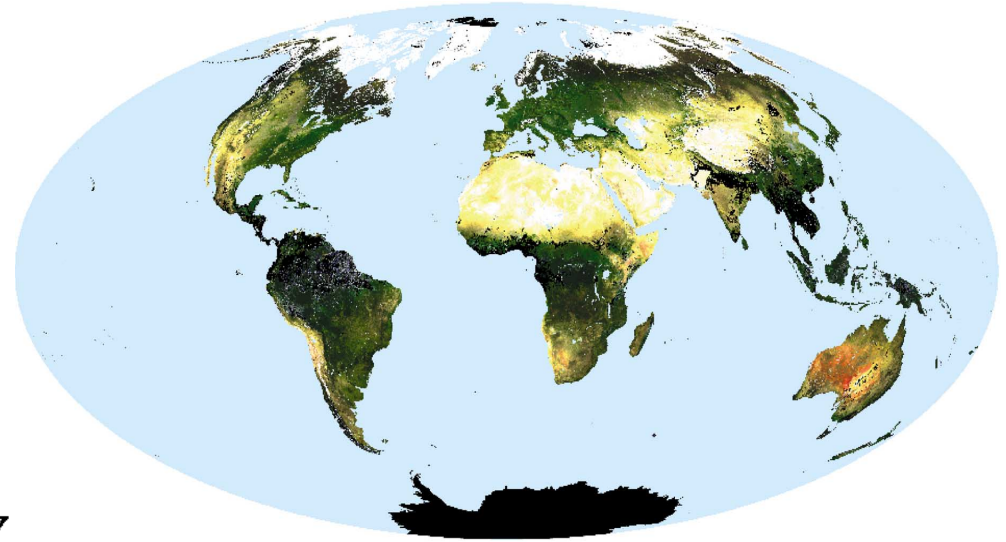
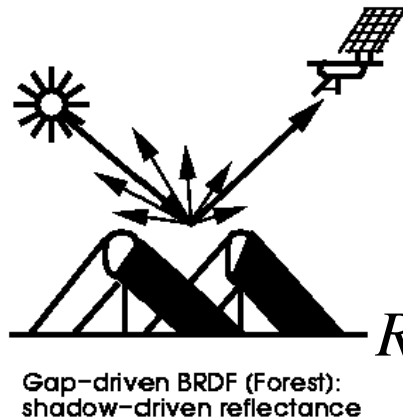
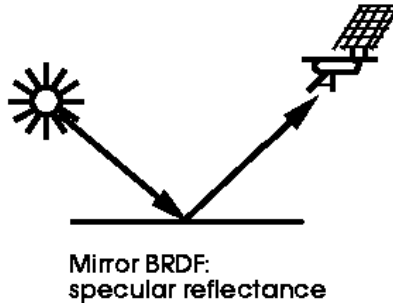
Volume scattering BRDF:
leaf/vegetation reflectance



Gap-driven BRDF (Forest):
shadow-driven reflectance

Viewing Geometry from MODIS

Bidirectional Reflectance
Distribution Functions: Causes

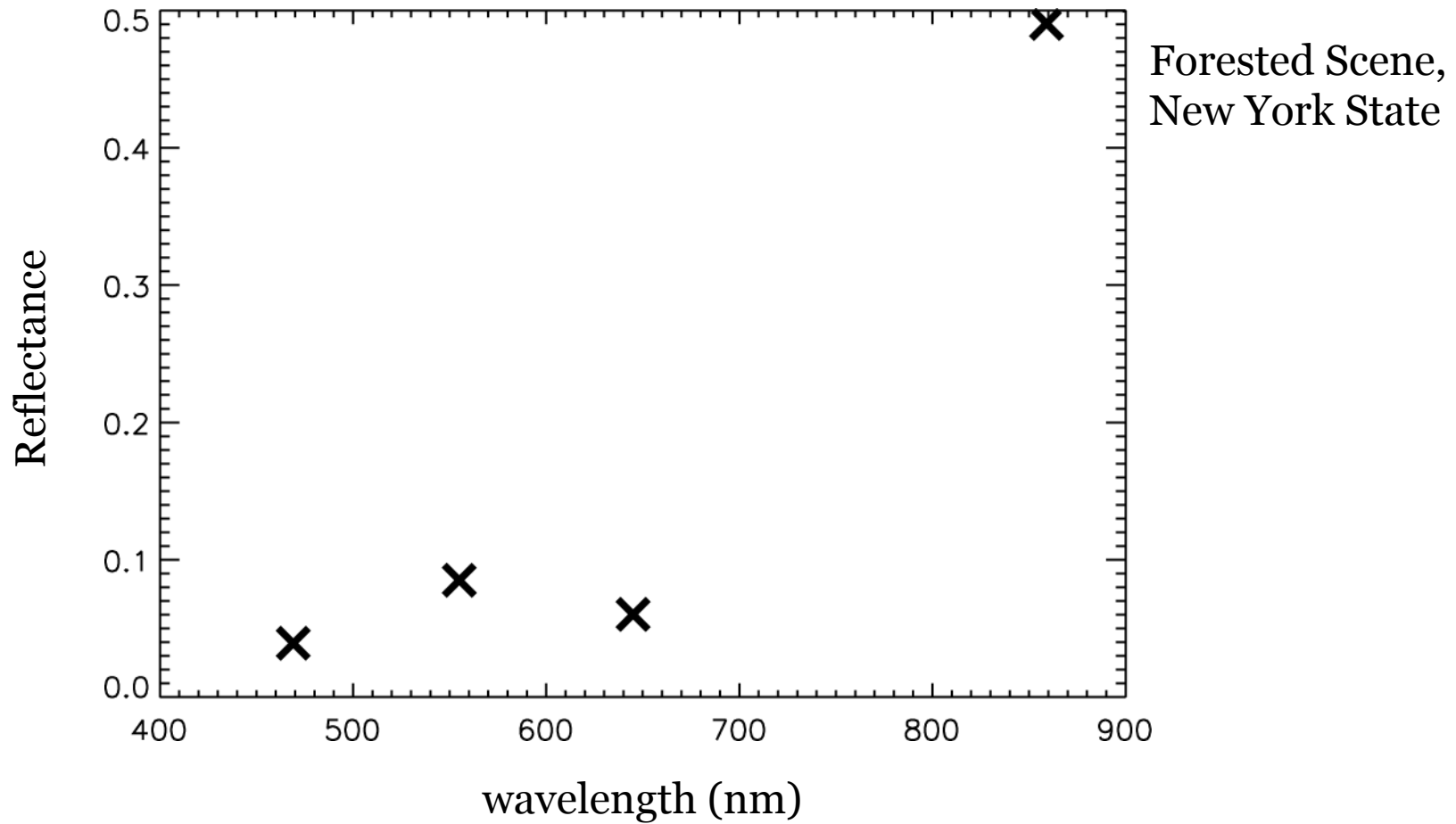


MODIS Composite Surface Reflectance
(True Color) [Schaaf et al. 2002]

$$R(\lambda, \theta, \vartheta, \phi) = f_{iso}(\lambda) + f_{vol}(\lambda)K_{vol}(\theta, \vartheta, \phi) + f_{geo}(\lambda)K_{geo}(\theta, \vartheta, \phi)$$

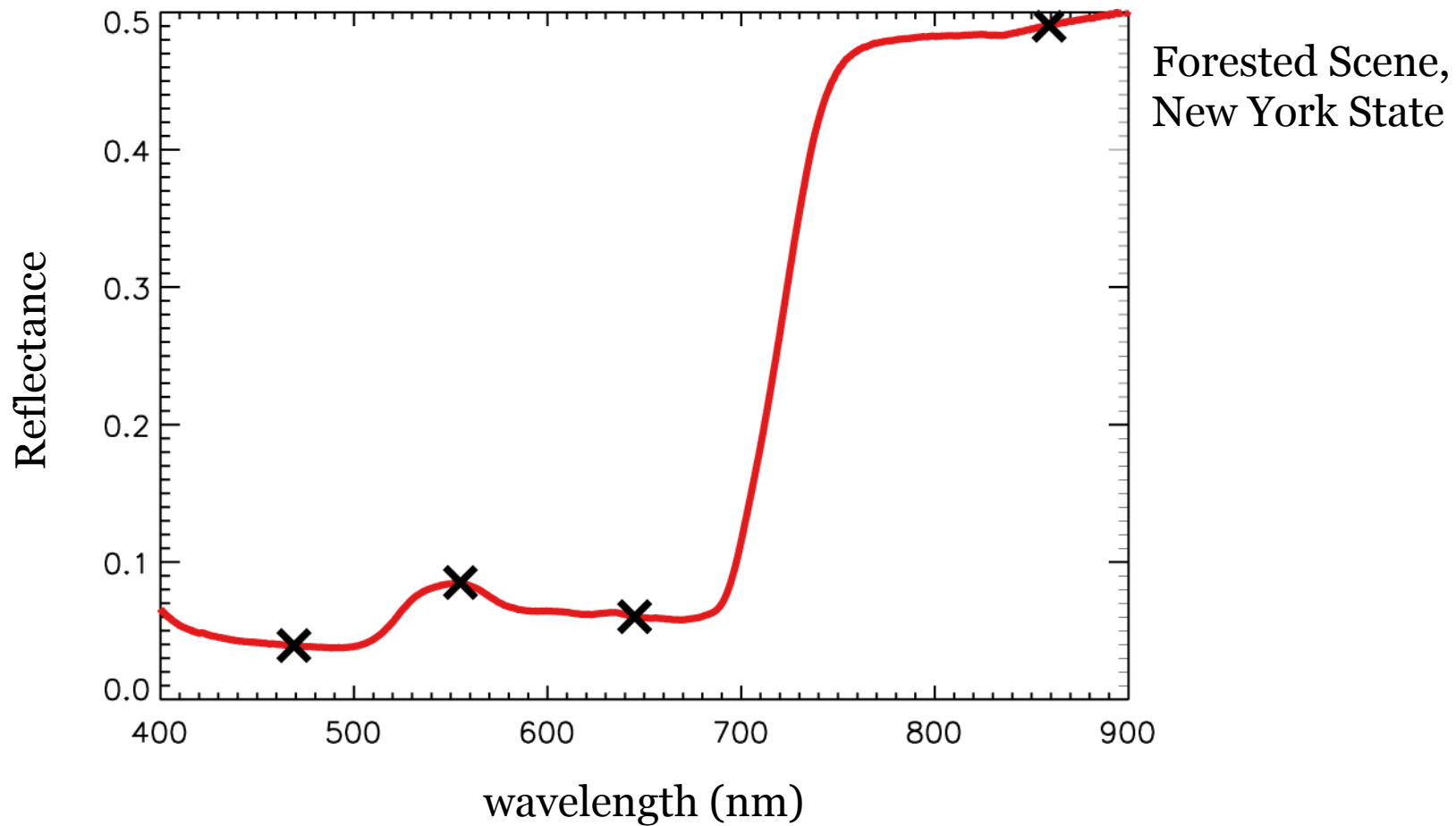
Visible Reflectance Spectrum

Example: Vegetated Scene (Summer)

