Elevated Winter Nitrate in the Upper Midwest

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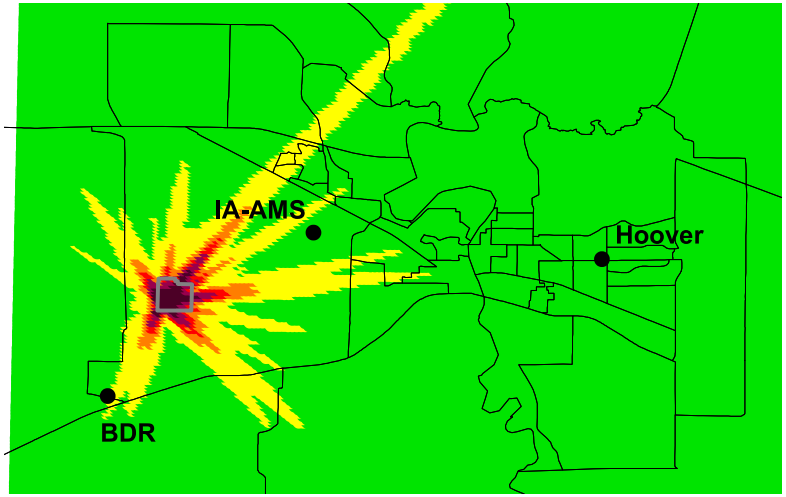
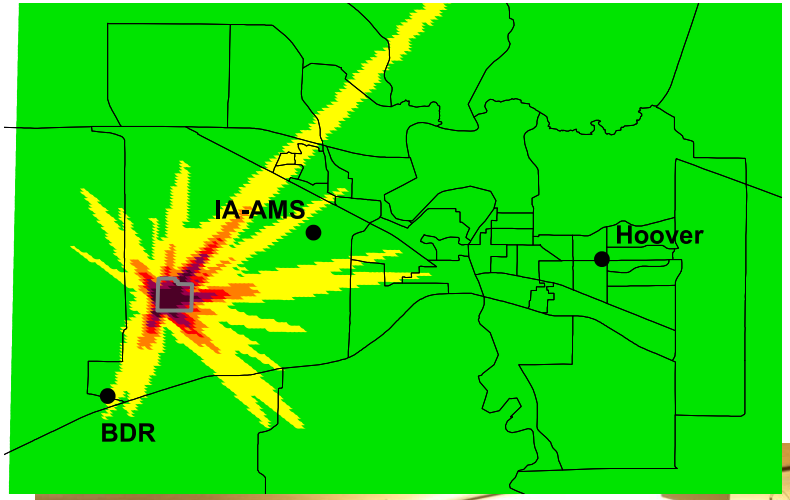
IIHR Hydroscience & Engineering

CENTER FOR GLOBAL AND REGIONAL ENVIRONMENTAL RESEARCH

The University of Iowa


IA-AMS
Hoover
BDR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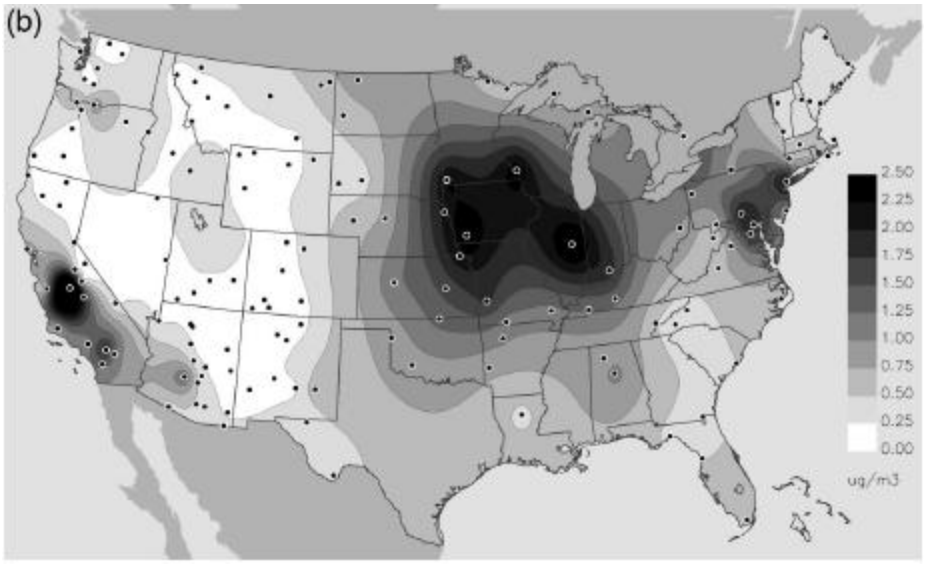
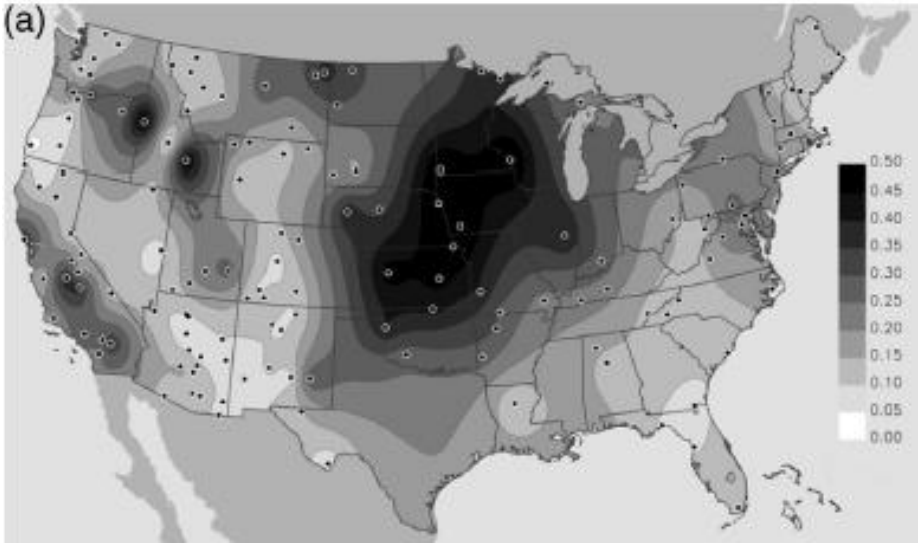
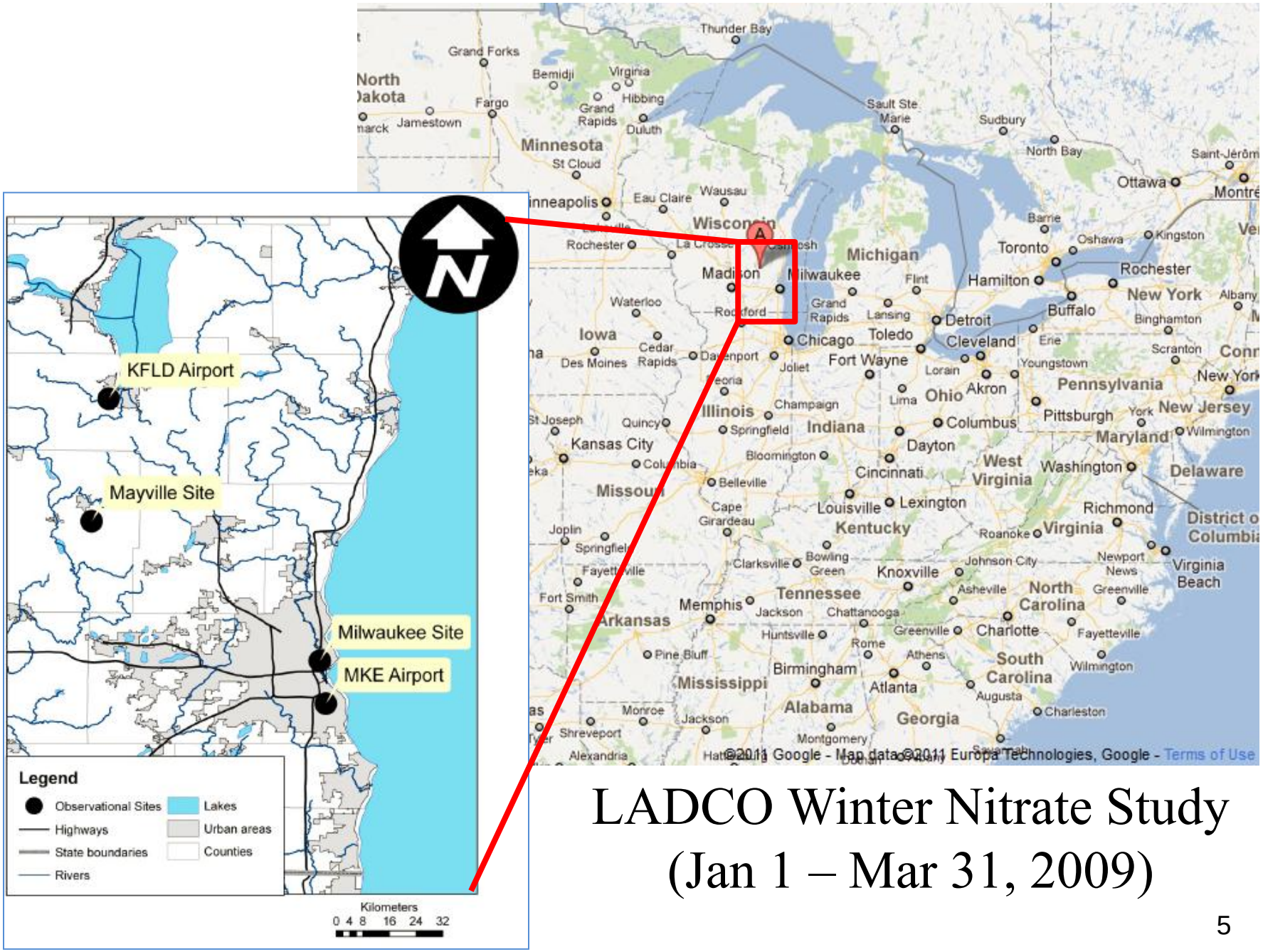


