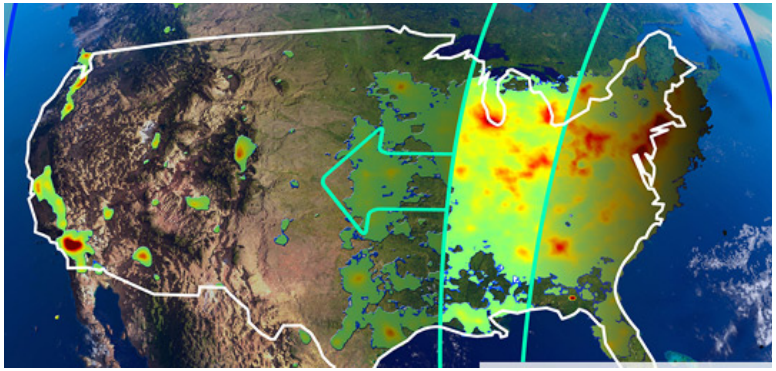
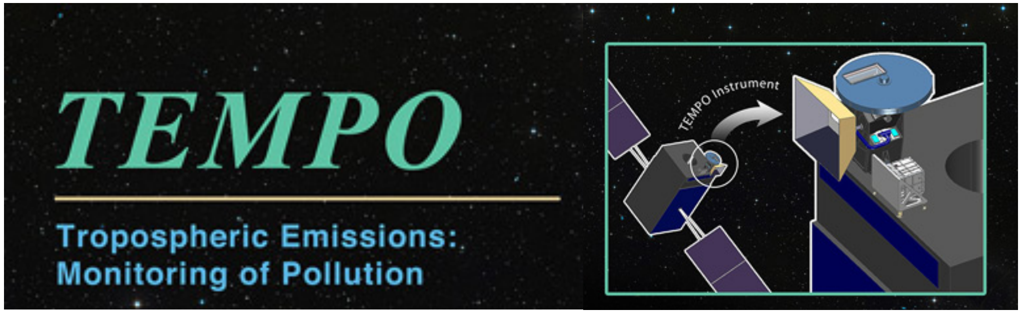
Geostationary Satellite Observations of Ozone Air Quality





Peter Zoogman
Harvard-Smithsonian Center for Astrophysics

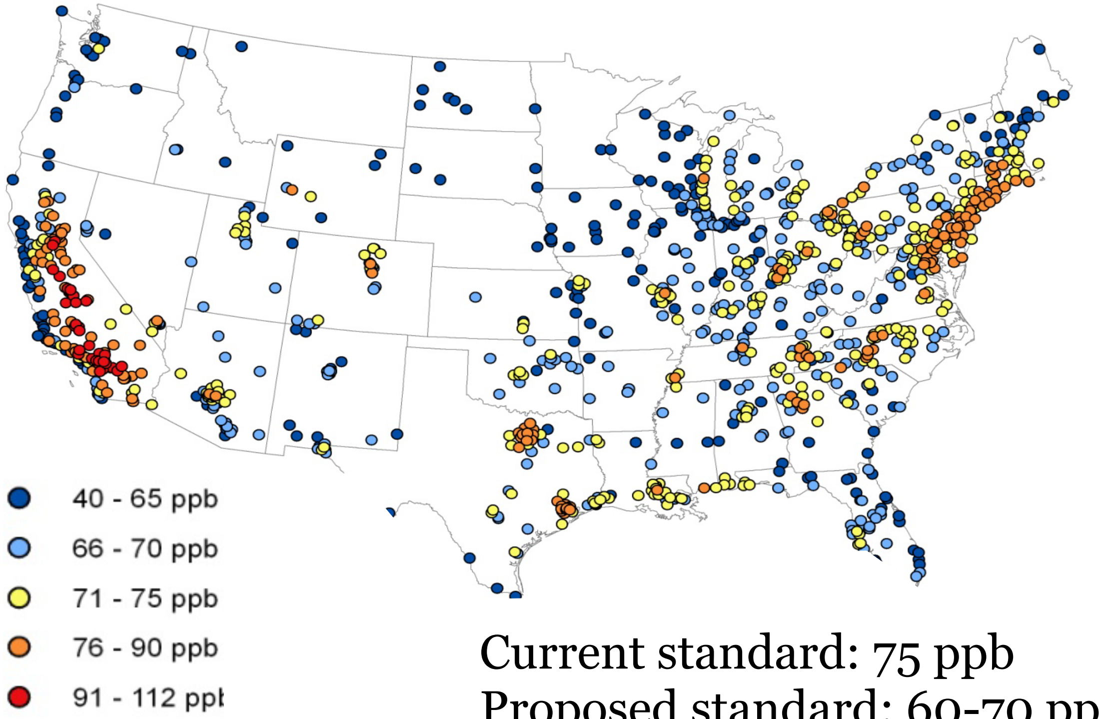
Thanks to: D.J. Jacob, K. Chance, X. Liu, M. Lin, A.M. Fiore, K. Travis, L. Zhang, P. Le Sager, A. Eldering, V. Natraj, S.S. Kulawik

Presented at NASA Langley   May 20, 2014

Ozone pollution is a national problem

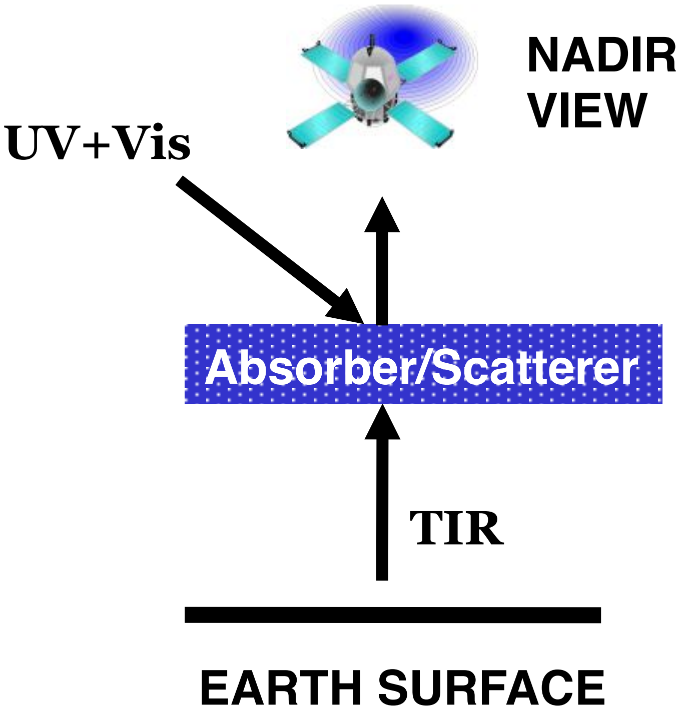
- Ozone in surface air is harmful to human health
- Surface ozone also causes crop damage
- MDA8 = maximum daily 8-hour average ozone

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



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

Satellite Observations of Ozone



NADIR VIEW

UV+Vis

Absorber/Scatterer

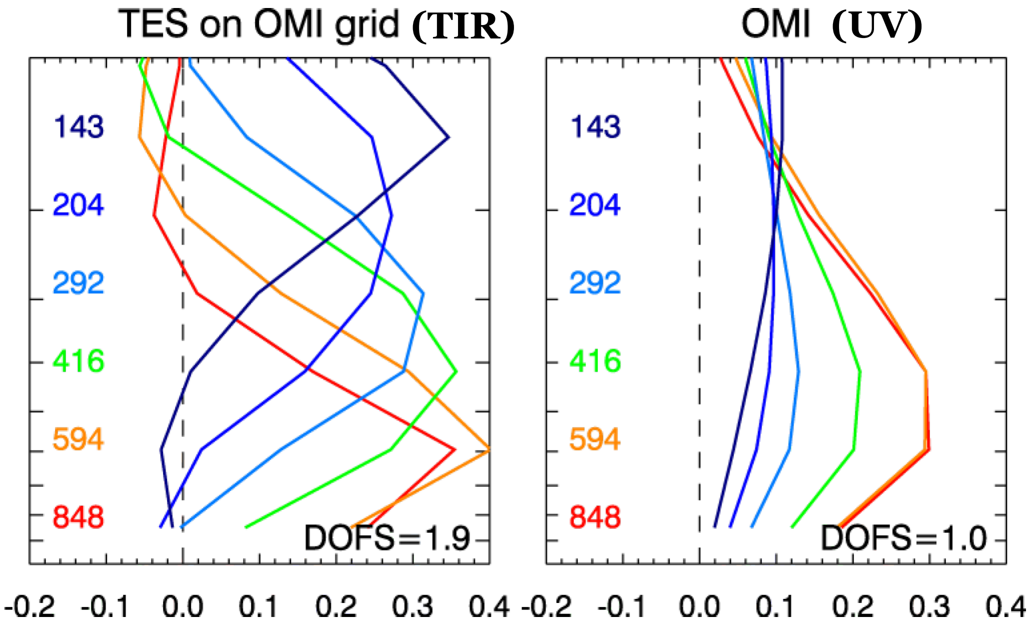
TIR

EARTH SURFACE

Averaging Kernel matrix **A** quantifies the vertical information provided by a satellite retreival

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

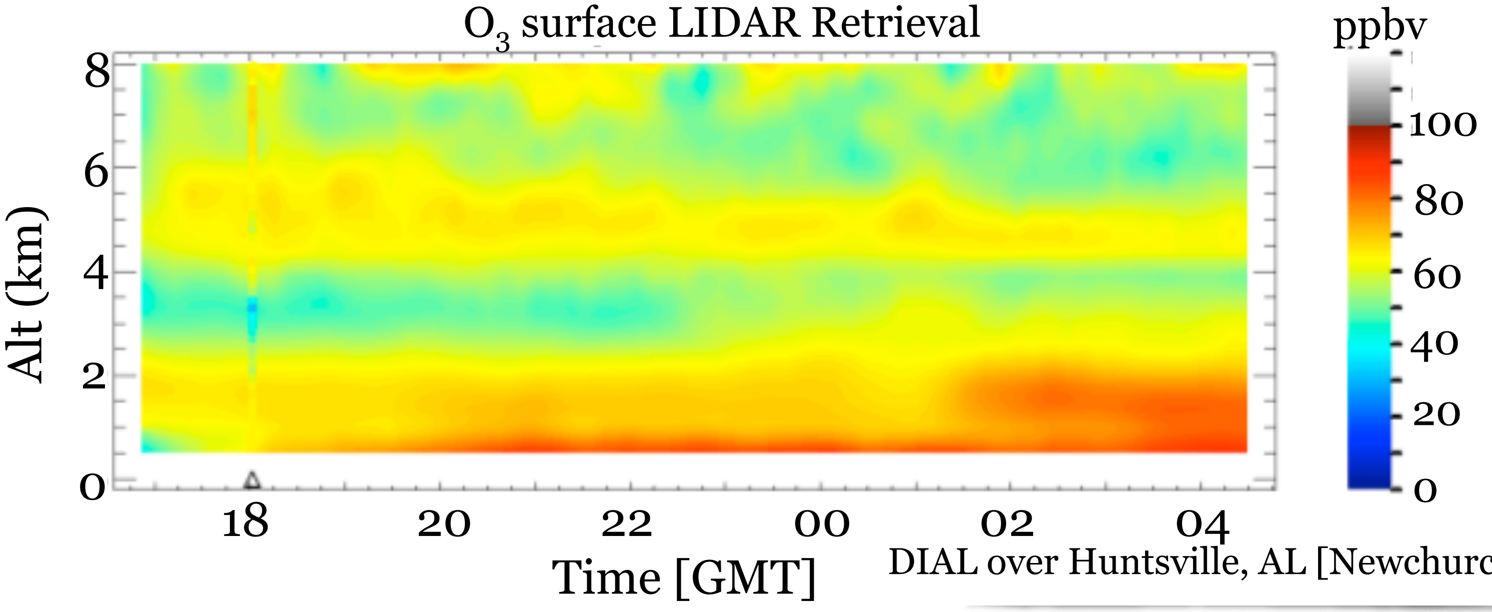
$$\mathbf{A} = \frac{\partial \mathbf{x}'}{\partial \mathbf{x}}$$



[Zhang et al. 2010]

The Difficulty of Ozone Air Quality from Space

- Ozone concentrations very heterogeneous both spatially and temporally



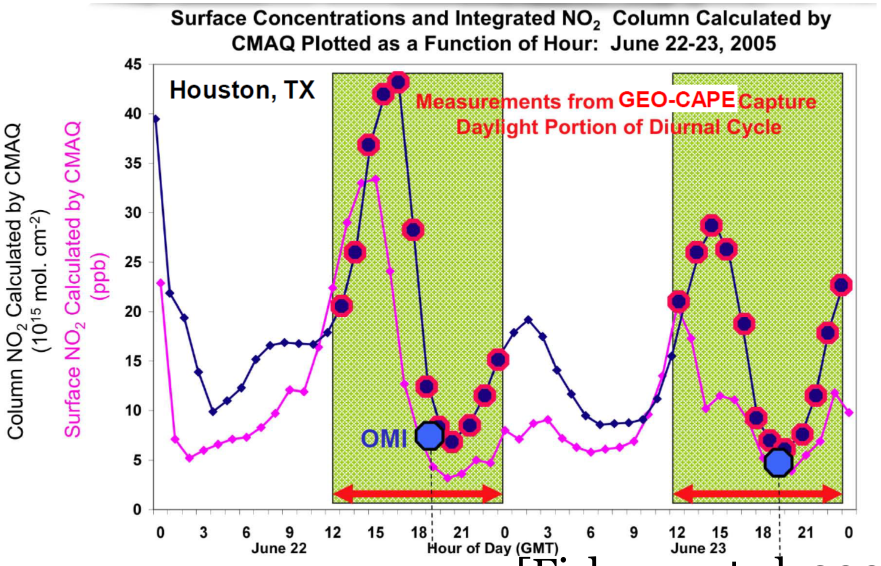
O_3 surface LIDAR Retrieval

DIAL over Huntsville, AL [Newchurch et al, 2009]

Ozone chemistry complex and non-linear

Short timescales → large diurnal variation

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



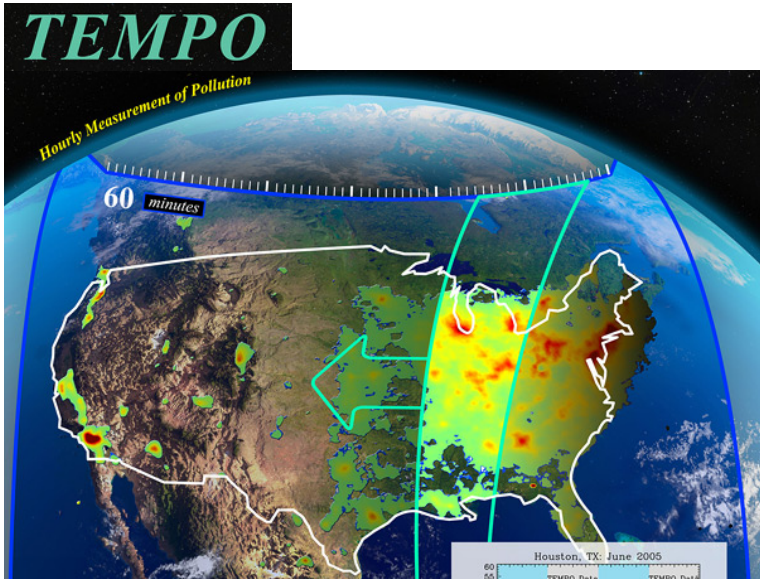
Surface Concentrations and Integrated NO_2 Column Calculated by CMAQ Plotted as a Function of Hour: June 22-23, 2005

[Fishman et al. 2008]

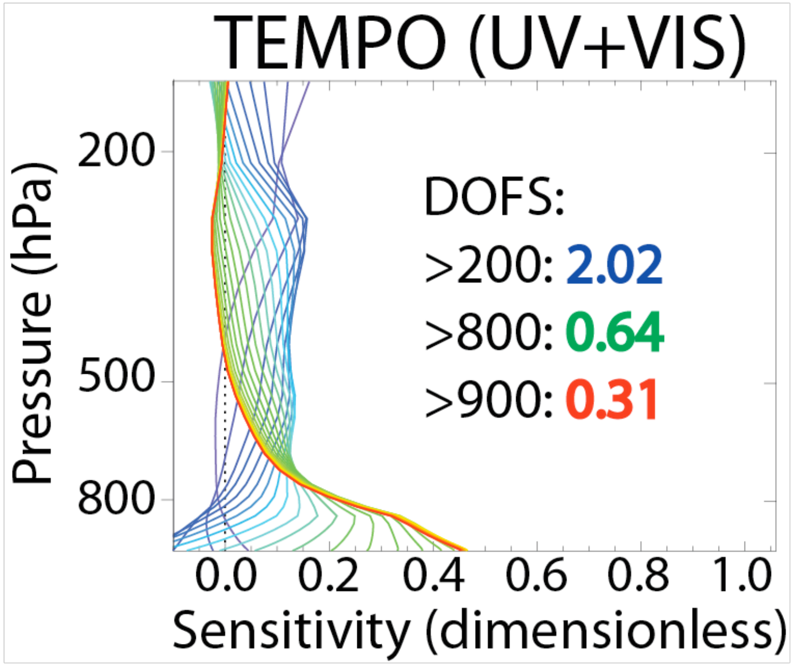
Observations from TEMPO

Features:

- High temporal resolution
- Multispectral observations for increased vertical information



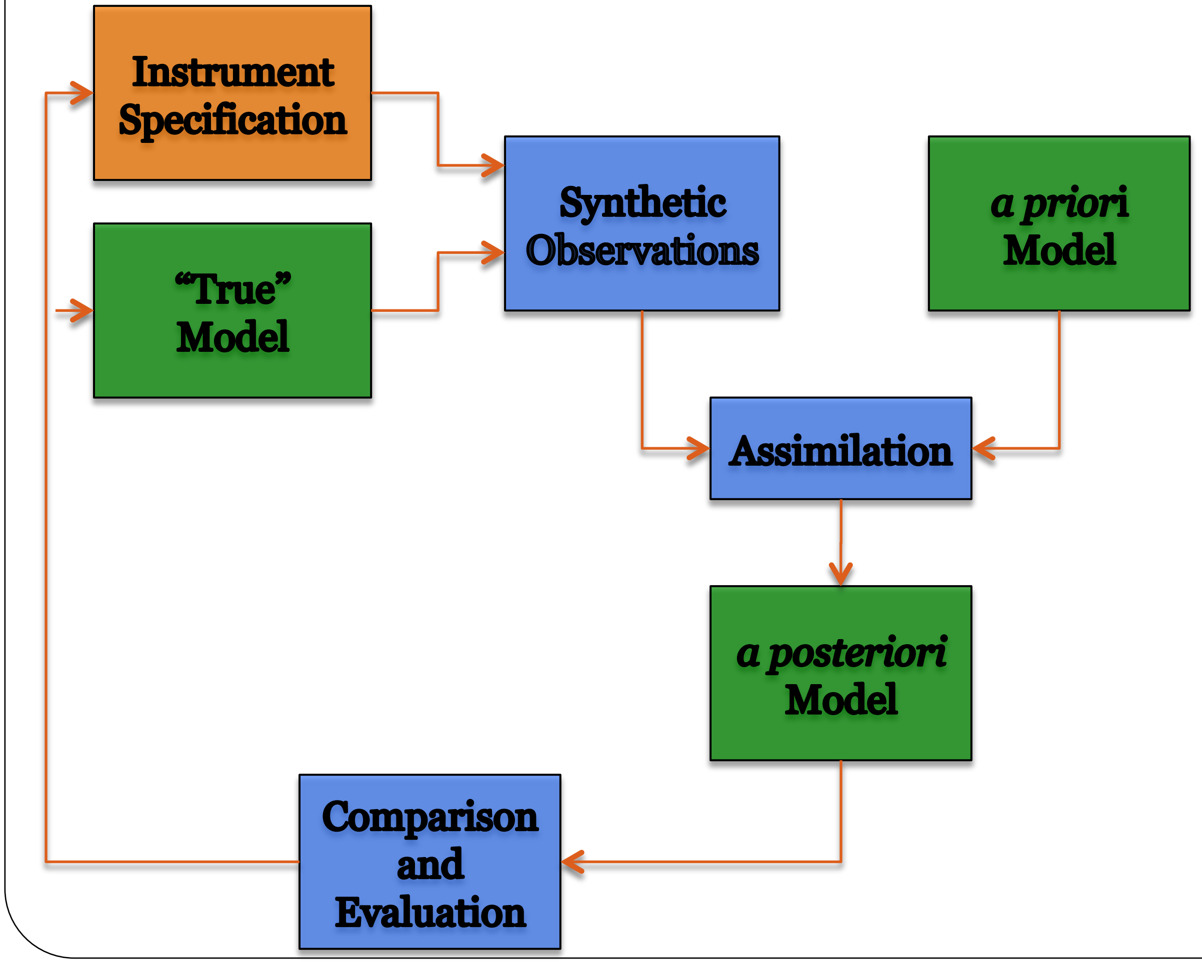
TEMPO Ozone
Averaging Kernel Matrix



[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?



