# Winds and TEMPO

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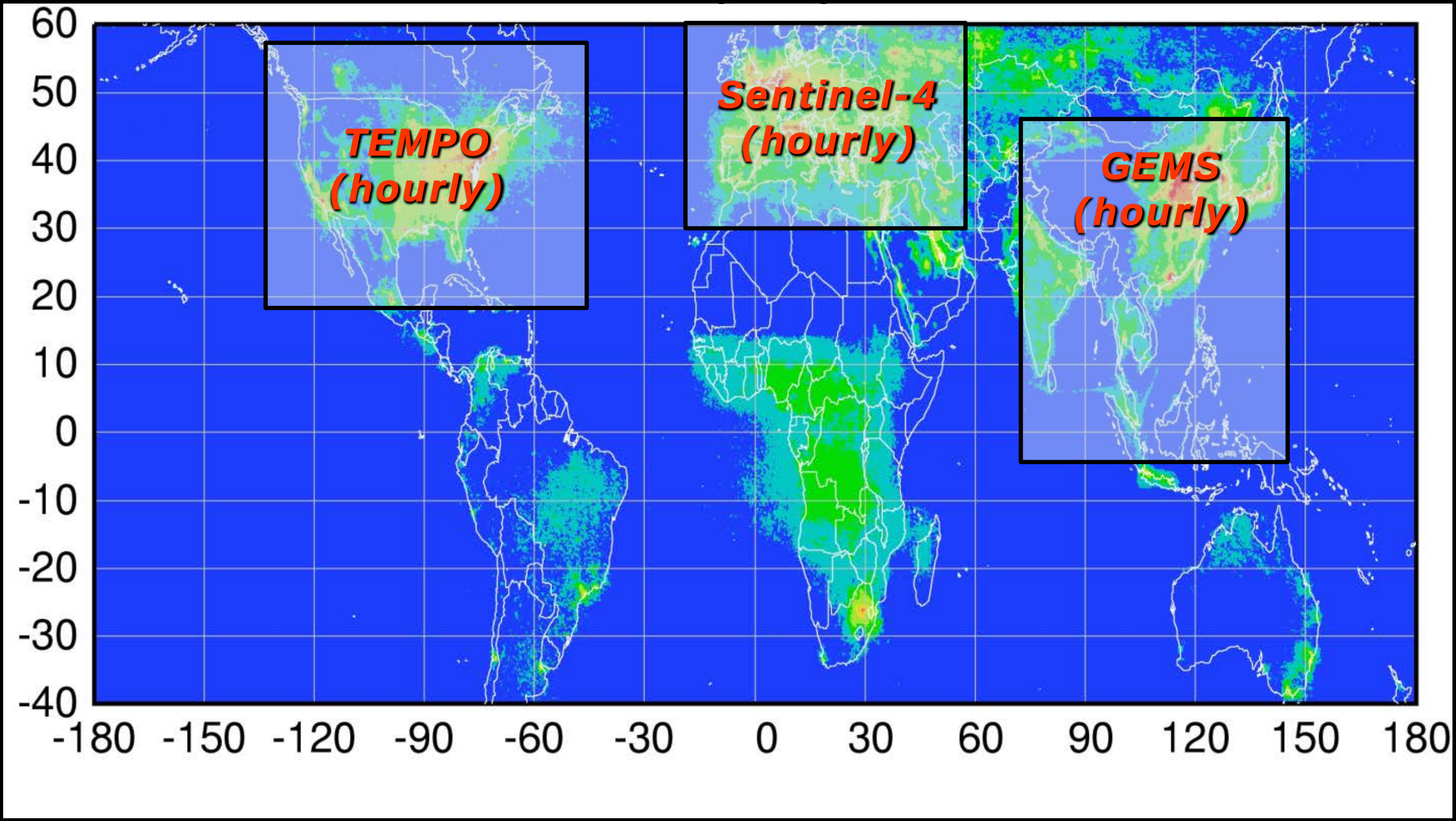
$ TEMPO, NASA ACMAP and GEOCAPE

High space and time resolution measurements of $NO_2$, $H_2CO$ and $O_3$ will soon be routinely available

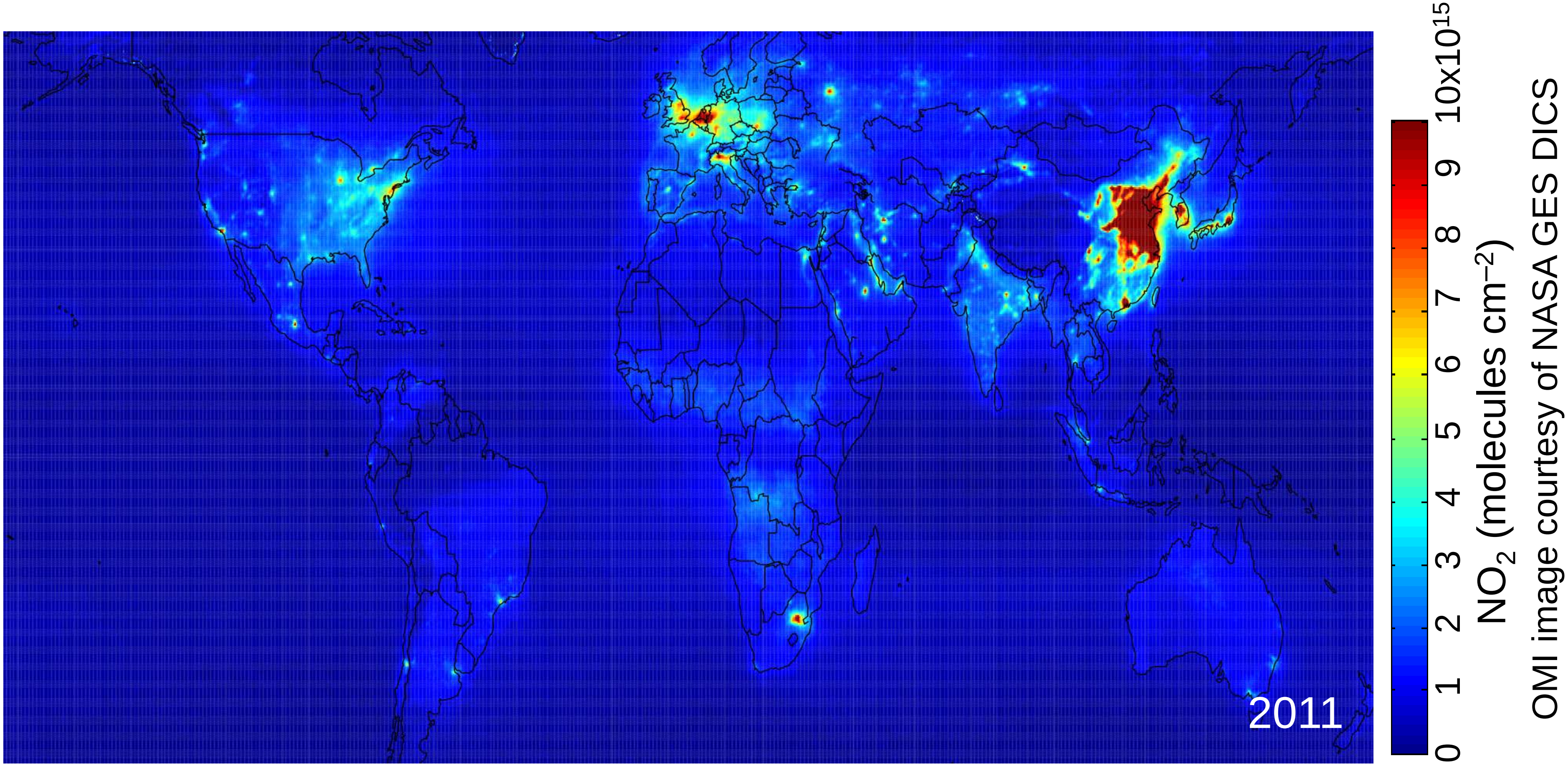


# Preparing for new science opportunities using GEO $NO_2$

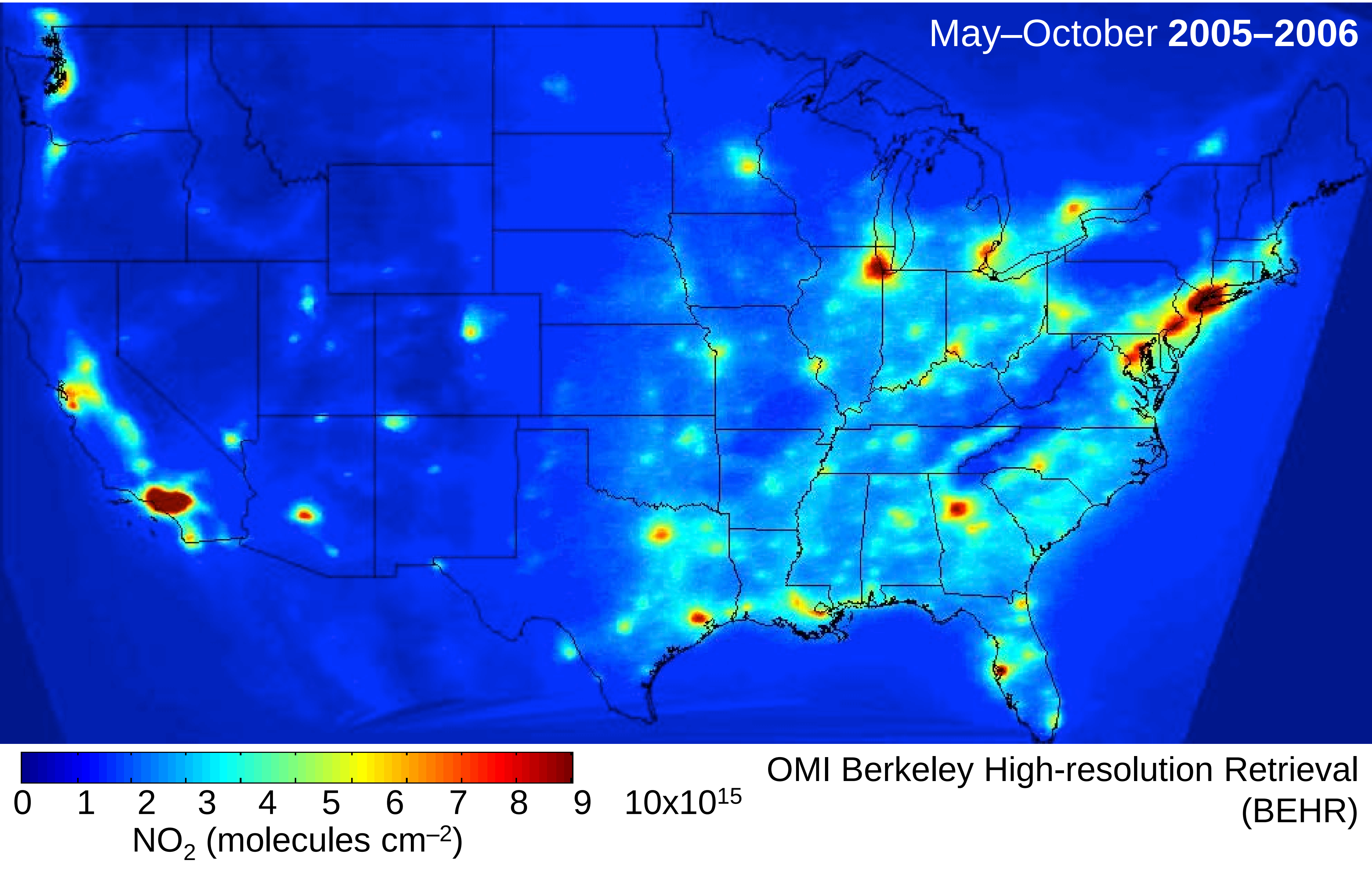
- Current State-of-the-Art
- Retrievals
- Data assimilation

# Examples of Current State-of-the-Art

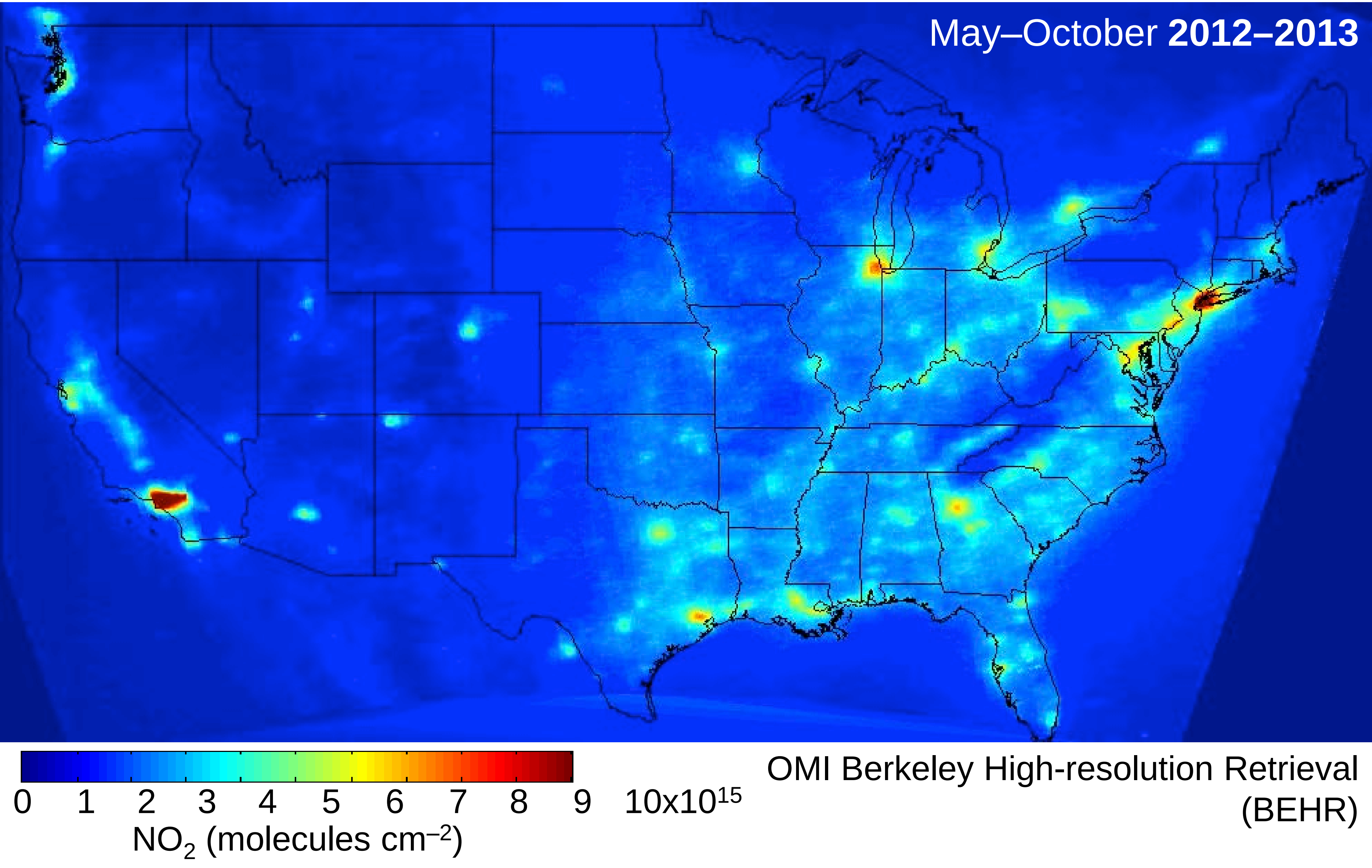
# 1) Beginning to understand how to quantitatively relate trends in slant columns to trends in emissions