2005-2006 Ammonium Nitrate from IMPROVE Network



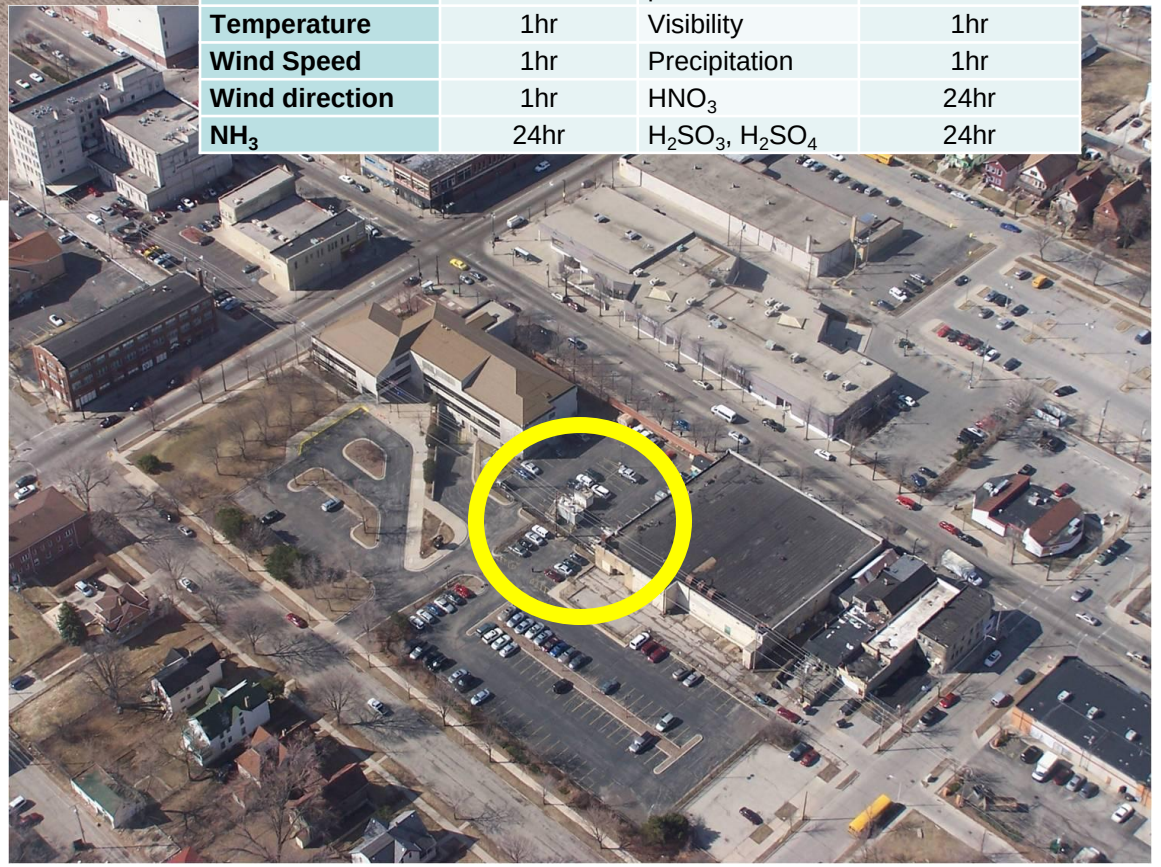
Jan 2006 Ammonium Nitrate Fraction of PM2.5

Pitchford et al. JAWMA (2009)



LADCO Winter Nitrate Study (Jan 1 – Mar 31, 2009)

Species	Averaging time (hr)	Species	Averaging time (hr)
$PM_{2.5}$	1hr	$PM_{2.5}$	24hr 1 in 3days
SO_4	1hr	NH_4	24hr 1 in 3days
NO_3	1hr	NO_3	24hr 1 in 3days
NH_4	1hr	SO_4	24hr 1 in 3days
HNO_3	1hr	OC	24hr 1 in 3days
NH_3	1hr	EC	24hr 1 in 3days
NO_y	1hr	O_3	1hr
NOx (note 6)	1hr	Relative Humidity	1hr
SO2 (note 7)	1hr	Surface pressure	1hr
Temperature	1hr	Visibility	1hr
Wind Speed	1hr	Precipitation	1hr
Wind direction	1hr	HNO_3	24hr
NH_3	24hr	H_2SO_3, H_2SO_4	24hr



Science Questions for the Study

Composition: Typical chemical composition during episodes and non-episodes?

Urban-rural contrast: Differences in $PM_{2.5}$ concentrations (frequency and severity), chemical composition, and source regions?

Meteorology: What meteorological conditions favor winter-time episodes? How can we best use this information to improve wintertime episode forecasting?

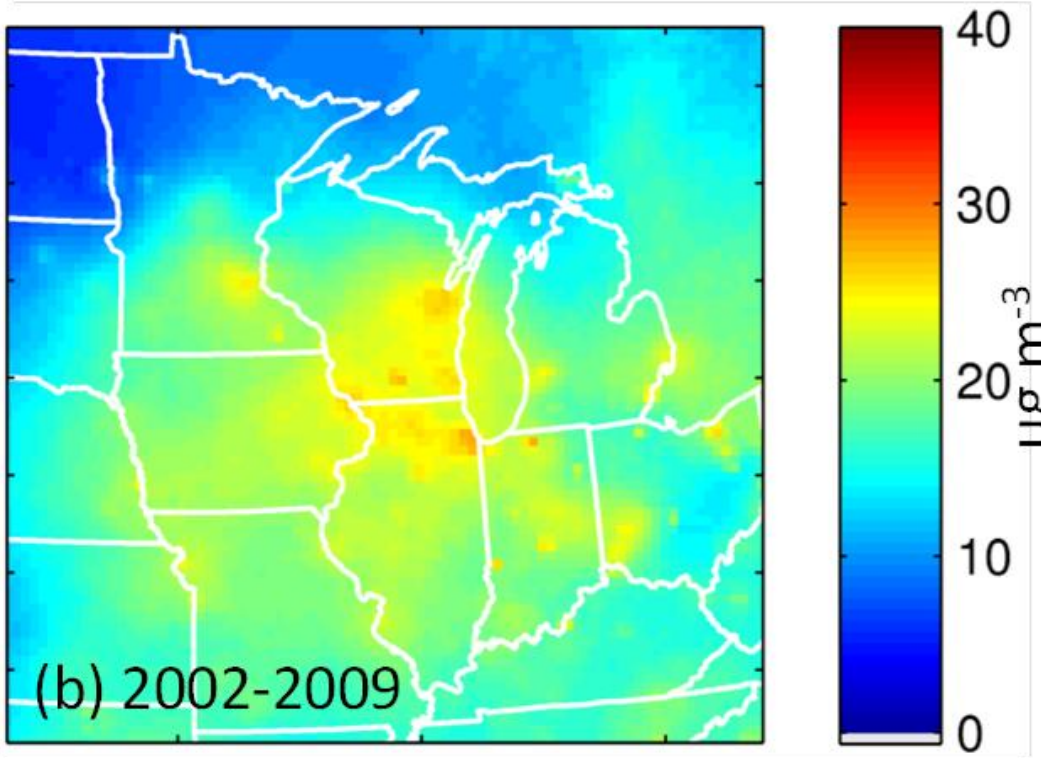
Nitrate formation chemistry: What do the data tell us the nitrate formation chemistry leading to events?