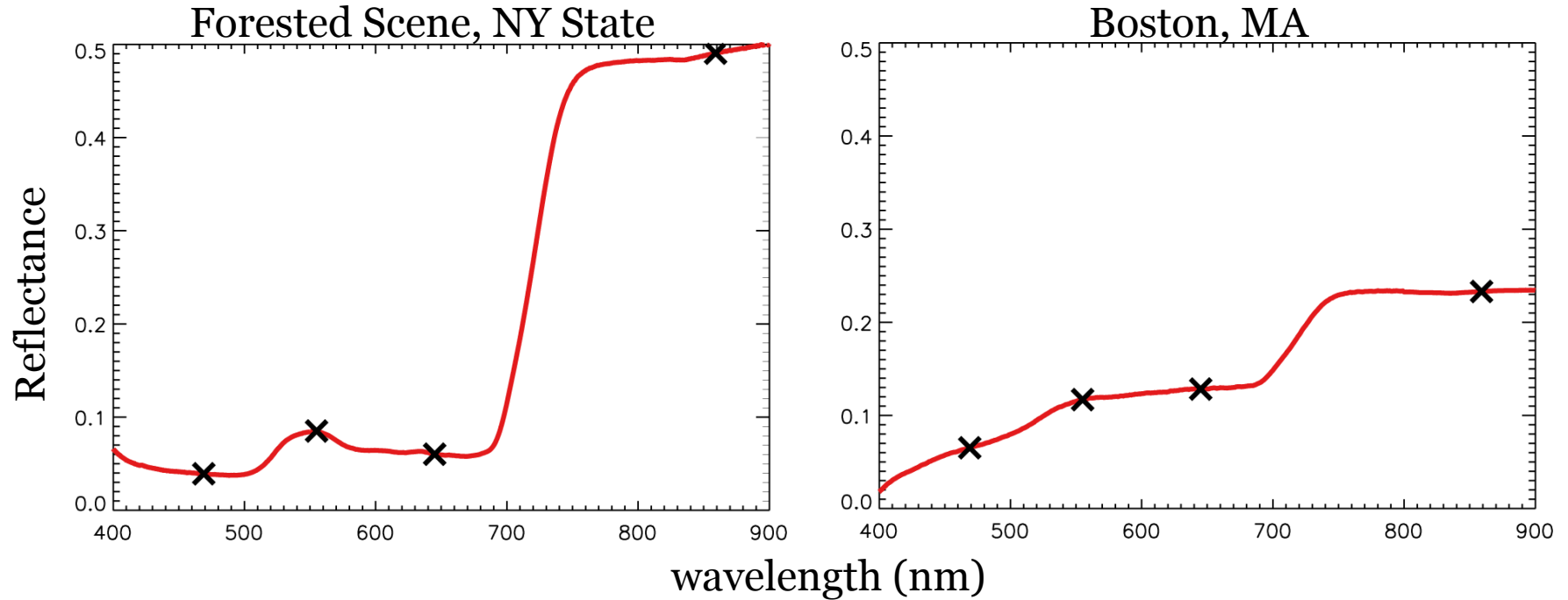


Visible Reflectance Spectrum

Example: Vegetated Scene (Summer)

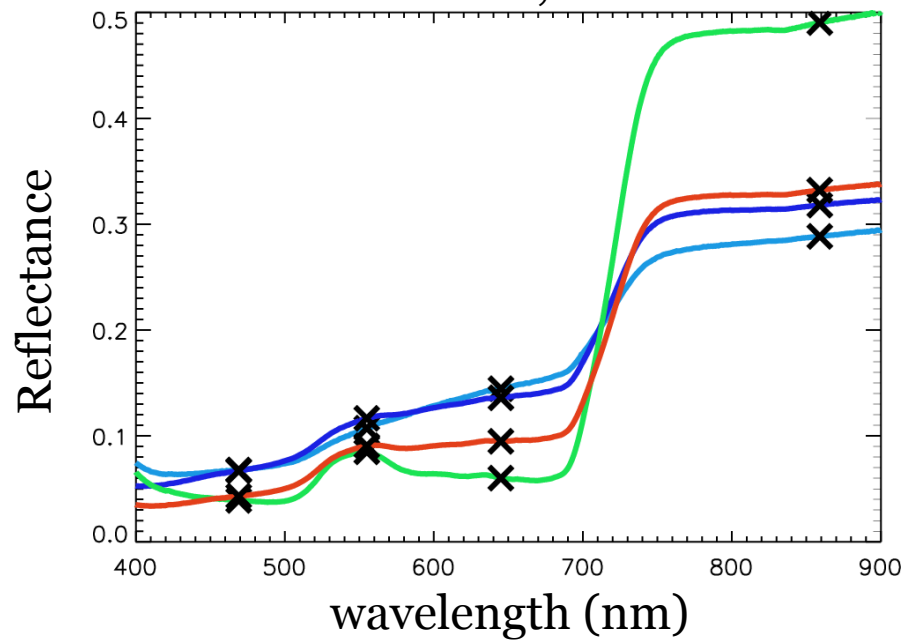


Visible Reflectance Spectrum Vegetated vs. Urban (Summer)