a priori = Chemical Transport Model

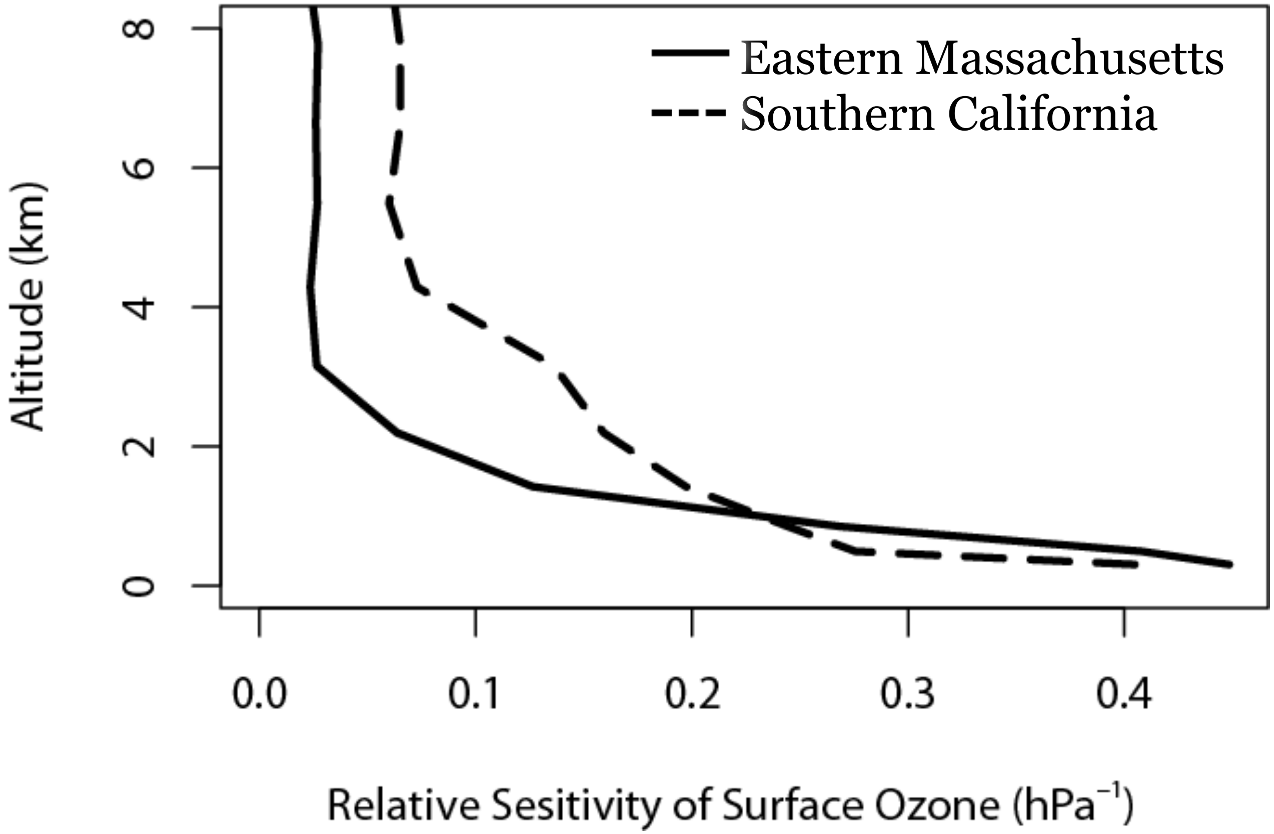
"True" = independent model

a posteriori = *a priori* + assimilation of synthetic observations

→ attempt to reproduce "true" atmosphere

Surface Ozone Sensitivity

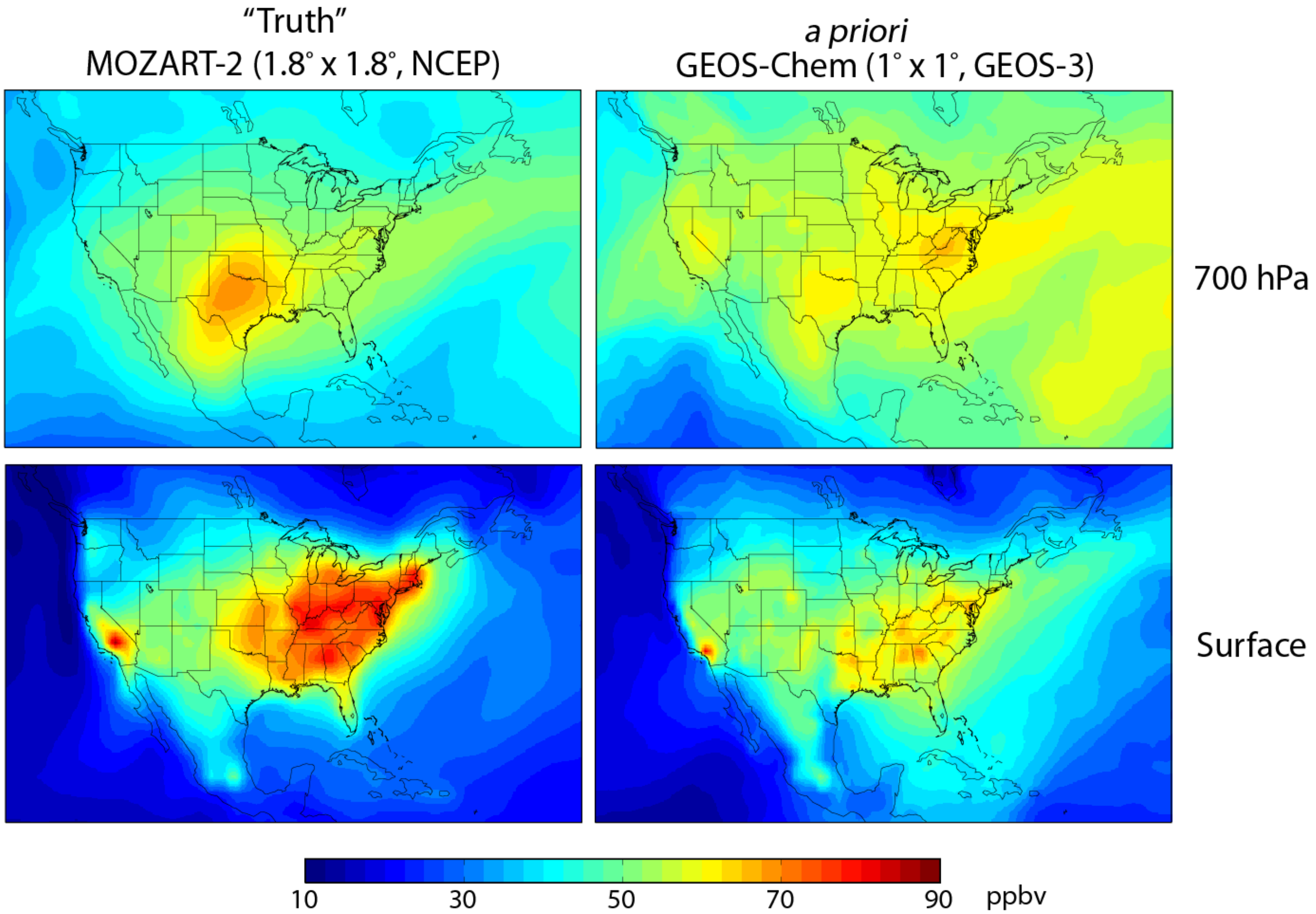
- Adjoint model – receptor based rather than source based approach
- Sensitivity of surface ozone to ozone produced at each vertical layer



Surface ozone primarily sensitive to production below 2 km

Simulation Models are Different

MDA8 Ozone averaged for July 2001



"Truth"
MOZART-2 (1.8° x 1.8°, NCEP)

a priori
GEOS-Chem (1° x 1°, GEOS-3)

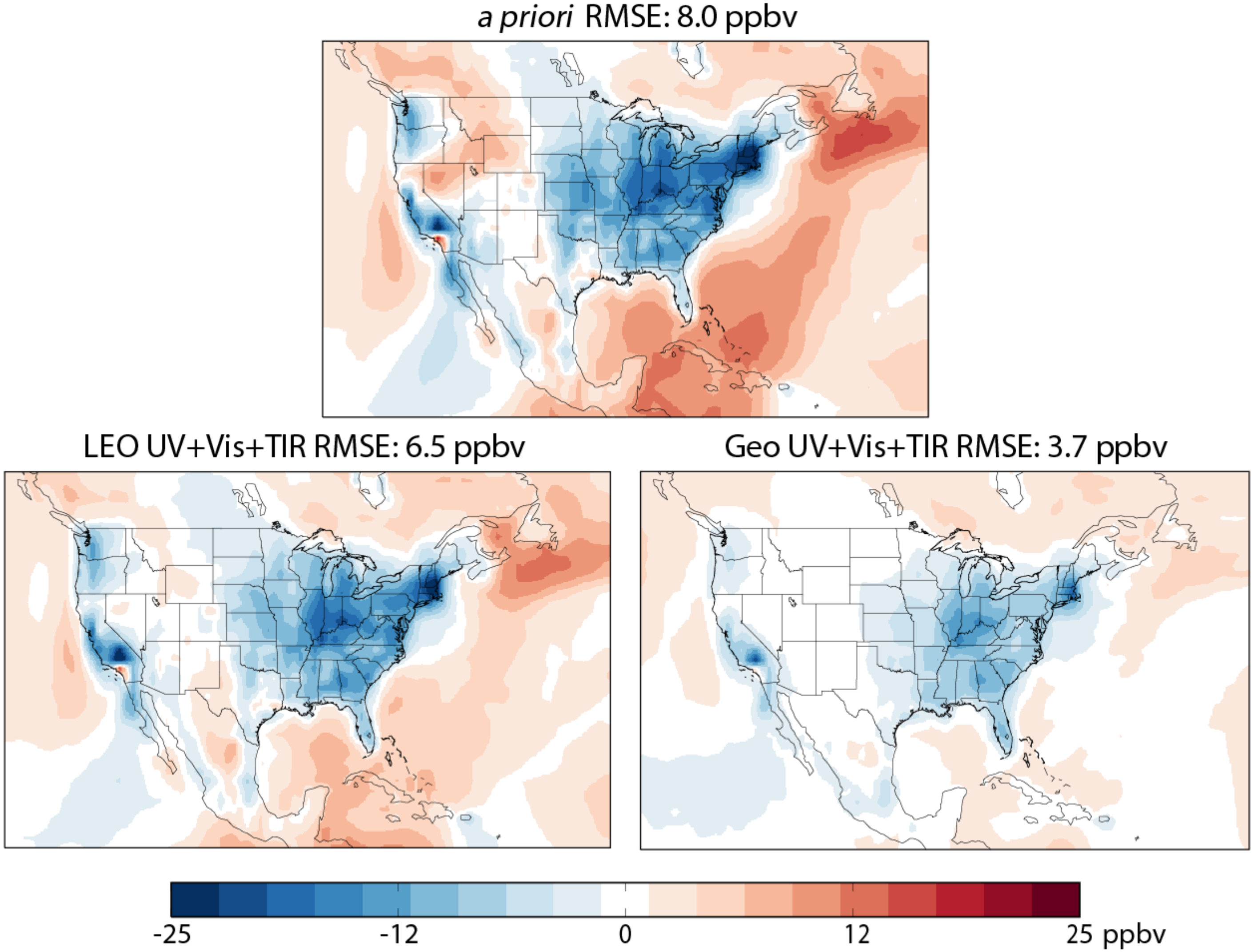
700 hPa

Surface

- "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

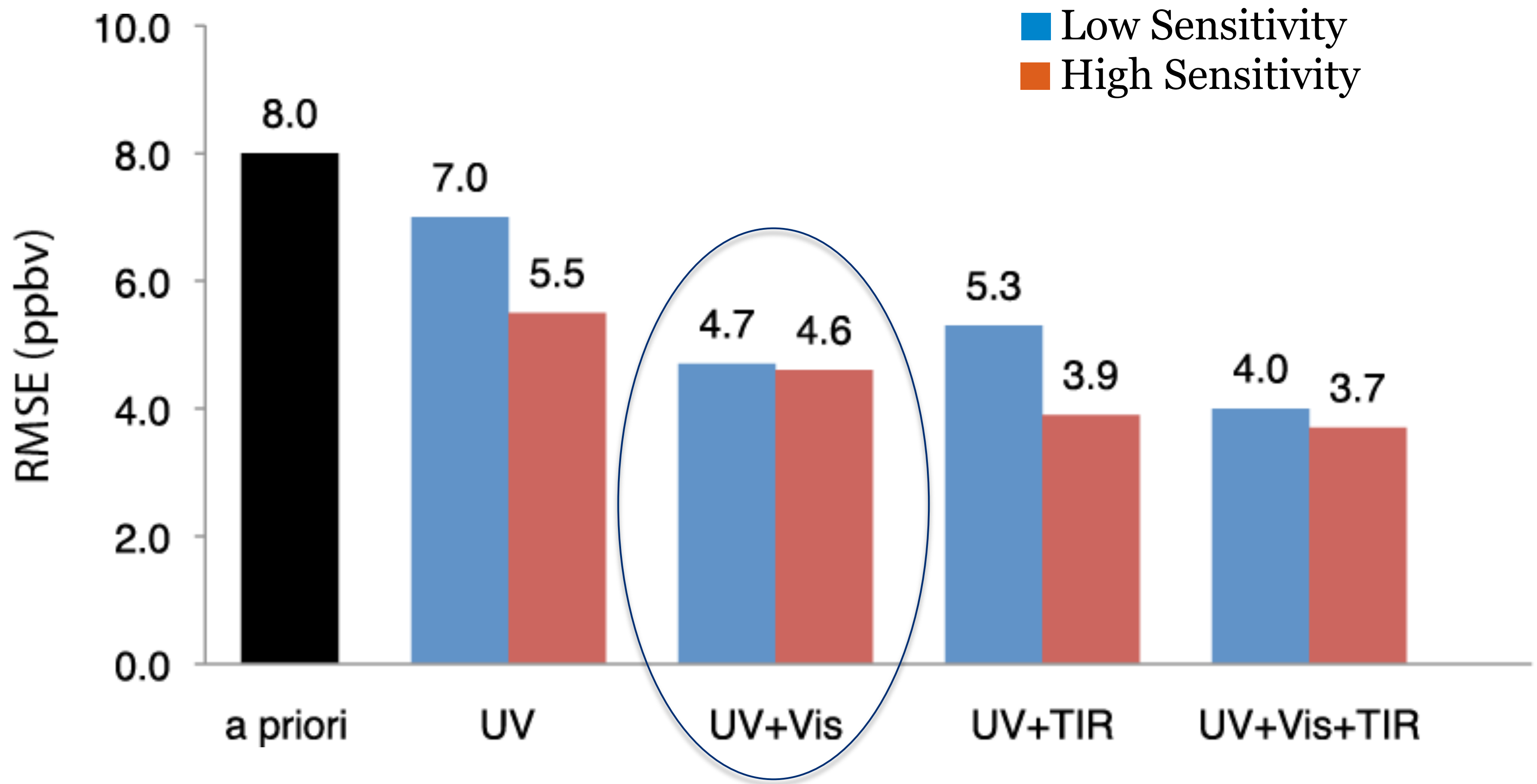
LEO UV+Vis+TIR RMSE: 6.5 ppbv

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

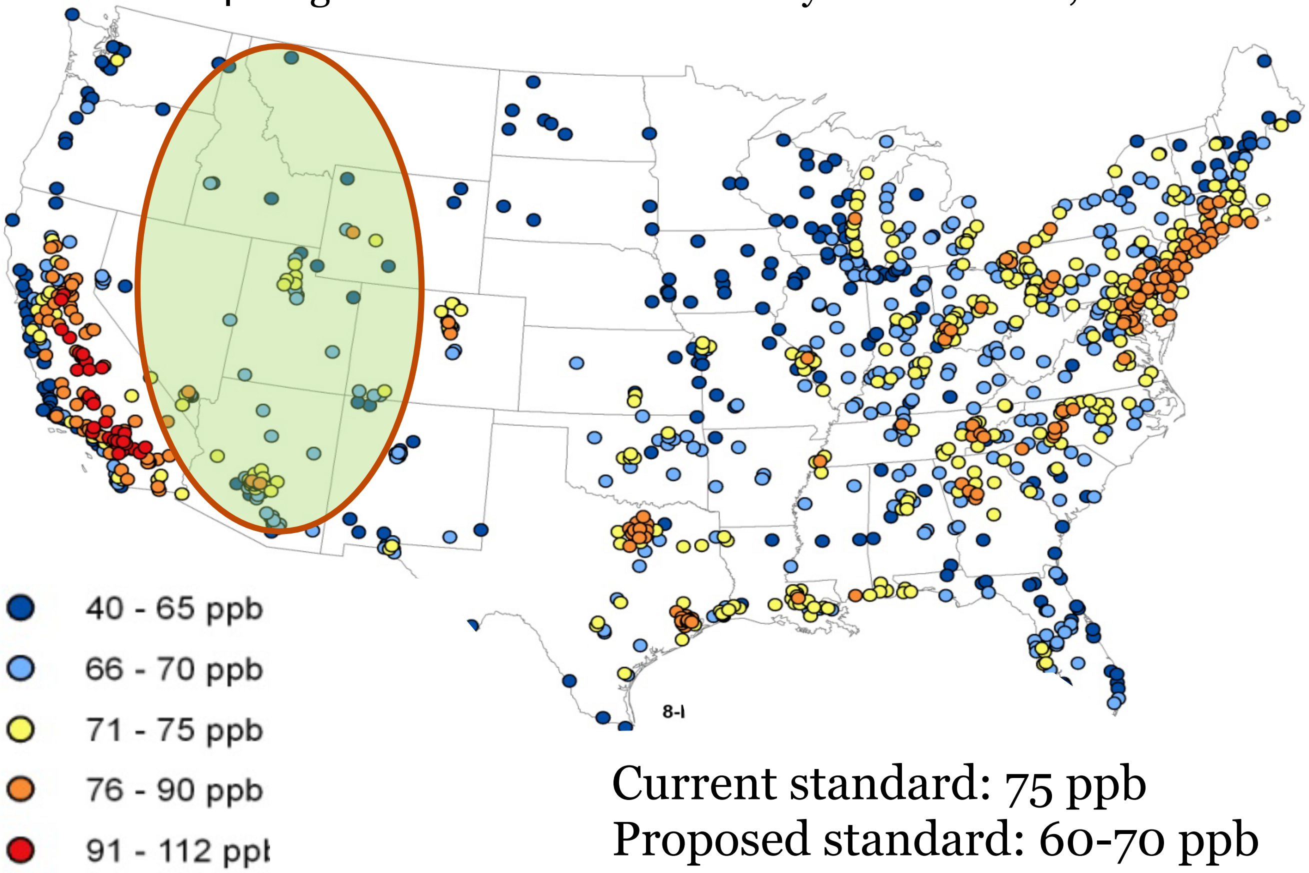
Error in ozone surface air concentration over the US after assimilation of observations in different spectral combinations



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

North American Background Ozone

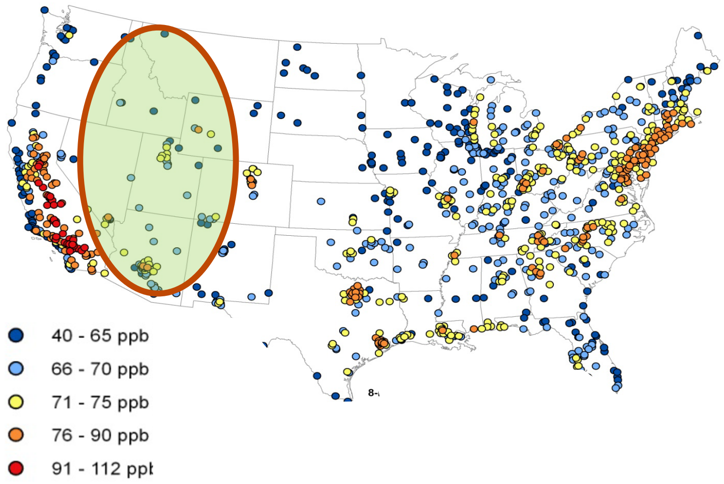
4th-highest annual maximum daily 8-hour ozone, 2008-2010