# 2005-2006


May–October **2005–2006**
0 1 2 3 4 5 6 7 8 9 10x10^15
NO2 (molecules cm^-2)
OMI Berkeley High-resolution Retrieval
(BEHR)

# 2012-2013


May–October **2012–2013**
0
1
2
3
4
5
6
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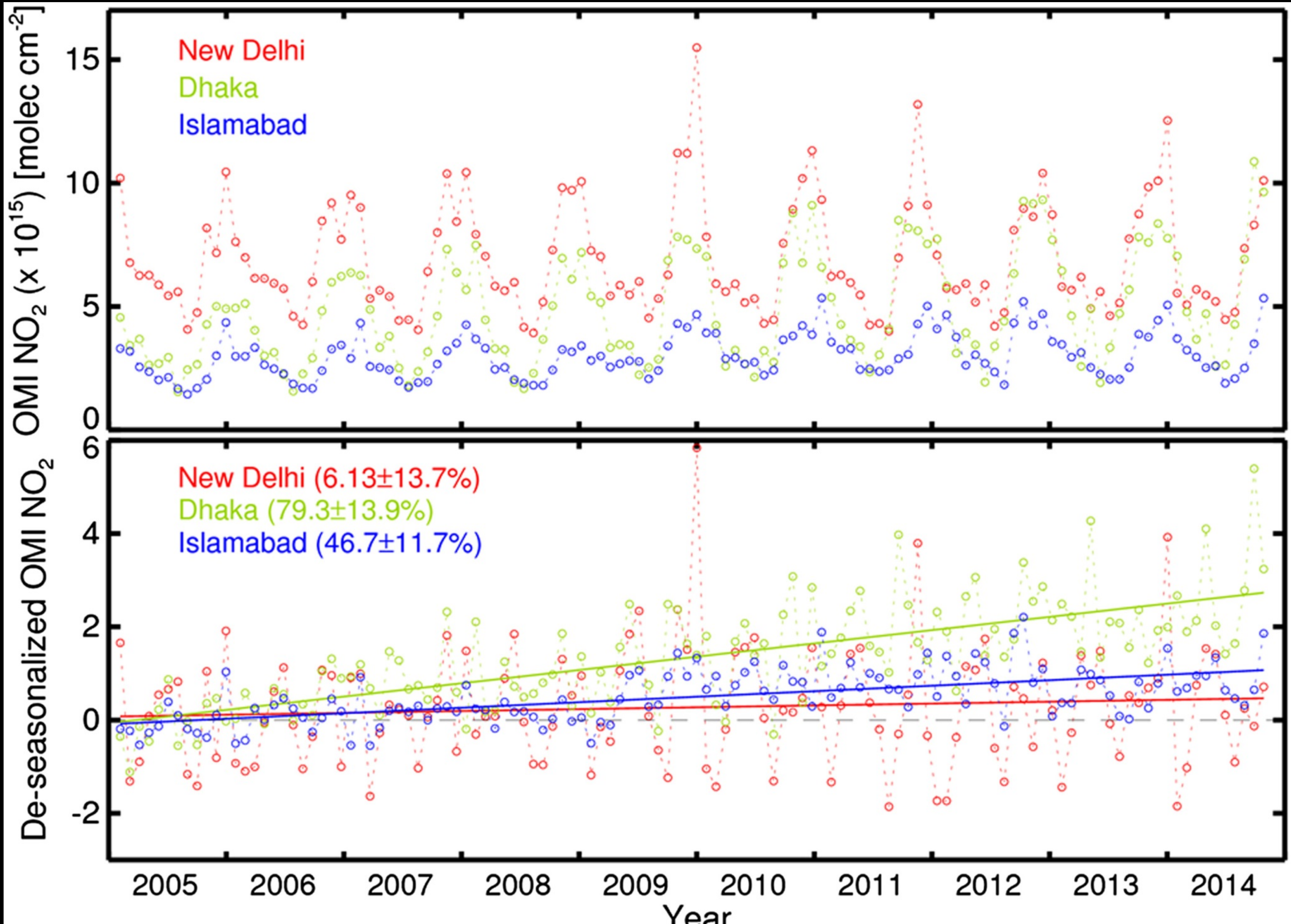
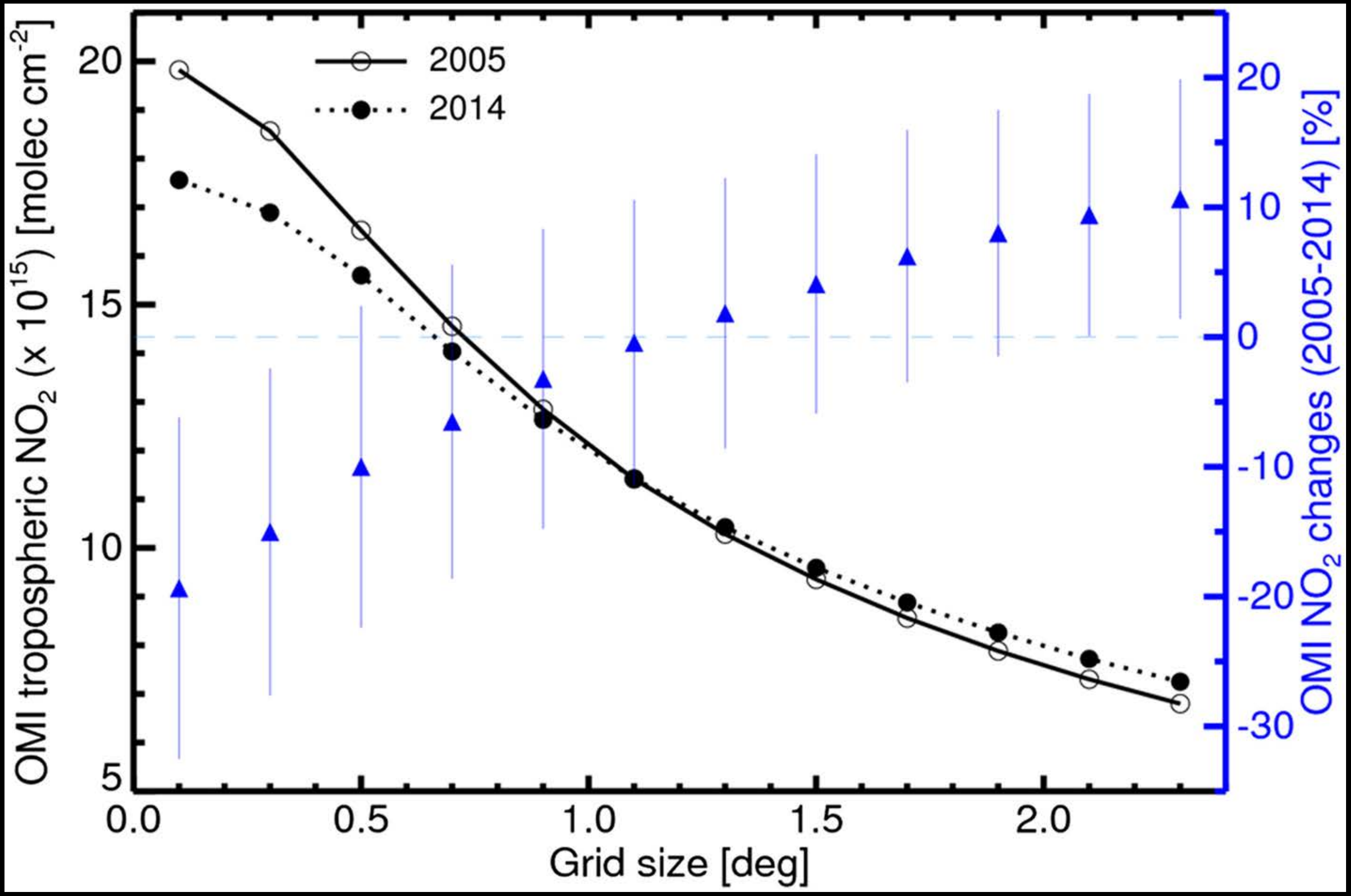
8
9
10x10^15
NO2 (molecules cm^–2)
OMI Berkeley High-resolution Retrieval (BEHR)