Seasonal Variation

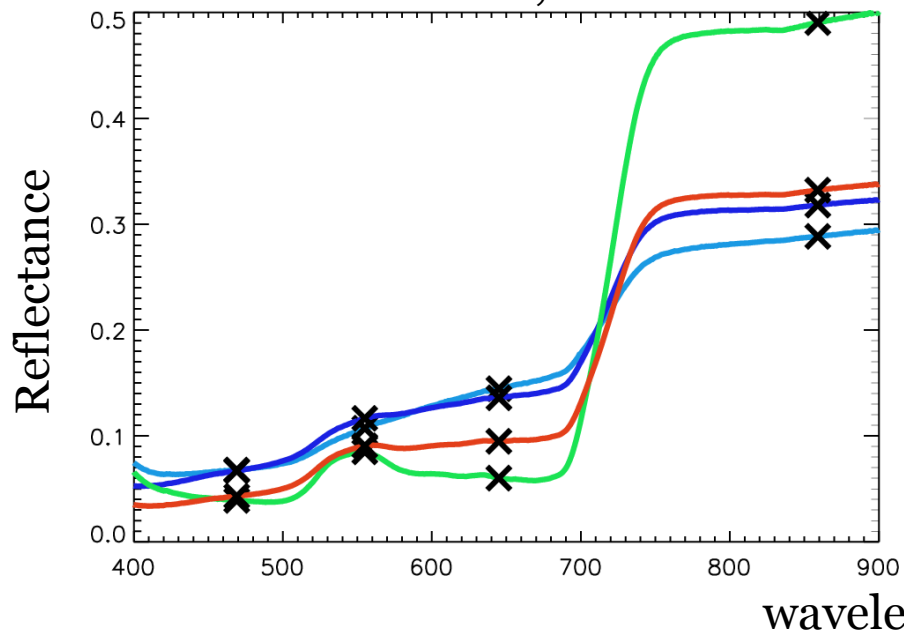
Forested Scene, NY State



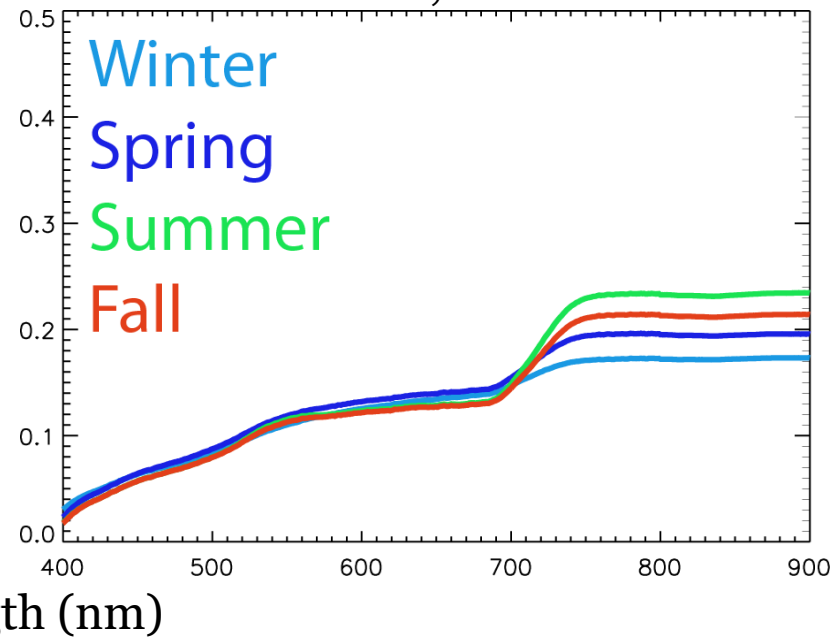
Winter
Spring
Summer
Fall

Seasonal Variation

Forested Scene, NY State



Boston, MA

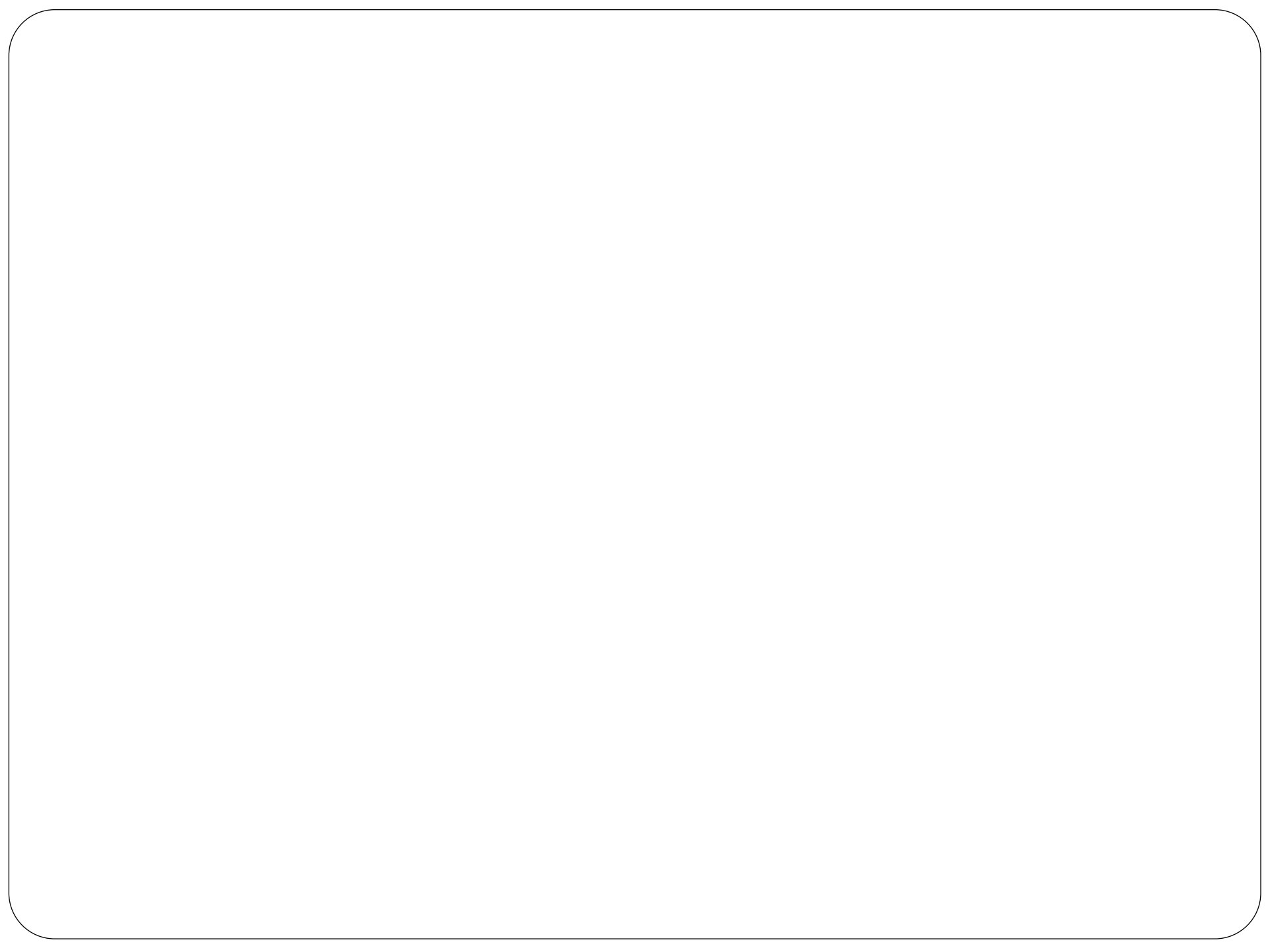


Conclusions

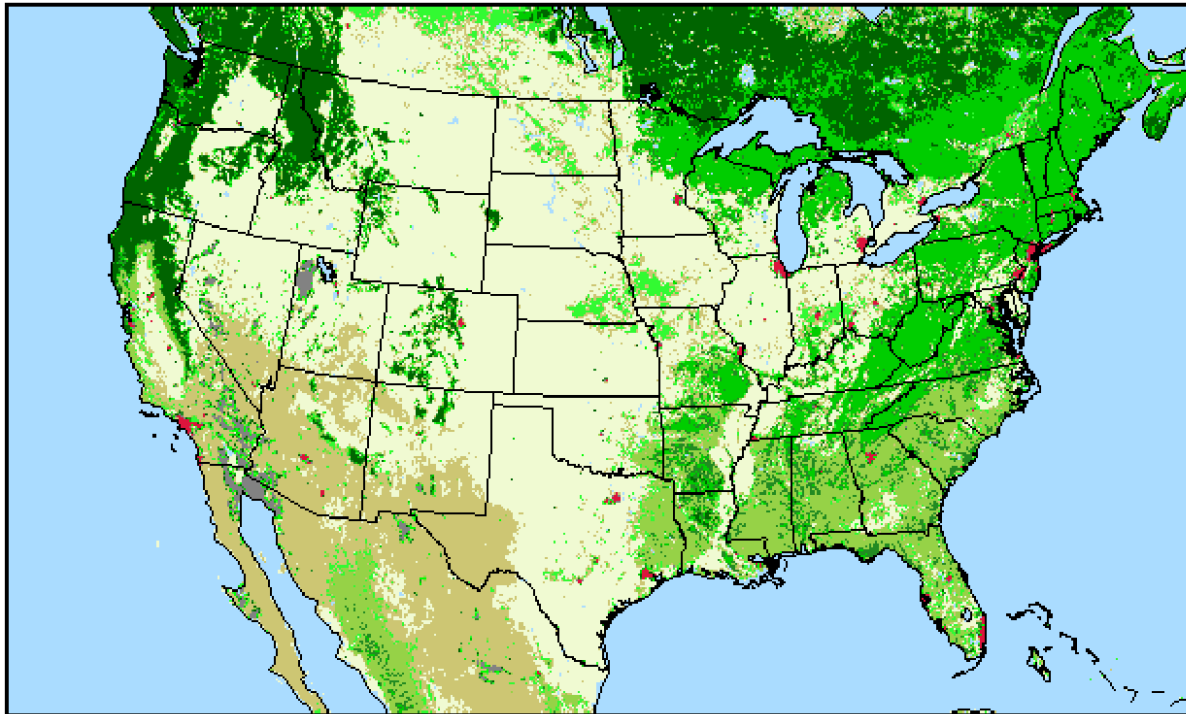
- OSSEs have been used to make the case for GEO UV+Vis design
- TEMPO will provide the capability to monitor air quality exceedances
- High temporal and vertical resolution will allow viewing/attribution of exceptional events
- Surface Reflectance in the visible has strong variability (spectral, spatial, seasonal)
 - Working on validation with GOME-2

Acknowledgements

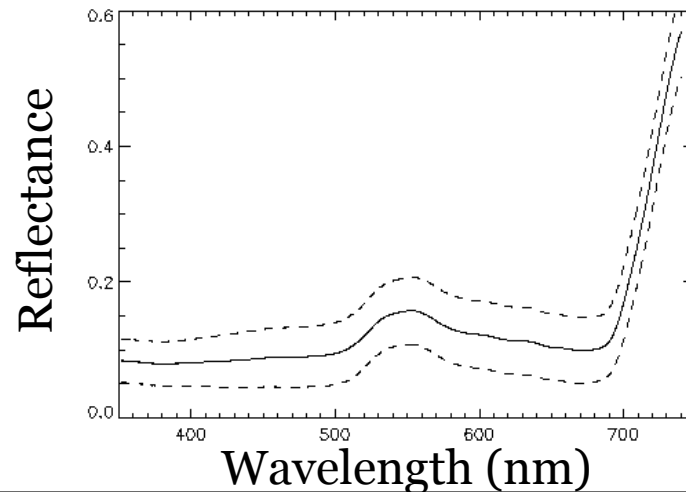
NASA Earth and Space Science Fellowship, NASA Atmospheric Composition and Modeling Program, NASA Earth Science Division, GEO-CAPE Science Team, TEMPO Science Team



Variation by Land Cover



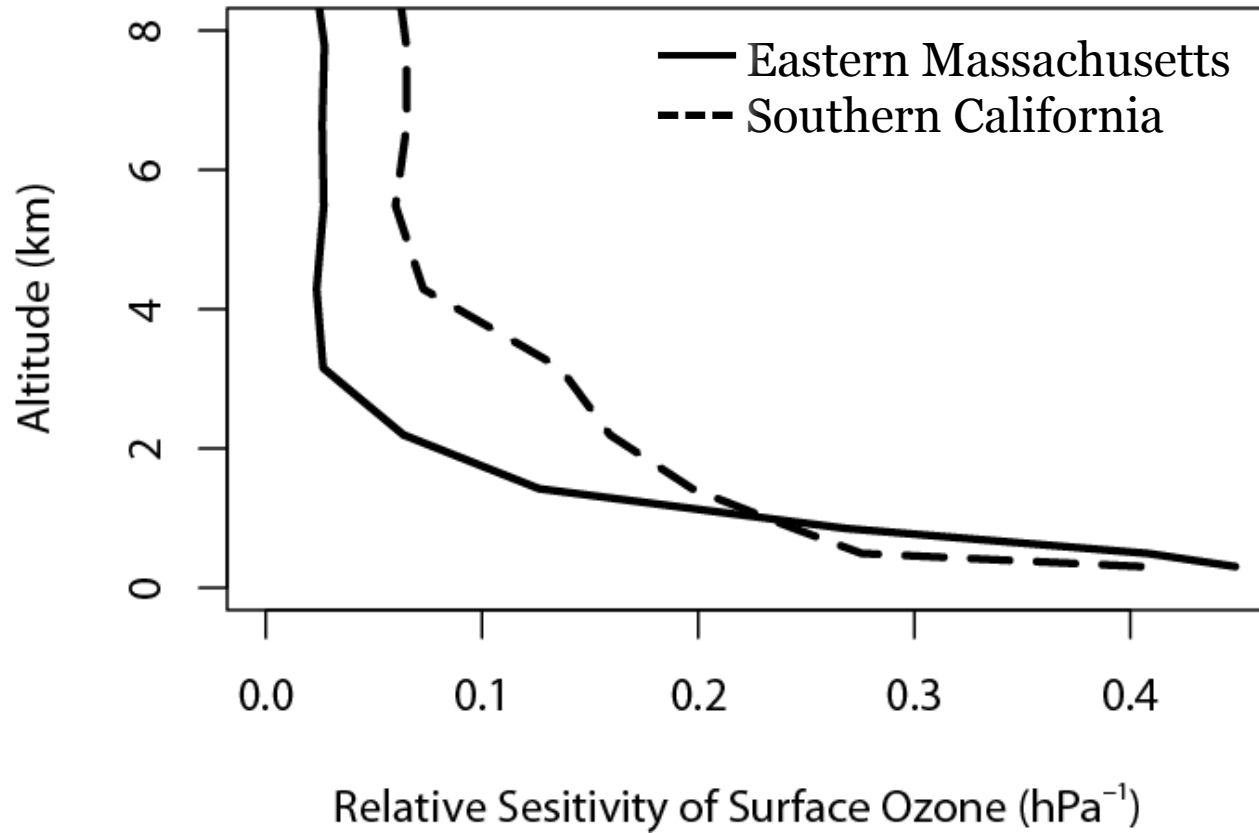
- Water
- Grasses/Cereal Crops
- Shrubs
- Broad-leaf crops
- Savannah
- Evergreen Broadleaf Forest
- Deciduous Broadleaf Forest
- Evergreen Needleleaf Forest
- Deciduous Needleleaf Forest
- Barren Ground
- Urban



Grasses/Cereals
(51 samples)

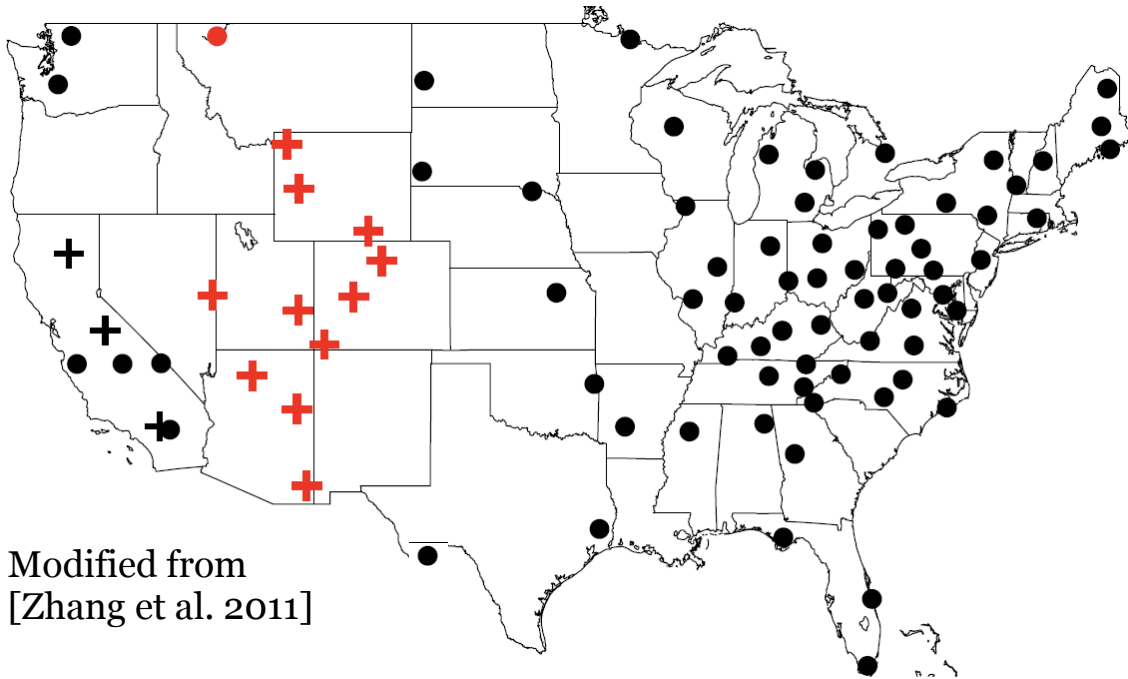
Surface Ozone Sensitivity

- Adjoint model – receptor based rather than source based approach
- Sensitivity of surface ozone to ozone produced at each vertical layer