Sensitivity of episodes:

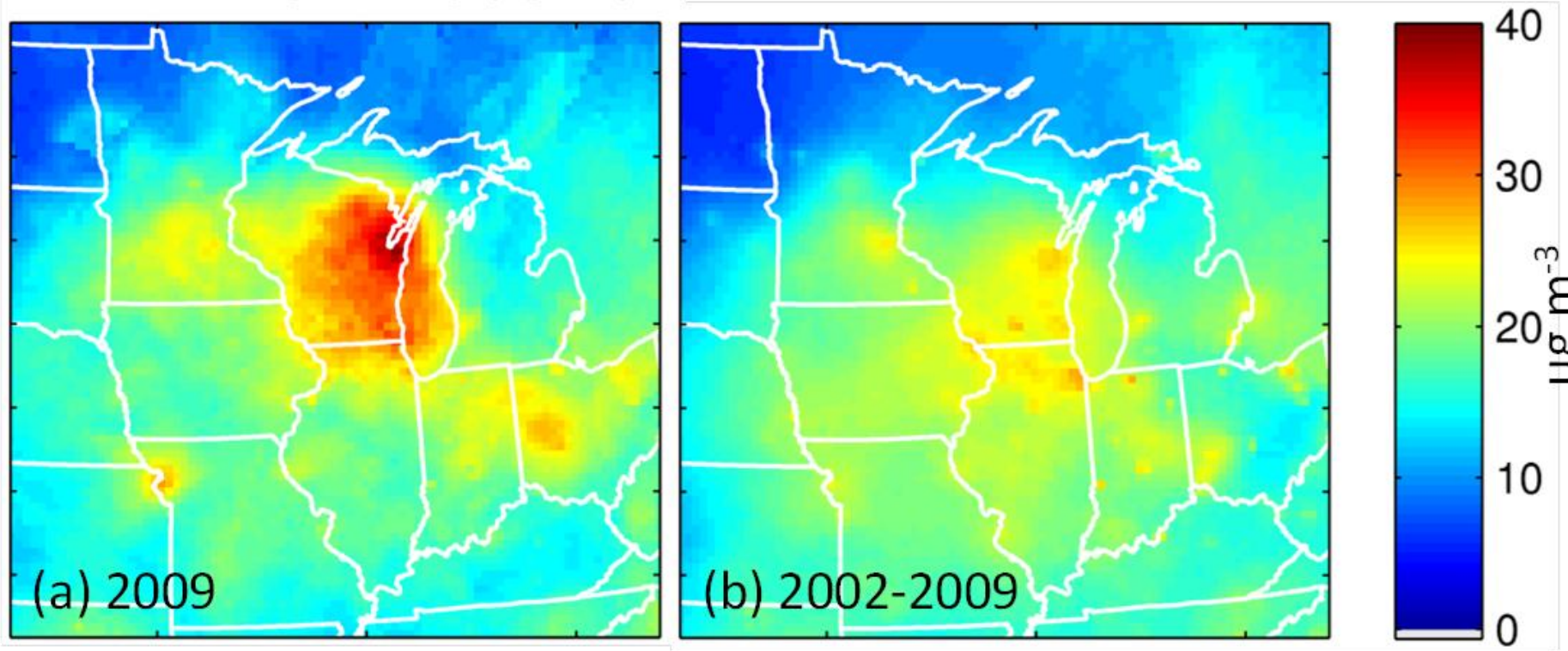
- How sensitive are concentrations to hypothetical changes in total nitrate, total ammonia, and total sulfate?
- What sources categories have leverage on episodes? Do local sources have influence?

3D Model skill: Can photochemical modeling accurately predict $PM_{2.5}$ concentrations during the observed winter-time episodes?

OBSERVATIONAL HIGHLIGHTS



5th Highest Jan-Mar $PM_{2.5}$ Concentration



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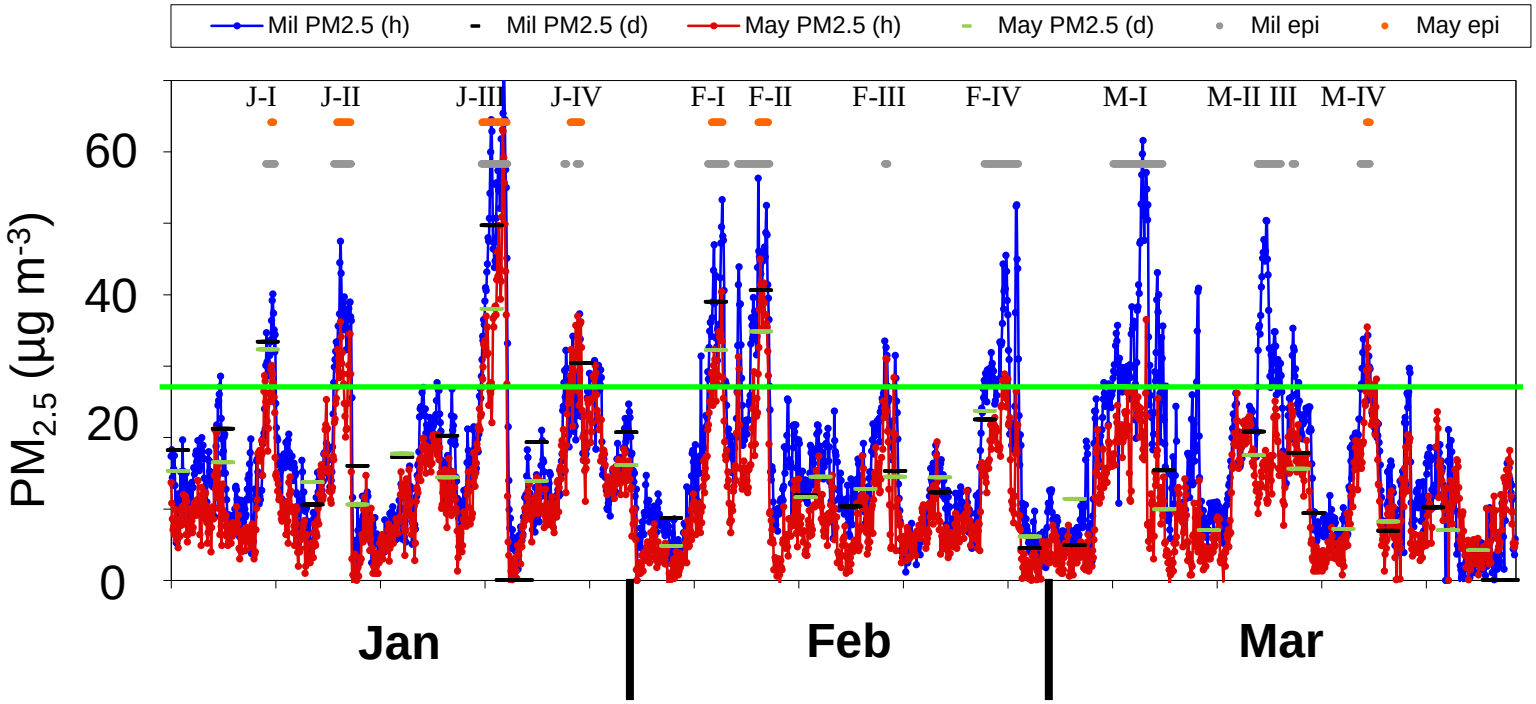
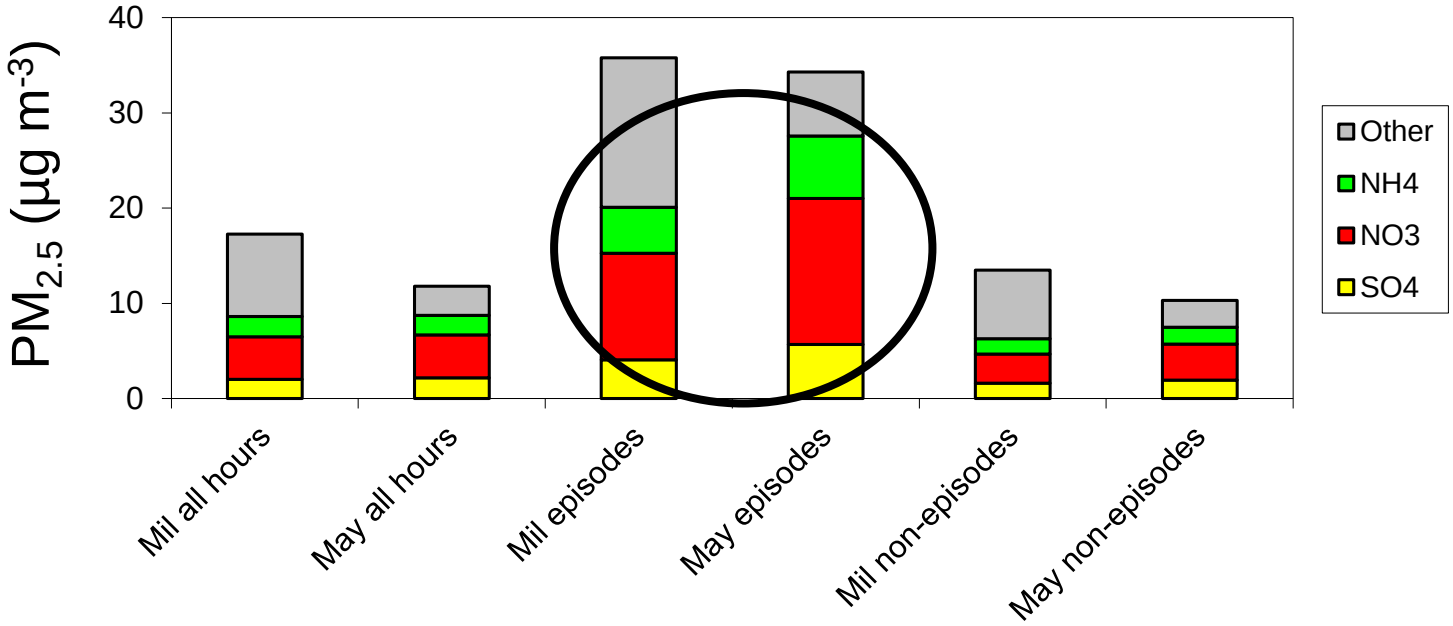