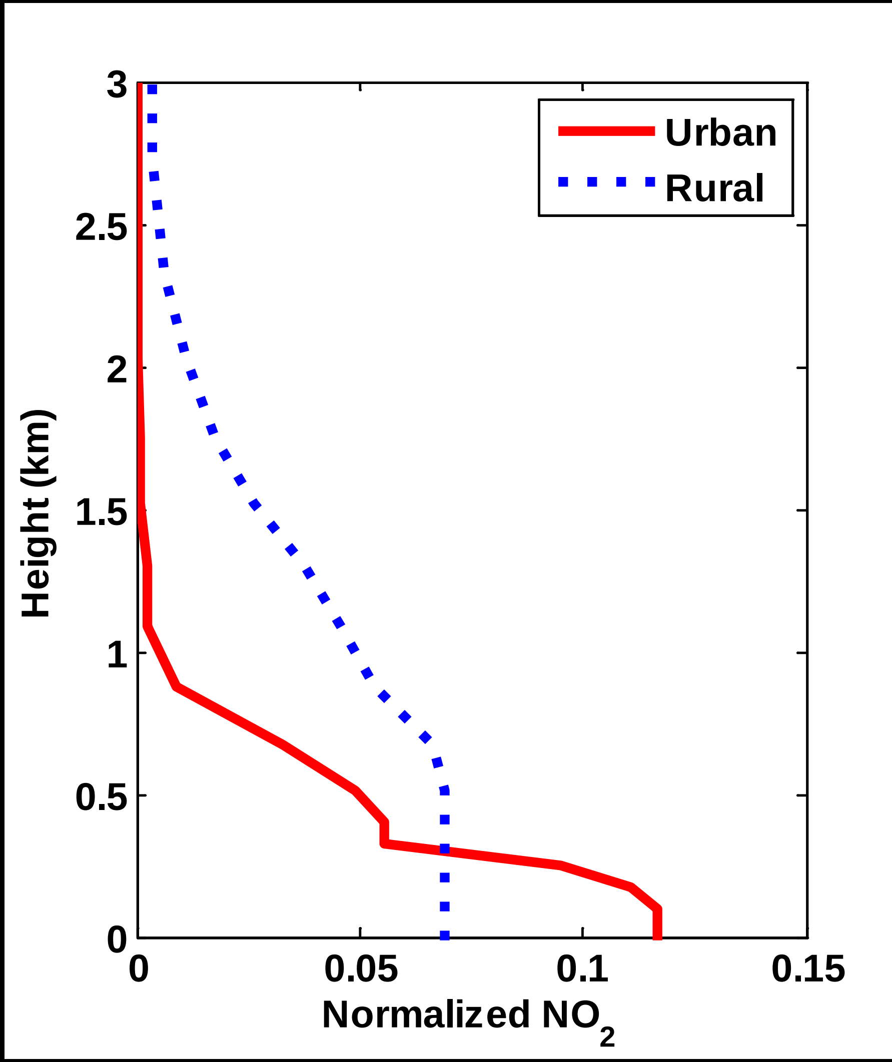

e.g. Duncan et al. JGR 2016

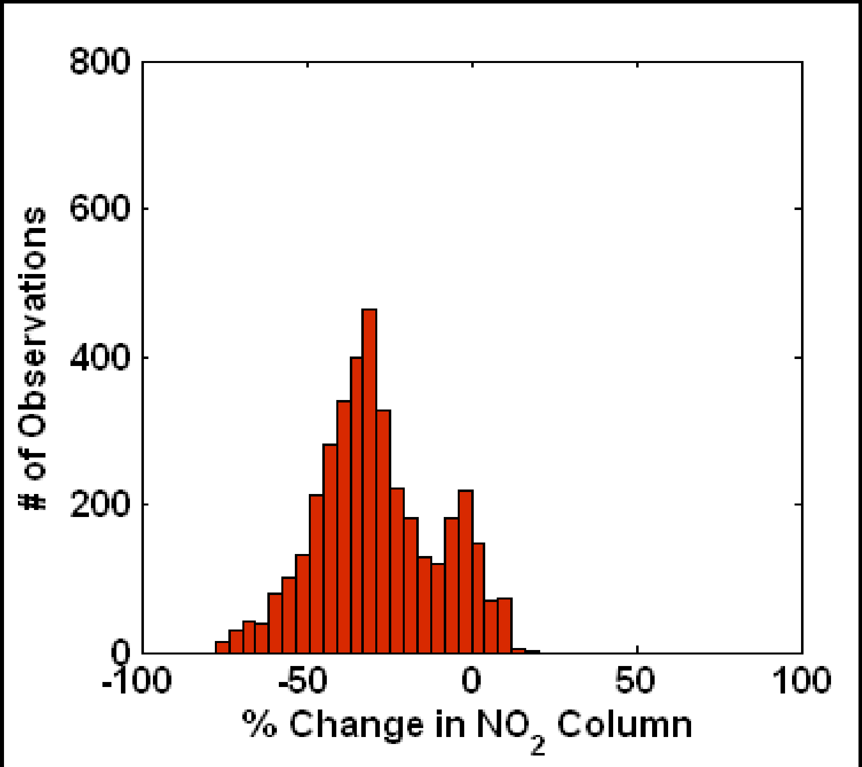
# Resolution matters




e.g. Duncan et al. JGR 2016

# Resolution matters (e.g. BEHR Retrieval)




PDF of systematic errors

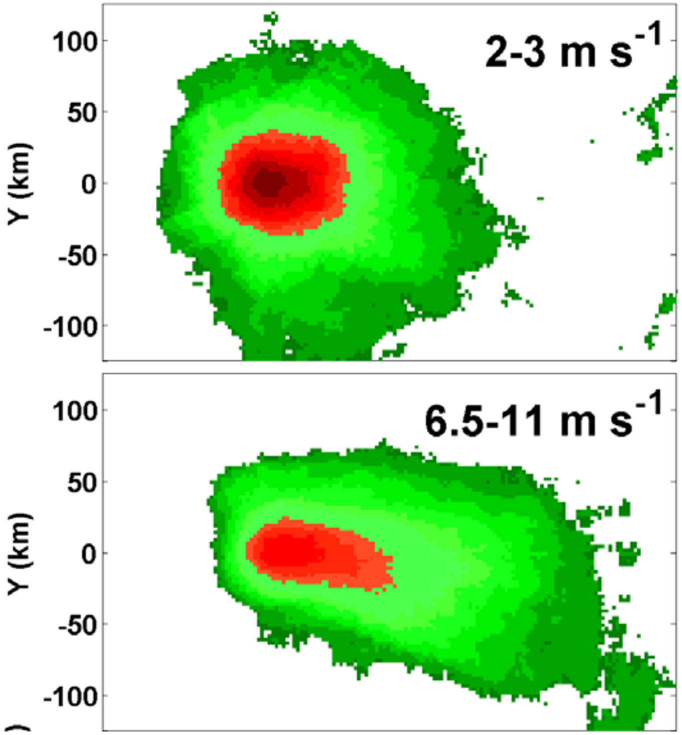
Russell et al., Atmos Chem & Phys, 2011

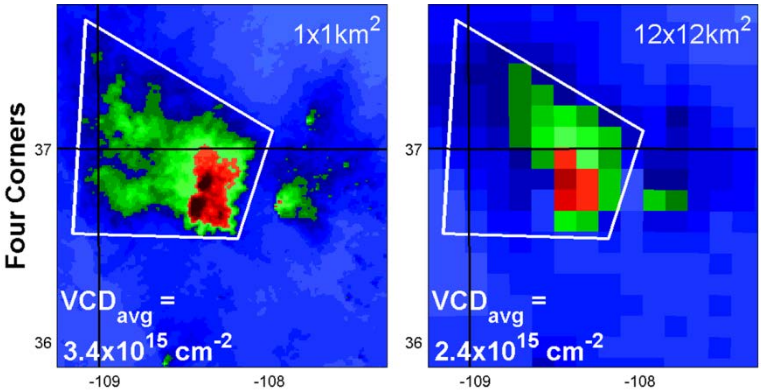
# 2) Beginning to understand how to quantitatively assess absolute emissions

Two key ideas:

Winds are coupled to lifetime

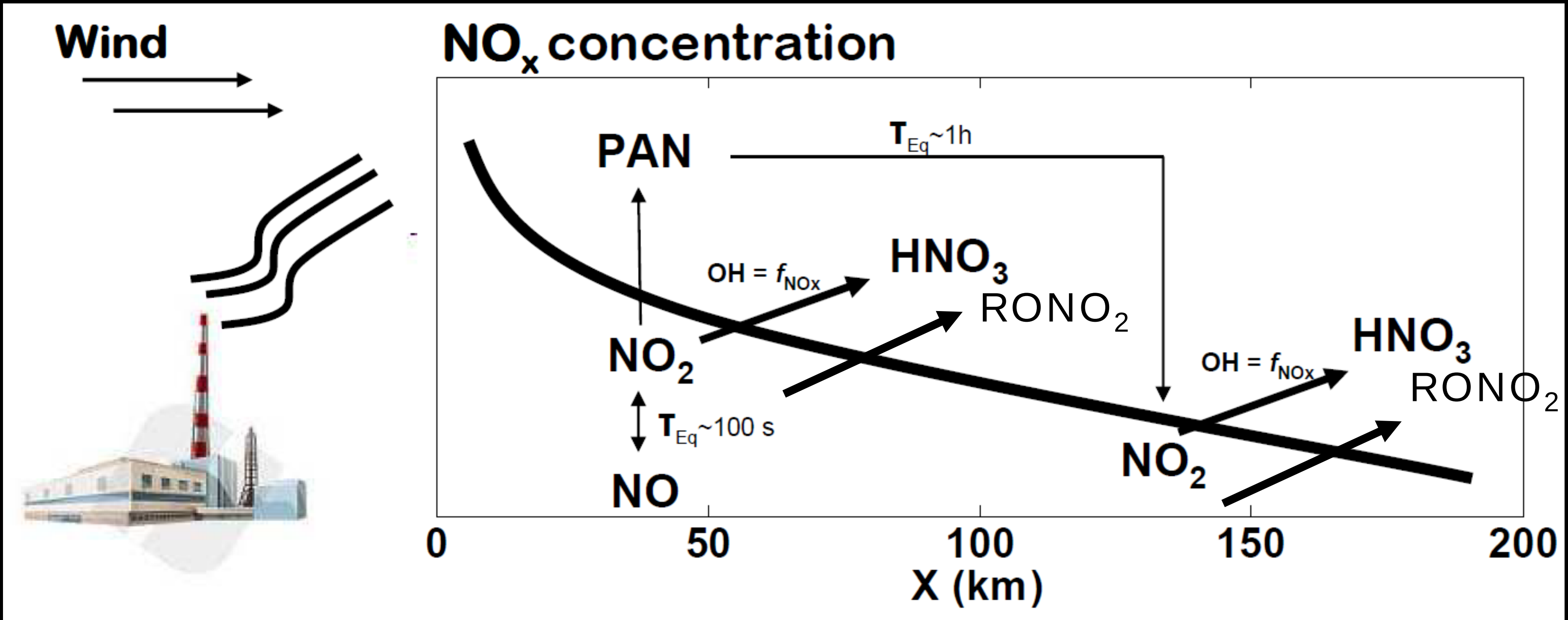
Resolution matters



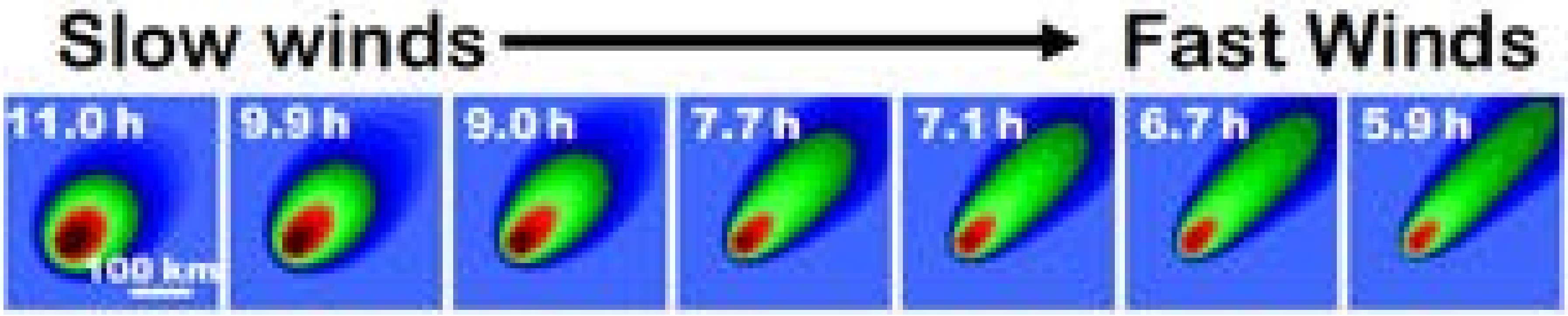

L Valin et al., *GRL* 2013

# Daytime



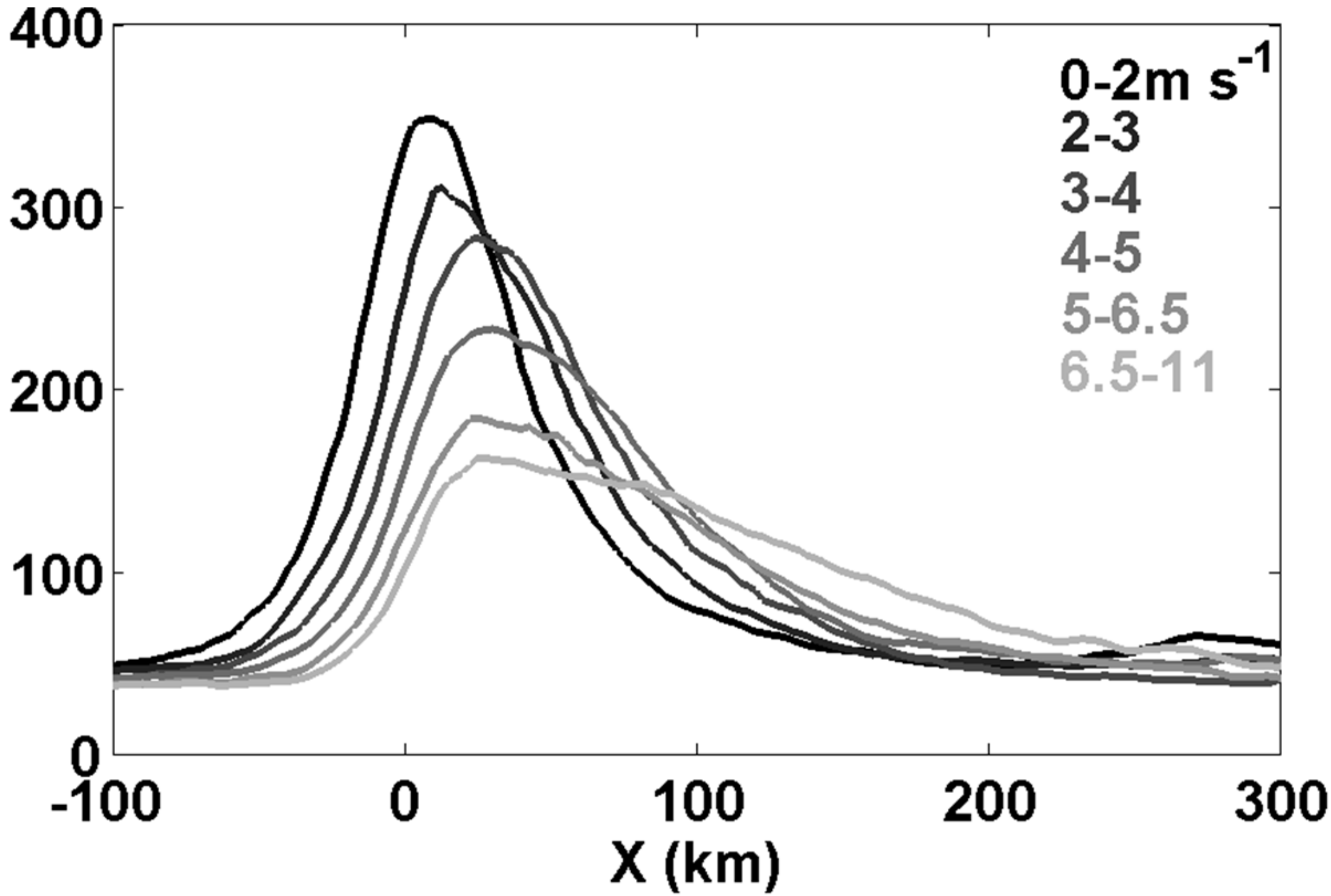
Wind
NOx concentration
PAN
TEq~1h
HNO3
OH = fNOx
RONO2
NO2
TEq~100 s
NO
HNO3
OH = fNOx
RONO2
NO2
0
50
100
150
200
X (km)