Surface ozone primarily sensitive to production below 2 km

Surface Measurements from CASTNet



Modified from
[Zhang et al. 2011]



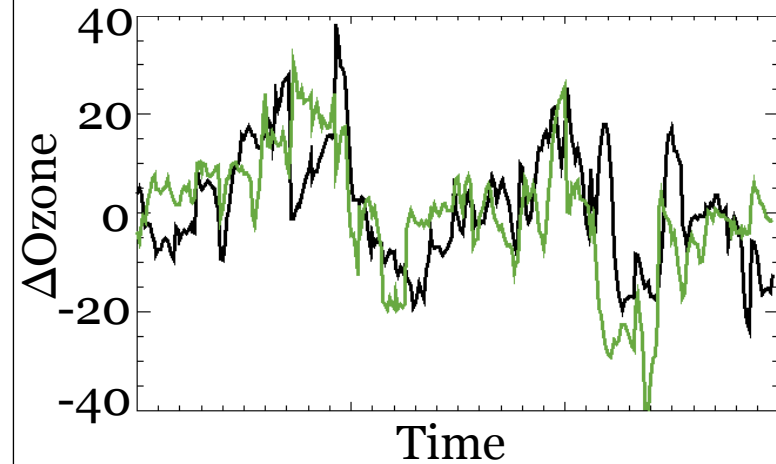
Rocky Mountain NP [EPA]

CASTNet ozone monitoring sites in the continental United States
Sites in the intermountain West in red.

- Surface measurements can provide information in their vicinity, but how far away?

Error Correlation Length Scales

- Distance/Magnitude of correction is quantified by the ozone error correlation

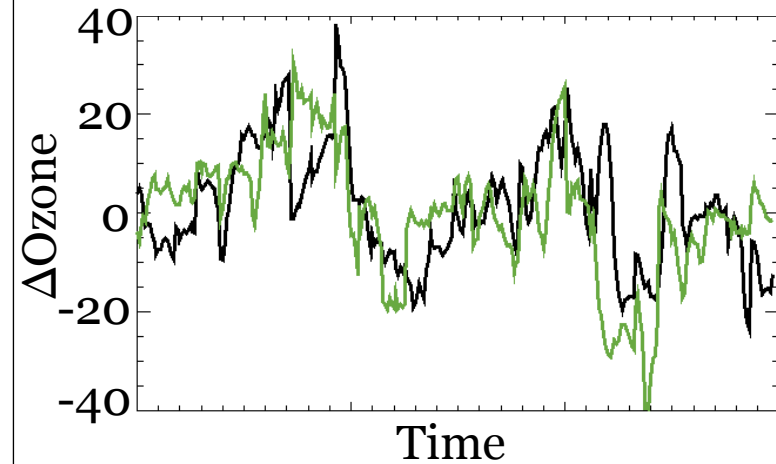


$R=0.50$, $D=340$ km

- Find correlation of model error at each pair of CASTNet sites

Error Correlation Length Scales

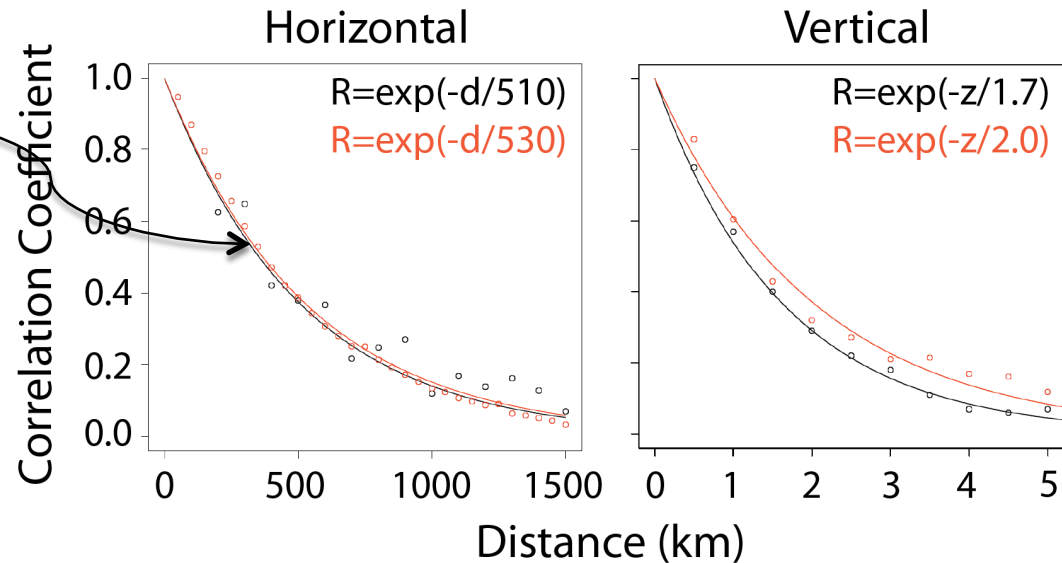
- Distance/Magnitude of correction is quantified by the ozone error correlation



$R=0.50, D=340$ km

- Plot R vs. distance to find error correlation length scale

- Find correlation of model error at each pair of CASTNet sites



III. Joint Assimilation of ozone and CO

Context: CO has been used to provide information about ozone and is easier to measure

Goal: Evaluate benefit of concurrent GEO CO measurements for monitoring ozone

Approach:

Quantify ozone-CO model error correlations

Implement a joint assimilation system

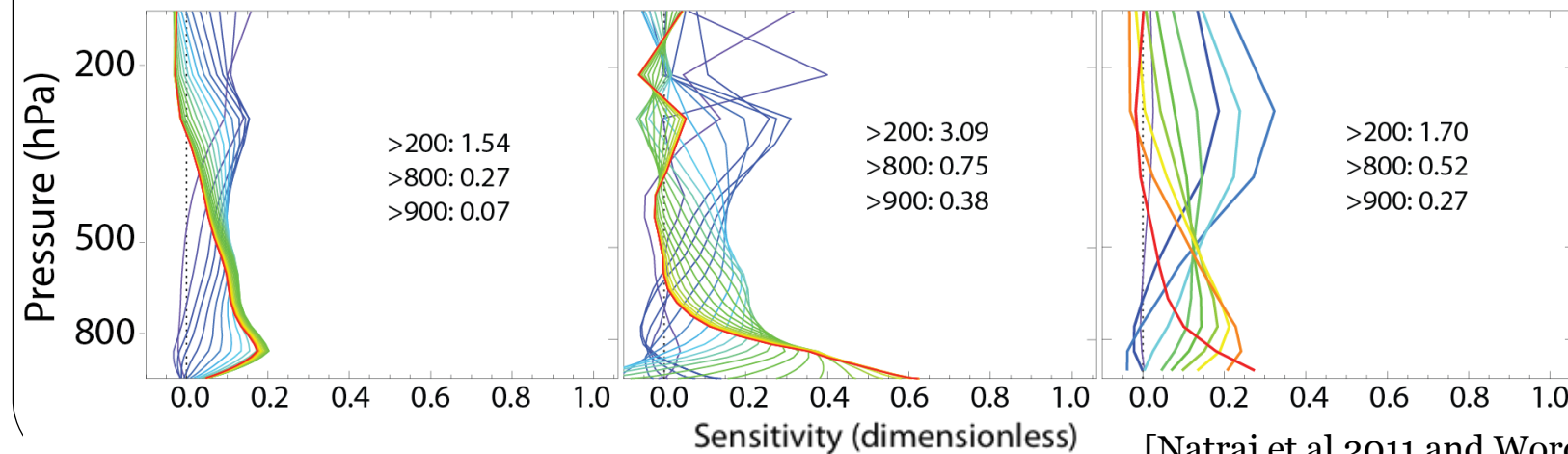
Theoretical Ozone sensitivities

UV Ozone

UV+Vis+TIR Ozone

CO sensitivity, MOPITT

NIR+TIR CO

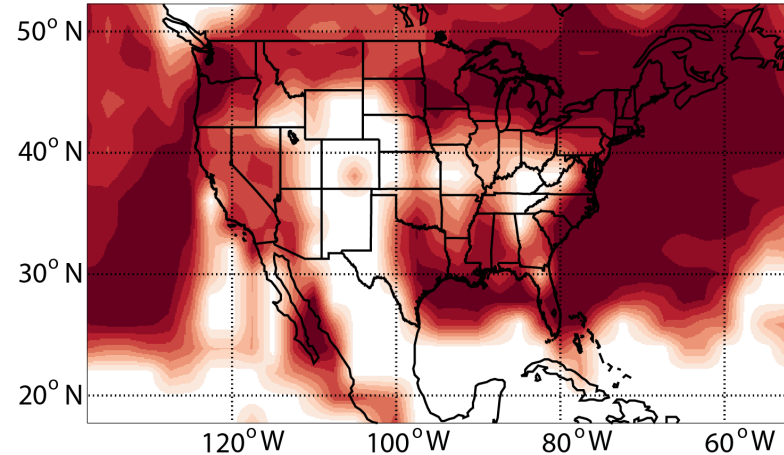


[Natraj et al 2011 and Worden et al 2010]

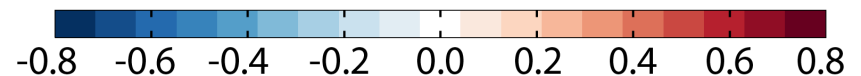
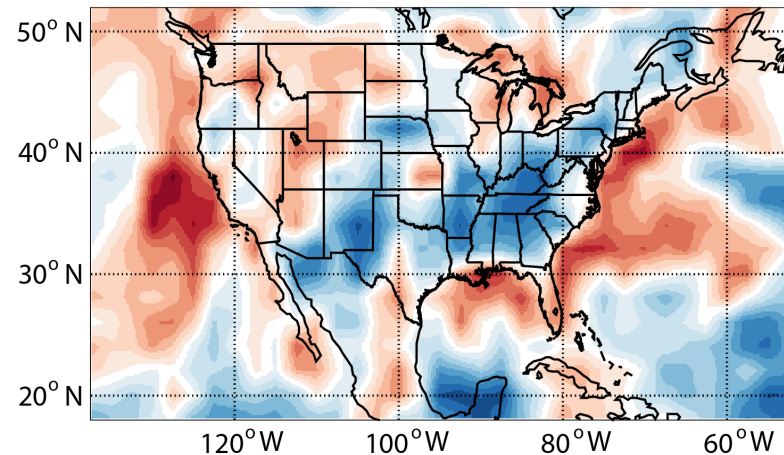
Model/Model Error Correlations

- Positive **concentration** correlations over North American region
- But! model **error** correlations can differ greatly from **concentration** correlations!