Parameter	Milwaukee (Urban)	Mayville (Rural)
$PM_{2.5}$ (µg m^{-3})	17.1	11.7
Total nitrate (µg m^{-3})	5.6	4.8
Total ammonia (µg m^{-3})	3.8	4.0
Gas ammonia (ppb)	2.3	2.4
Nitrate aerosol / total nitrate	78%	69%
NO_y (ppb)	27	6.3
Temperature (°C)	-3	-5
Ozone (ppb)	22	31
OC (µg m^{-3})	3.6	3.2
EC (µg m^{-3})	0.5	0.3

Composition and Urban-Regional Differences

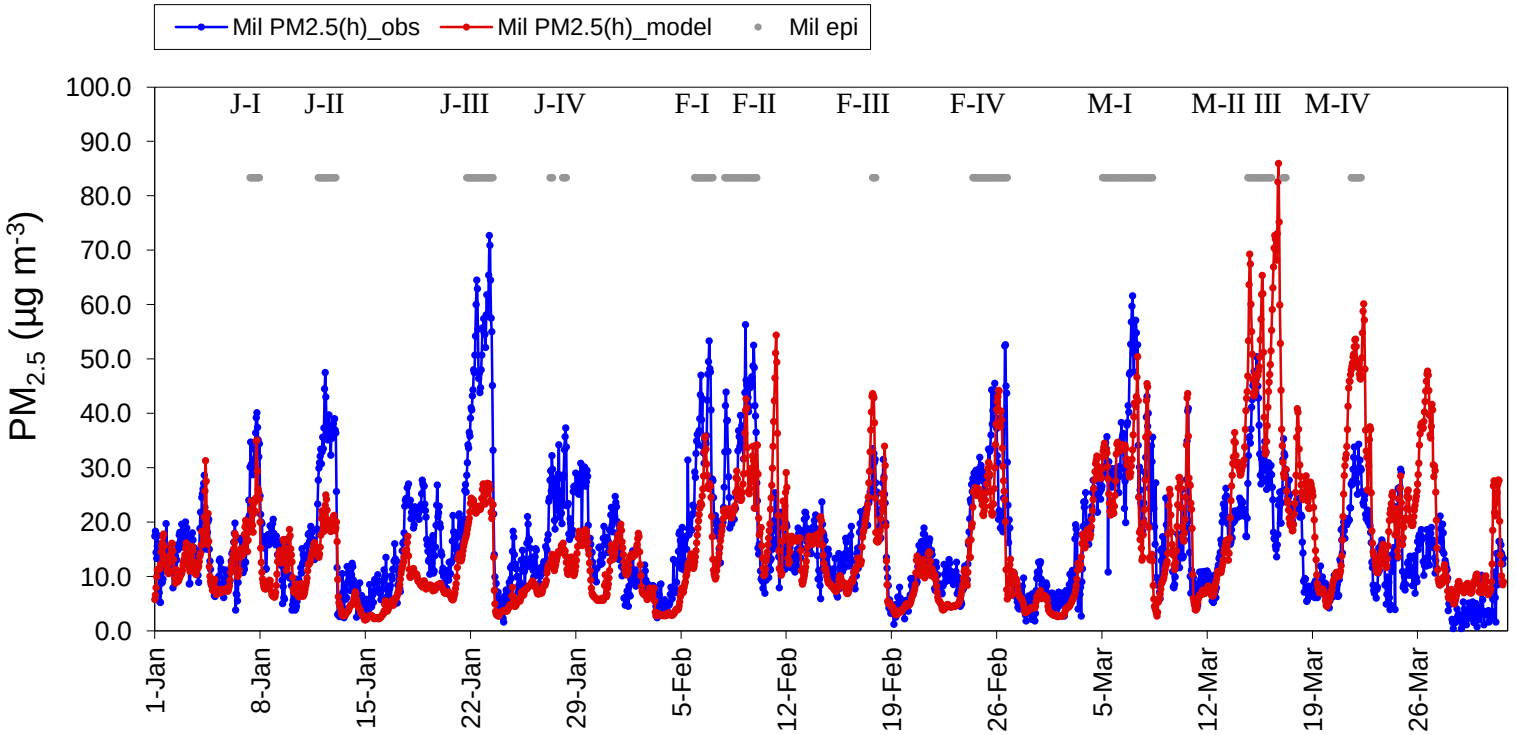


- Gas ratios (ammonia availability) ranged from 1.2-3.1. Lowest at the rural site during episodes.
- Evidence of gas ratio ↓ during episodes at multiple sites in the region.
- Secondary species mainly regional (small urban excess)
- OC, EC, and NOy have strong urban excess

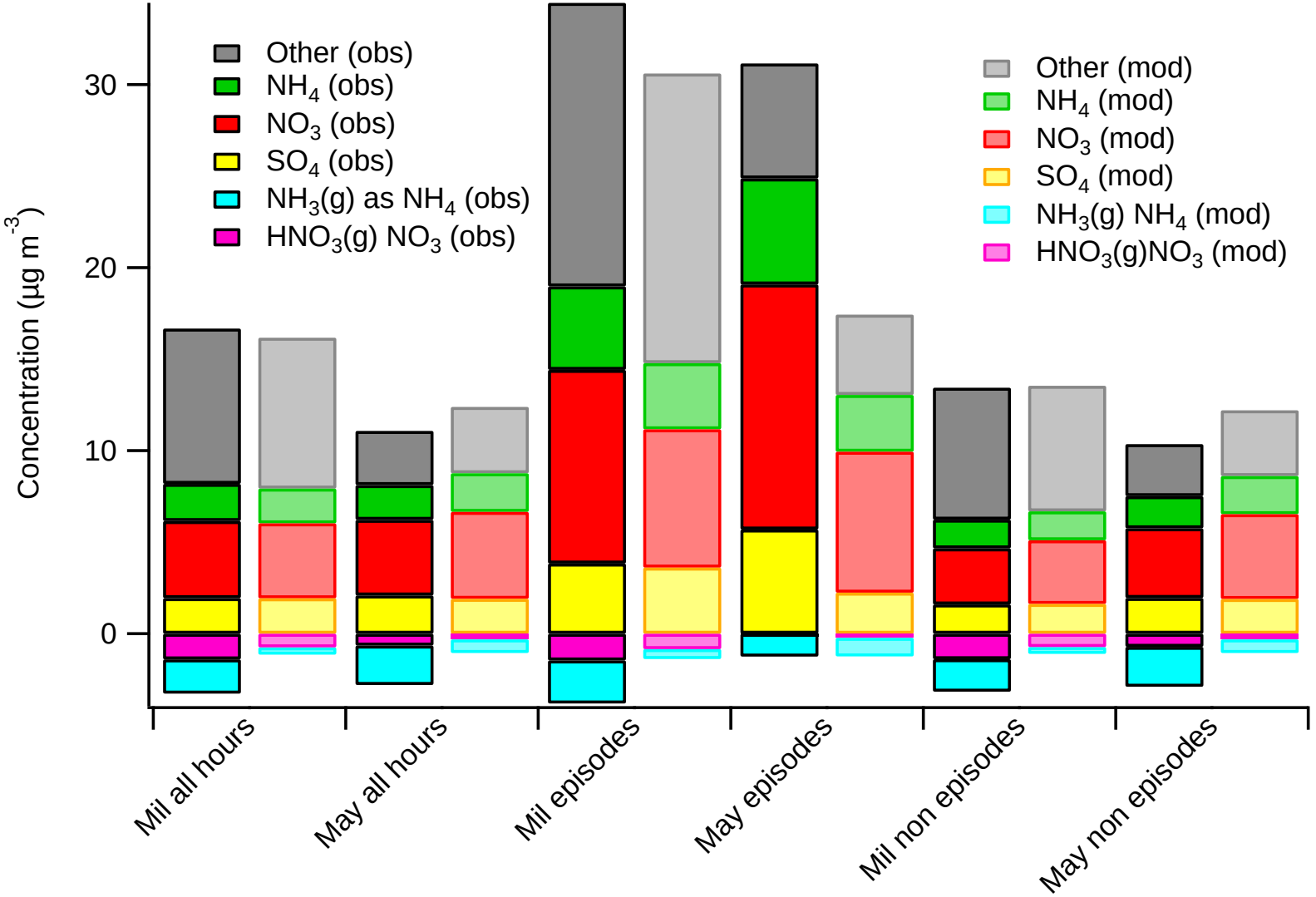
INSIGHTS FROM MODELING

U of I
Model Skill

Network	Species	Observed	Model
AQS	Ozone	29.8	35.0
Improve	$PM_{2.5}$	7.0	8.6
	SO_4	1.8	2.6
STN	$PM_{2.5}$	12.1	15.4
	NO_3	3.0	3.0
	NH_4	1.7	2.0
	SO_4	2.4	3.6



Model Skill



- Total ammonia underprediction during almost all periods and sites.
- Shows as deficit in gas phase ammonia.
- Nitrate underprediction during episodes.
- Systematic OC underprediction (not shown) but offset by CMAQ other inorganics

Model Skill

Table 3.8.2. Performance analyses of simulated $PM_{2.5}$ in the 12km domain at STN sites.