# Model $NO_x$ lifetime vs. wind speed.

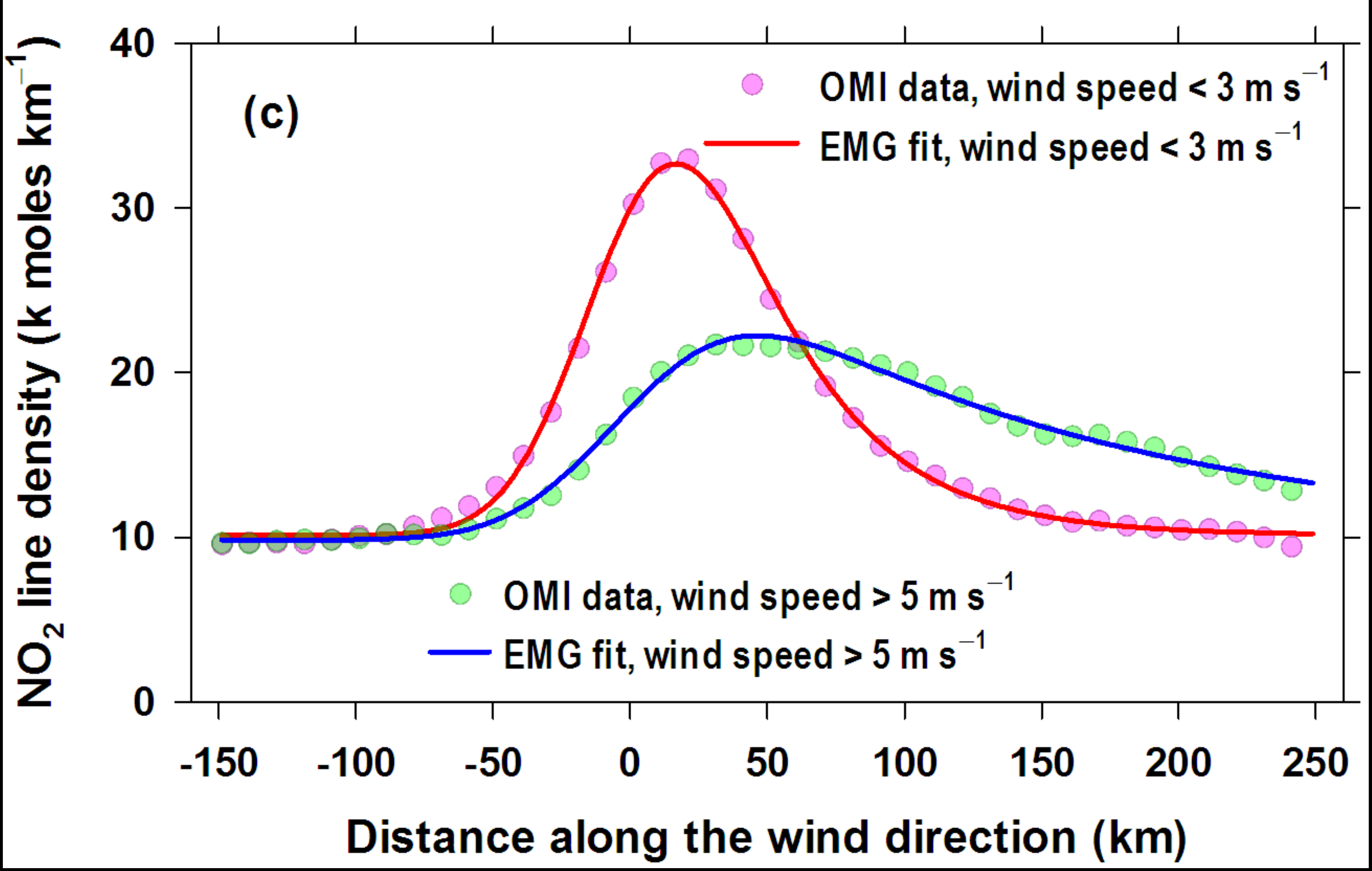



L Valin et al., *GRL* 2013

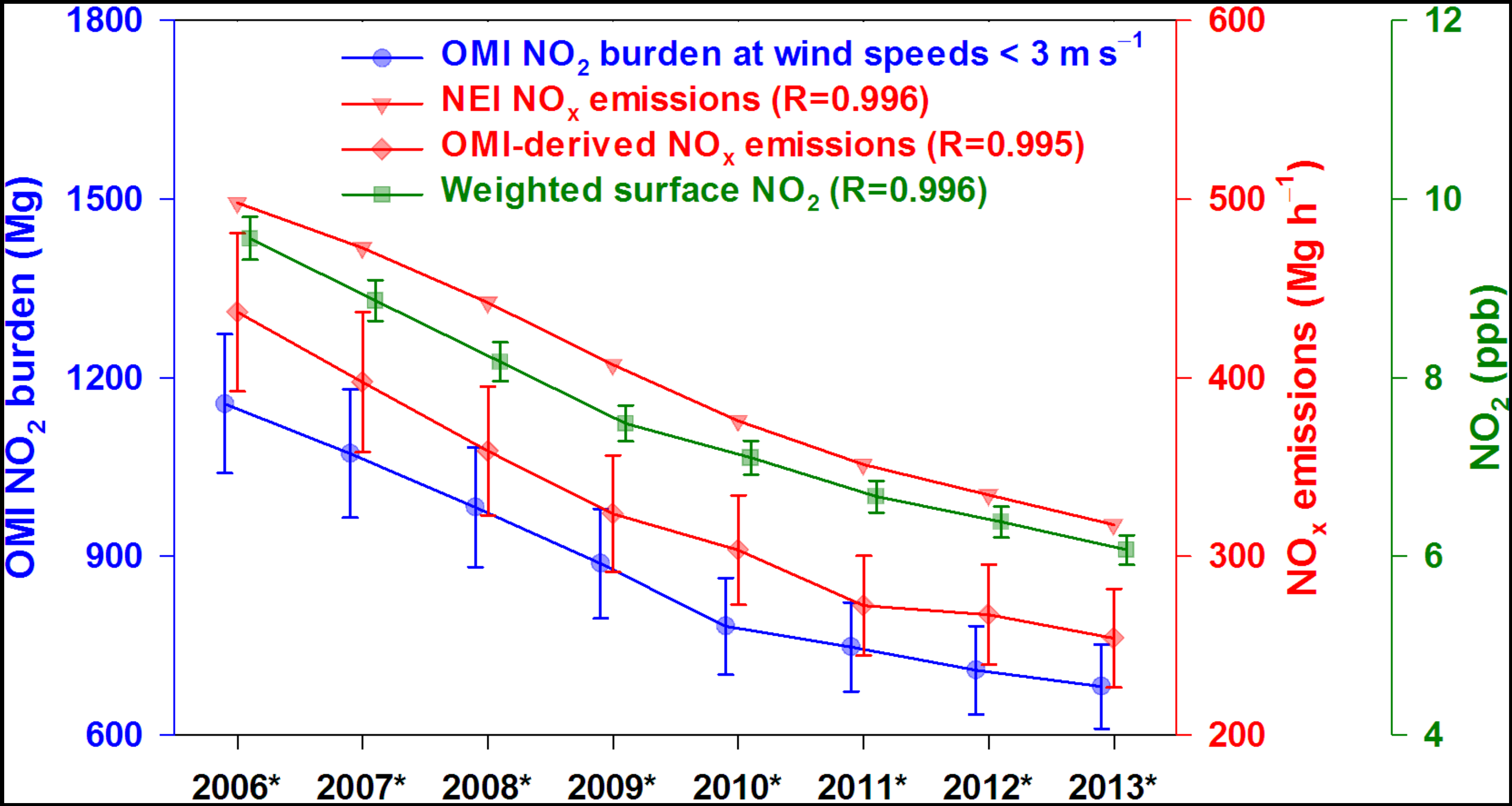
# Observations vs. wind speed.




L Valin et al., *GRL 2013*




Lu et al. ACP 2015

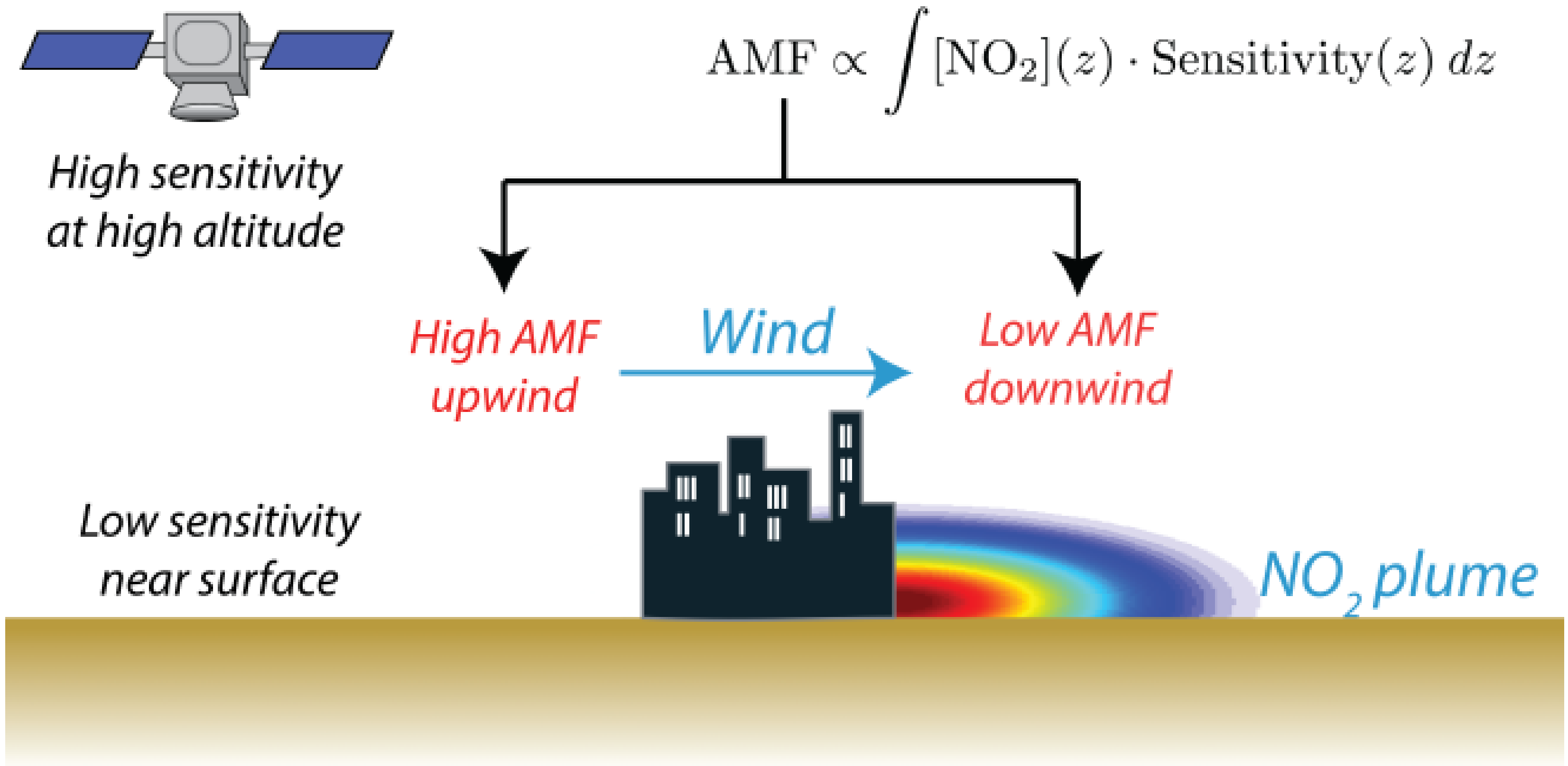



Lu et al. ACP 2015

# Retrievals

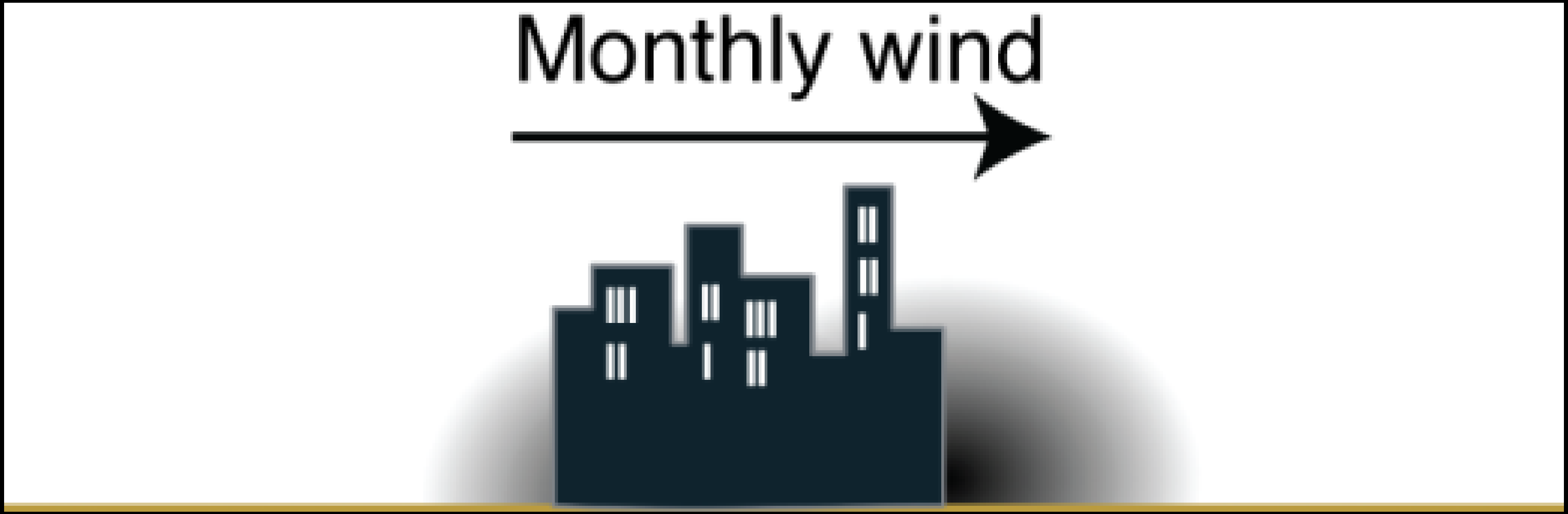
Josh Laughner

# AMFs convert slant columns to vertical columns

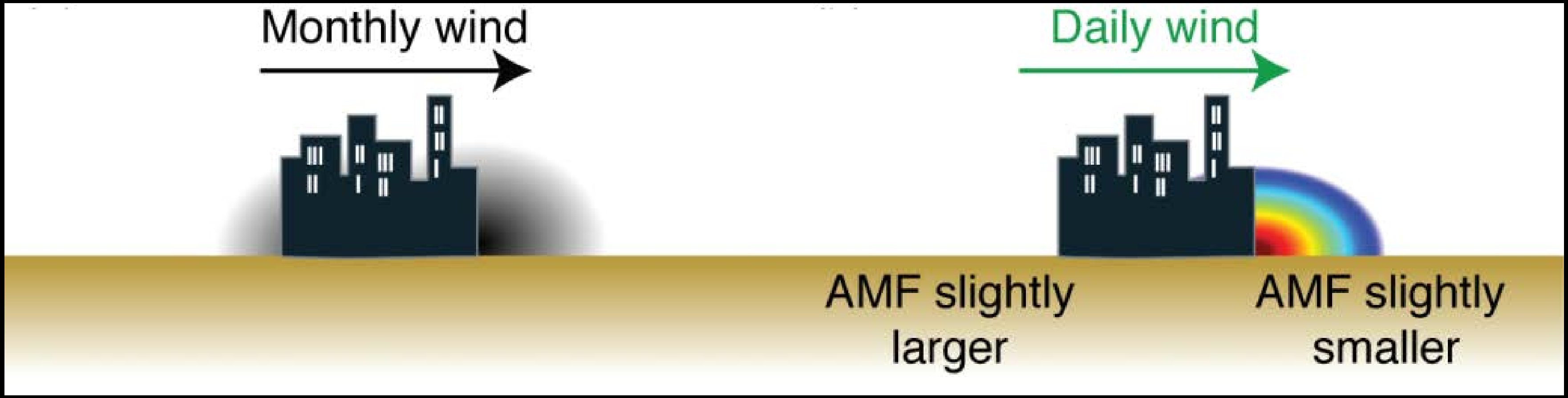



$$\mathrm{AMF} = \frac{\mathrm{SCD}}{\mathrm{VCD}} \Rightarrow \mathrm{VCD} = \frac{\mathrm{SCD}}{\mathrm{AMF}}$$