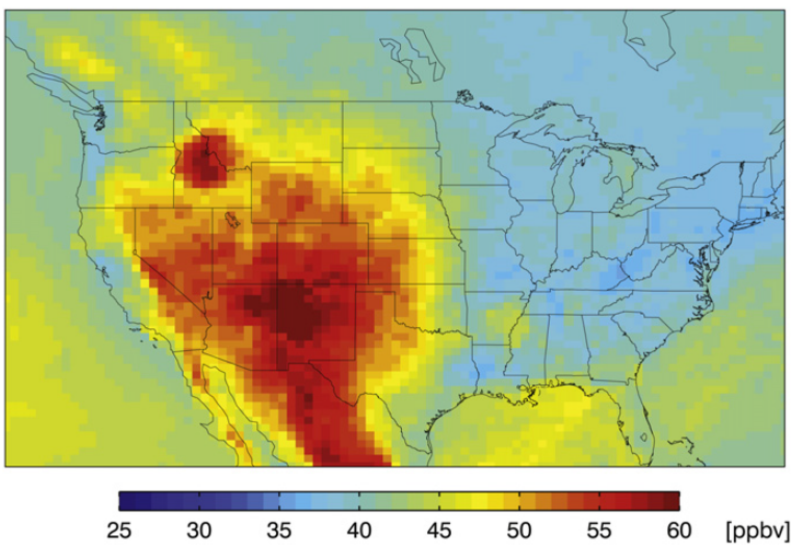
Current standard: 75 ppb
Proposed standard: 60-70 ppb

North American Background Ozone

- O_3 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



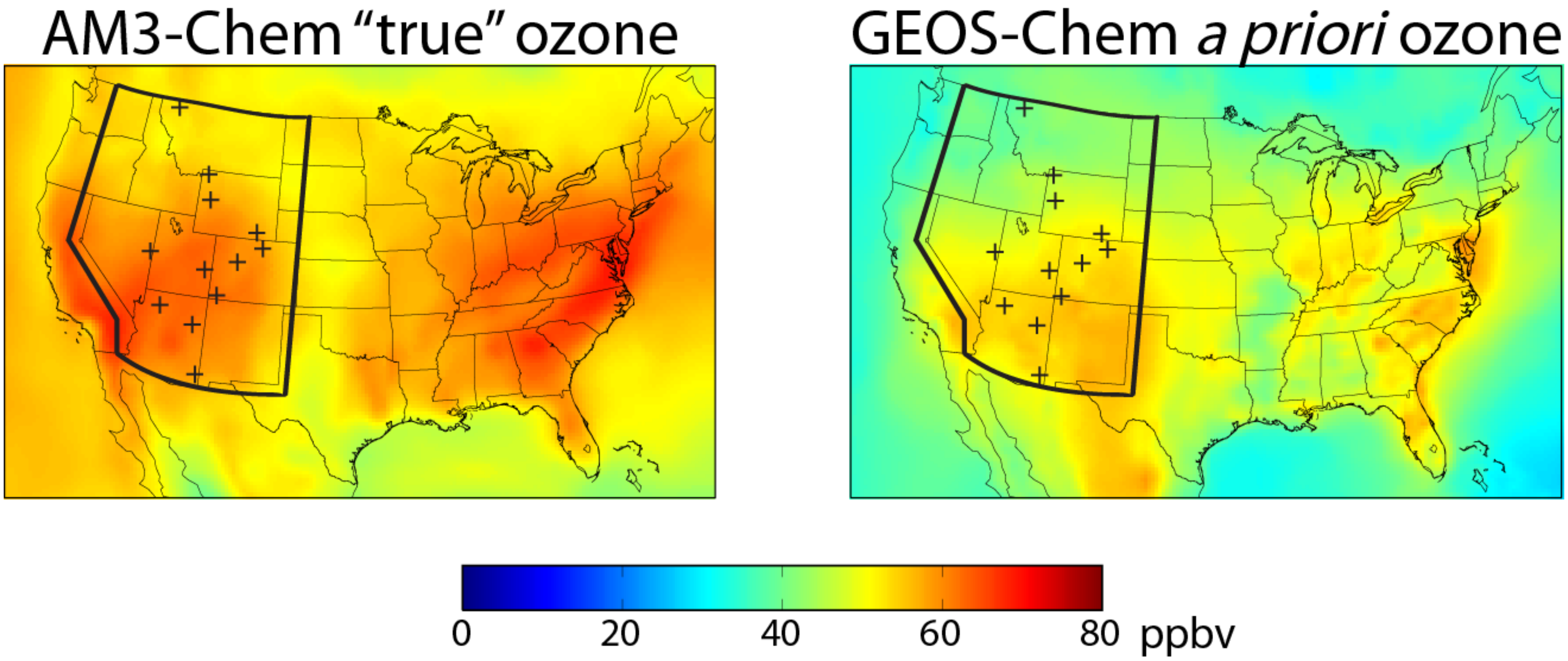
Annual 4th highest PRB ozone for 2006-2008



[Zhang et al. 2011]

Simulation Models

Surface MDA8 Ozone averaged for April-June 2010



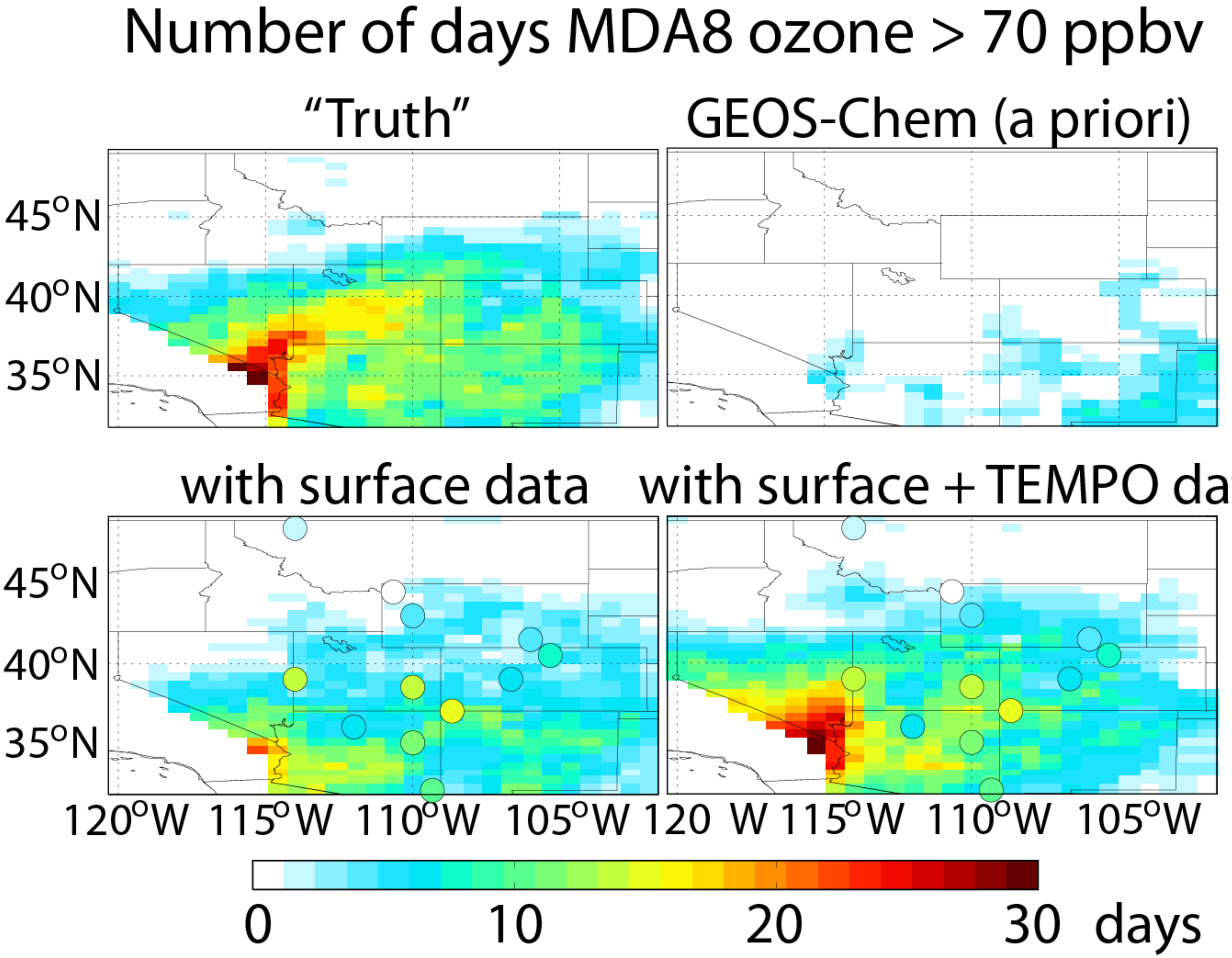
AM3-Chem “true” ozone

GEOS-Chem *a priori* ozone

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

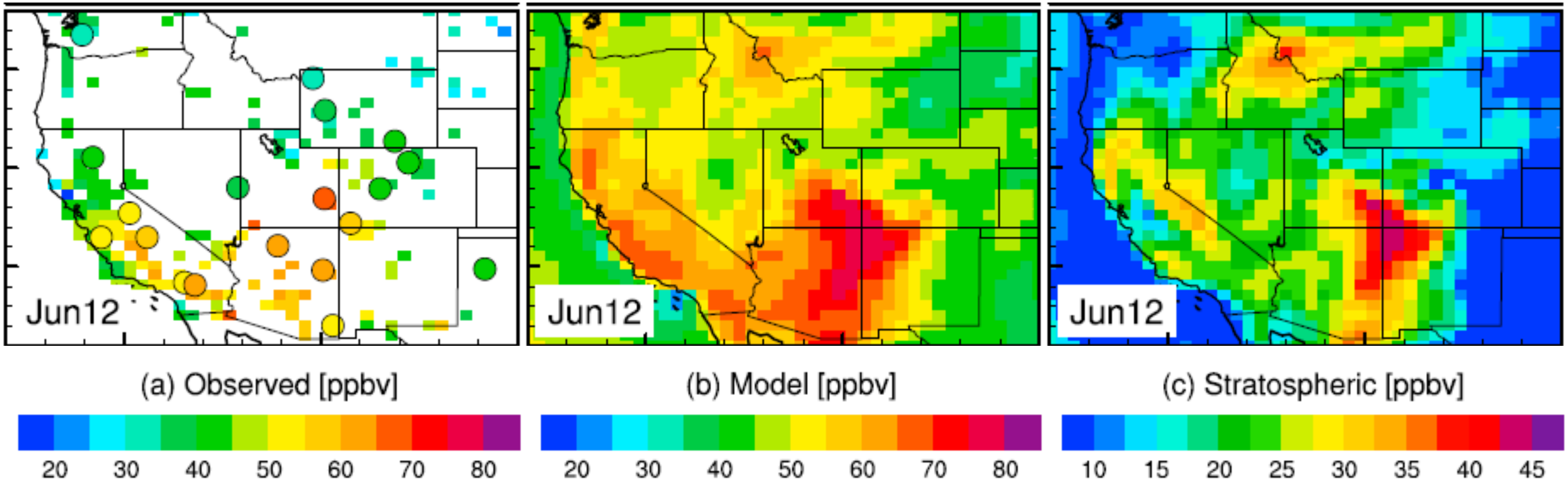
AM3-Chem is biased high but can simulate high-ozone events

Observing high-ozone days



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



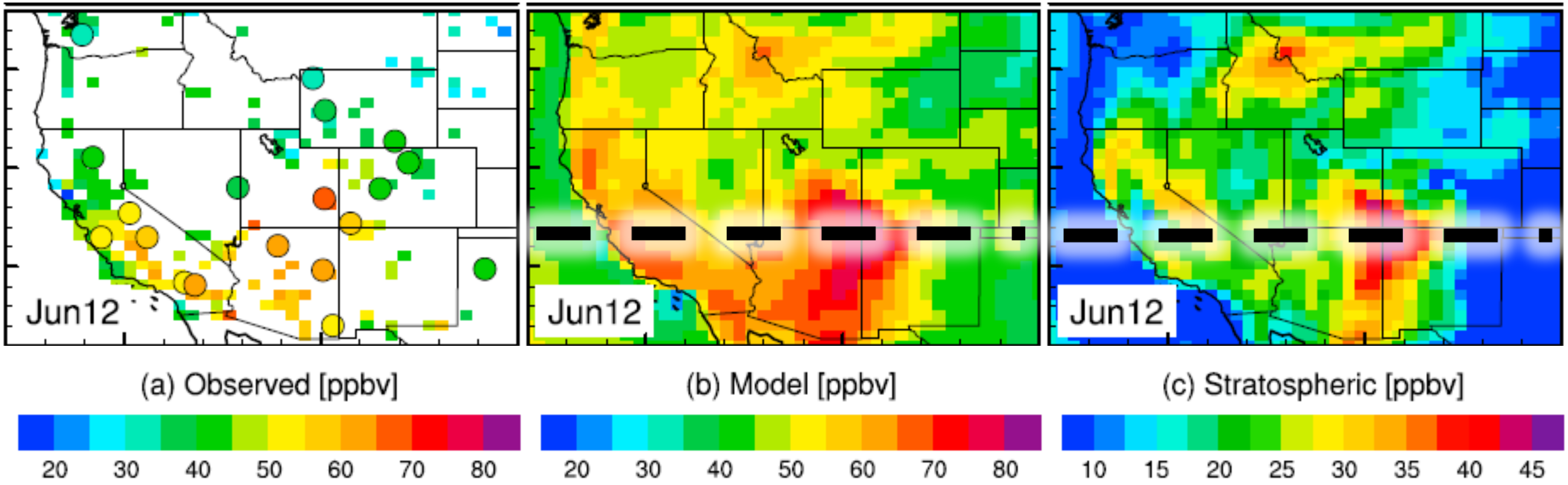
(a) Observed [ppbv]

(b) Model [ppbv]

(c) Stratospheric [ppbv]

[Lin et al. 2012]

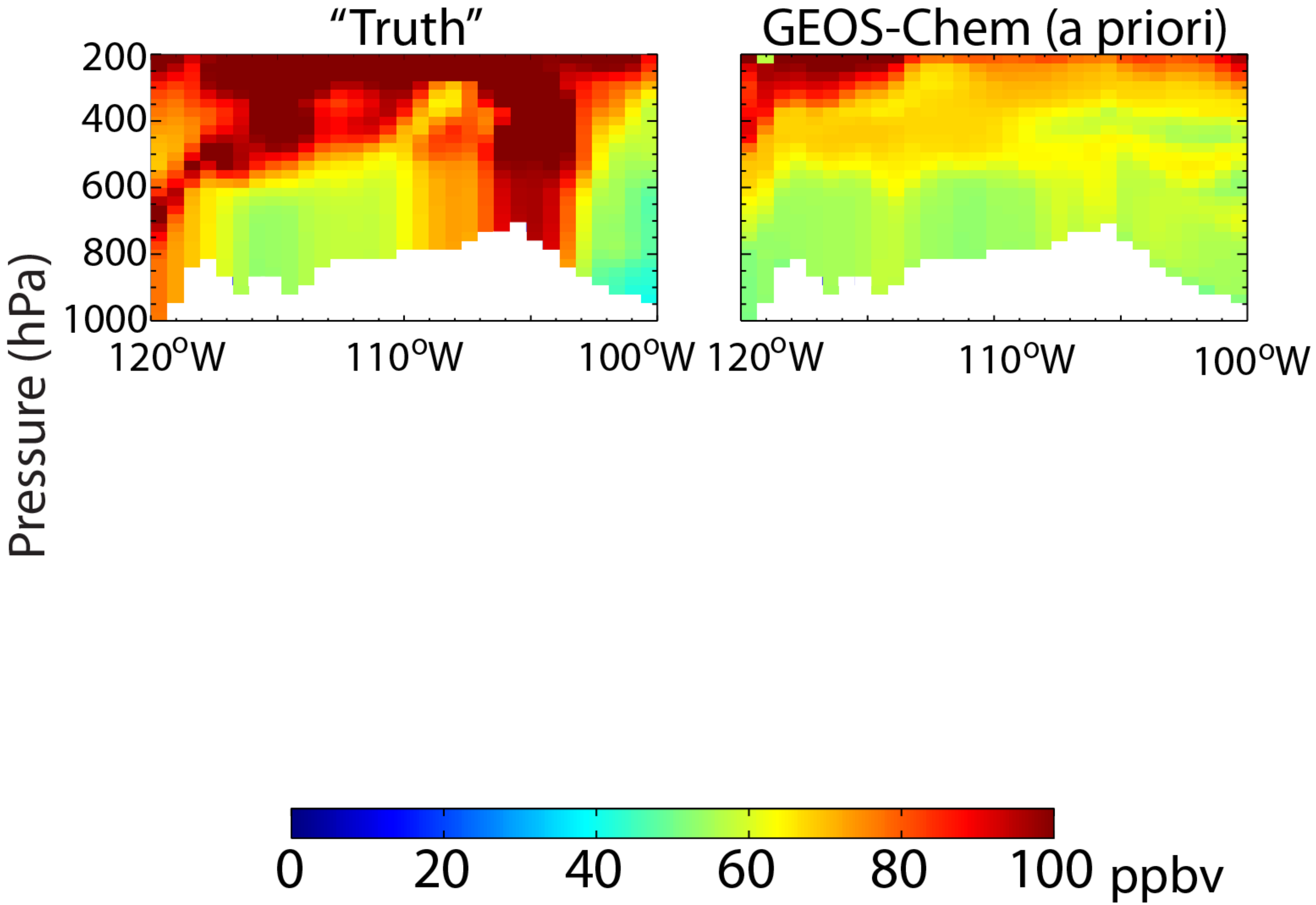
Seeing a Stratospheric Intrusion



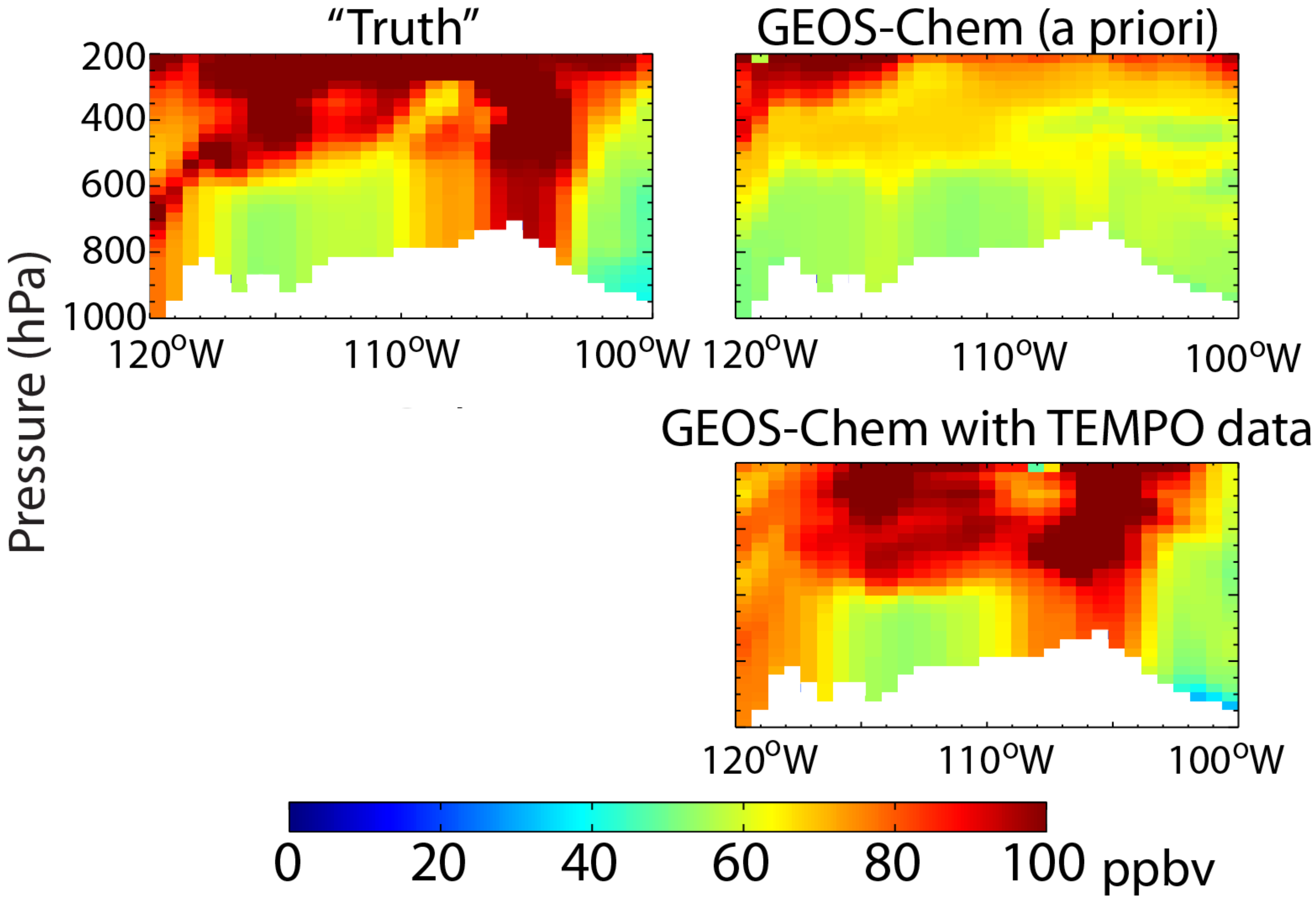
(a) Observed [ppbv] (b) Model [ppbv] (c) Stratospheric [ppbv]