		No.	CMAQ	OBS	MB	ME	NB	NE	FB(%)	FE(%)	R
Base case	Jan	548	11.97	12.87	-0.90	6.49	0.06	0.53	-13	52	0.30
	Feb	384	15.05	12.71	2.34	6.77	0.72	0.99	11	47	0.37
	Mar	453	19.79	10.73	9.06	10.58	1.02	1.18	39	60	0.57

Table 3.8.3. Performance analyses of simulated $PM_{2.5}$ in the 12km domain at IMPROVE sites

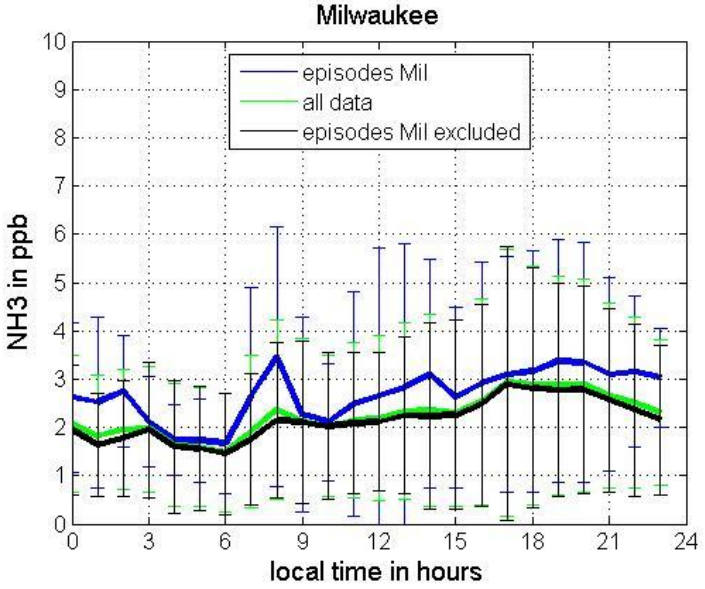
		No.	CMAQ	OBS	MB	ME	NB	NE	FB(%)	FE(%)	R
Base case	Jan	311	6.49	6.64	-0.15	2.96	0.15	0.53	-4	46	0.52
	Feb	253	8.45	6.96	1.50	2.95	0.34	0.53	15	38	0.62
	Mar	289	11.00	7.31	3.69	5.14	0.62	0.81	28	52	0.57