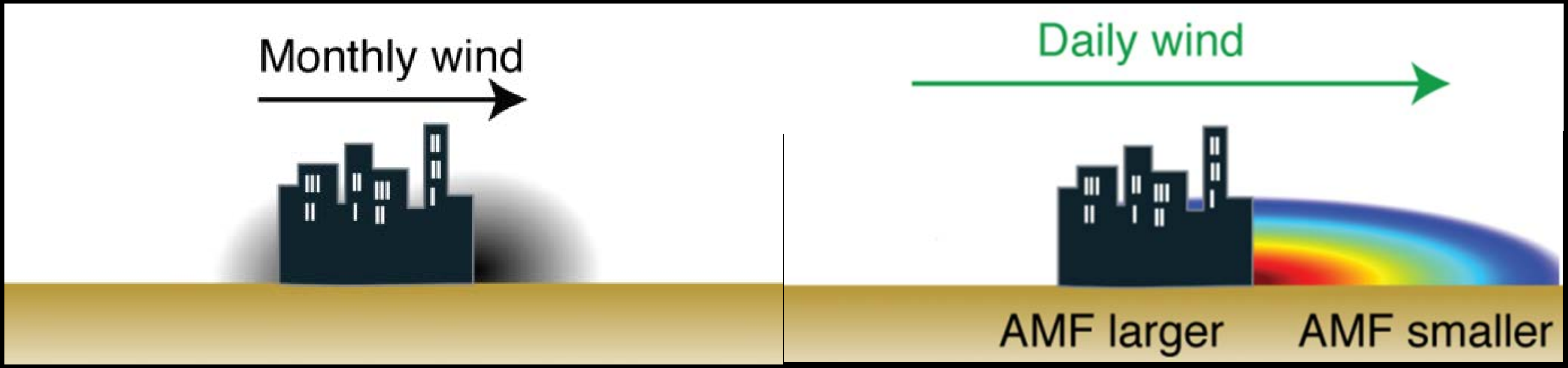
# Winds and the a priori



# Monthly Average a priori and daily wind similar speed and direction

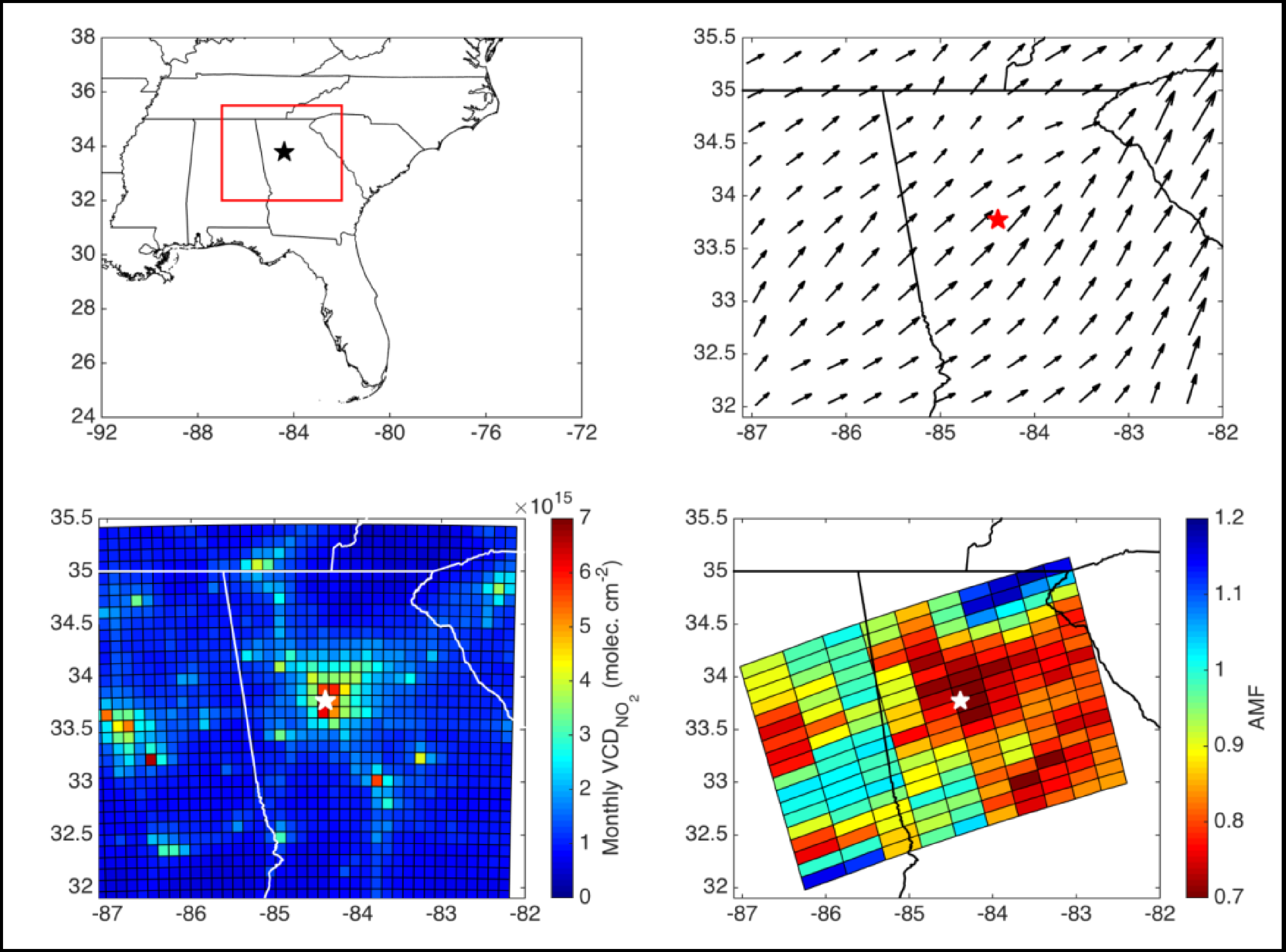


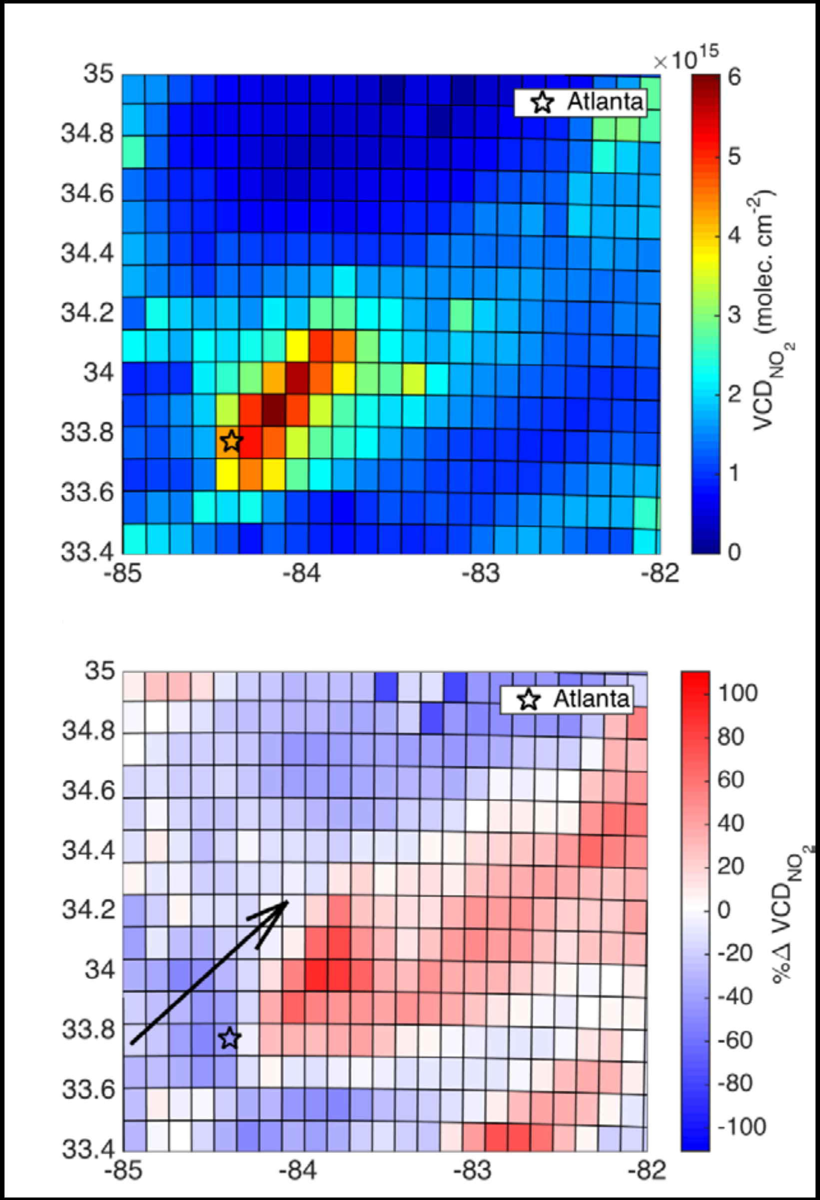
# Monthly Average a priori with daily wind faster



# Monthly Average a priori and daily wind same speed and opposite direction

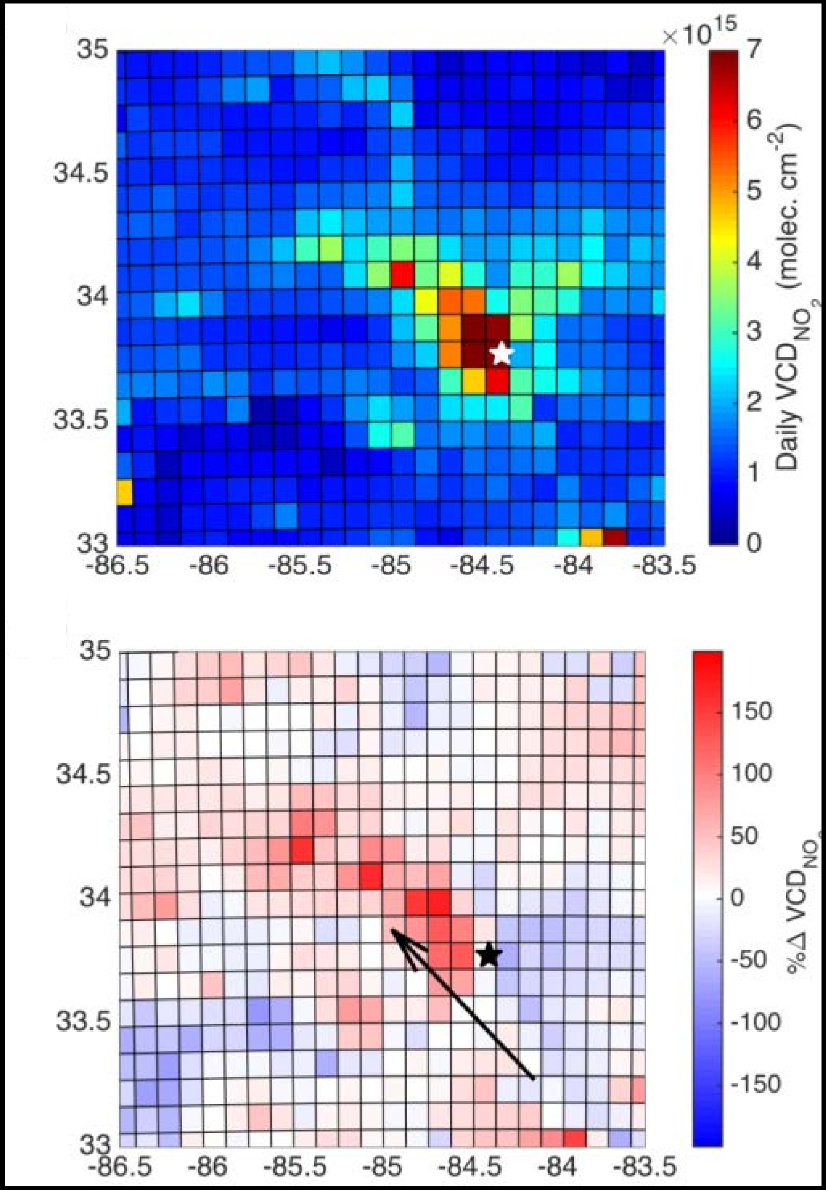
# Theory says this should matter. Does it? Case study of Atlanta