[Lin et al. 2012]

Seeing a Stratospheric Intrusion

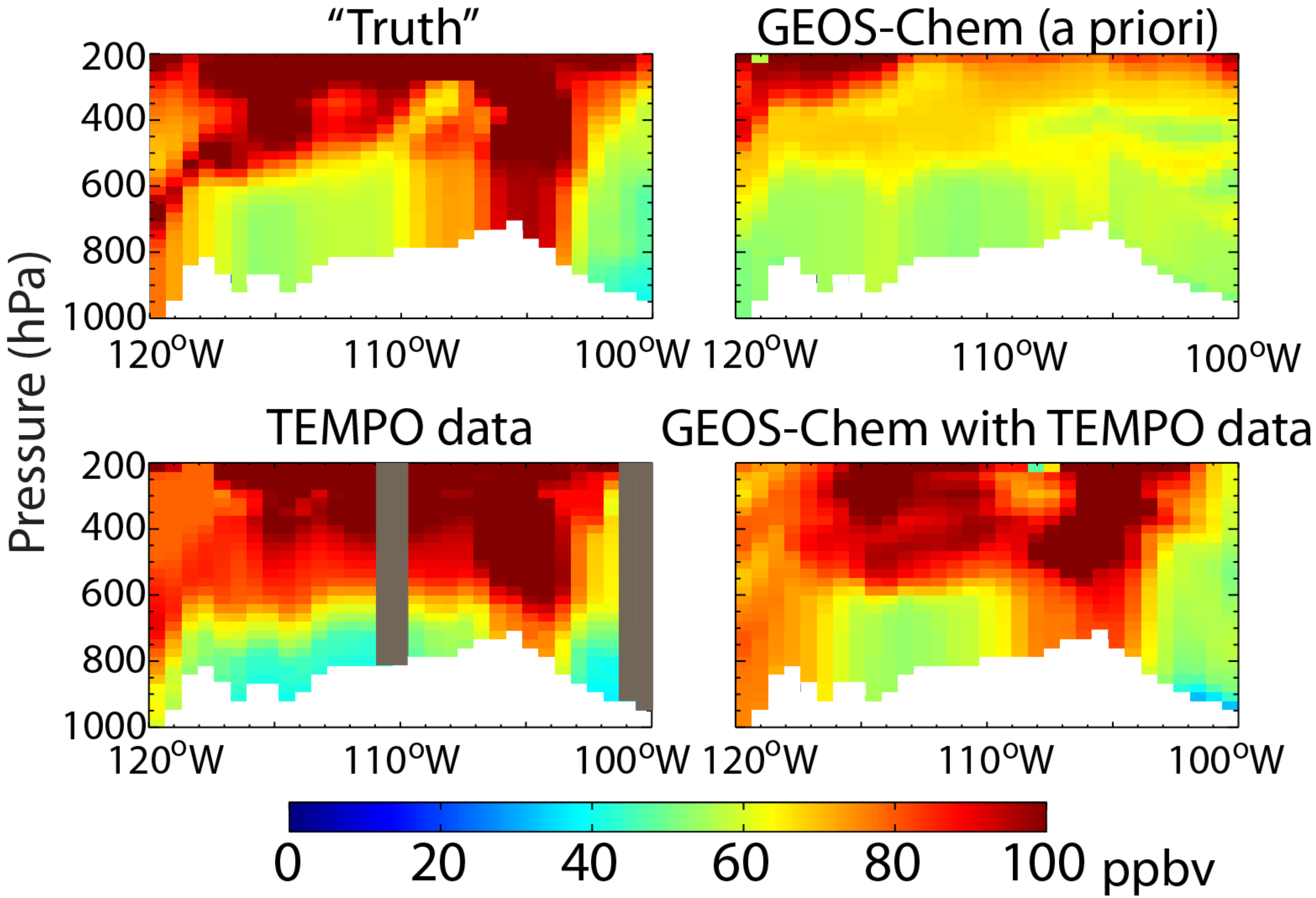


Seeing a Stratospheric Intrusion



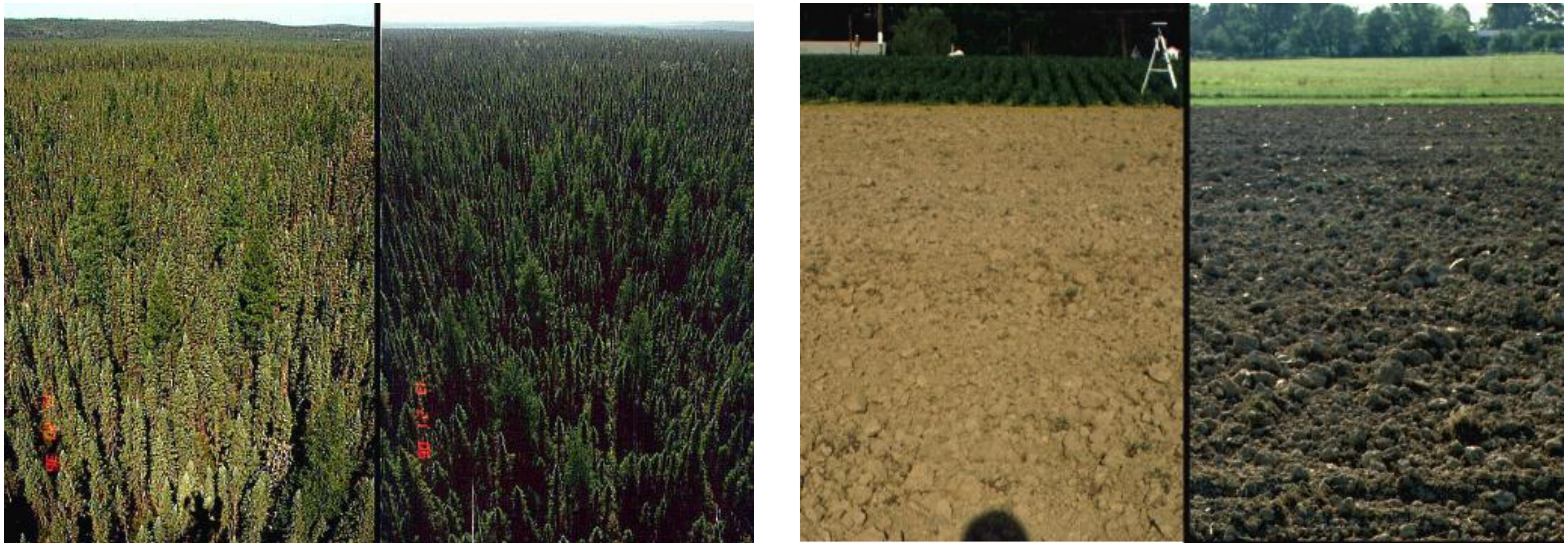
Assimilation of TEMPO observations into GEOS-Chem recaptures structure of intrusion

Seeing a Stratospheric Intrusion



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

Surface Reflectance in the Visible

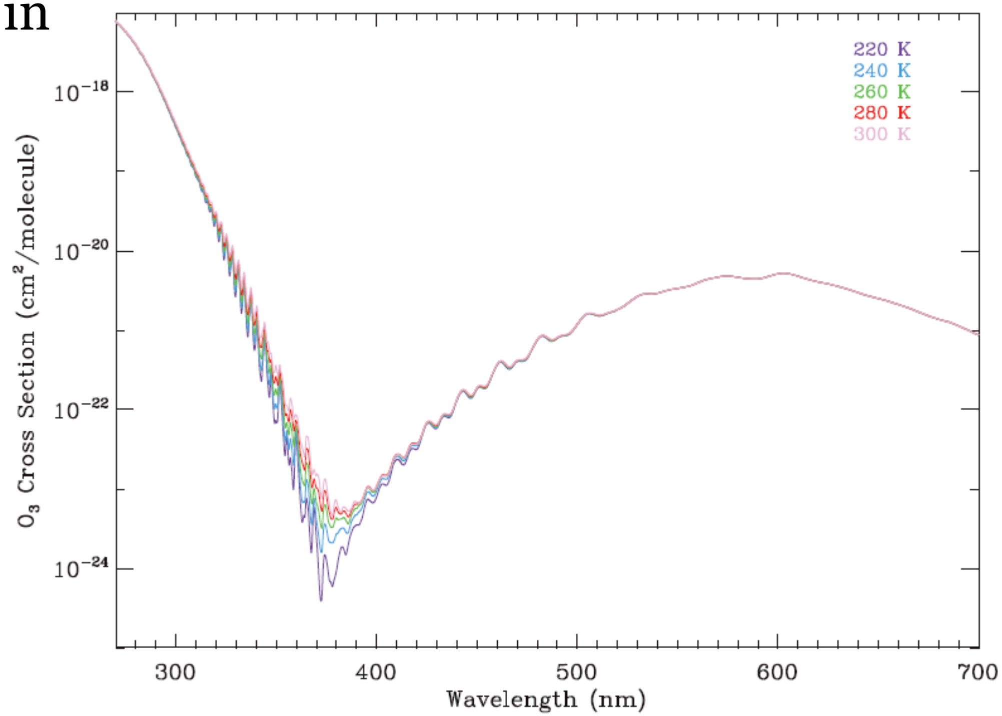


Pictures by Don Deering

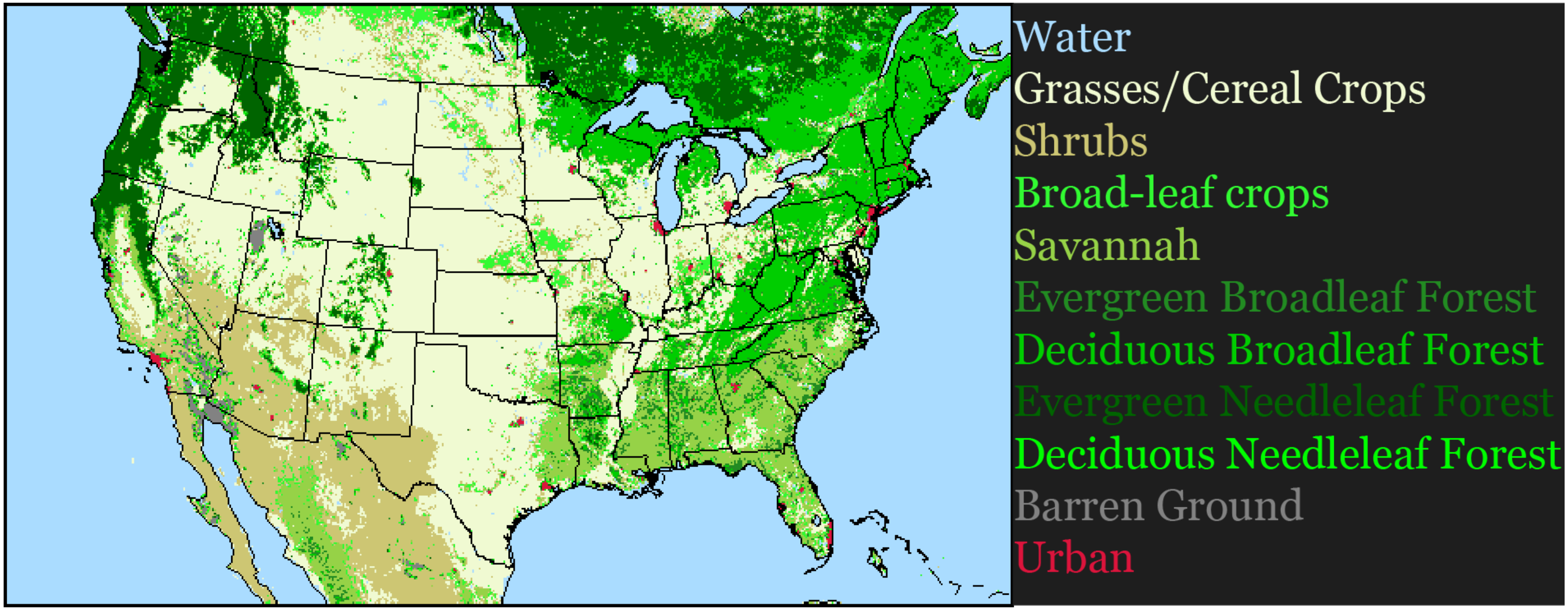
- Spectral variation
- Dependence on land cover
- Changes with viewing geometry

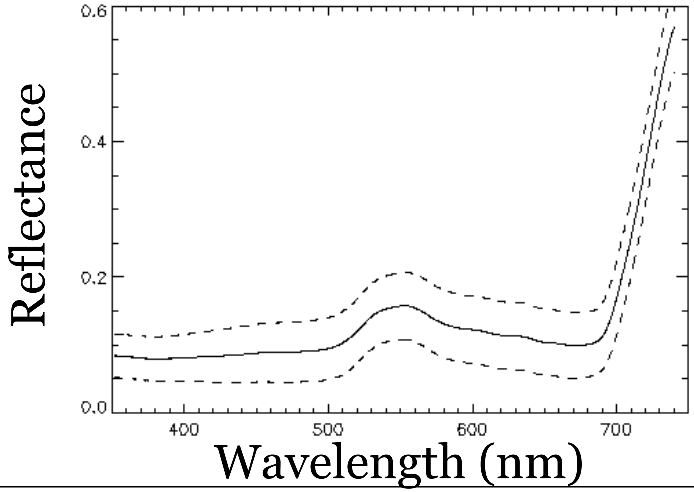
Ozone absorption in the Visible

- 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
  → **surface reflectance**



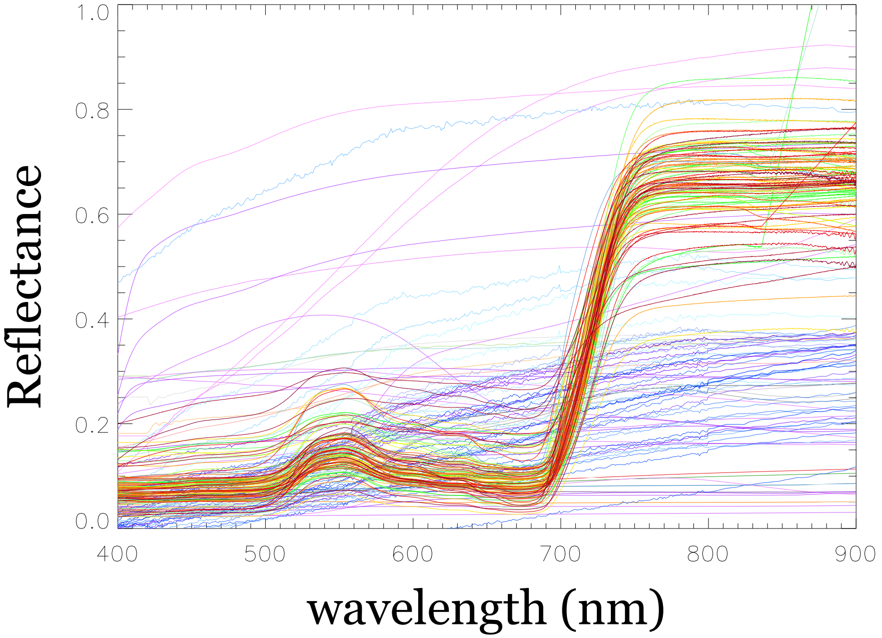
Variation by Land Cover





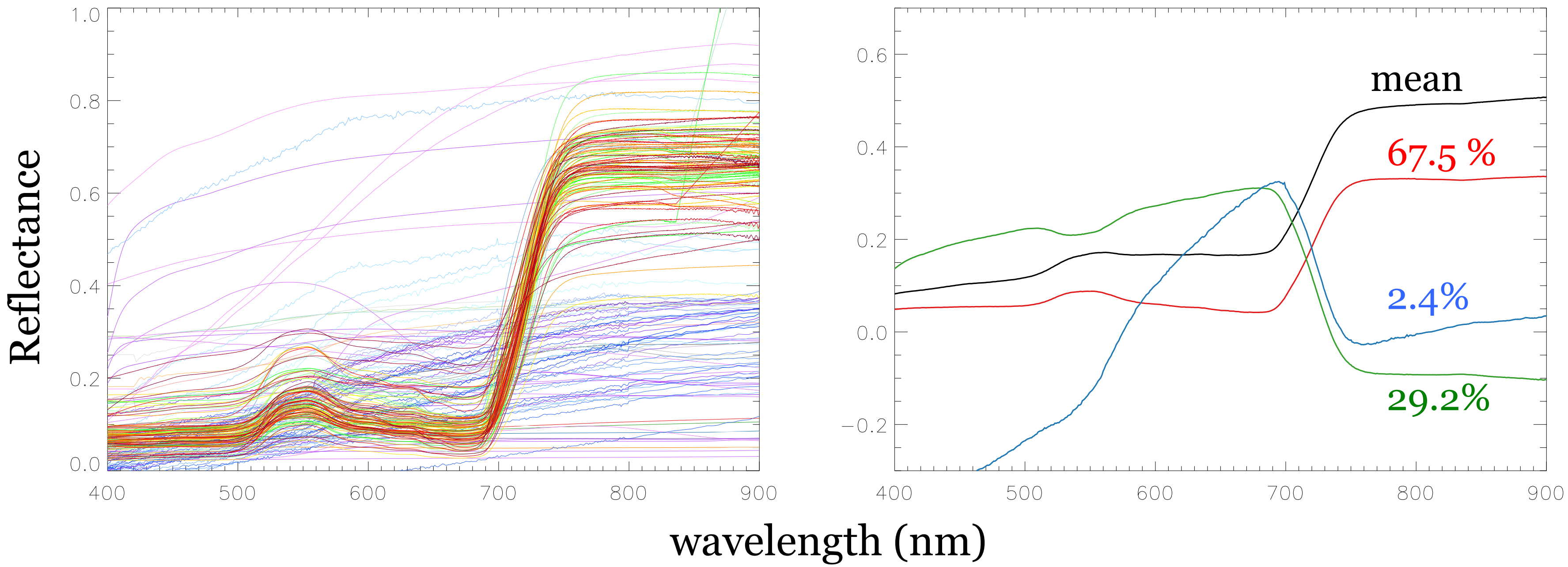
Grasses/Cereals
(51 samples)