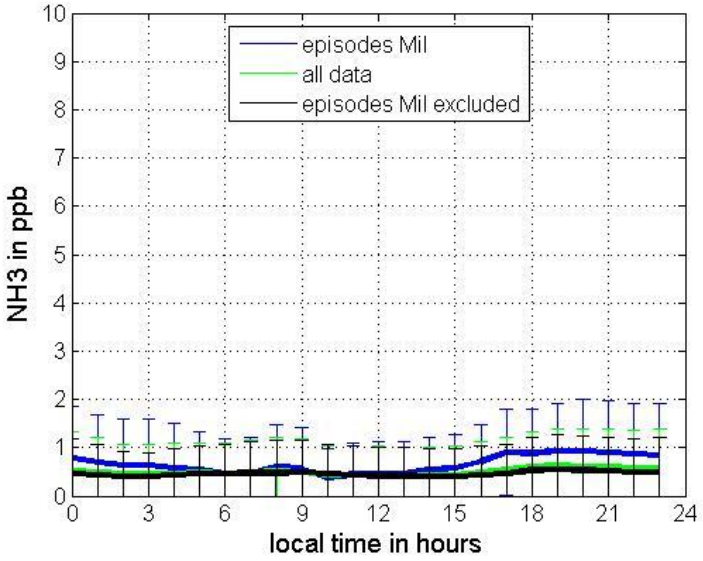
Diurnal Patterns – $NH_3(g)$

Observations

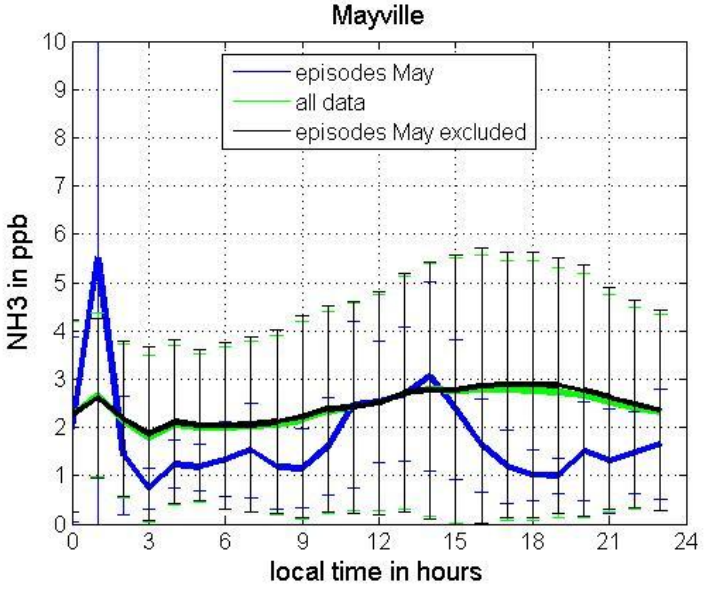
Model

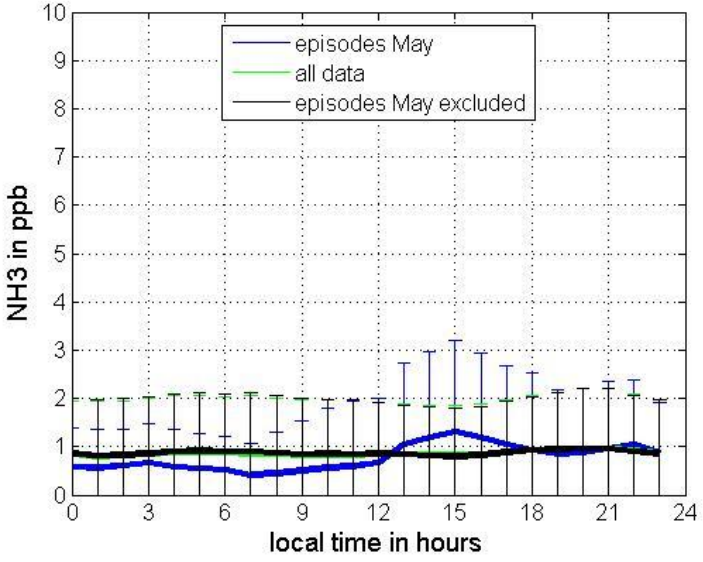
Urban





Rural

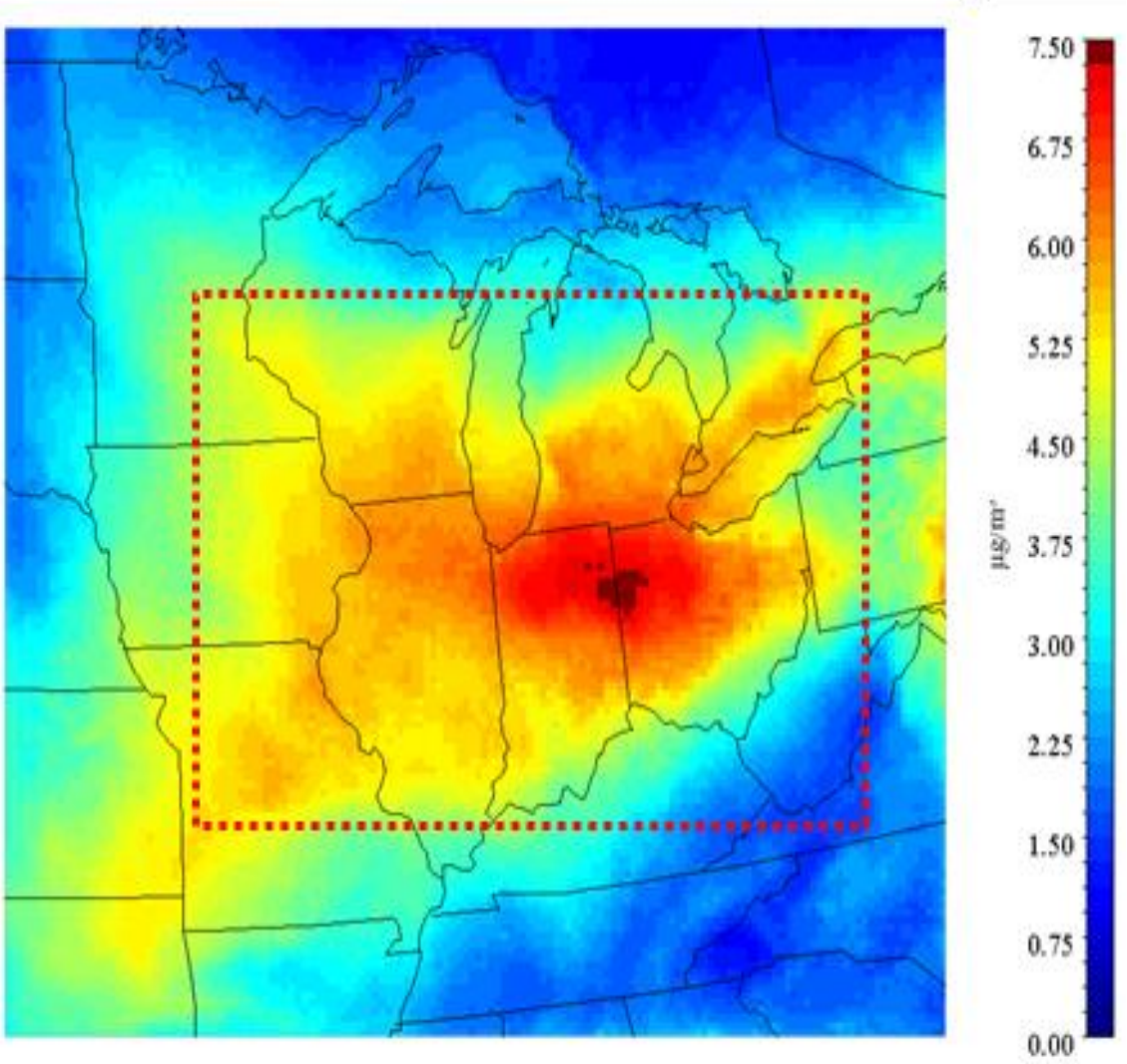




Predictability of PM2.5 Episodes

	Number of Observed Episodes	Number of Observed Episodes with Modeled Episode	Number of Modeled False Positive Episodes
Milwaukee	13	10	2
Mayville	7	4	4

PROCESS ANALYSIS



Mean total nitrate Jan – Mar 2009. CMAQ.

Nitrate formation analysis by process analysis

$NO_2 + OH \rightarrow HNO_3$ (b)

Daytime

$NO_2 + O_3 \rightarrow NO_3 + O_2$ (a)

$NO_3 + NO_2 \leftrightarrow N_2O_5$ (c)

$NO_3 + VOC \rightarrow$ organic products (g)

$N_2O_5 + H_2O(g) \rightarrow 2HNO_3$ (d)

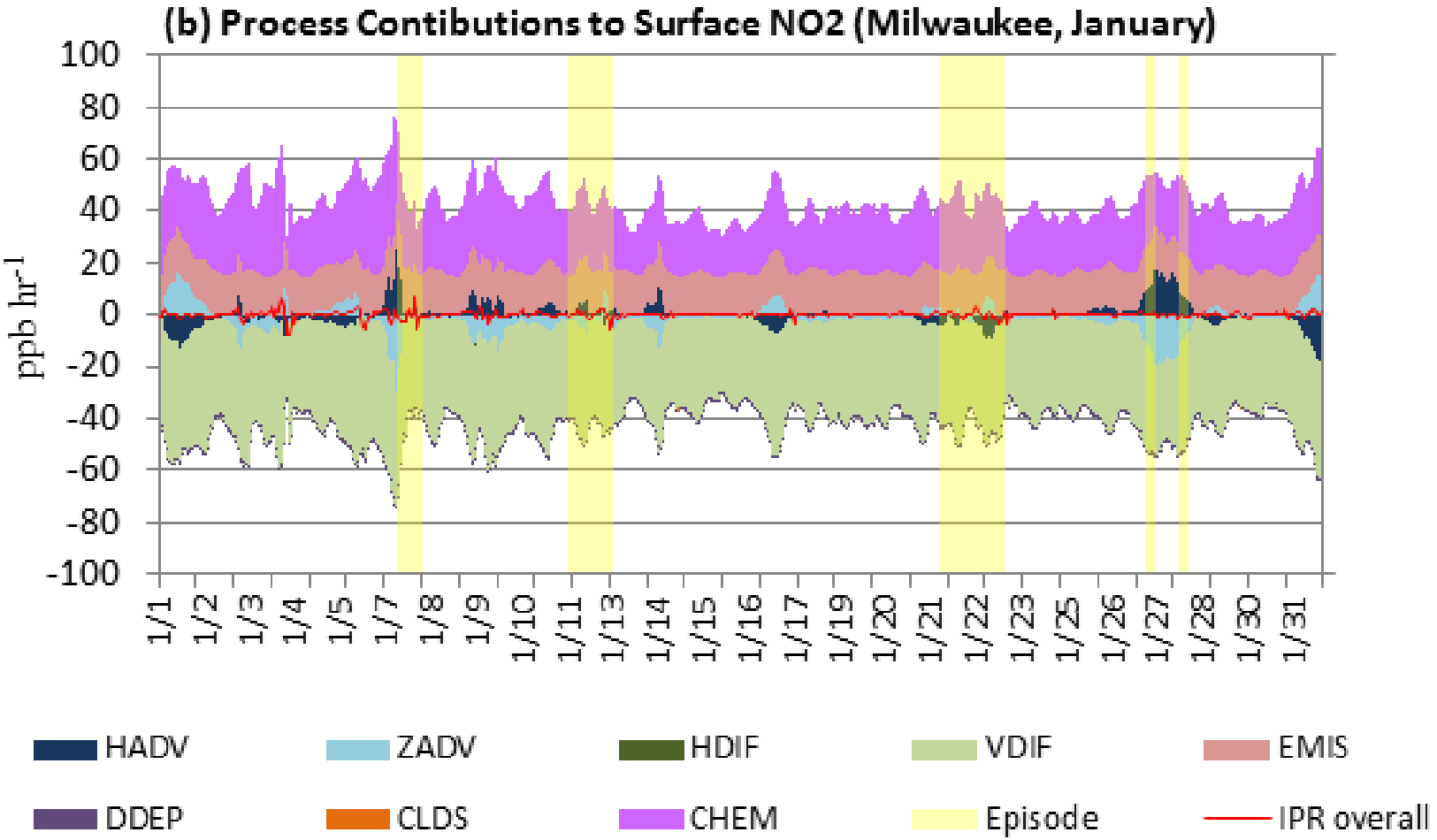
$N_2O_5 + H_2O(l) \rightarrow 2HNO_3$ (e)

Nighttime

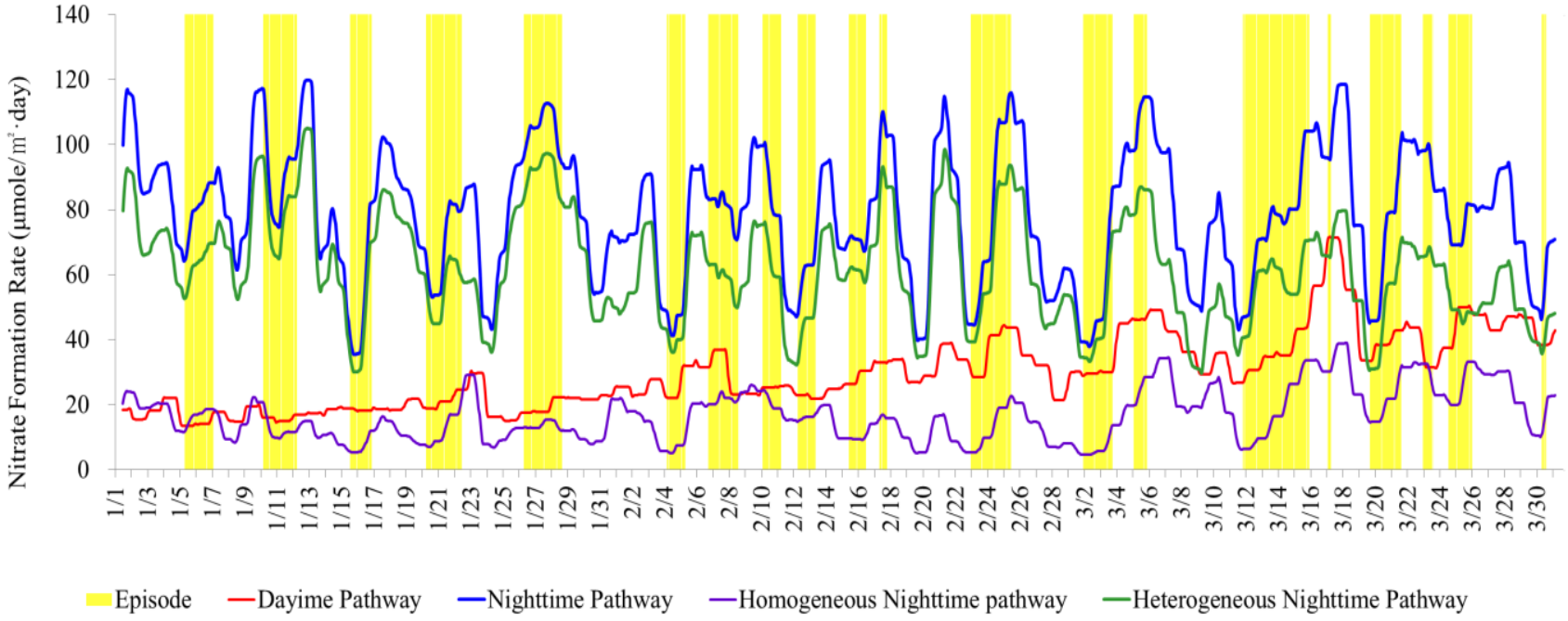
RH and composition dependent accommodation coefficient, uncertain