$NO_2$ VCD

% Change daily a priori

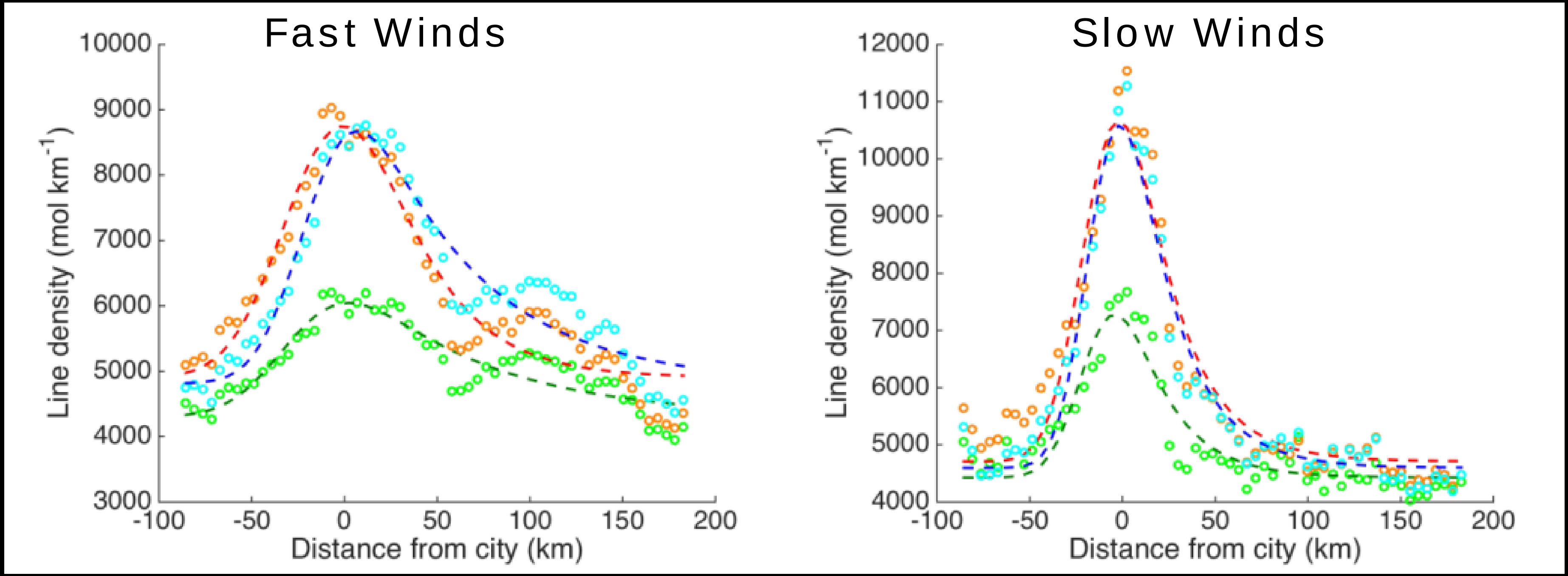



NO$_2$ VCD

% Change daily a priori

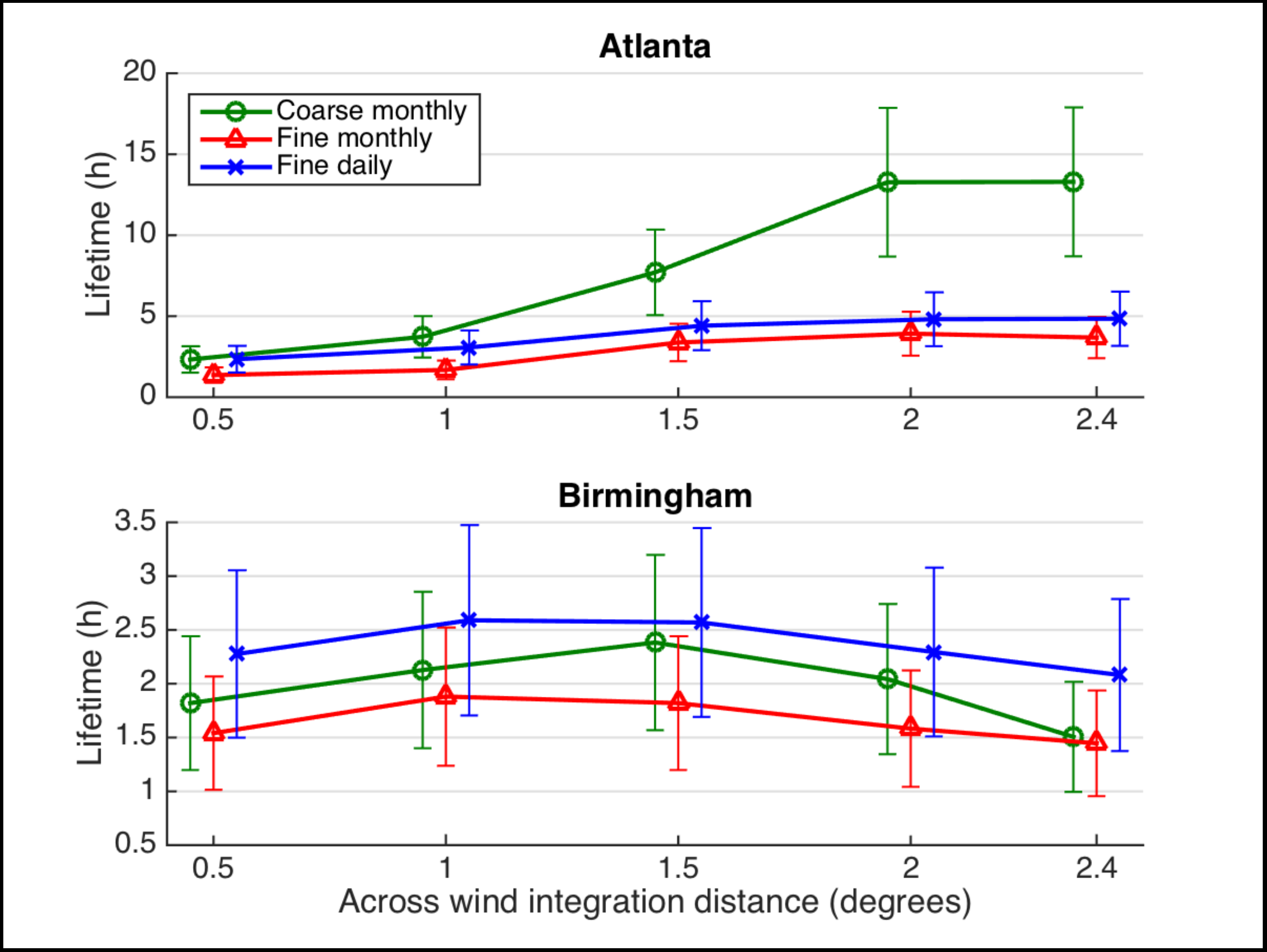
# Fits to monthly average plumes

- Green: monthly a priori, low res
- Orange: monthly a priori, high res
- Blue: daily a priori, high res



# Derived Lifetime and a priori

# Blue: most near to truth

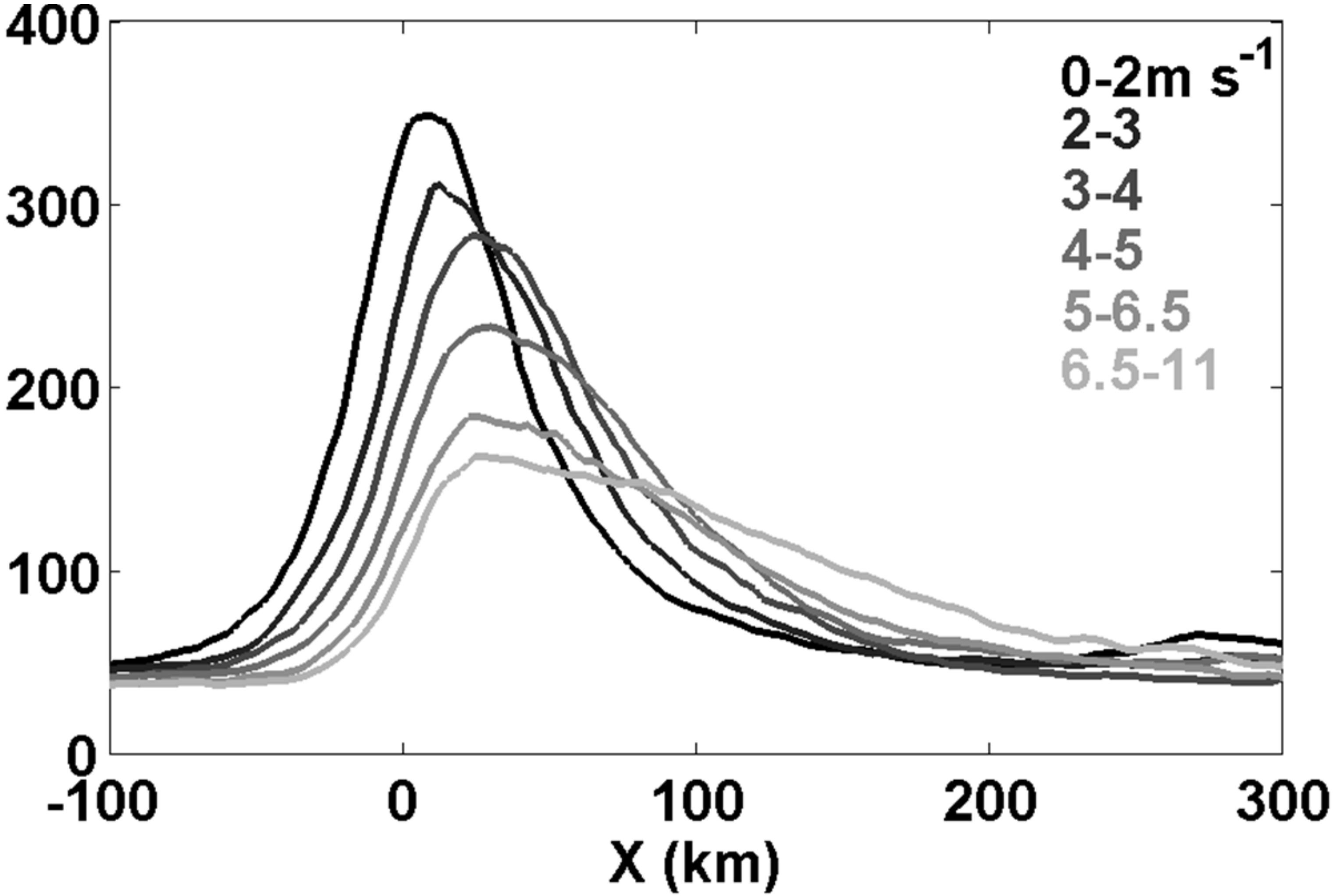


WRF-NEI Emissions (Mg $NO_x$ $h^{-1}$) 13.74

| | Wind Speed | Monthly/108 km | Monthly/12km | Daily/12km |
|---|---|---|---|---|
| Emissions (Mg $NO_x$ $h^{-1}$) | >3m/s | 3.39 | 11.66 | 7.55 |
| | >5m/s | 7.8 | 13.41 | 12.13 |
| Lifetime (h) | >3m/s | 3.73 | 1.68 | 3.07 |
| | >5m/s | 2.44 | 2.18 | 2.48 |

Variation in results arises from combining wind speeds. Emissions are almost certainly constant but columns vary with wind speed Substantially in narrow windows of speed.

# Observations vs. wind speed.




L Valin et al., *GRL 2013*

Summary retrievals:

Emissions and lifetimes to even ~20% accuracy from remote sensing of $NO_2$ will require:

high resolution *a priori* using daily wind fields

And new strategies for analysis that allow use of narrow wind ranges

# Emissions and Winds from Data Assimilation

Xueling Liu

# Ensemble Kalman Filter-Data Assimilation

Xueling Liu

Also: A. P. Mizzi, J. L. Anderson, NCAR
I. Fung, UC Berkeley

# Data Assimilation of $NO_2$ column observations

Xueling Liu, RC Cohen, A. Mizzi, I. Fung, J. Anderson

- Forecast model: WRF-Chem CTM

➢ d01 (coarse domain) dx=12km, Grids=220*140 : Met Initialization and lateral boundary conditions from NARR.

➢ d02 (fine domain) dx=3km, Grids=281*221: Both met and chemistry initialized and forced by d01.

- •Anthr: NEI 2011
- •Bio: MEGAN
- •Met input: NARR
- •PBL scheme:YSU
- •Chem mechanism: RADM2

one-way nested domain


- Data Assimilation Engine: NCAR Data Assimilation Research Testbed

➢ Ensemble Adjustment Kalman Filter

Updated chem variables: $NO_x$ Emission, NO, $NO_2$, $HNO_3$, and $O_3$

$$\mathbf{x}_i^b = M\mathbf{x}_{i-1}^a$$

$$\overline{\mathbf{x}_i^b} = \overline{\mathbf{x}_i^b} + \mathbf{K}_i(\mathbf{y}_i^o - H\overline{\mathbf{x}_i^b})$$

$$\mathbf{K}_i = \mathbf{P}_i^b\mathbf{H}^T[\mathbf{H}\mathbf{P}_i^b\mathbf{H}^T + \mathbf{R}]^{-1}$$

$$\mathbf{X}_i^a = \mathbf{T}_i\mathbf{X}_i^b \qquad \mathbf{x}_i^a = \overline{\mathbf{x}_i^a} + \mathbf{X}^a$$

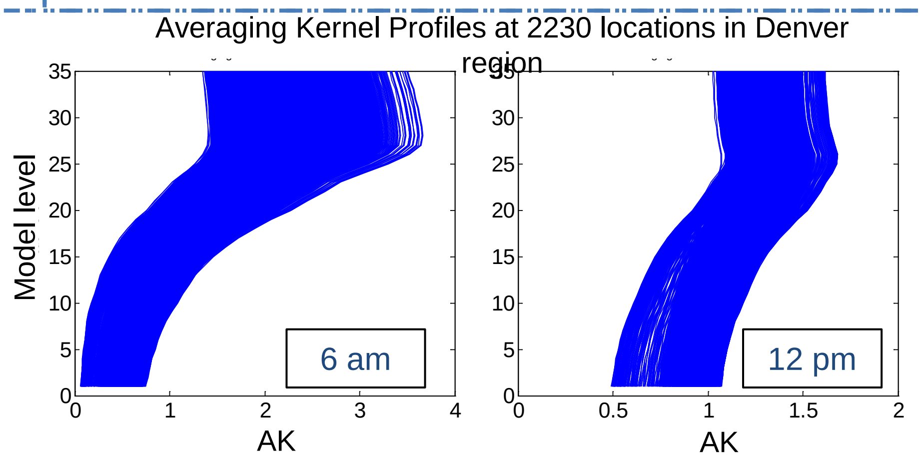
- Observation Simulator for TEMPO

Frequency: daytime hourly; resolution: $2{\times}4.5\text{km}^2$

➢ Generation of scene-dependent AKs

Assuming cloud-free scenes, calculate AK based on the parameters--terrain pressure, albedo, solar zenith angle, view zenith angle and relative azimuth angle.

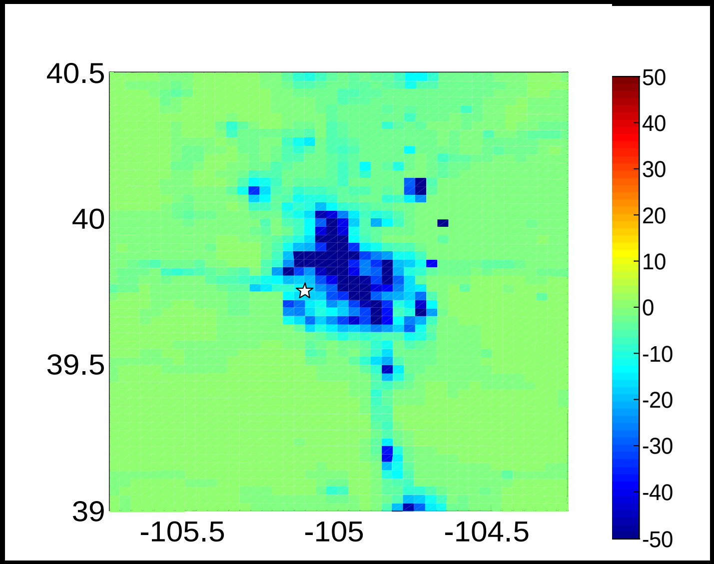
➢ Capture the spatial and temporal variation of AKs.