Reflectance Spectra by Surface Type



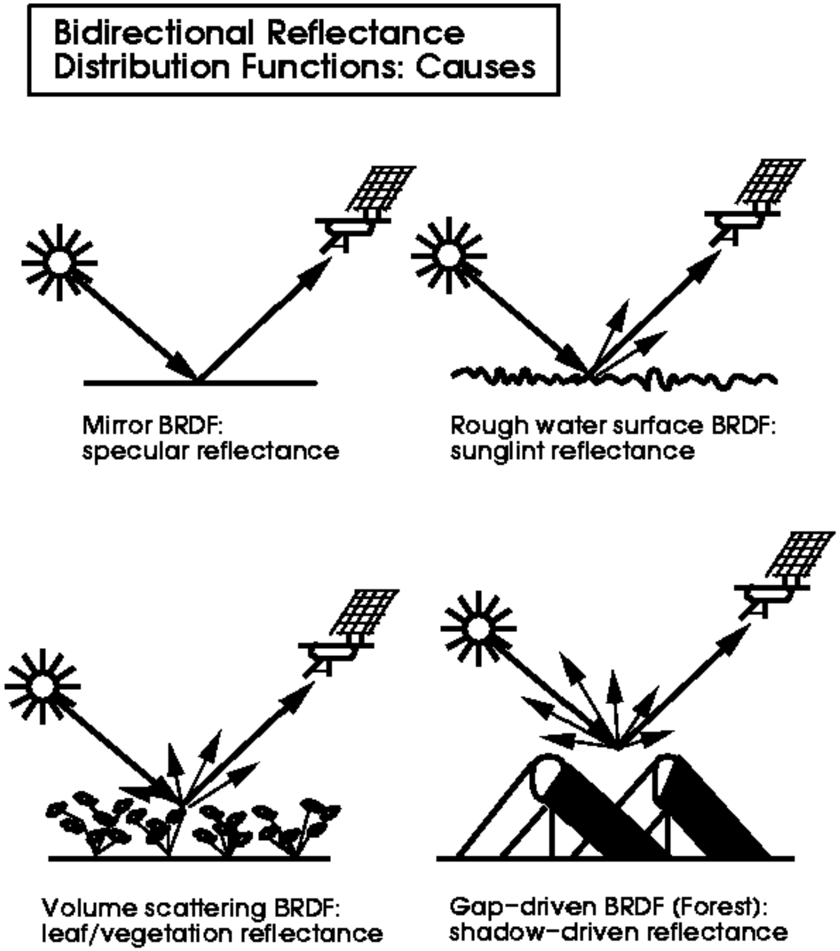
- Obtained lab spectra of possible ground cover
  - Includes vegetation, soils, rocks, manmade materials

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

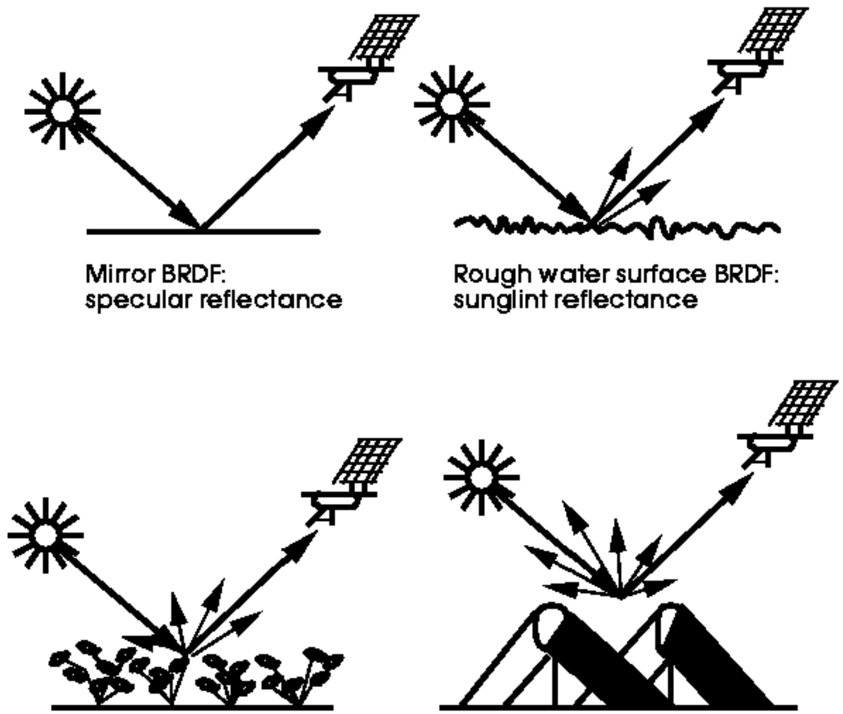
Rough water surface BRDF:
sunglint reflectance

Volume scattering BRDF:
leaf/vegetation reflectance

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

Viewing Geometry from MODIS

Bidirectional Reflectance Distribution Functions: Causes

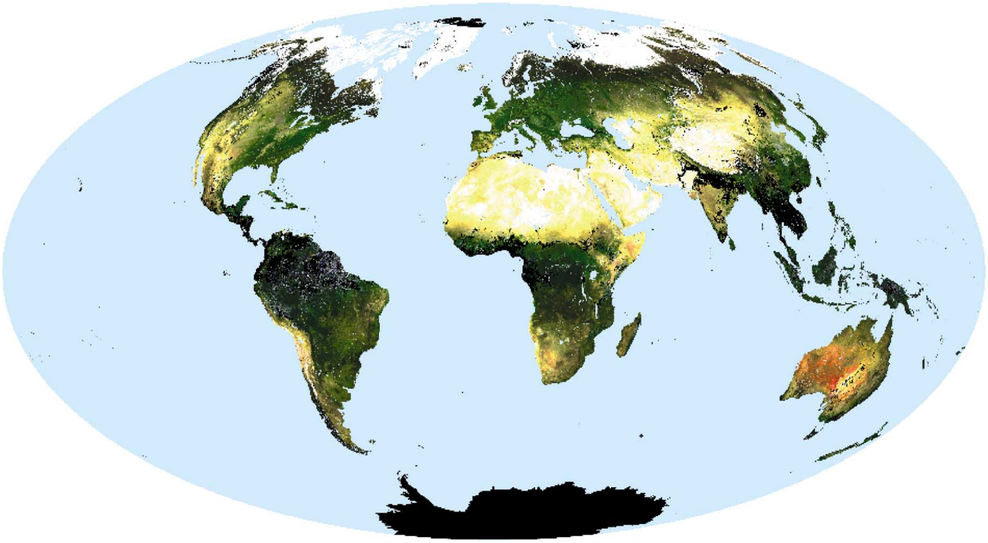


Mirror BRDF: specular reflectance

Rough water surface BRDF: sunglint reflectance

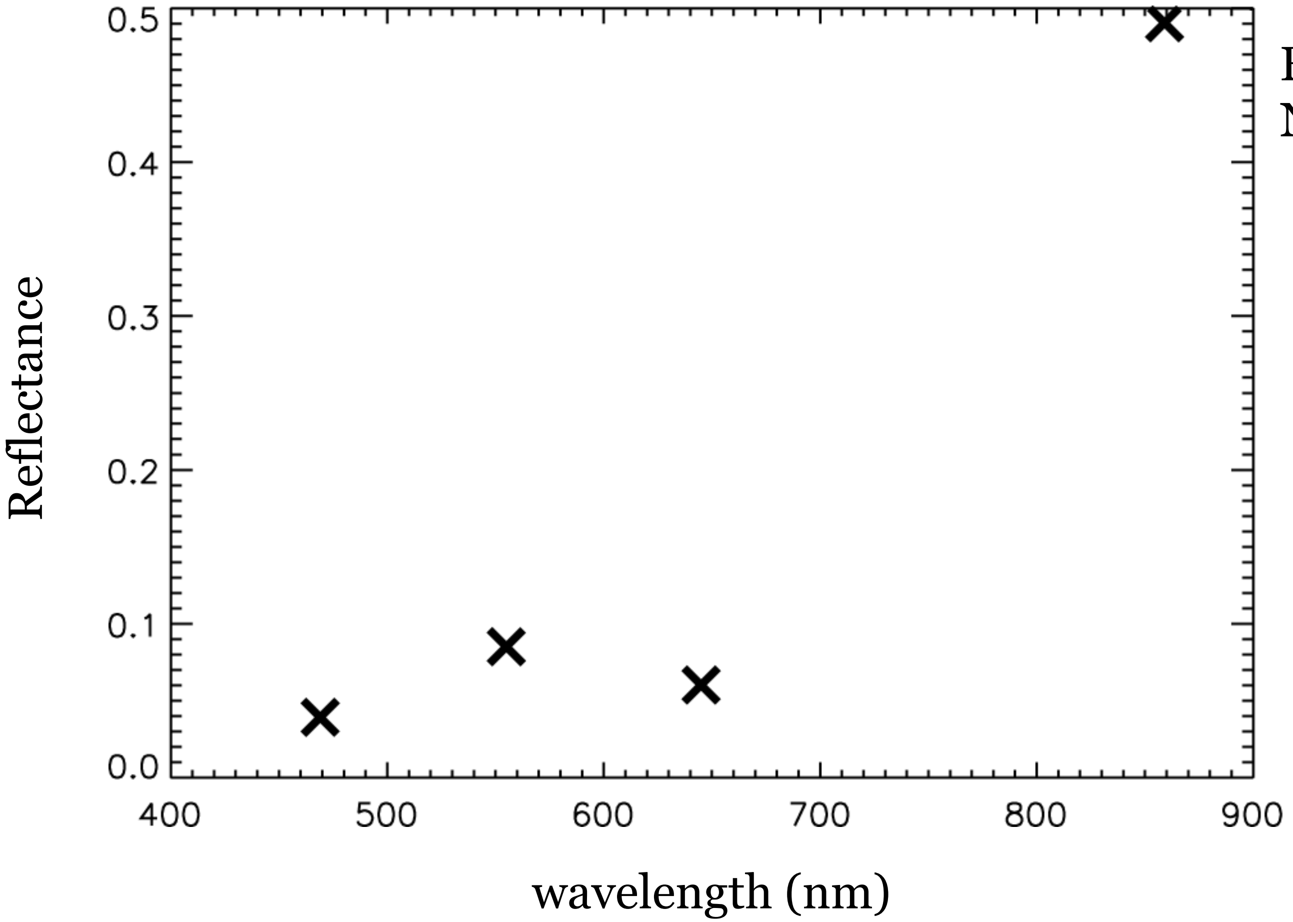
Volume scattering BRDF: leaf/vegetation reflectance

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



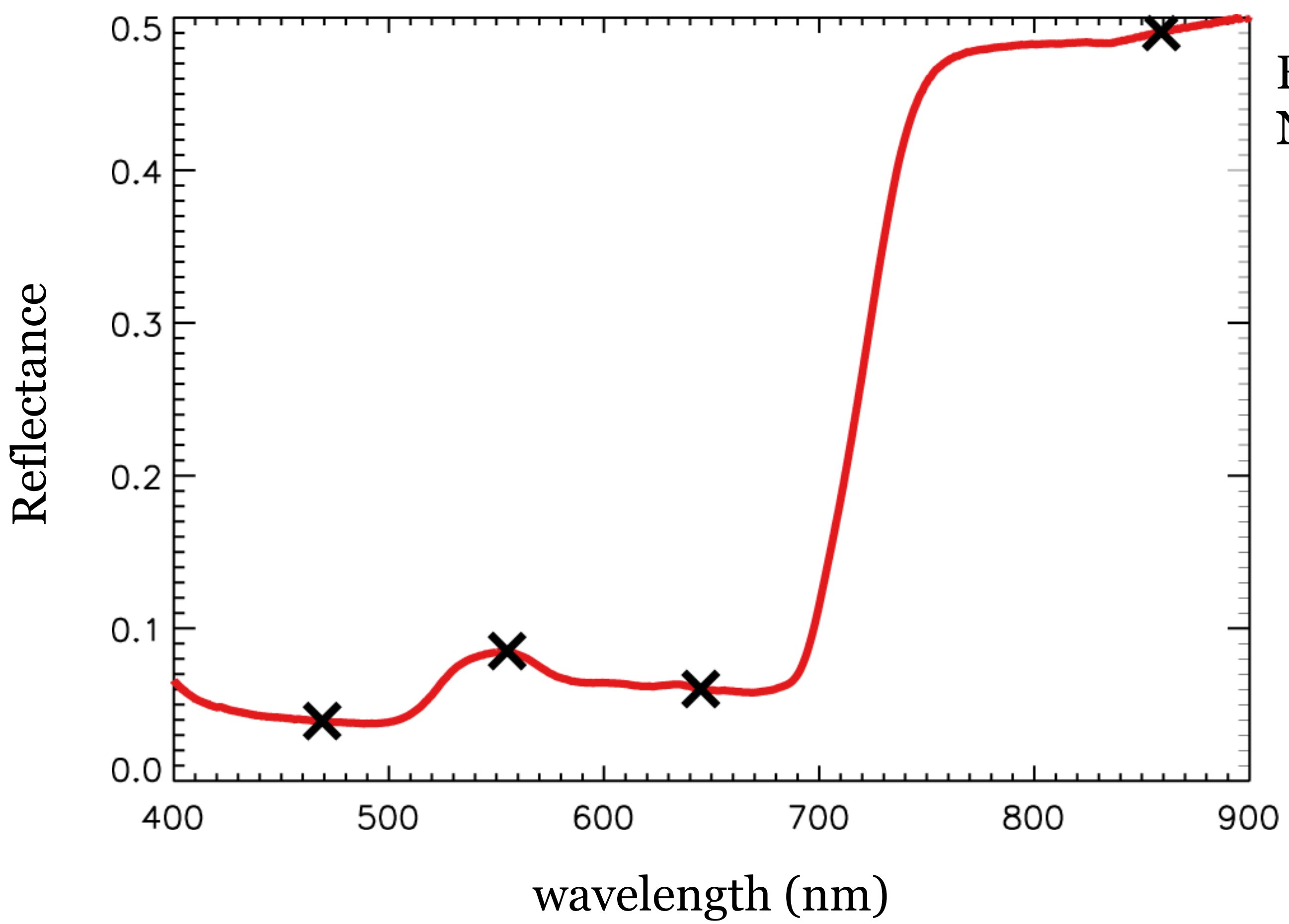
$$R(\lambda,\theta,\vartheta,\phi) = f_{iso}(\lambda) + f_{vol}(\lambda)K_{vol}(\theta,\vartheta,\phi) + f_{geo}(\lambda)K_{vol}(\theta,\vartheta,\phi)$$

Visible Reflectance Spectrum
Example: Vegetated Scene (Summer)



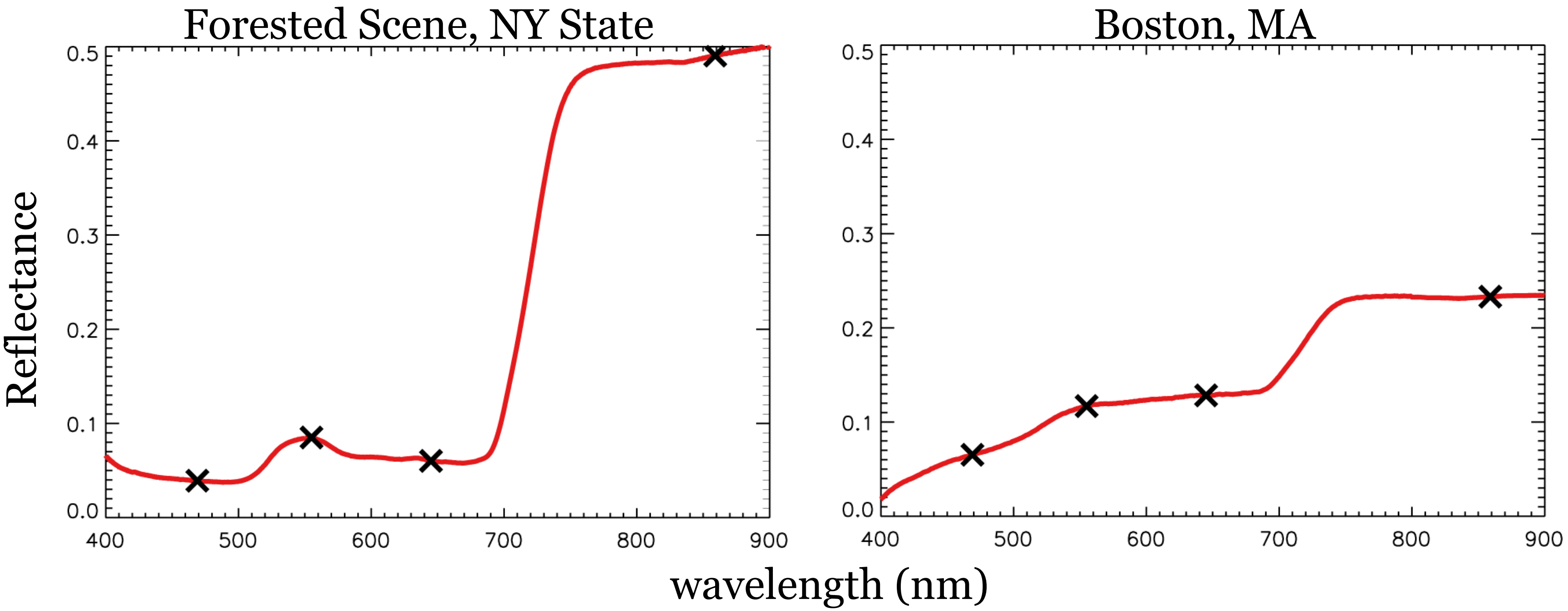
Forested Scene,
New York State

Visible Reflectance Spectrum
Example: Vegetated Scene (Summer)

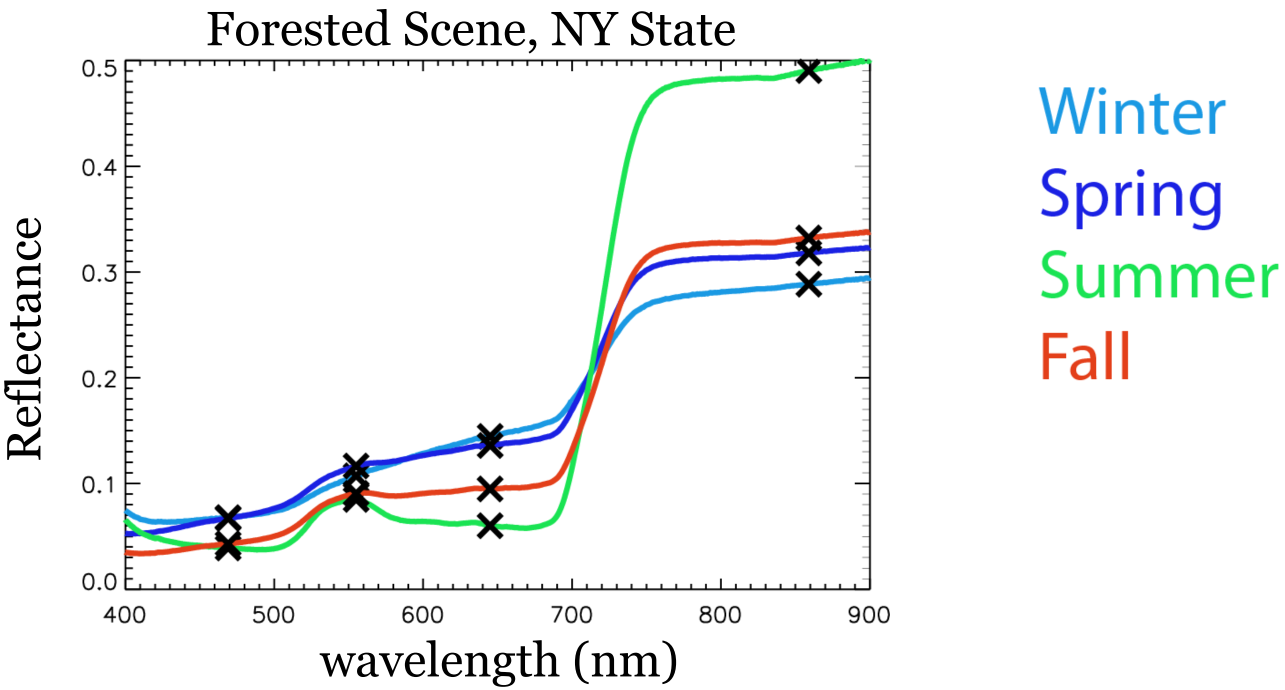


Forested Scene,
New York State

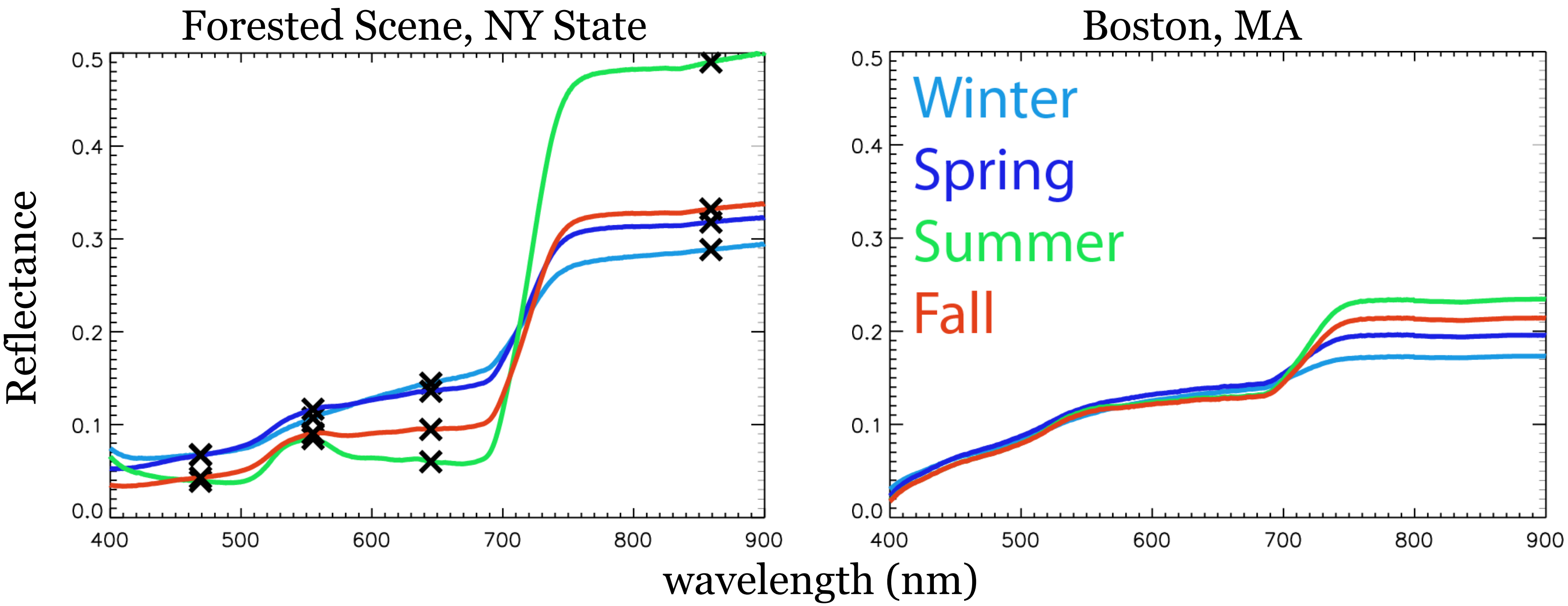
Visible Reflectance Spectrum
Vegetated vs. Urban (Summer)