Ozone-CO Concentration Correlation



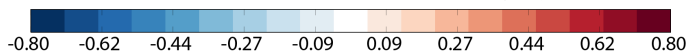
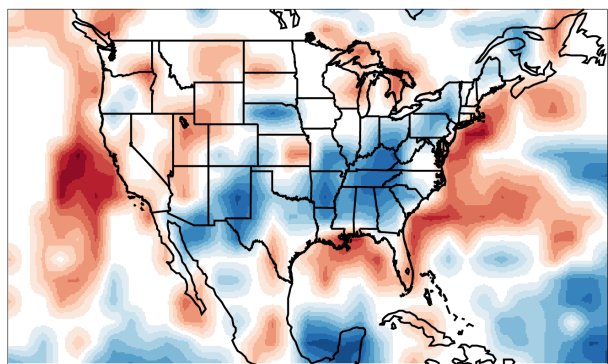
Ozone-CO Error Correlation



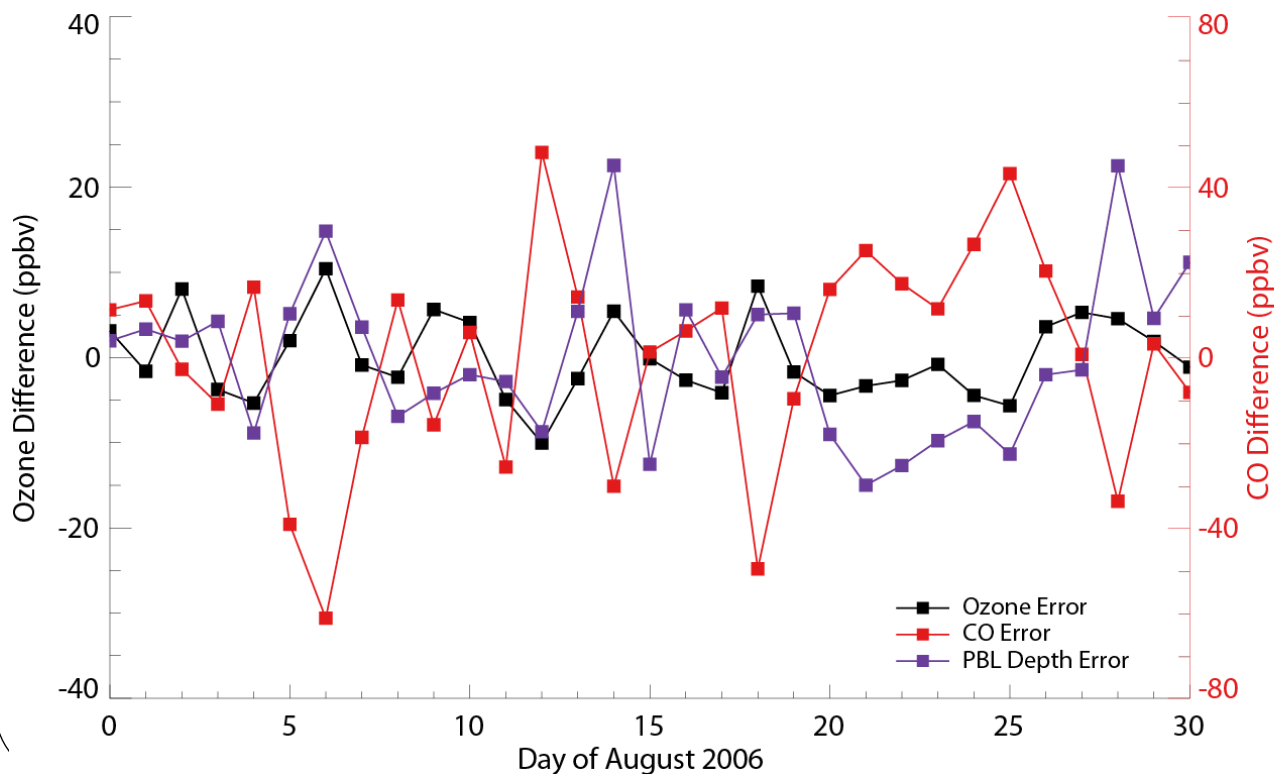
Correlation Coefficient (R)

Error Correlations Investigated

ozone-CO error correlations (model/model)



Negative error correlations over land
driven by differences in vertical mixing

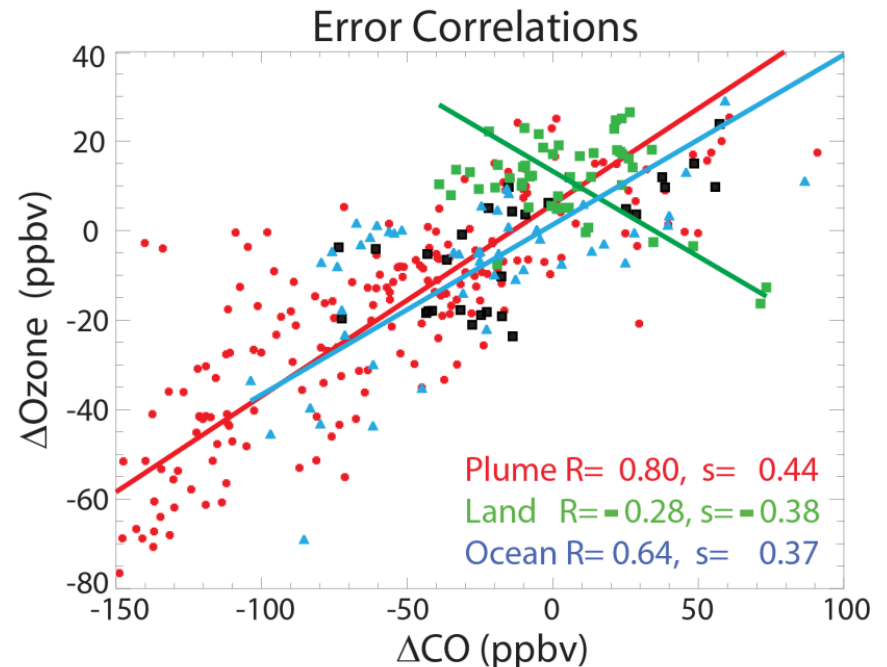
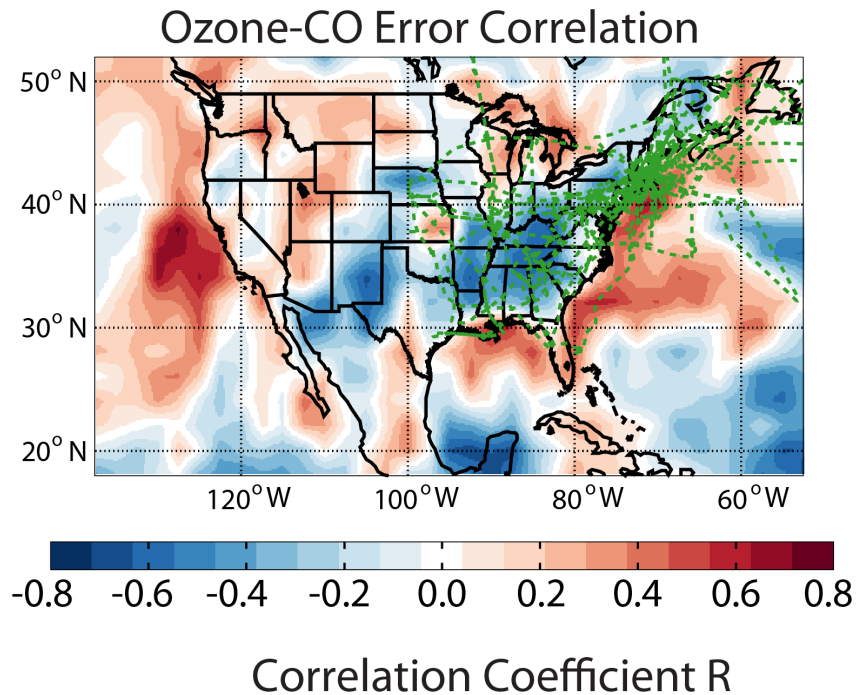


$$R_1 (\text{Ozone:CO}) = -.68$$
$$R_2 (\text{PBLH:CO}) = -.65$$



Model/Observation Error Correlations

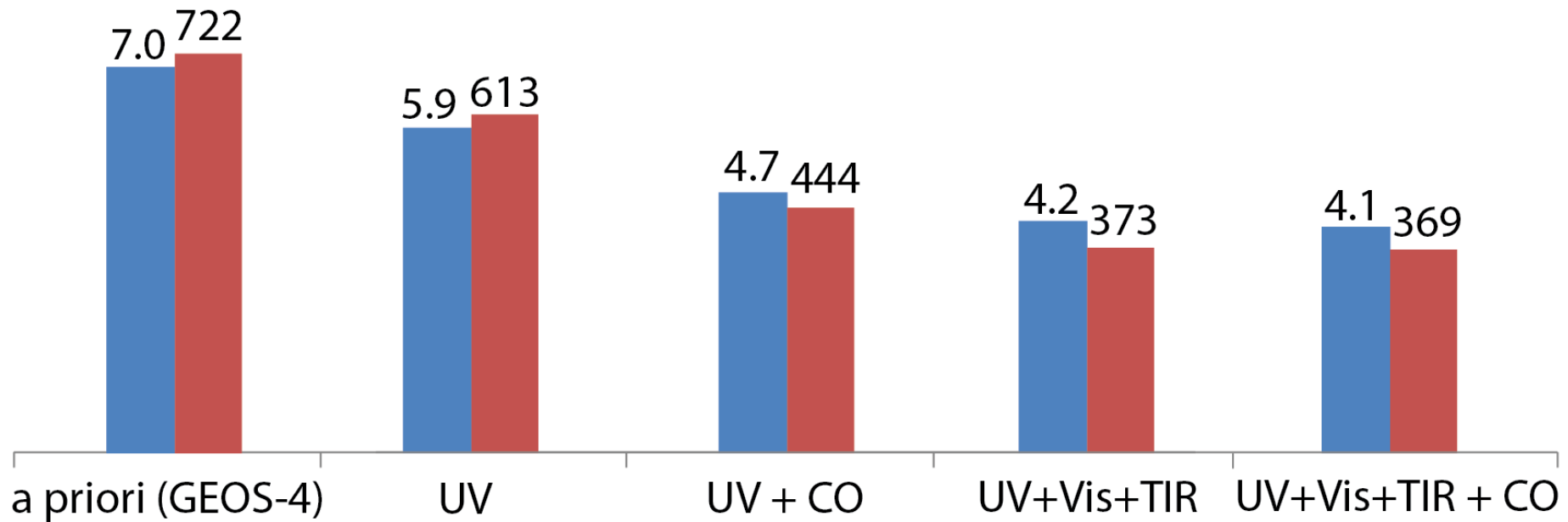
- Negative model error correlations reproduced when comparing to aircraft observations