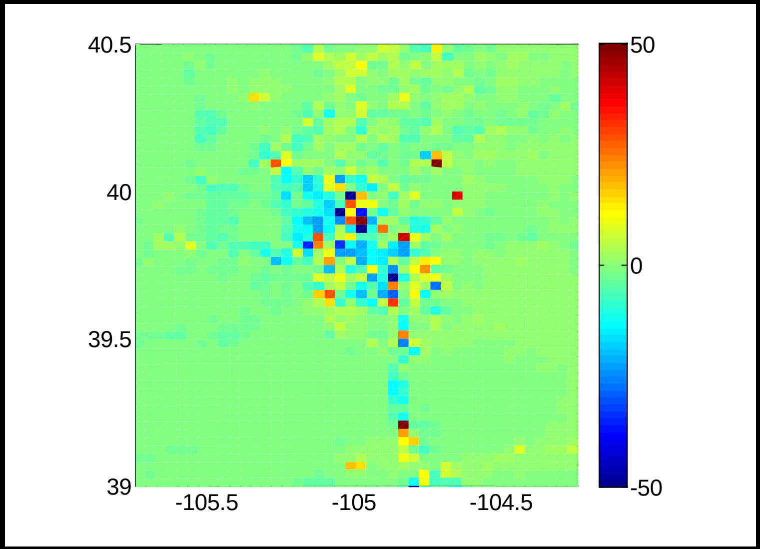
# Data Assimilation—another talk

***Data assimilation will be effective for constraining emissions—possibly on hourly/daily timescales***

Emissions： Prior – truth (mol/km$^2$/hr)

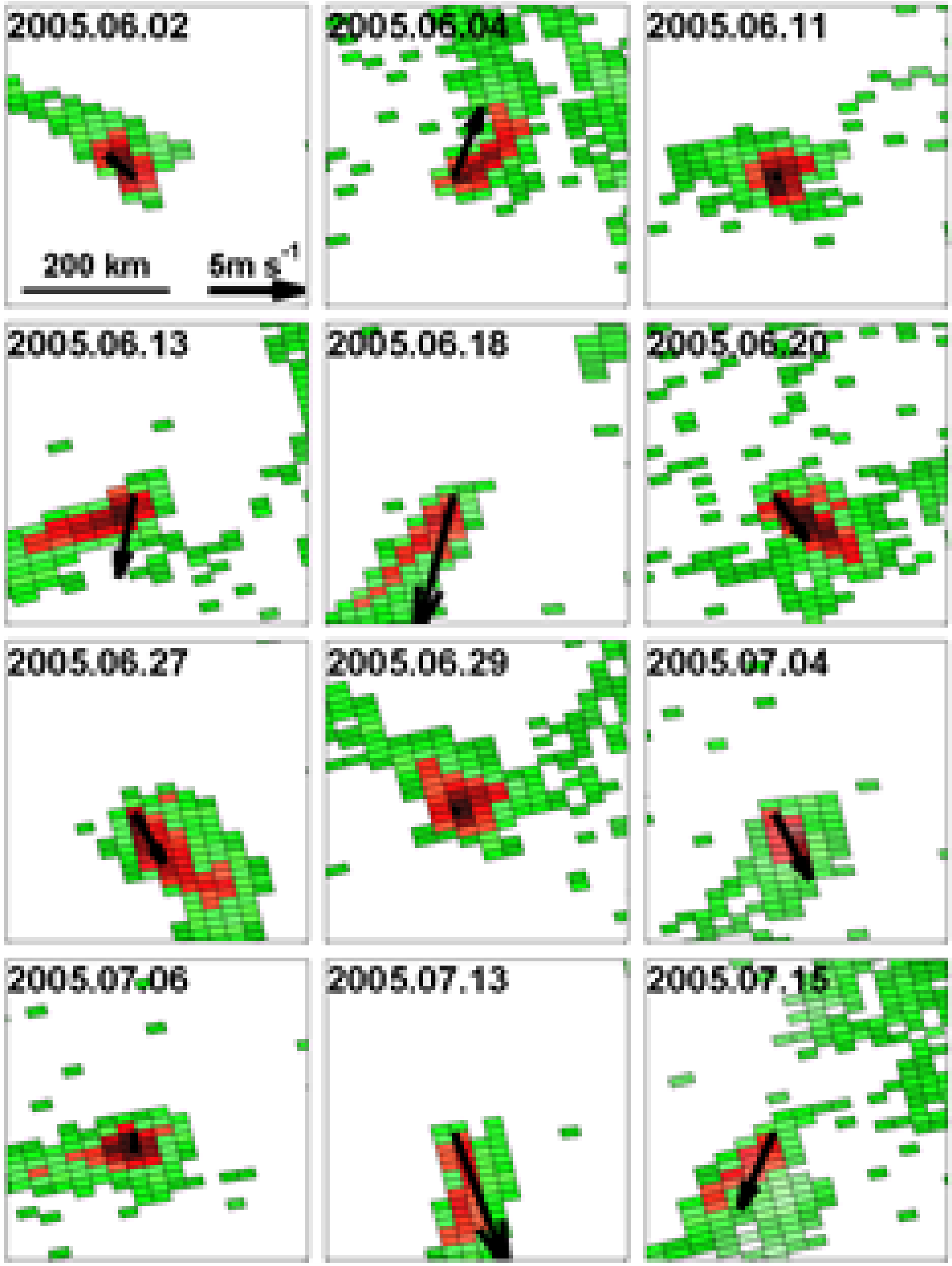



Emissions： Posterior – truth (mol/km$^2$/hr)

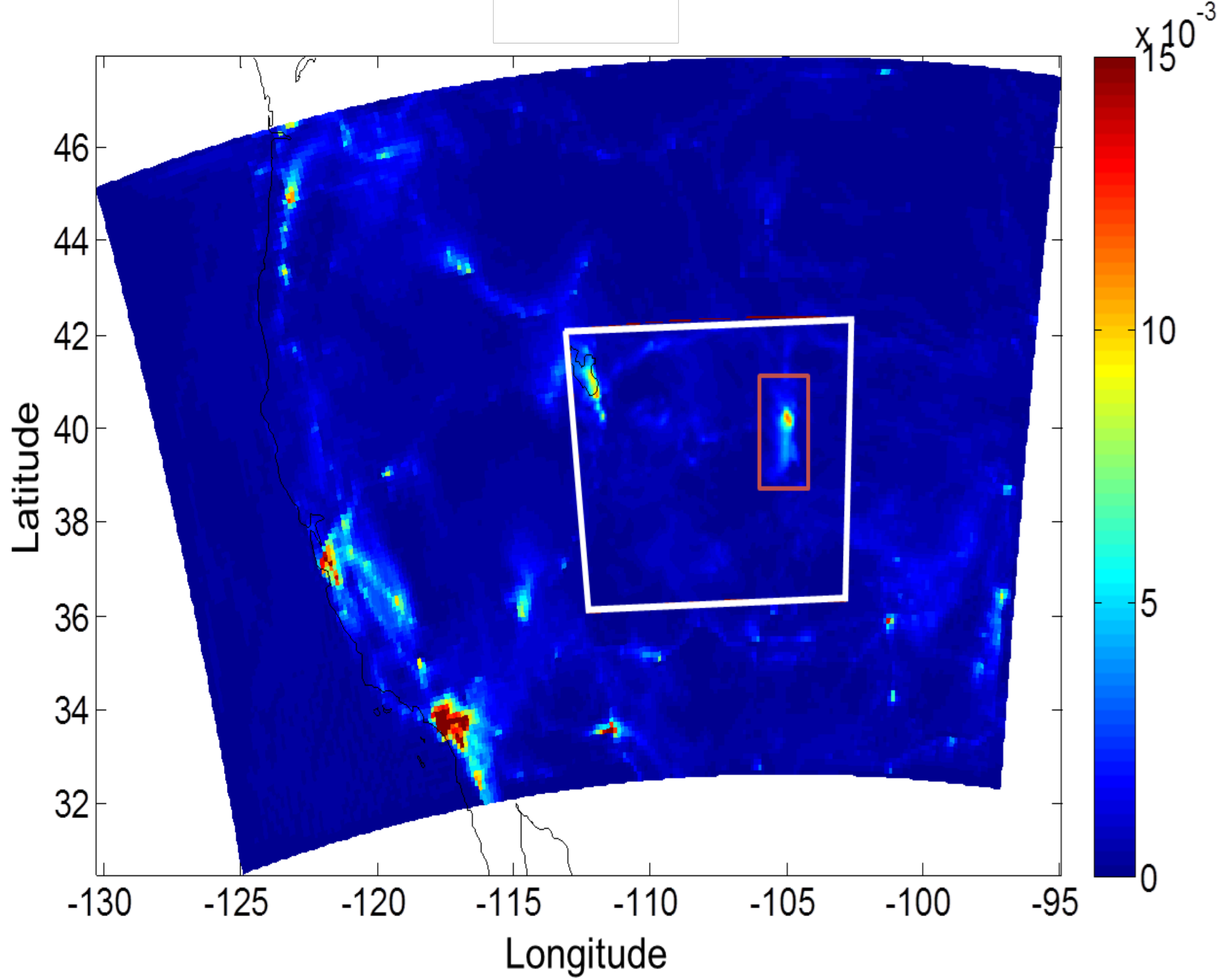



X. Liu, Cohen et al. in preparation

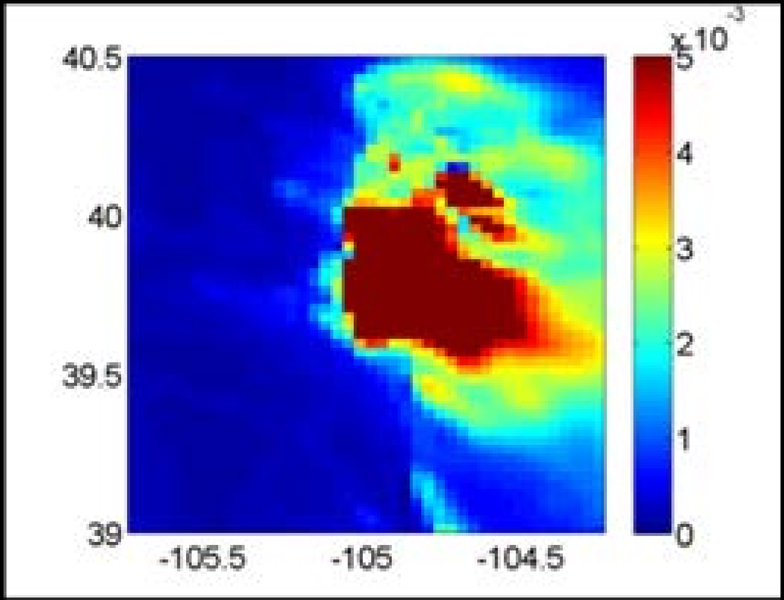
# Riyadh



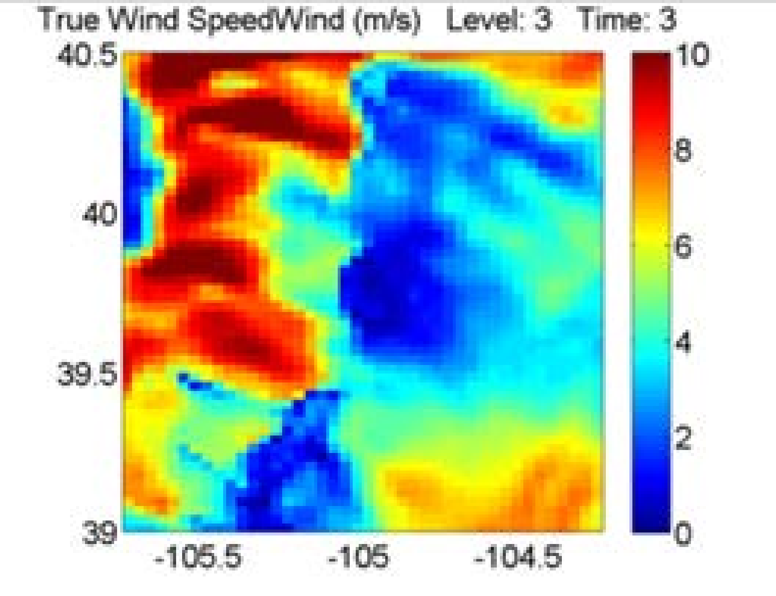

L Valin et al., *GRL* 2013


x 10^-3
15
10
5
0
46
44
42
40
38
36
34
32
Latitude
-130
-125
-120
-115
-110
-105
-100
-95
Longitude