Reaction	Reactants	Products
R1	NO_2 + hv	NO + O
R3	O_3 + NO	NO_2
R4	O + NO_2	NO
R5	O + NO_2	NO_3
R6	O + NO	NO_2
R7	NO_2 + O_3	NO_3
R14	NO_3	NO_2 + O
R15	NO_3	NO
R16	NO_2 + NO	2 NO_2
R17	NO_3 + NO_2	NO + NO_2
R18	NO_3 + NO_2	N_2O_5
R19	N_2O_5 + H_2O	2 HNO_3
R20	N_2O_5 + H_2O + H_2O	2 HNO_3
R21	N_2O_5	NO_3 + NO_2
R22	NO + NO + O_2	2 NO_2
R23	NO + NO_2 + H2O	HONO
R24	NO + OH	HONO
R25	HONO	NO + OH
R26	OH + HONO	NO_2
R27	HONO + HONO	NO + NO_2
R28	NO_2 + OH	HNO_3
R29	OH + HNO_3	NO_3
R30	HO_2 + NO	OH + NO_2
R31	HO_2 + NO_2	PNA
R32	PNA	HO_2 + NO_2
R33	OH + PNA	NO_2
R46	NO_3 + O	NO_2
R47	NO_3 + OH	HO_2 + NO_2
R48	NO_3 + HO_2	HNO_3
R49	NO_3 + O_3	NO_2
R50	NO_3 + NO_3	2 NO_2
R51	PNA	0.61HO_2 + 0.61NO_2 + 0.39OH + 0.39NO_3
R52	HNO_3	OH + NO_2
R53	N_2O_5	NO_2 + NO_3
R89	PAN	C_2O_3 + NO_2
R90	PAN	C_2O_3 + NO_2

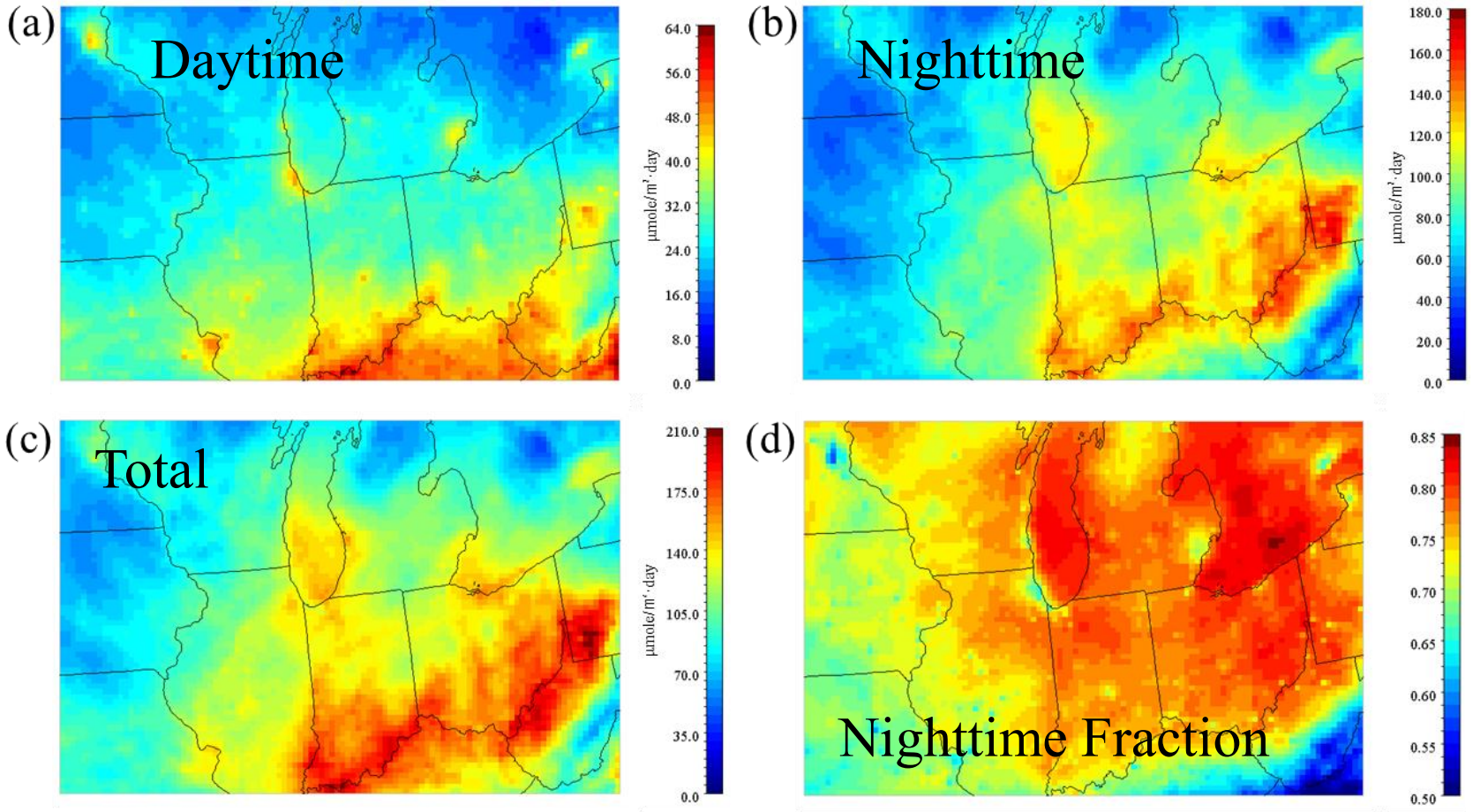
Integrated Reaction Rate Analysis

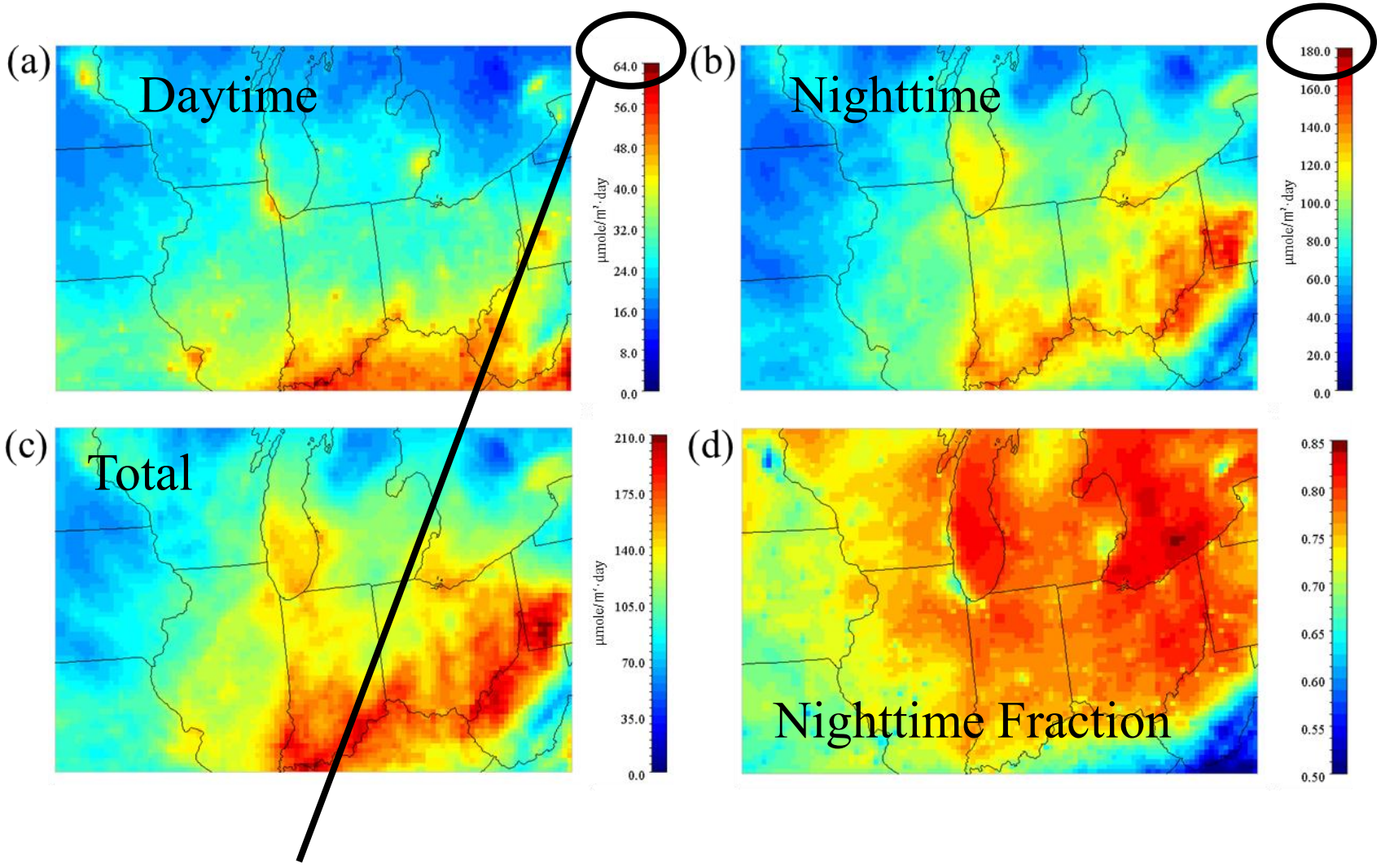

(b) Process Contibutions to Surface NO2 (Milwaukee, January)
ppb hr-1
100
80
60
40
20
0
-20
-40
-60
-80
-100
1/1
1/2
1/3
1/4
1/5
1/7
1/8
1/9
1/10
1/11
1/13
1/14
1/15
1/16
1/17
1/19
1/20
1/21
1/22
1/23
1/25
1/26
1/27
1/28
1/30
1/31
HADV
ZADV
HDIF
VDIF
EMIS
DDEP
CLDS
CHEM
Episode
IPR overall