Air Quality Information from Error Correlations

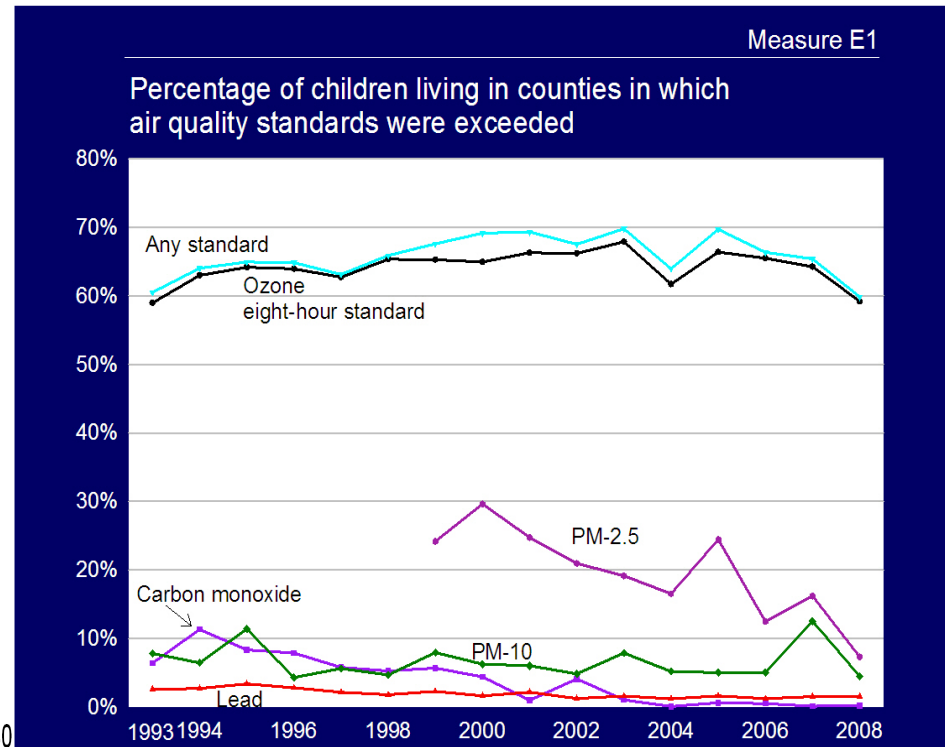
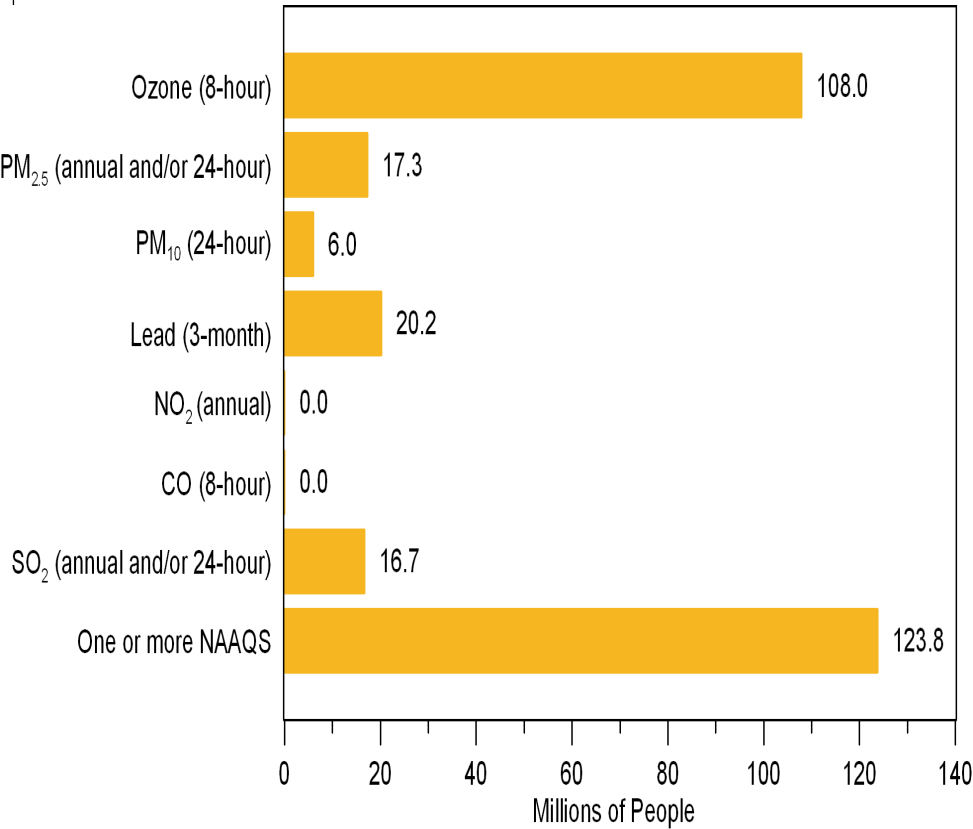
Air Quality Error for August 2006

■ RMSE of MDA8 ozone (ppbv)
■ Number of misdiagnosed exceedances

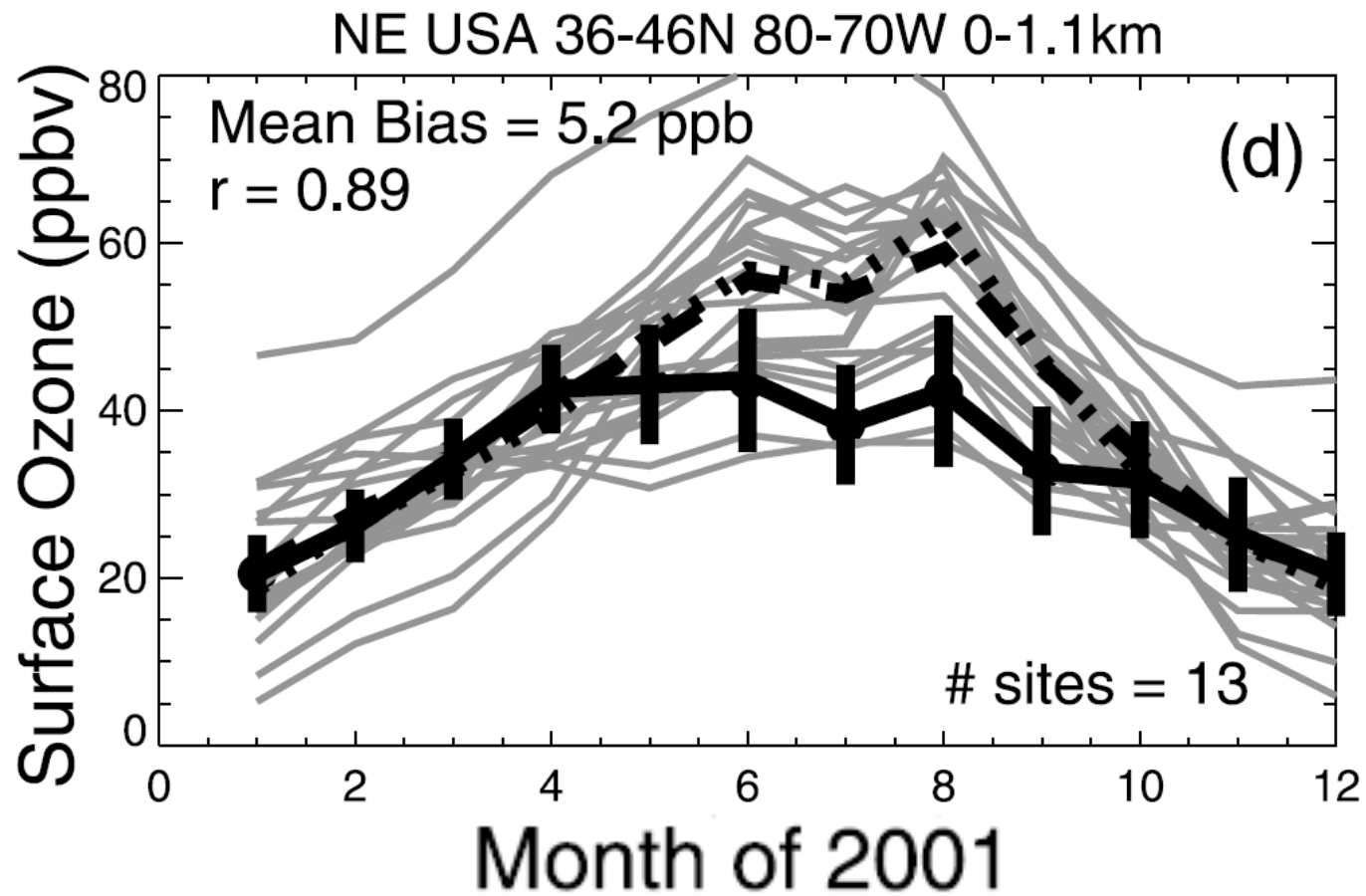


Error Correlations provide additional information for surface ozone (spatial pattern consistent with regions of strong error correlation)

If its polluted, there's ozone



Difficulty of Modeling Ozone



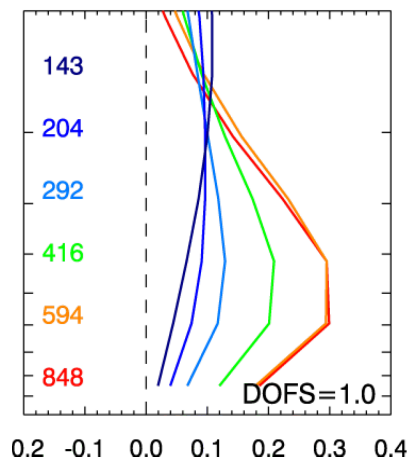
[Fiore et al. 2009]

Multispectral Satellite Observations of Ozone

Averaging Kernel matrix \mathbf{A} quantifies the vertical information provided by a satellite retrieval

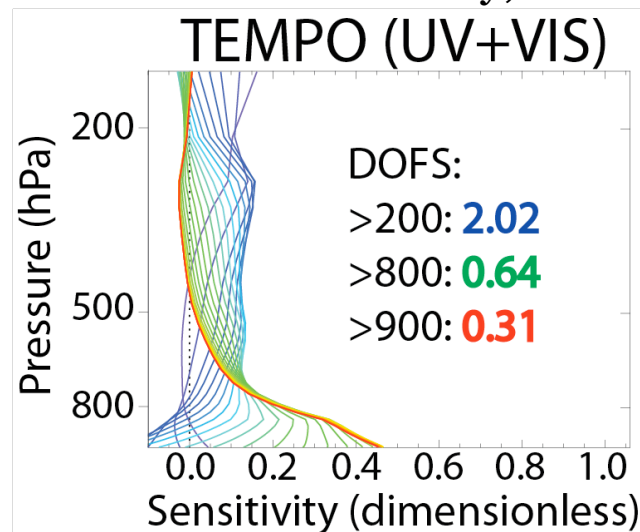
$$\mathbf{x}' = \mathbf{x}_a + \mathbf{A}(\mathbf{x} - \mathbf{x}_a) + \varepsilon \quad \mathbf{A} = \frac{\partial \mathbf{x}'}{\partial \mathbf{x}}$$