Seasonal Variation



Seasonal Variation

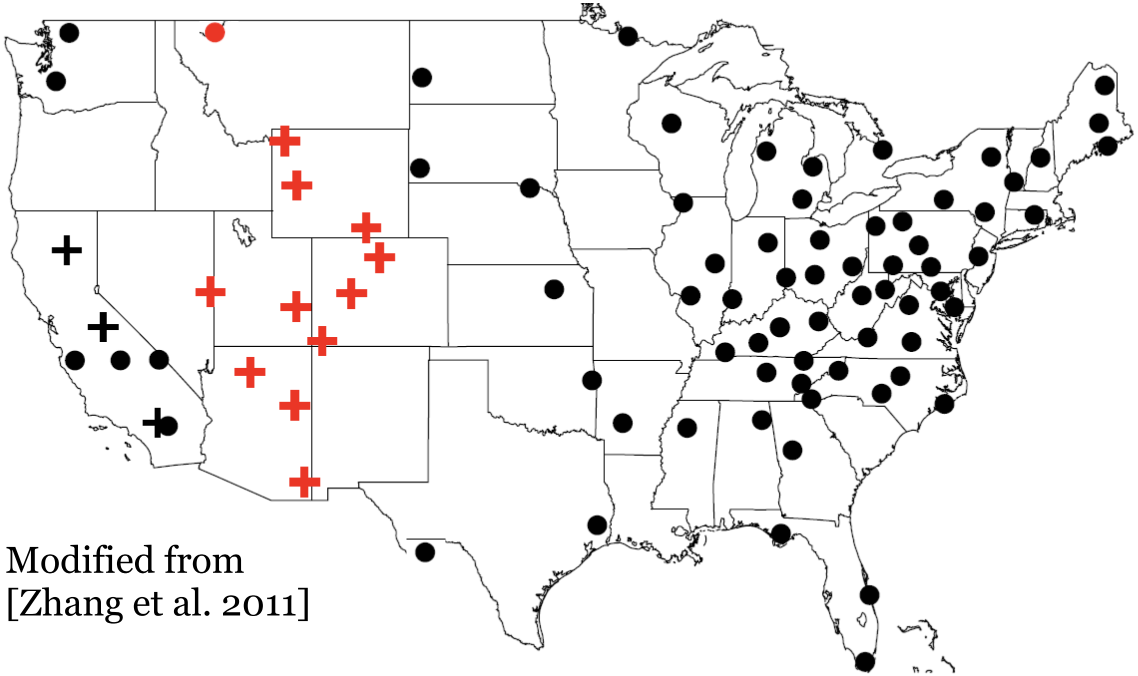


Conclusions

- 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) which we have captured using EOF decomposition
  - More work needed on water, snow/ice scenes; field validation

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

Surface Measurements from CASTNet



Modified from
[Zhang et al. 2011]

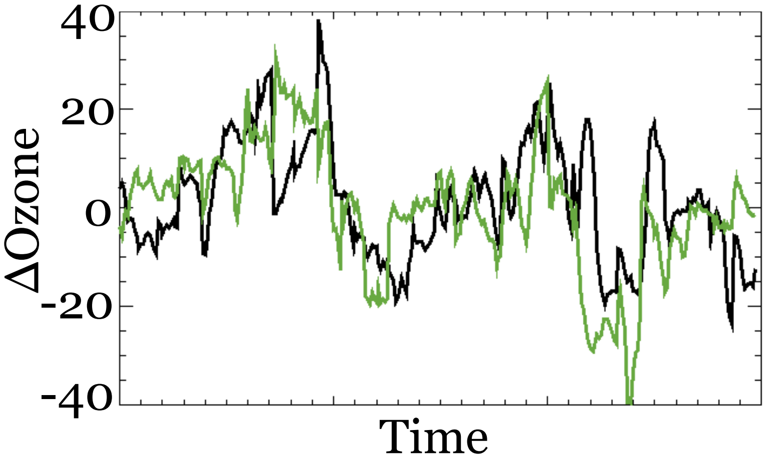
CASTNet ozone monitoring sites in the continental United States
Sites in the intermountain West in red.

Rocky Mountain NP [EPA]

- 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

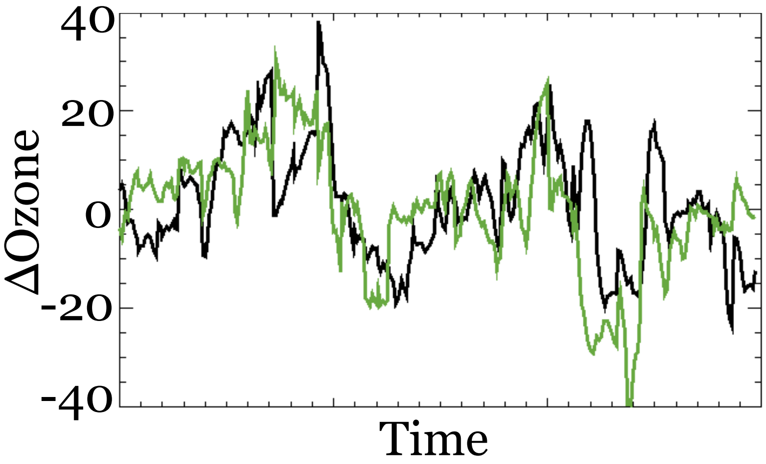


R=0.50, D=340 km

- 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



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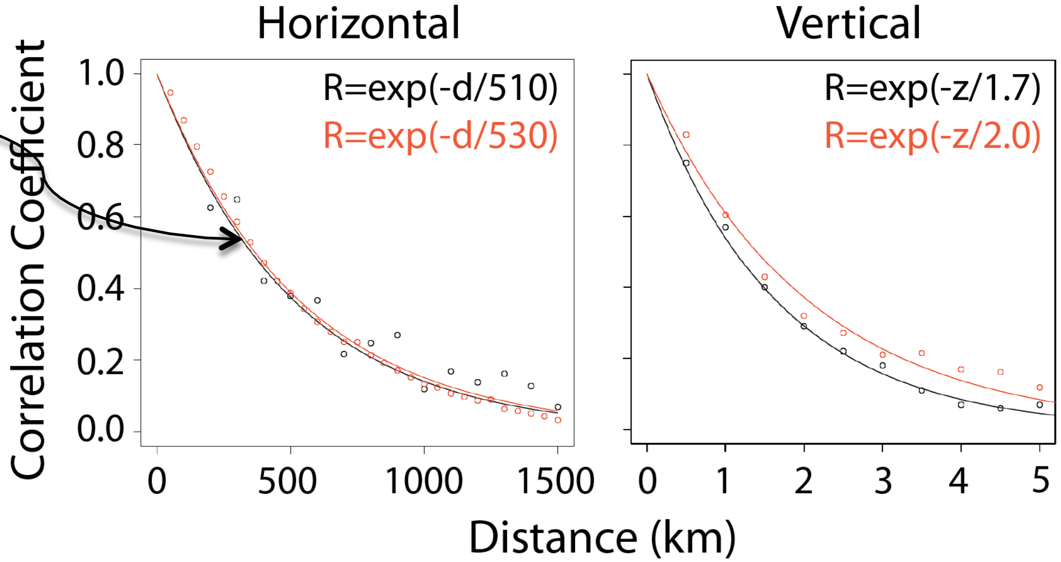


- Plot R vs. distance to find error correlation length scale

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

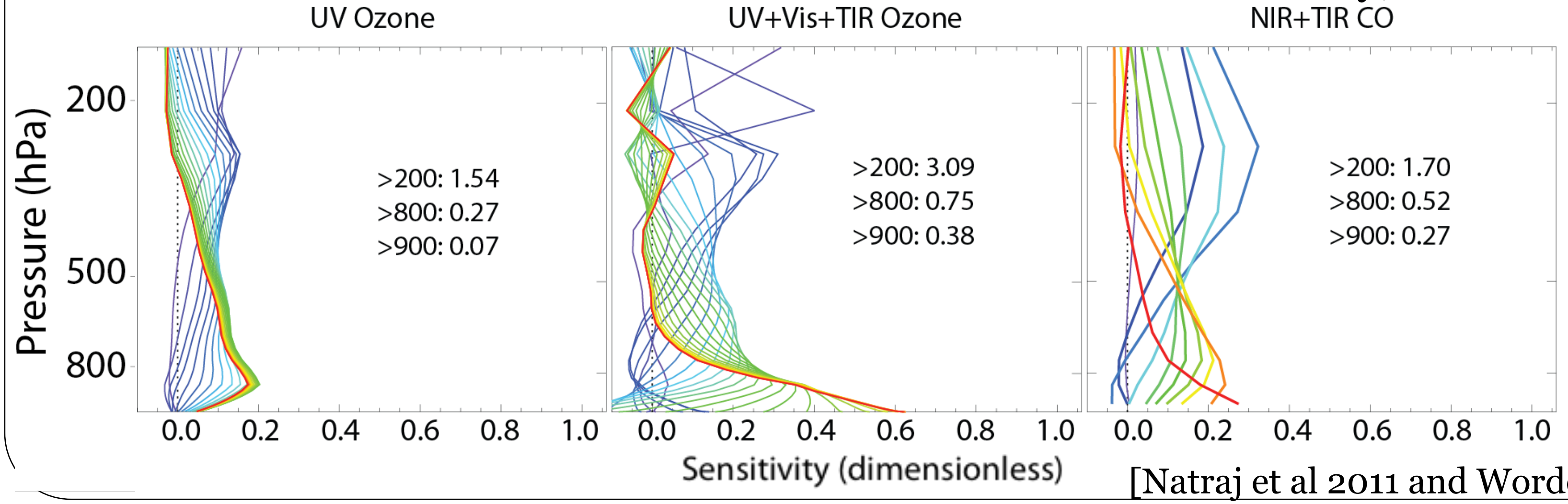
Approach:

Quantify ozone-CO model error correlations

Implement a joint assimilation system

Theoretical Ozone sensitivities

CO sensitivity, MOPITT

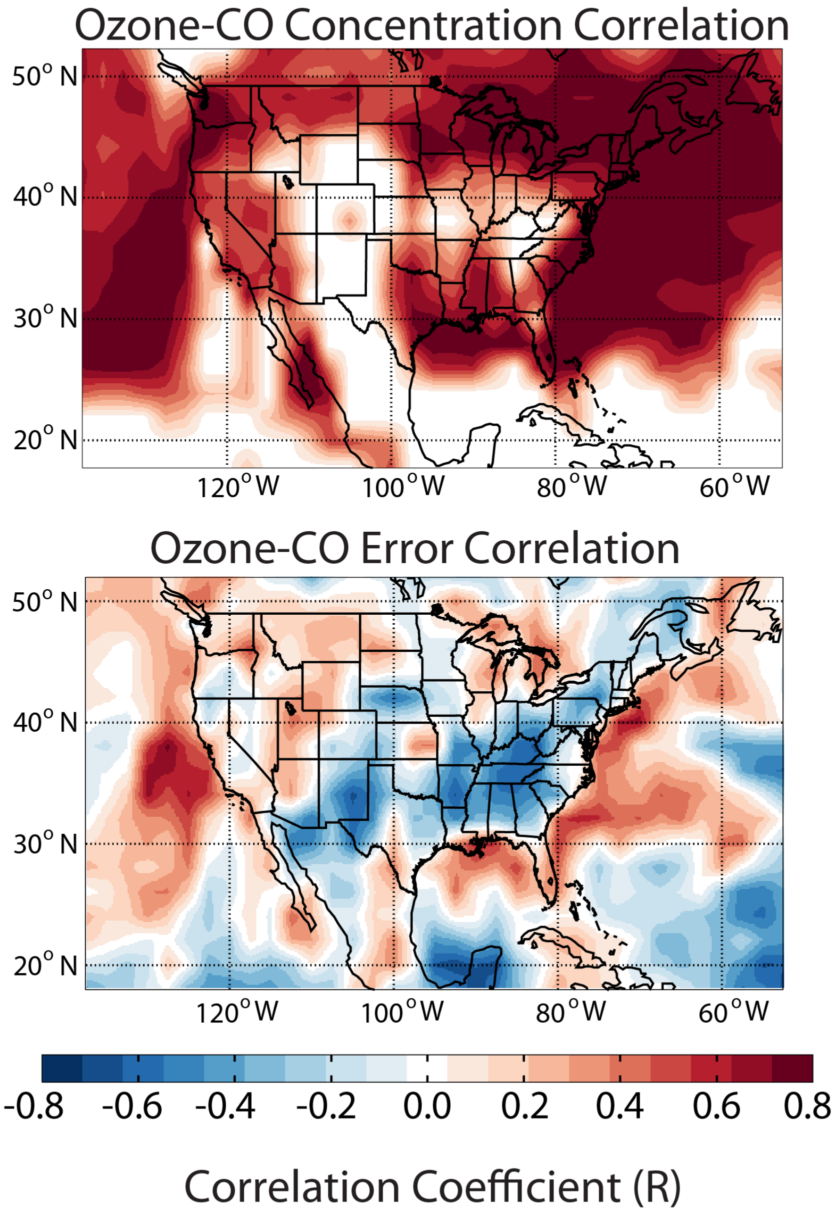


[Natraj et al 2011 and Worden et al 2010]

Model/Model Error Correlations

- Positive **concentration** correlations over North American region

- But! model **error** correlations can differ greatly from **concentration** correlations!

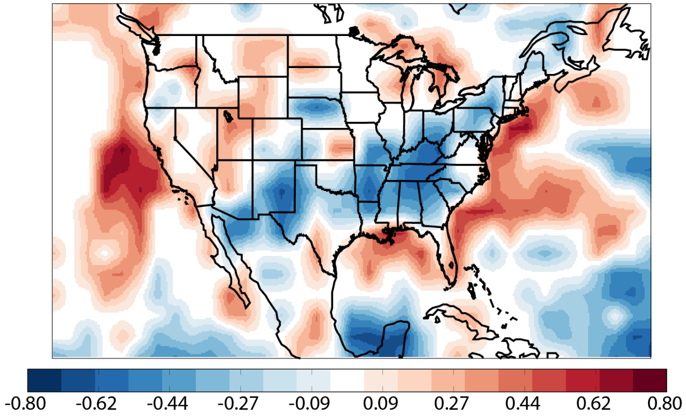


Ozone-CO Concentration Correlation

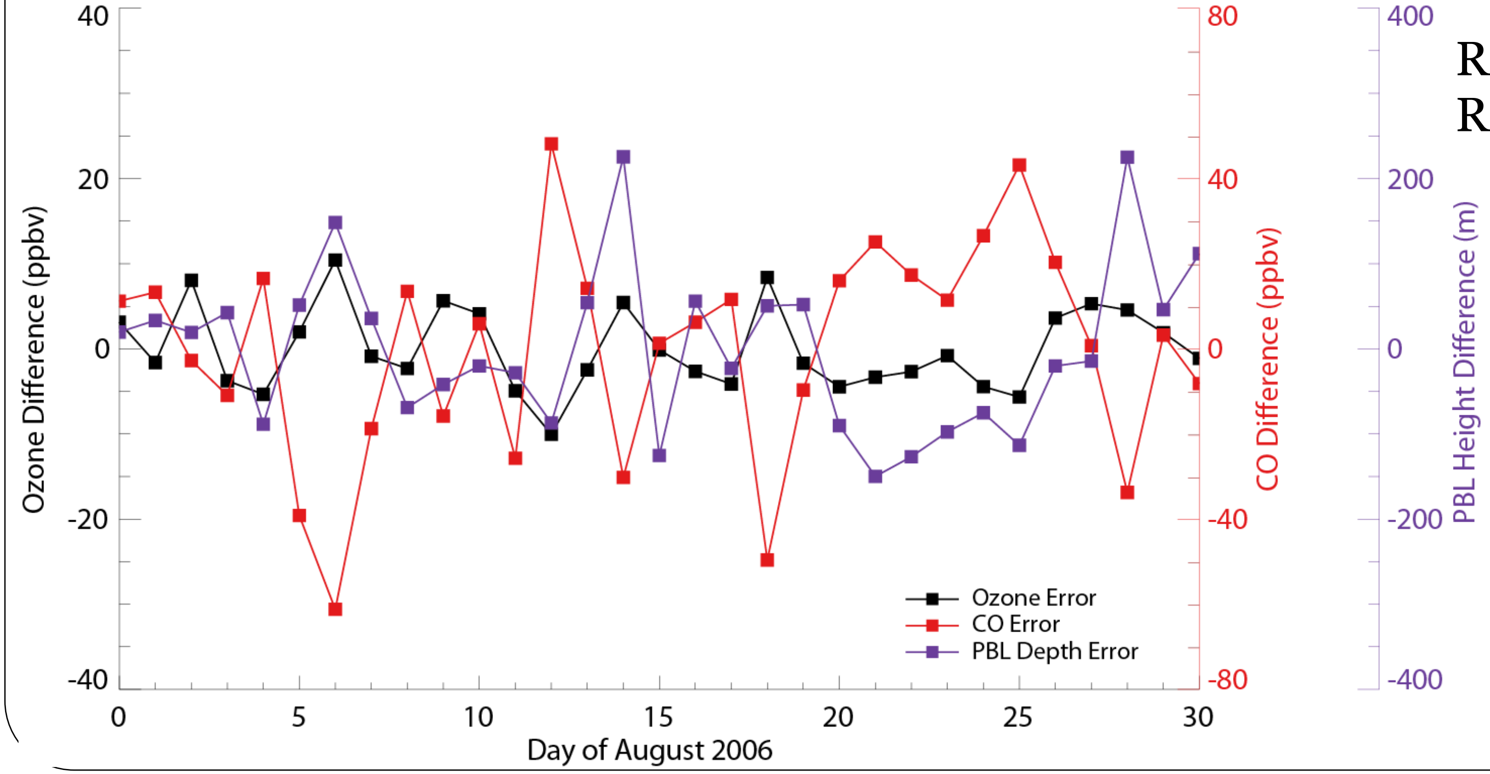
Ozone-CO Error Correlation

Error Correlations Investigated

ozone-CO error correlations (model/model)