# Truth (Denver)

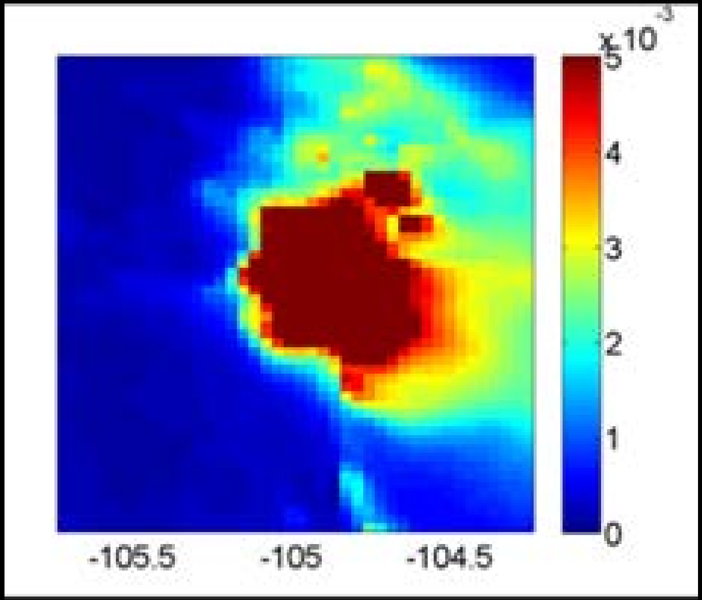



$NO_2$ Column

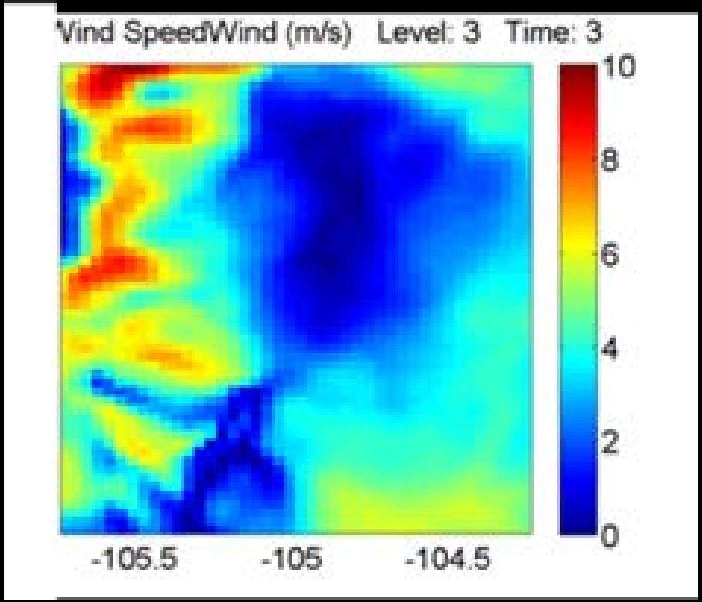



Winds

# Prior with biased winds

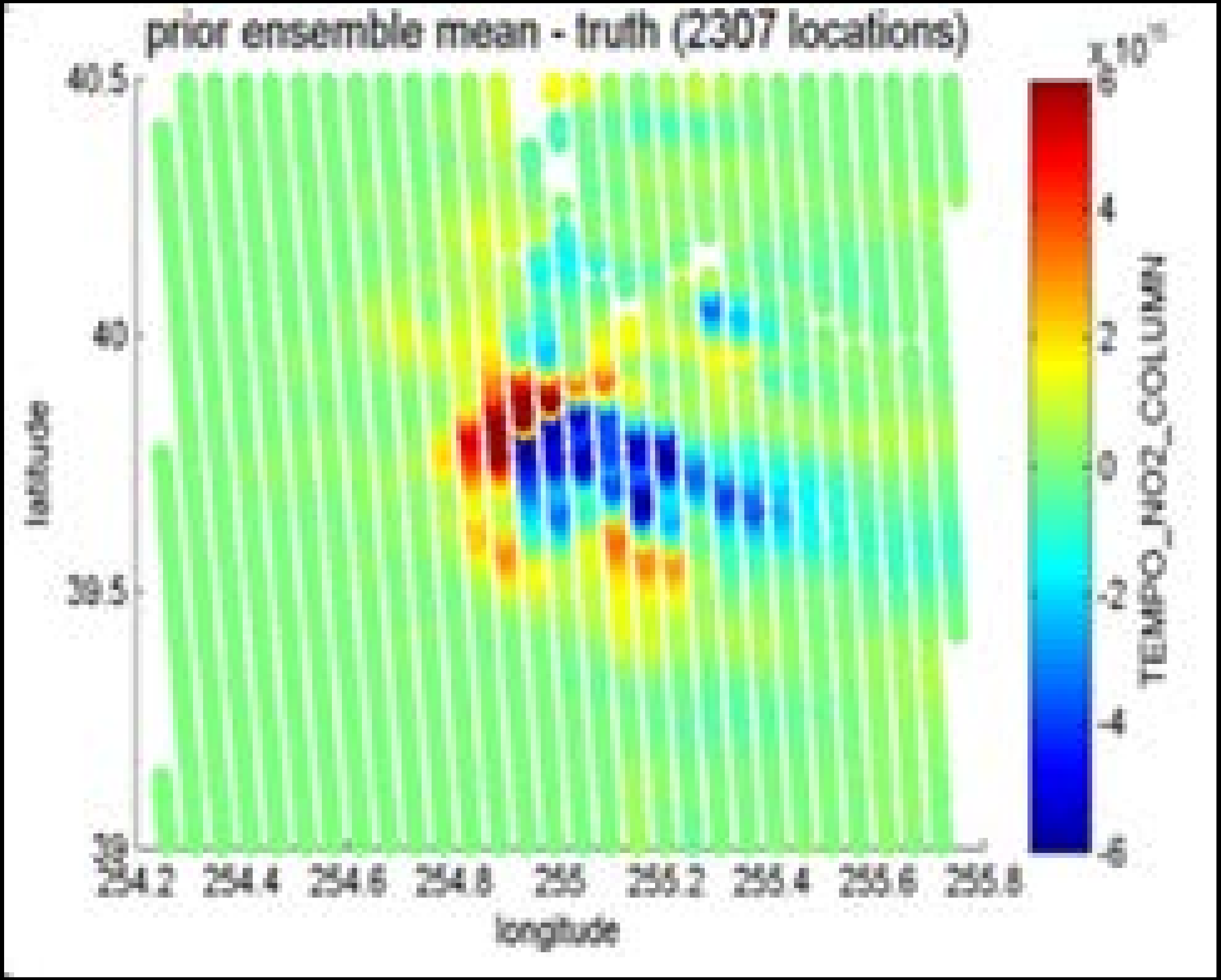



$NO_2$ Column

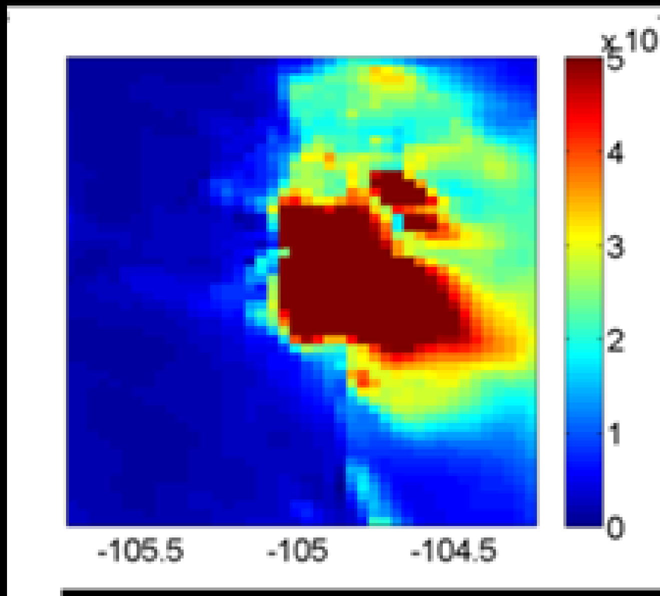



Winds

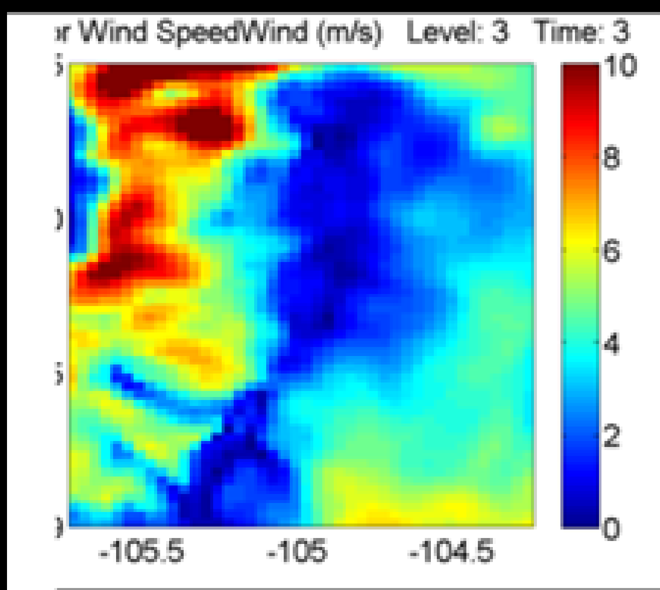
# Truth – Prior (Denver) Sampled with TEMPO



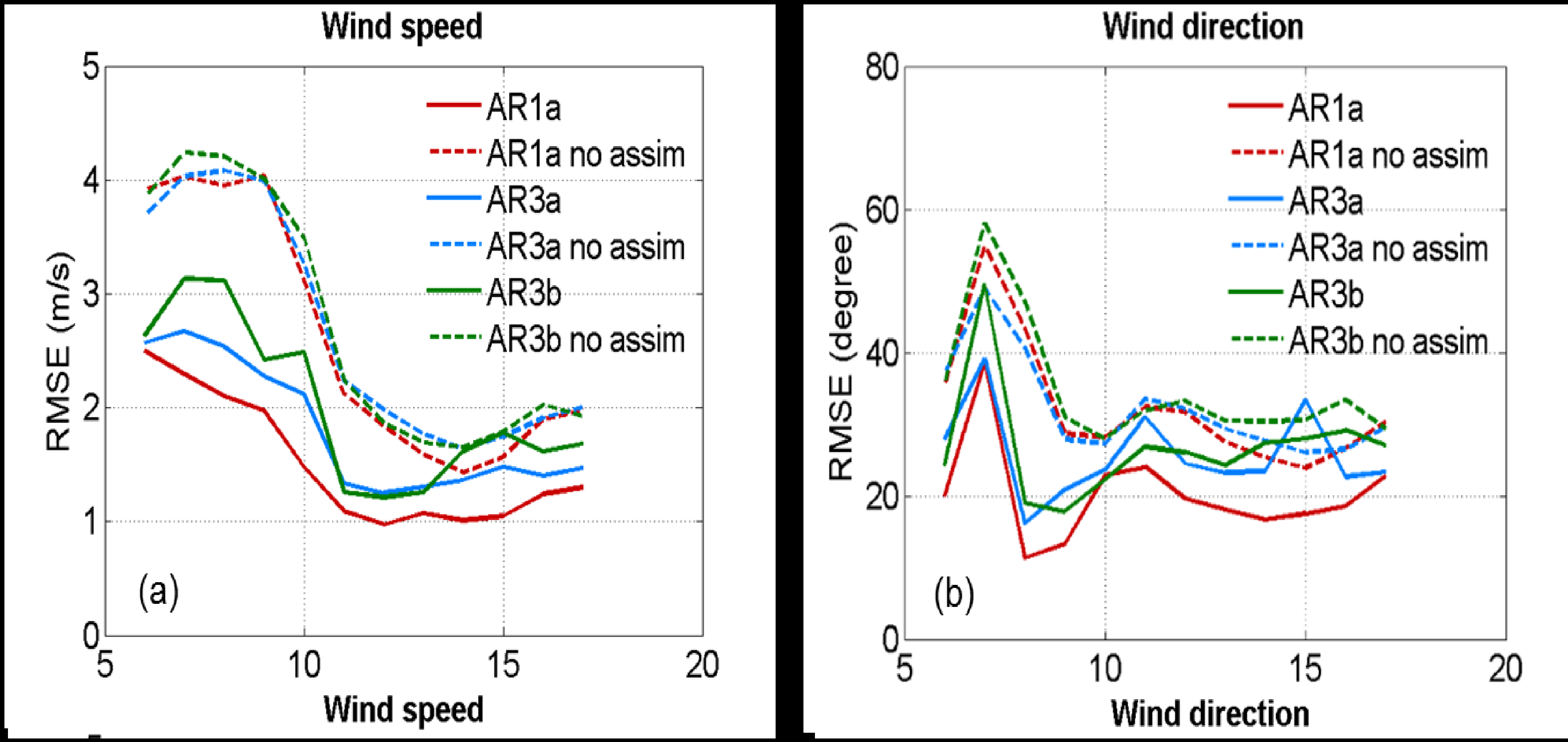
# Posterior After Assimilation




$NO_2$ Column




Winds


Wind speed
5
4
3
2
1
0
RMSE (m/s)
AR1a
AR1a no assim
AR3a
AR3a no assim
AR3b
AR3b no assim
(a)
5
10
15
20
Wind speed
Wind direction
80
60
40
20
0
RMSE (degree)
AR1a
AR1a no assim
AR3a
AR3a no assim
AR3b
AR3b no assim
(b)
5
10
15
20
Wind direction

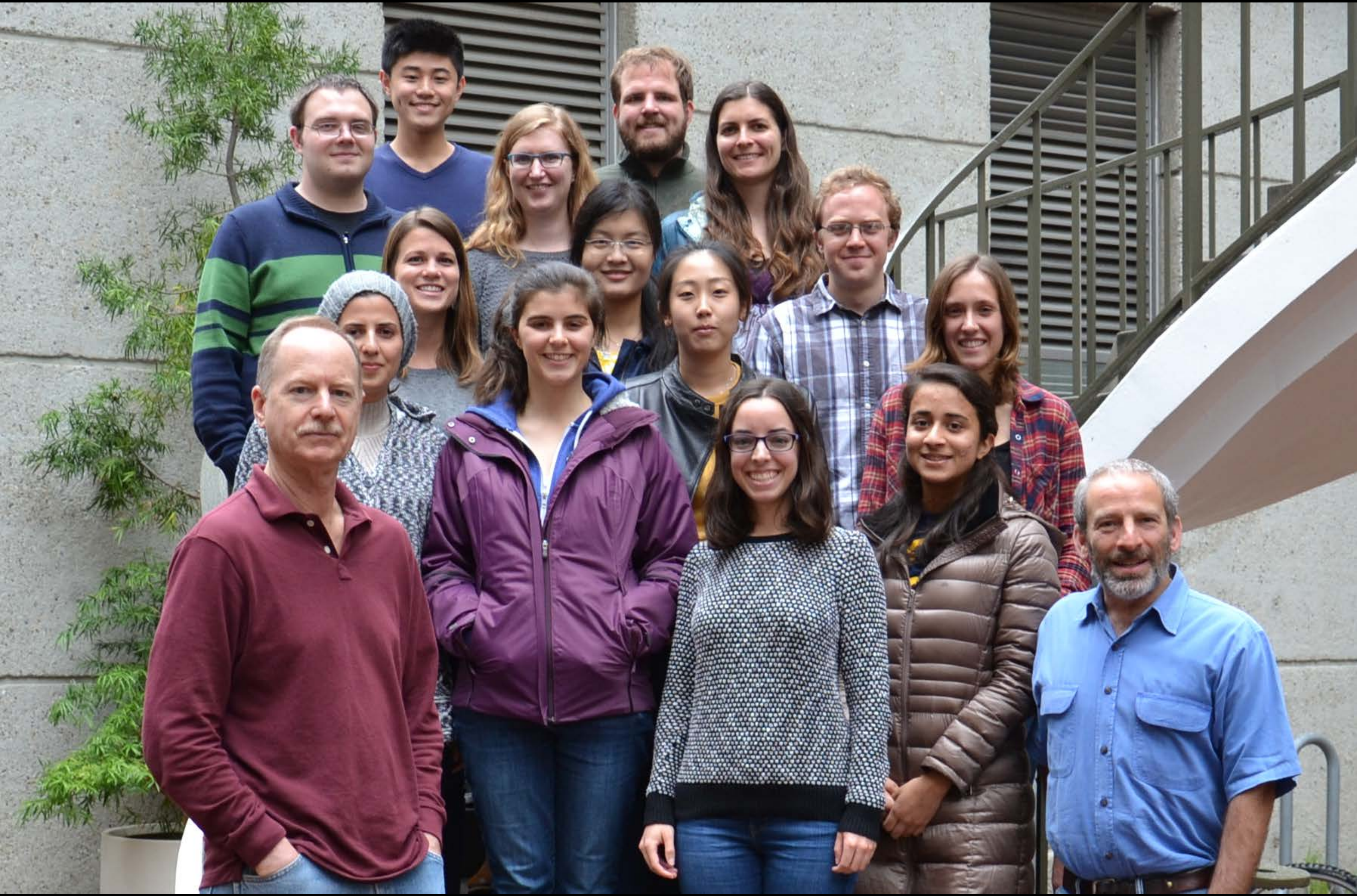
# Winds and TEMPO

1 ***Winds affect the $NO_2$ lifetime in interesting and important ways***

2 ***Retrievals that account for daily wind variations are needed for quantitative accuracy in our inferences of emissions and lifetime***

3 ***Data assimilation will be effective for constraining emissions—possibly on hourly/daily timescales***

4 ***Data assimilation will also be able to constrain meterological fields e.g. winds***



# *Thank you!*