Current ozone sensitivity, OMI (UV)

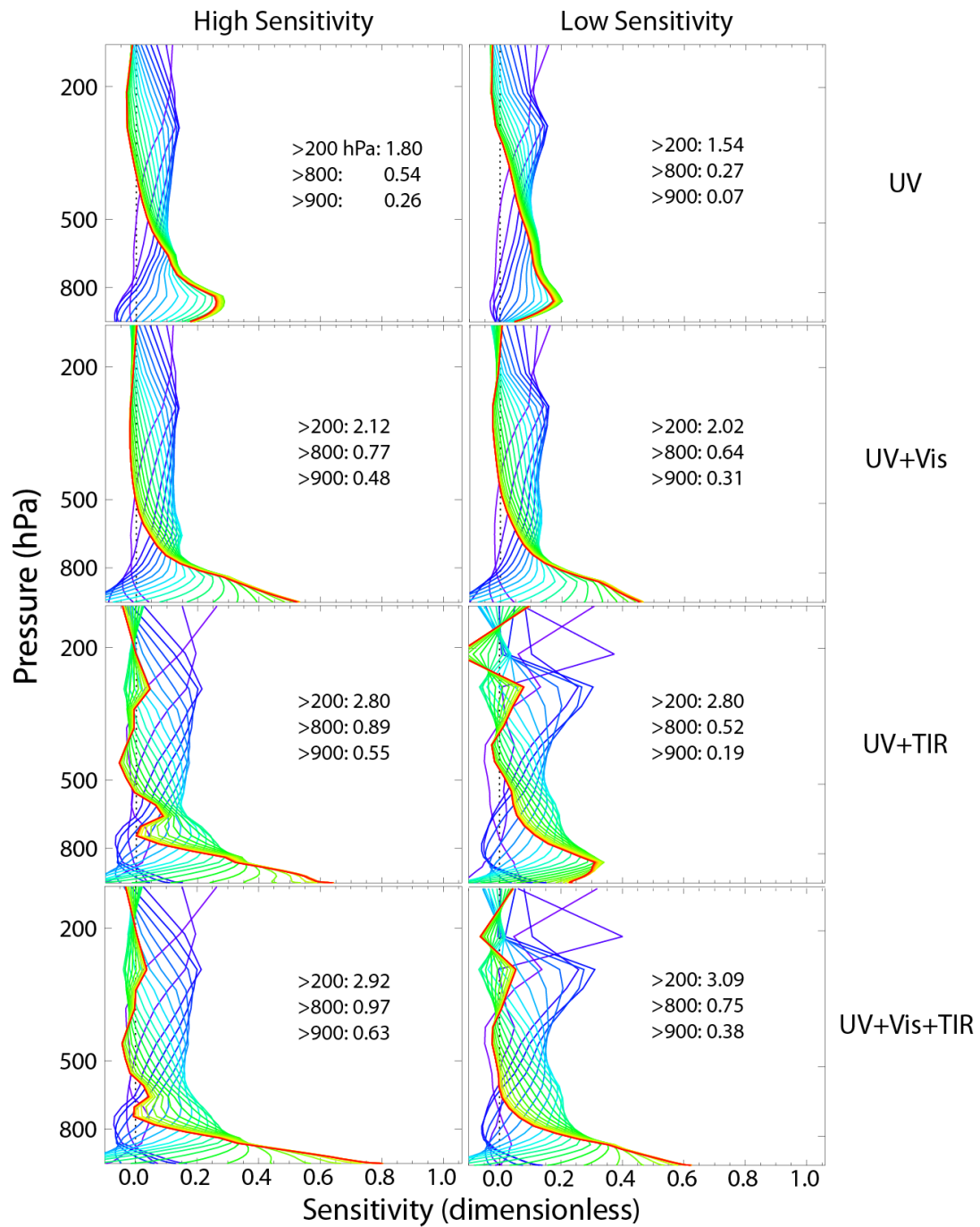


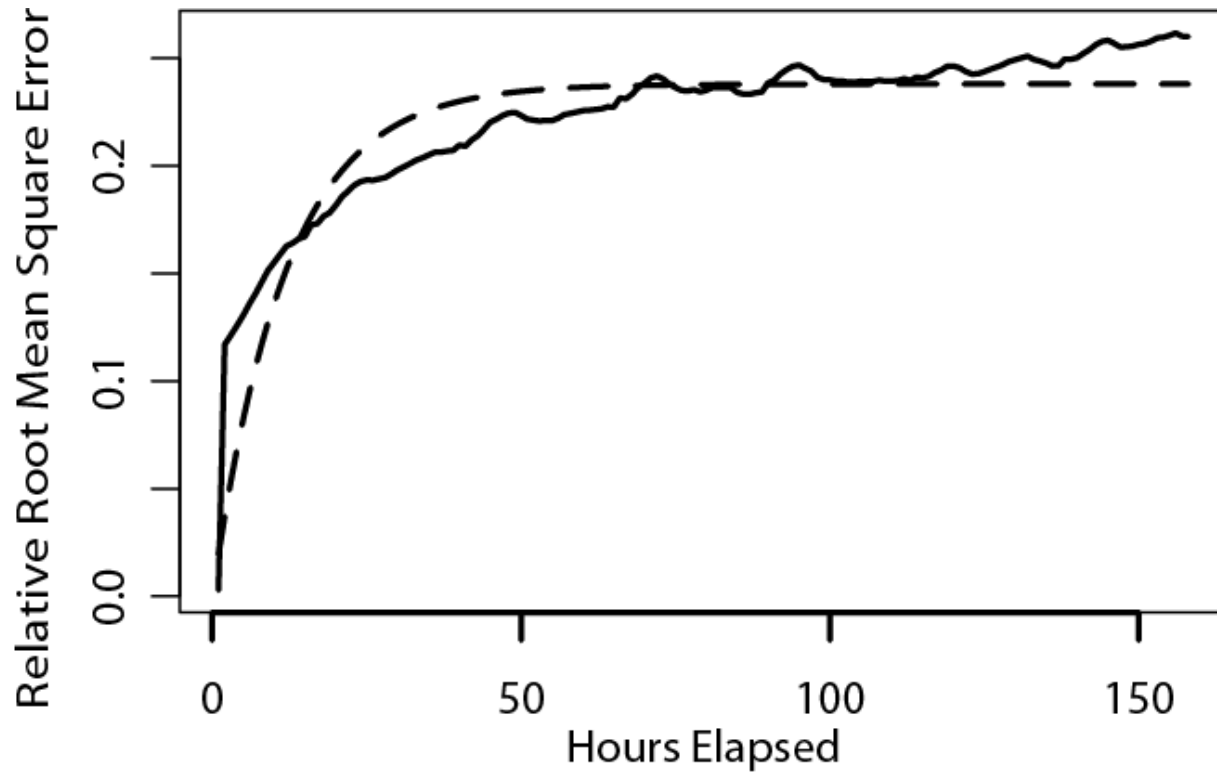
[Zhang et al. 2010]

Ozone sensitivity, future
TEMPO (UV+VIS)

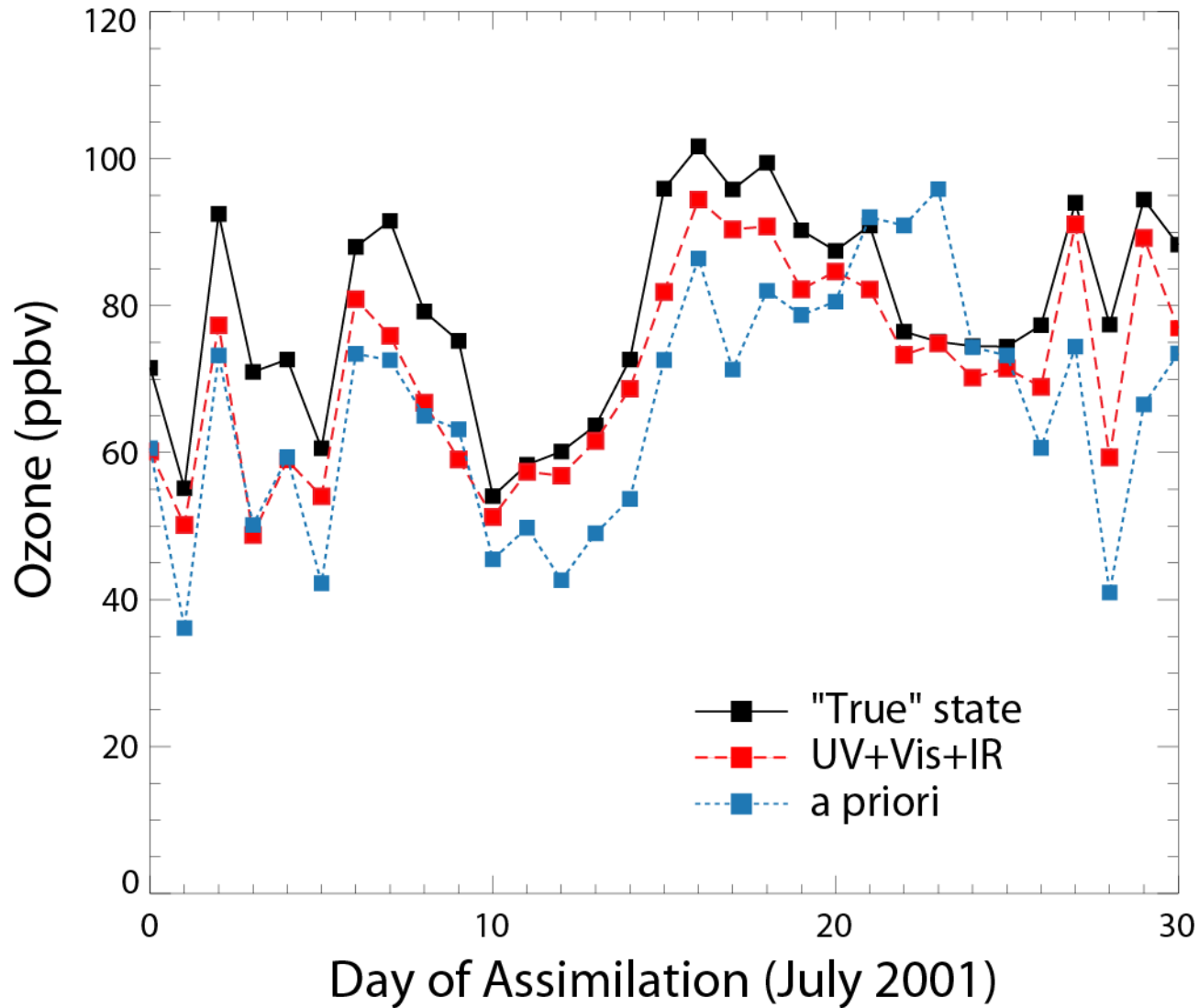


[Natraj et al, 2011]