Negative error correlations over land driven by differences in vertical mixing

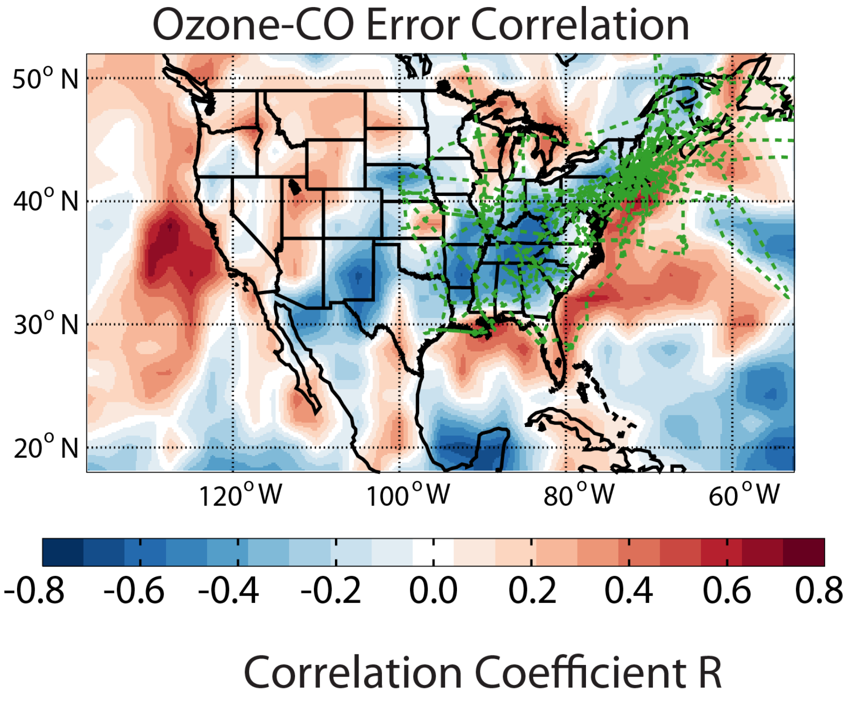


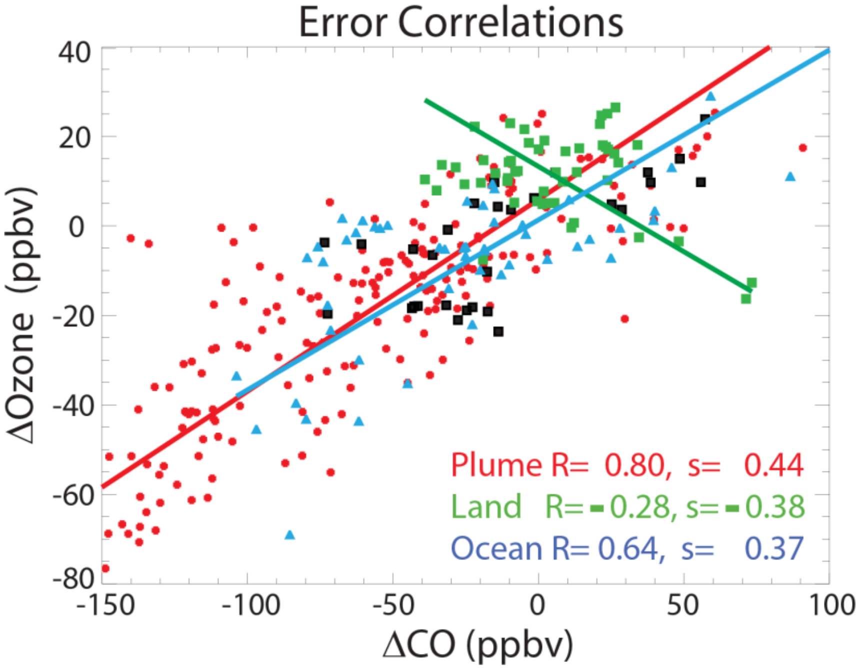
R_1 (Ozone:CO)= -.68

R_2 (PBLH:CO) = -.65

Model/Observation Error Correlations

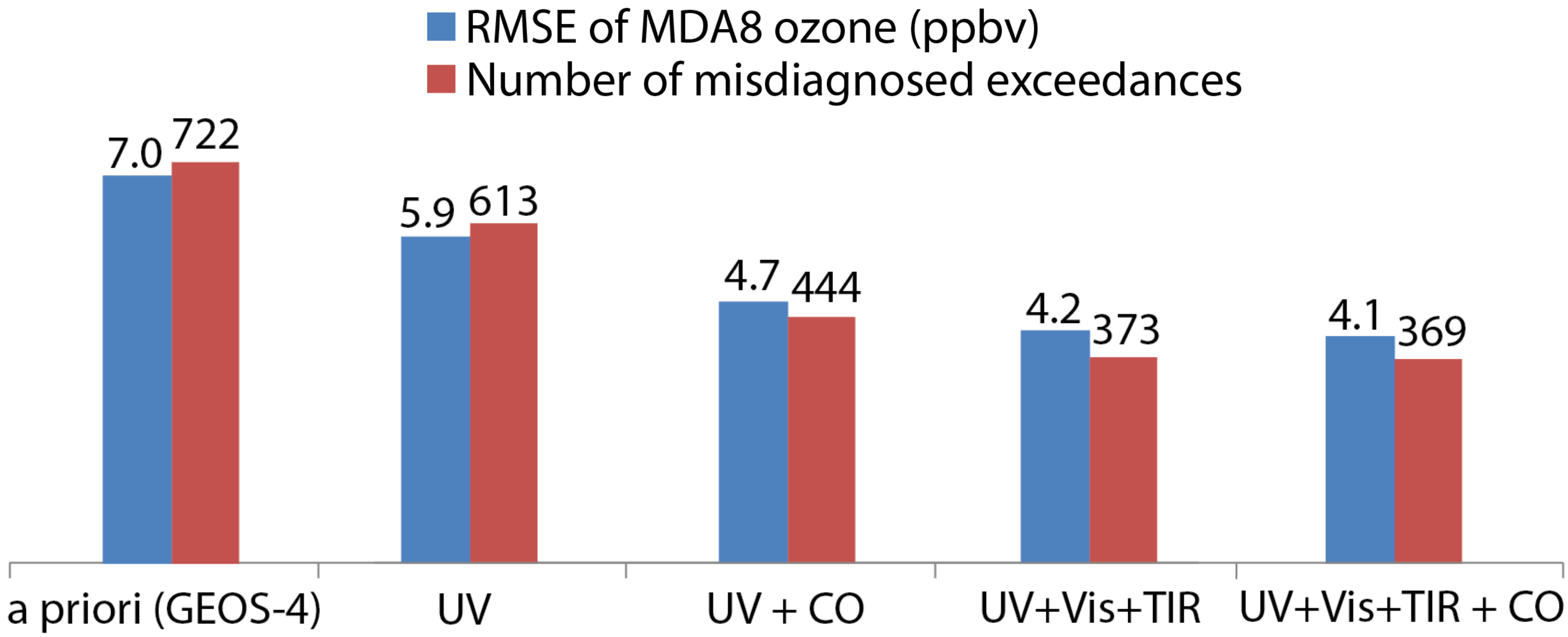
- Negative model error correlations reproduced when comparing to aircraft observations





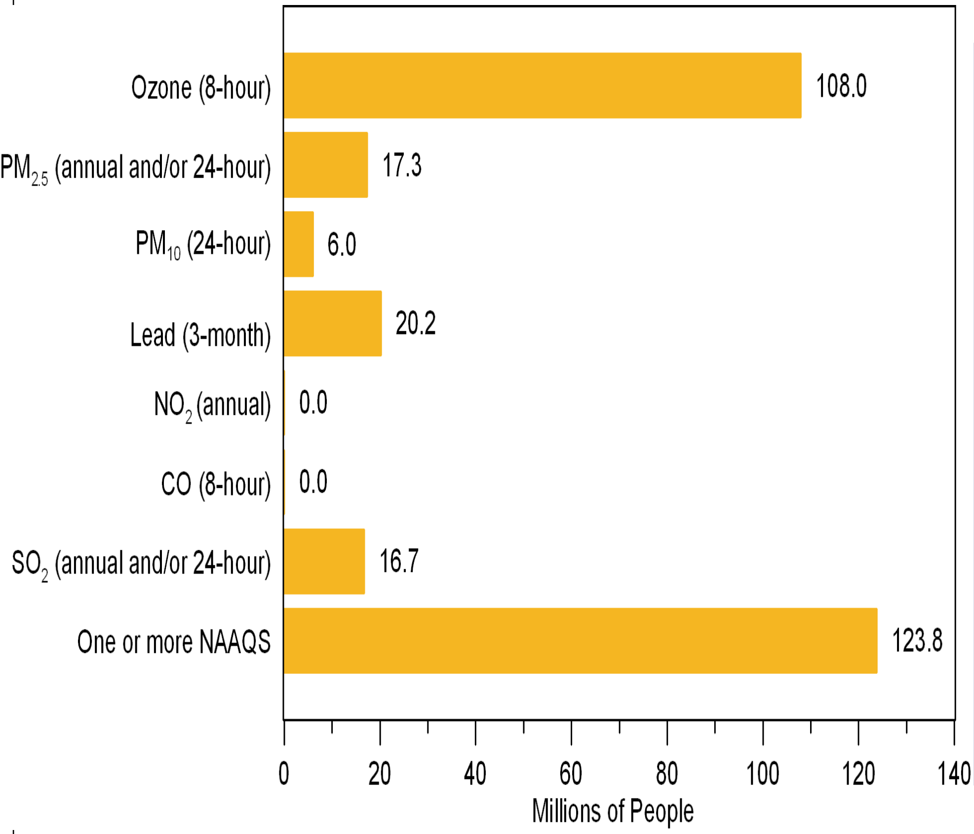
Air Quality Information from Error Correlations

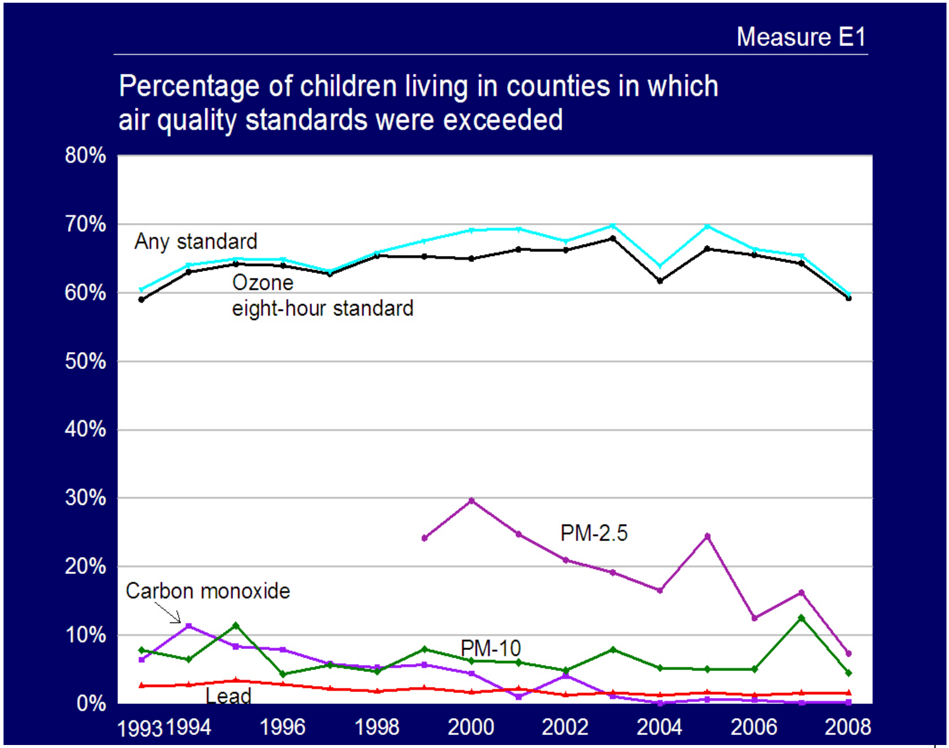
Air Quality Error for August 2006



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

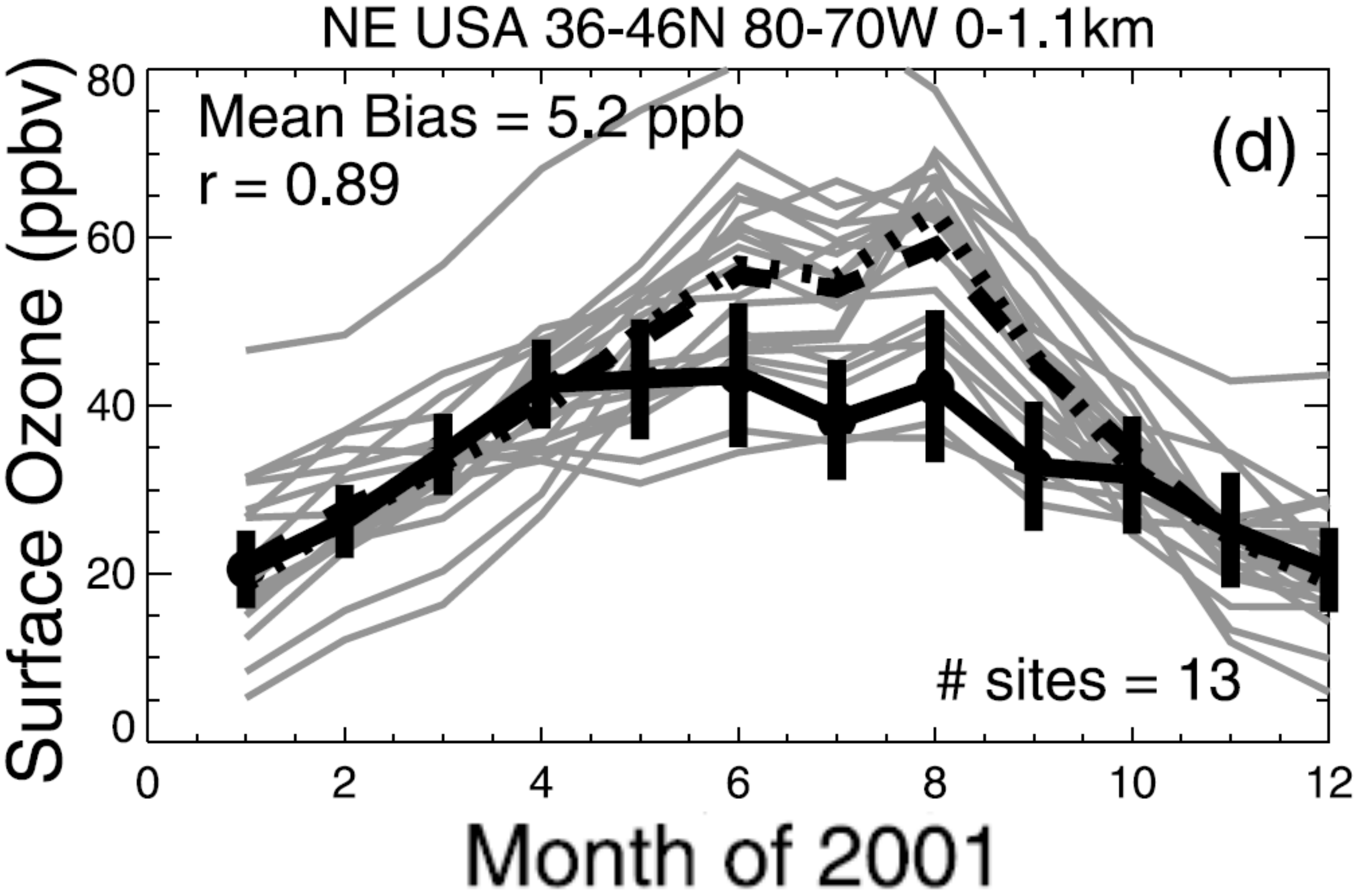
If its polluted, there's ozone





[EPA 2011]

Difficulty of Modeling Ozone



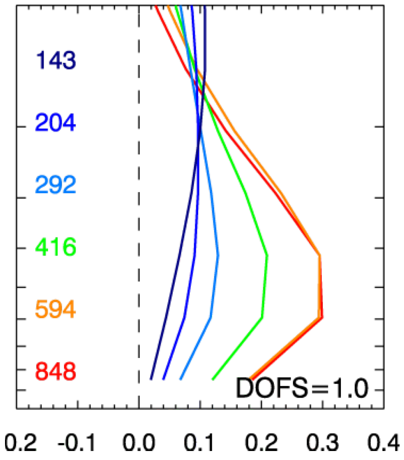
[Fiore et al. 2009]

Multispectral Satellite Observations of Ozone

Averaging Kernel matrix **A** quantifies the vertical information provided by a satellite retrieval

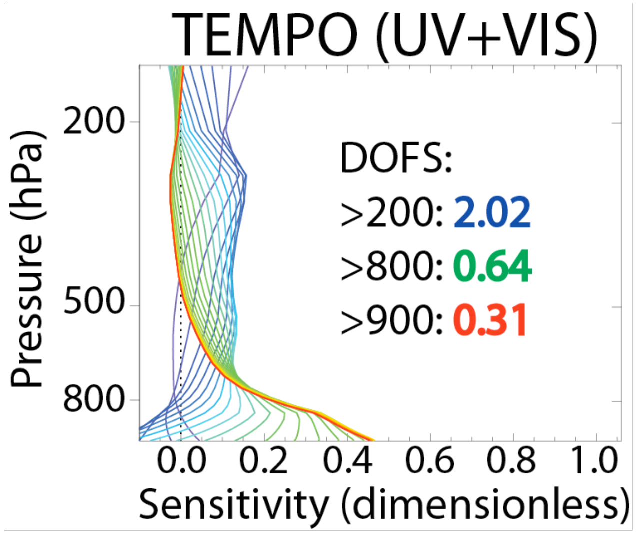
$$\mathbf{x}' = \mathbf{x}_a + \mathbf{A}(\mathbf{x} - \mathbf{x}_a) + \varepsilon \qquad \mathbf{A} = \frac{\partial \mathbf{x}'}{\partial \mathbf{x}}$$

Current ozone sensitivity, OMI (UV)

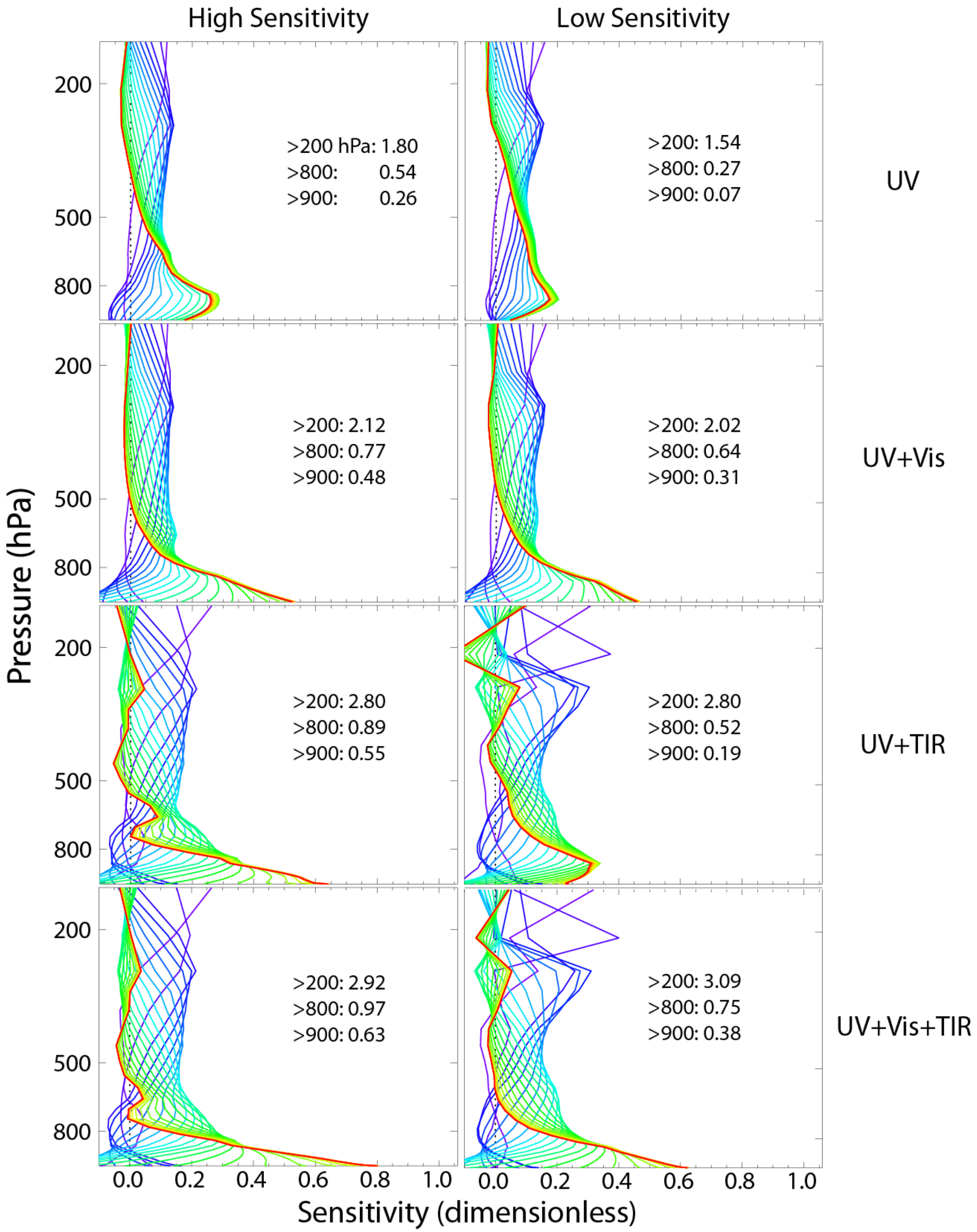


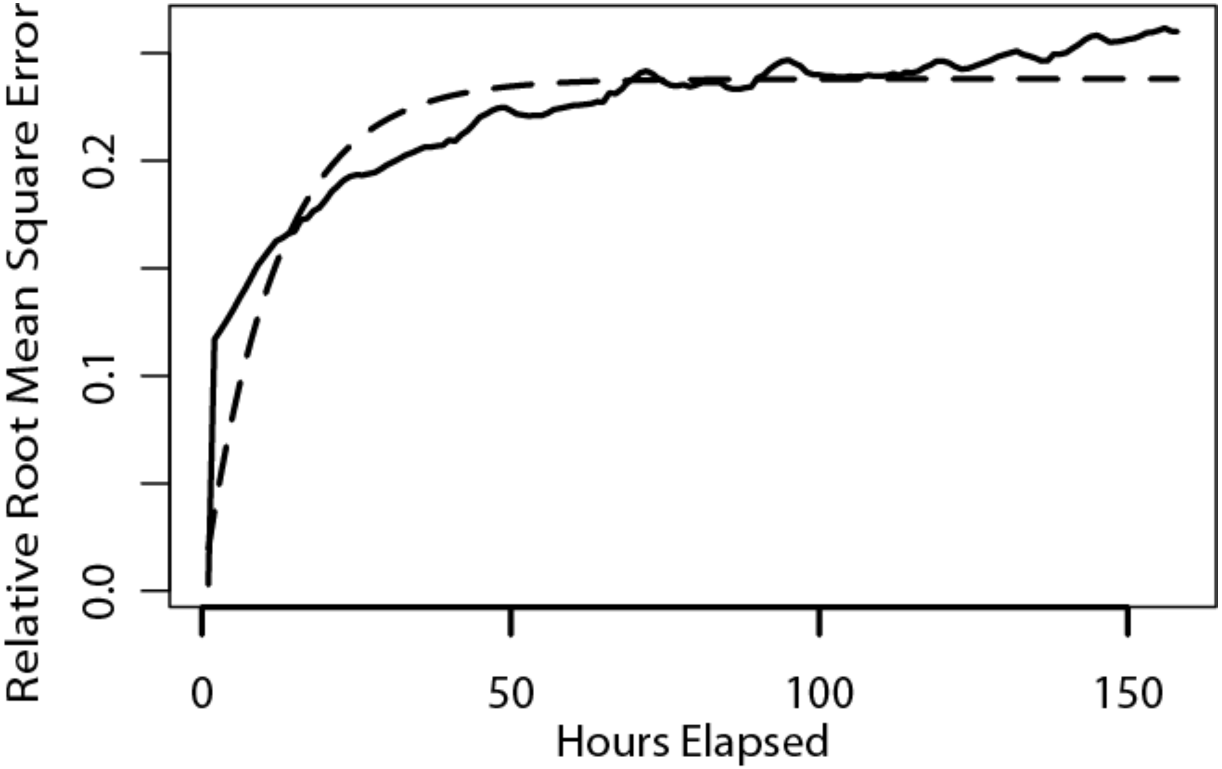
[Zhang et al. 2010]

Ozone sensitivity, future



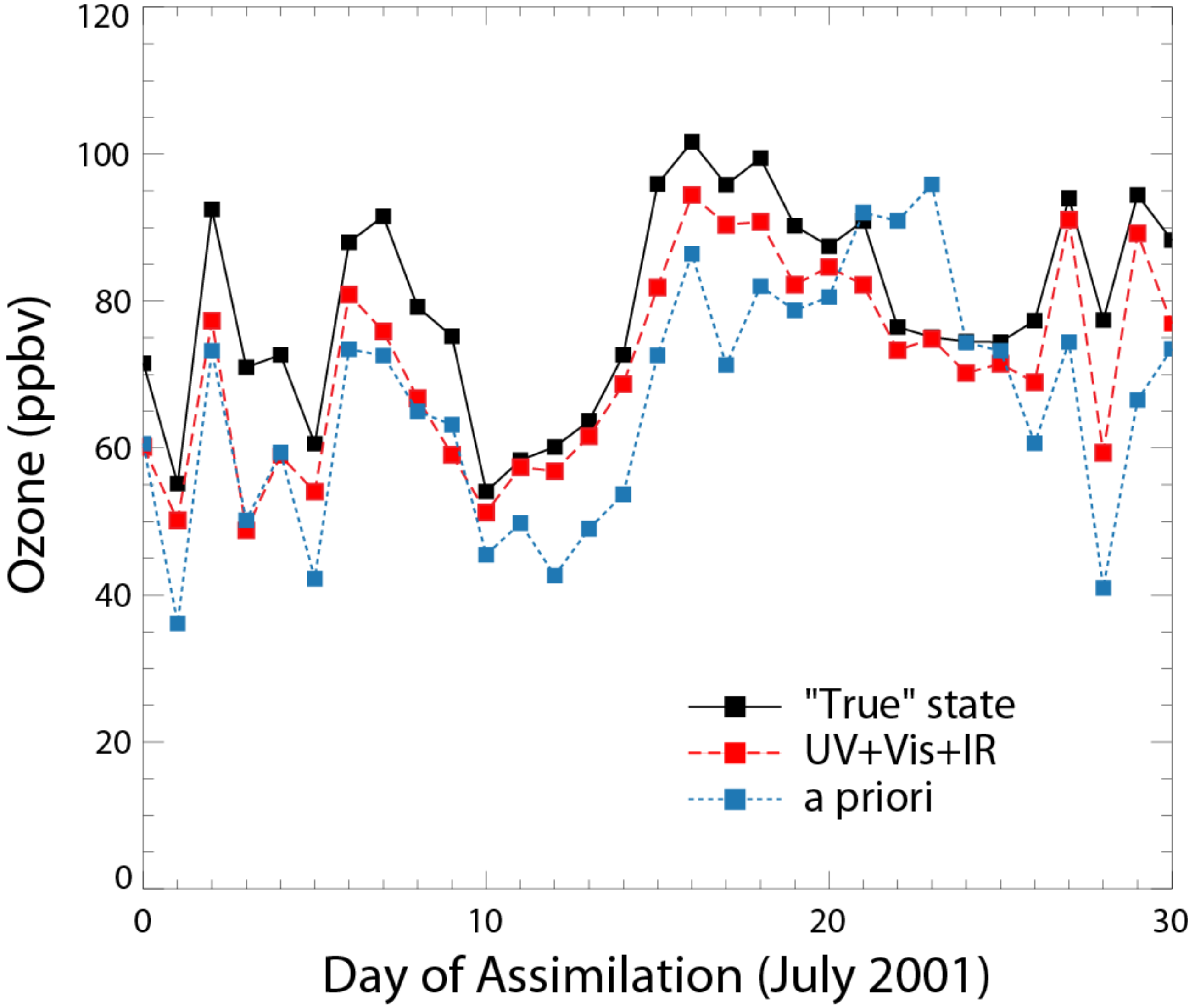
[Natraj et al, 2011]


High Sensitivity
Low Sensitivity
Pressure (hPa)
200
500
800
>200 hPa: 1.80
>800: 0.54
>900: 0.26
>200: 1.54
>800: 0.27
>900: 0.07
UV
>200: 2.12
>800: 0.77
>900: 0.48
>200: 2.02
>800: 0.64
>900: 0.31
UV+Vis
>200: 2.80
>800: 0.89
>900: 0.55
>200: 2.80
>800: 0.52
>900: 0.19
UV+TIR
>200: 2.92
>800: 0.97
>900: 0.63
>200: 3.09
>800: 0.75
>900: 0.38
UV+Vis+TIR
0.0
0.2
0.4
0.6
0.8
1.0
Sensitivity (dimensionless)

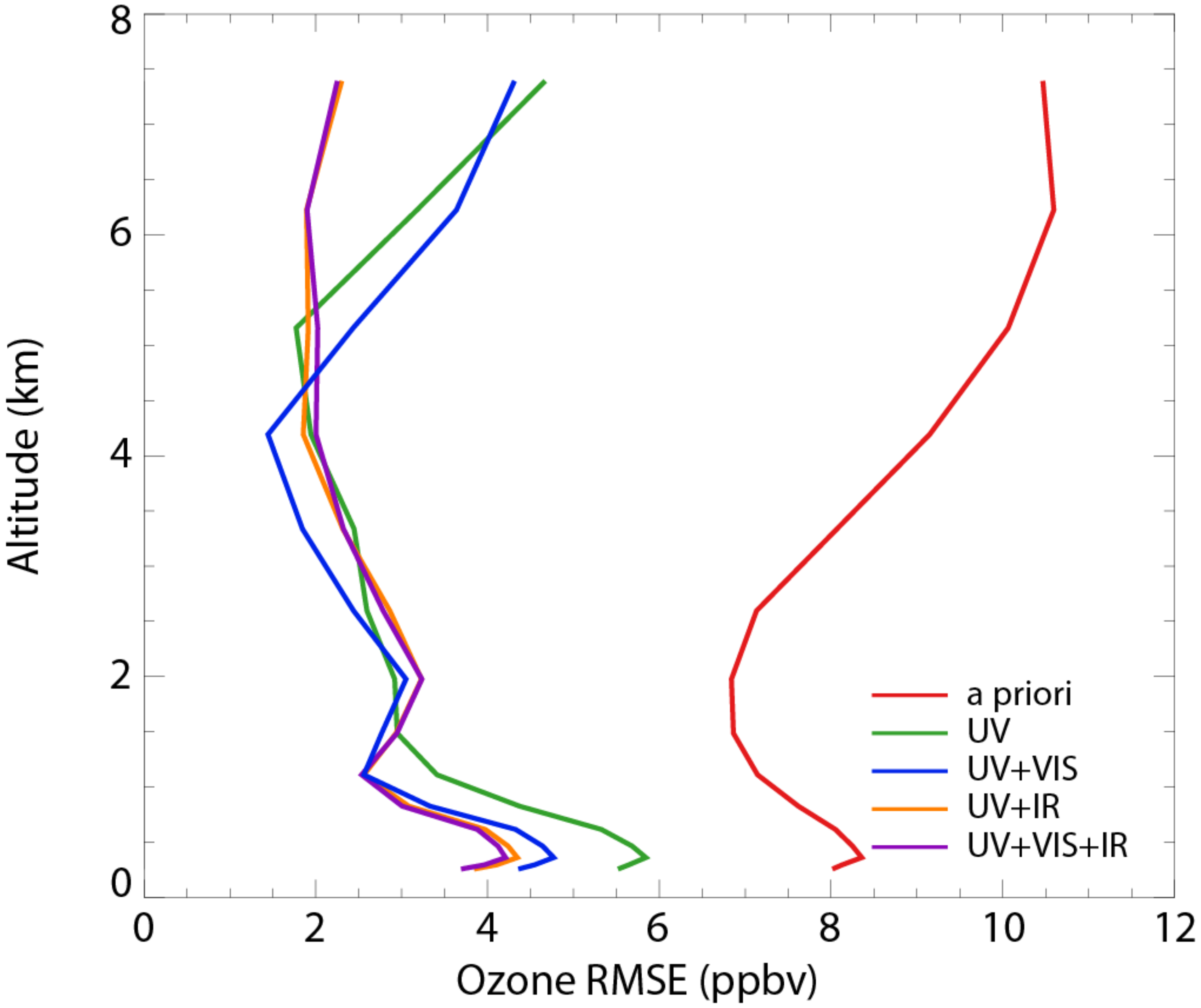


Relative Root Mean Square Error
0.0
0.1
0.2
0
50
100
150
Hours Elapsed

Pittsburgh timeseries

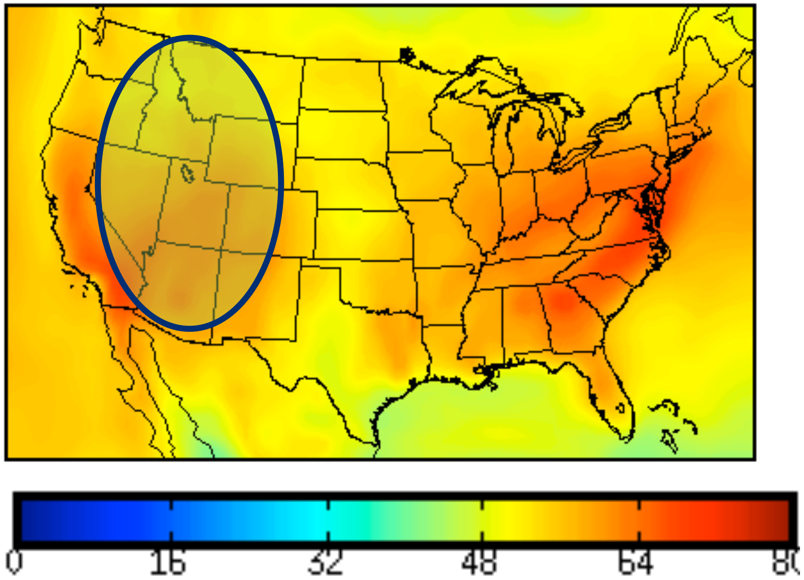


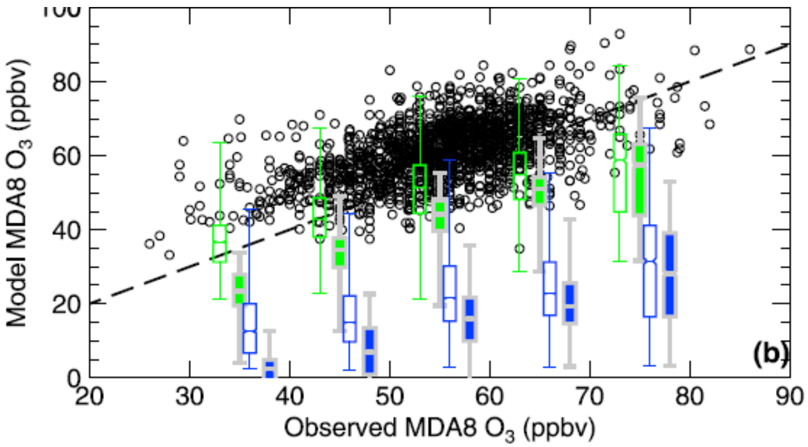
Vertical distribution of correction



AM3-Chem is too high

“Truth” = AM3-Chem model

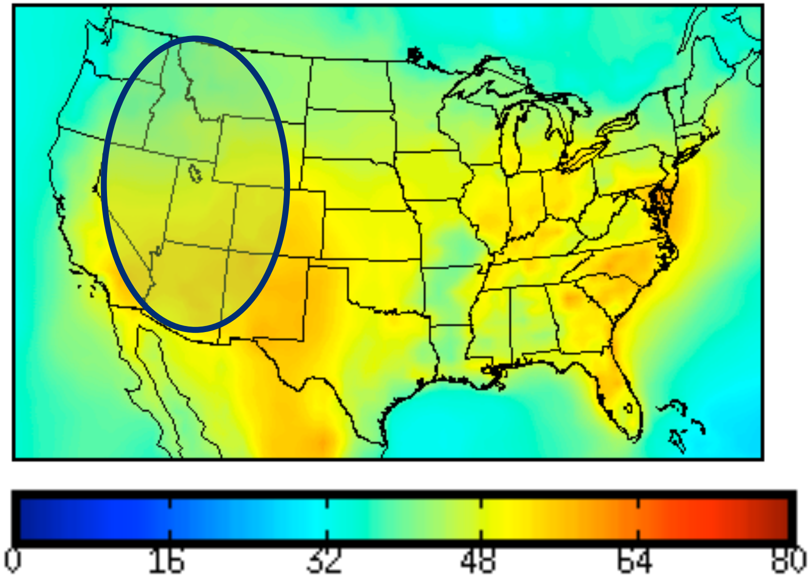


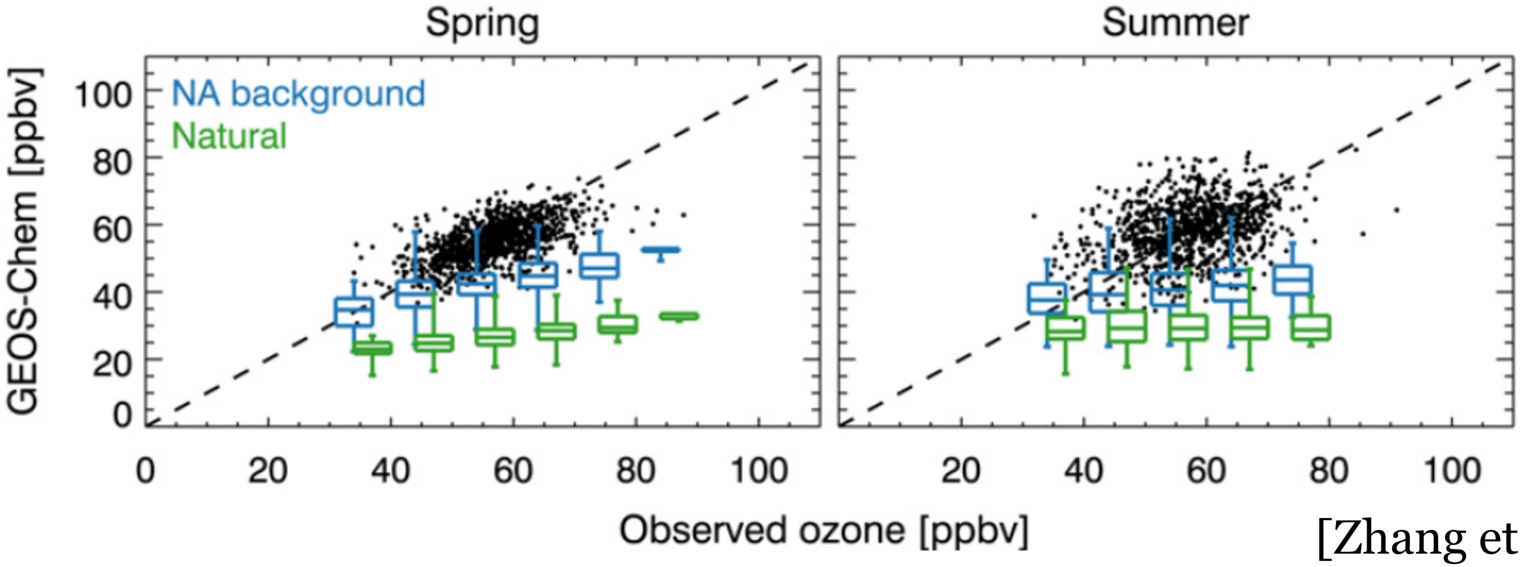


[Lin et al., 2012]

GEOS-Chem is too low

a priori = nested GEOS-Chem





[Zhang et al., 2012]

Observing System Information