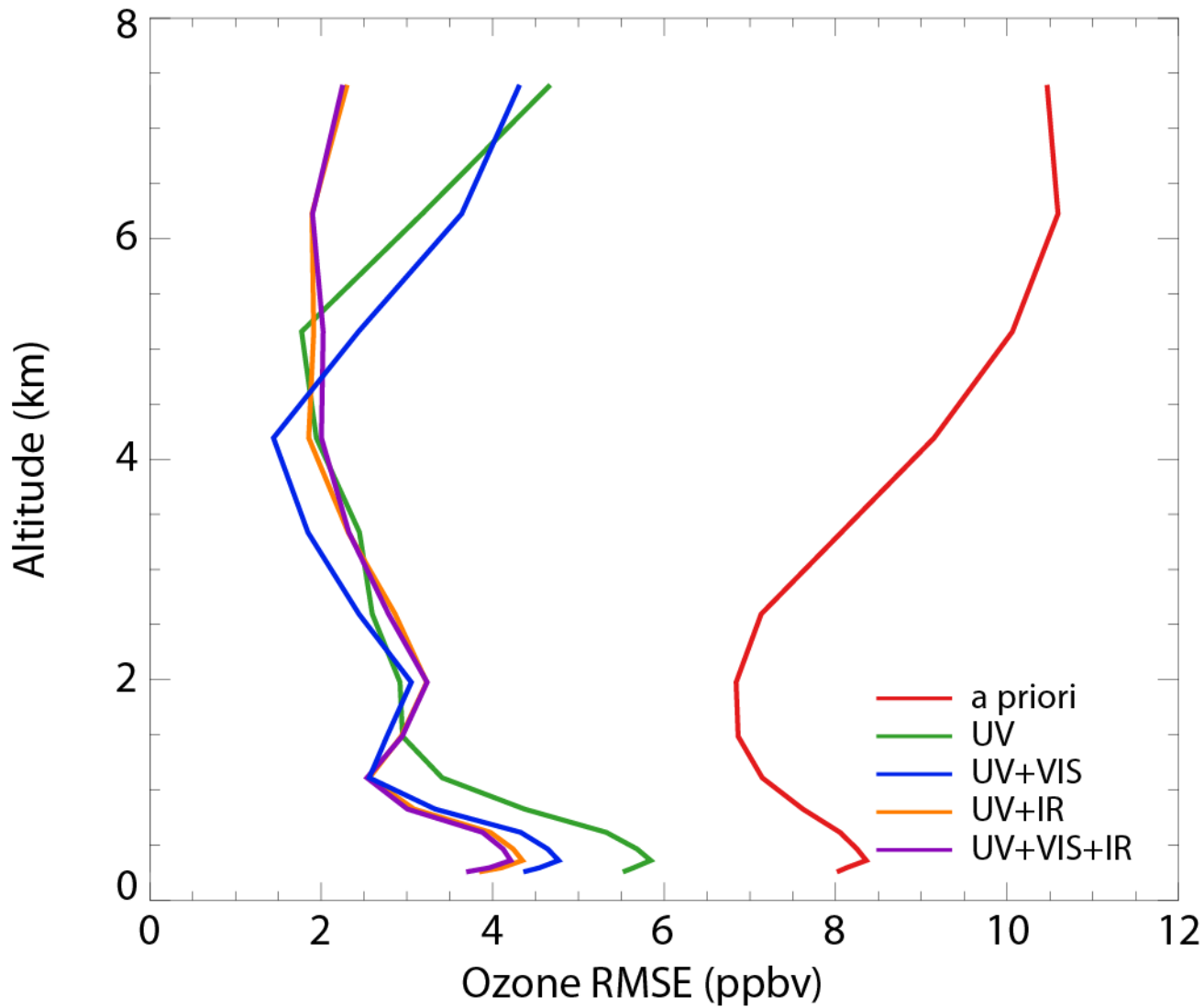




Pittsburgh timeseries

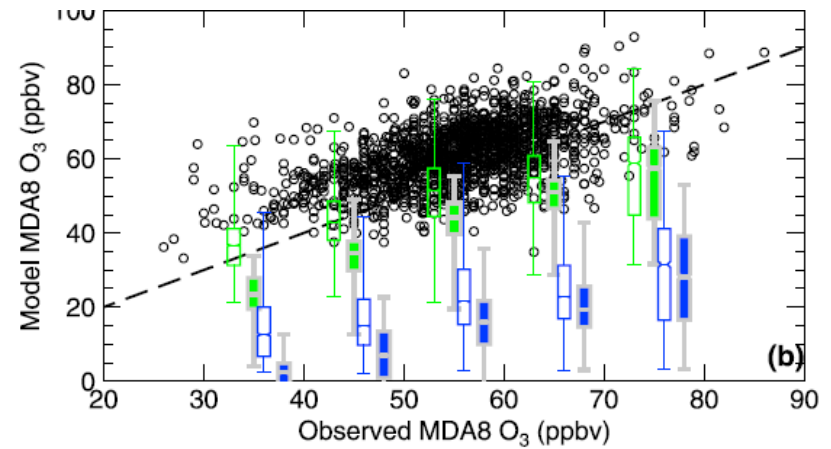
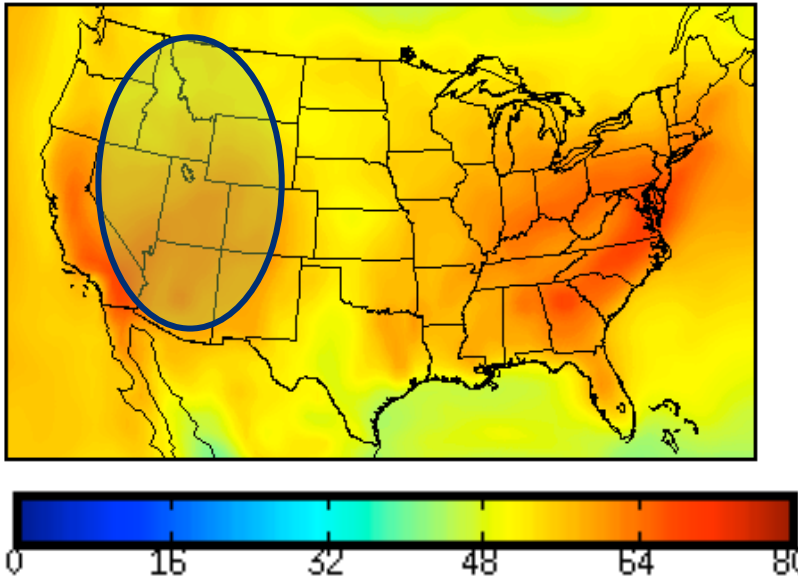


Vertical distribution of correction



AM3-Chem is too high

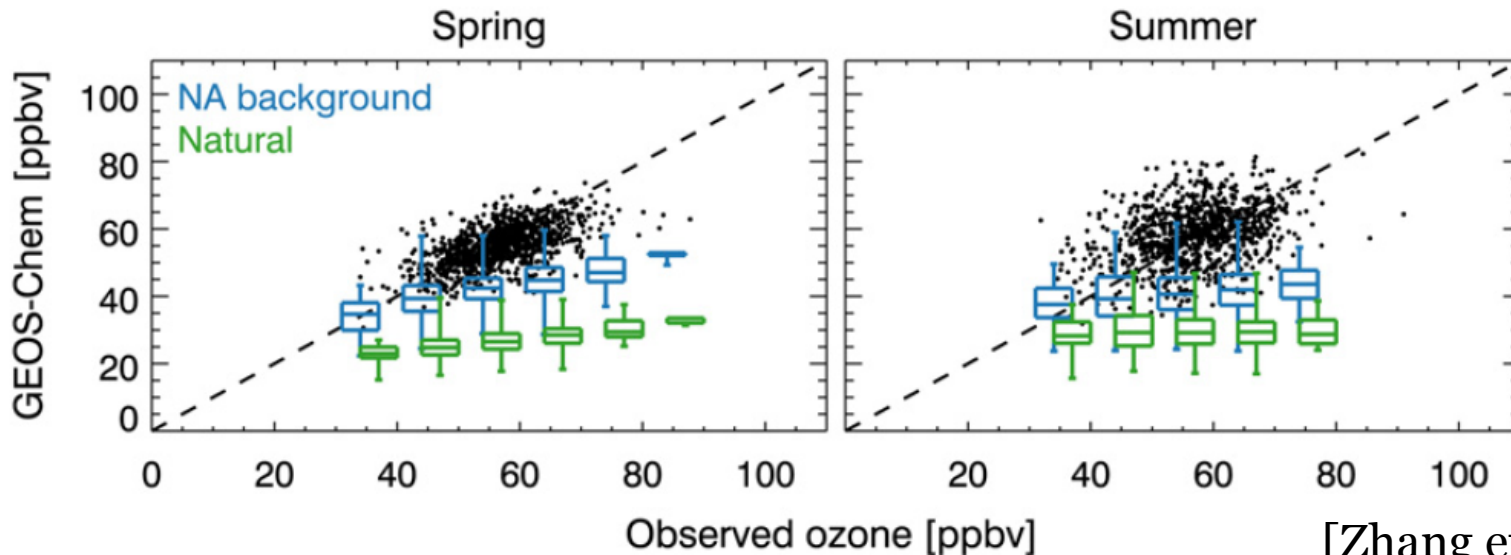
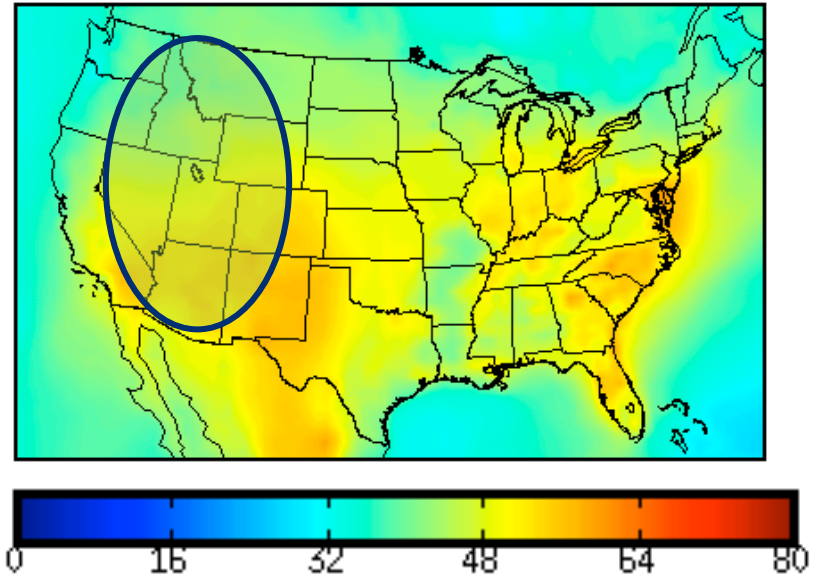
“Truth” = AM3-Chem model



[Lin et al., 2012]

GEOS-Chem is too low

a priori = nested GEOS-Chem



[Zhang et al., 2012]

Observing System Information