Through model layer 20 (~3.15 km)

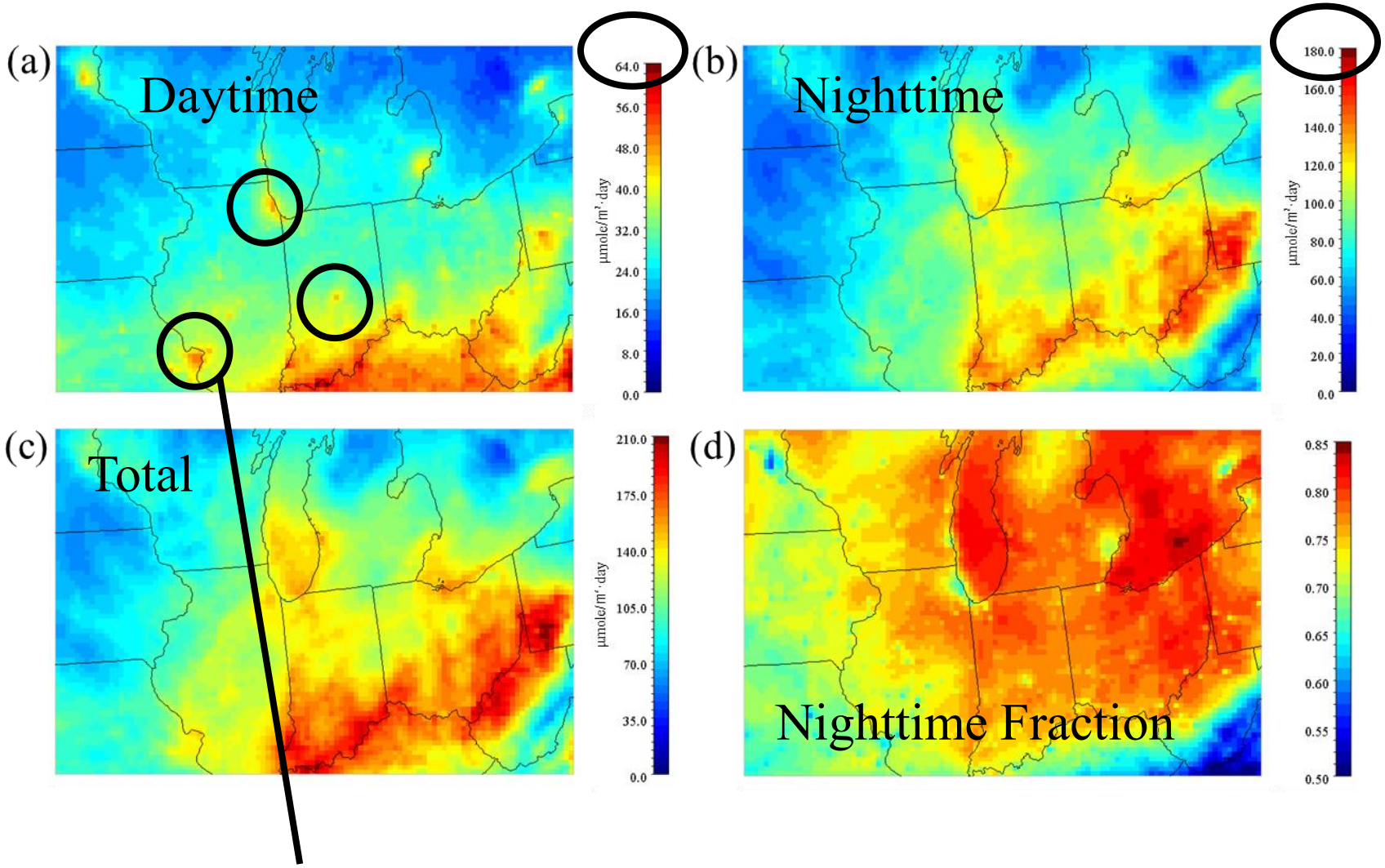


Daytime pathway (μmole/m²-day)	Nighttime pathway (μmole/m²-day)	Homogeneous nighttime pathway (μmole/m²-day)	Heterogeneous nighttime pathway (μmole/m²-day)
29.8	78.3	16.7	61.6

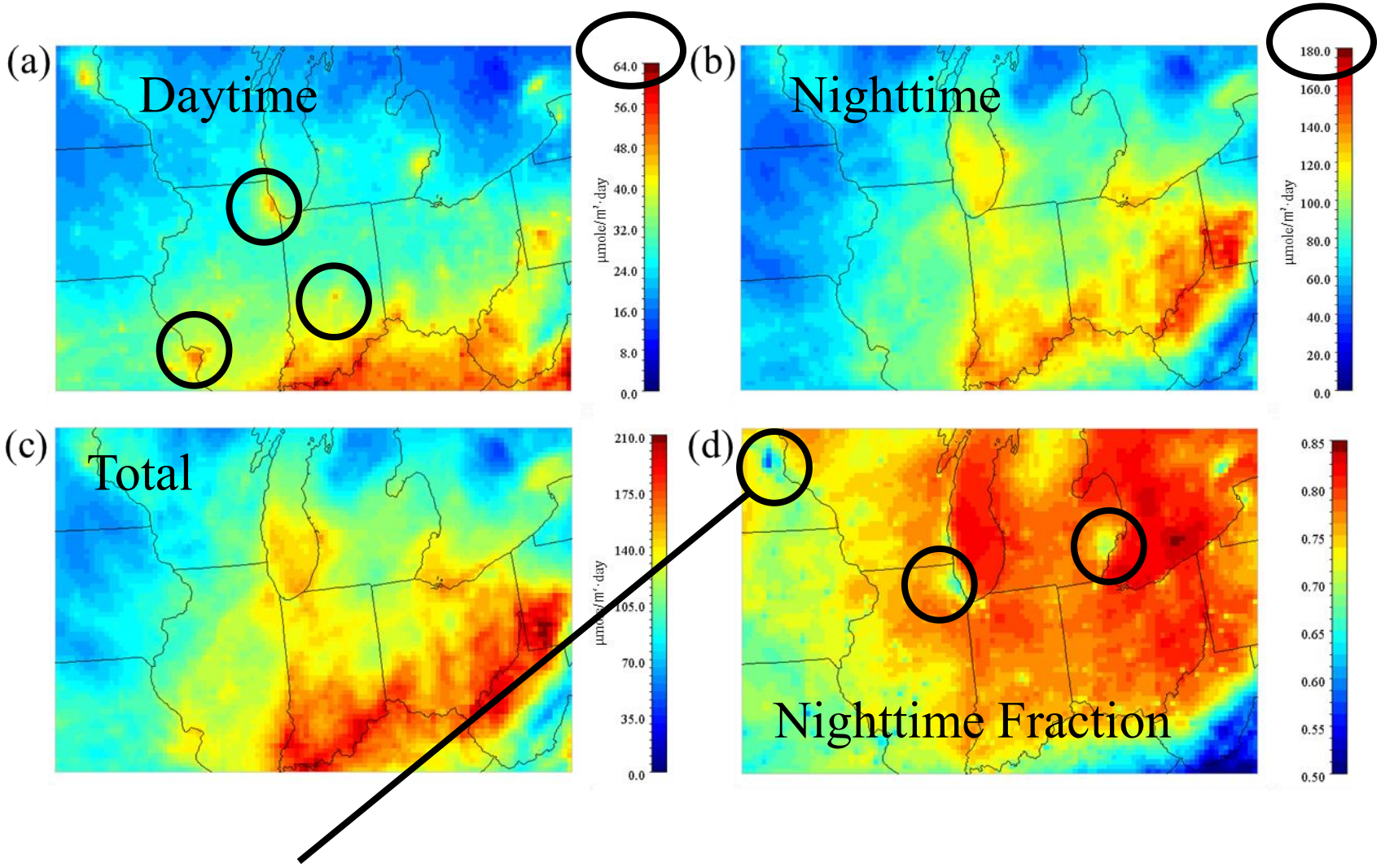

(a)
Daytime
64.0
56.0
48.0
40.0
32.0
24.0
16.0
8.0
0.0
µmole/m²·day
(b)
Nighttime
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
µmole/m²·day
(c)
Total
210.0
175.0
140.0
105.0
70.0
35.0
0.0
µmole/m²·day
(d)
Nighttime Fraction
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50



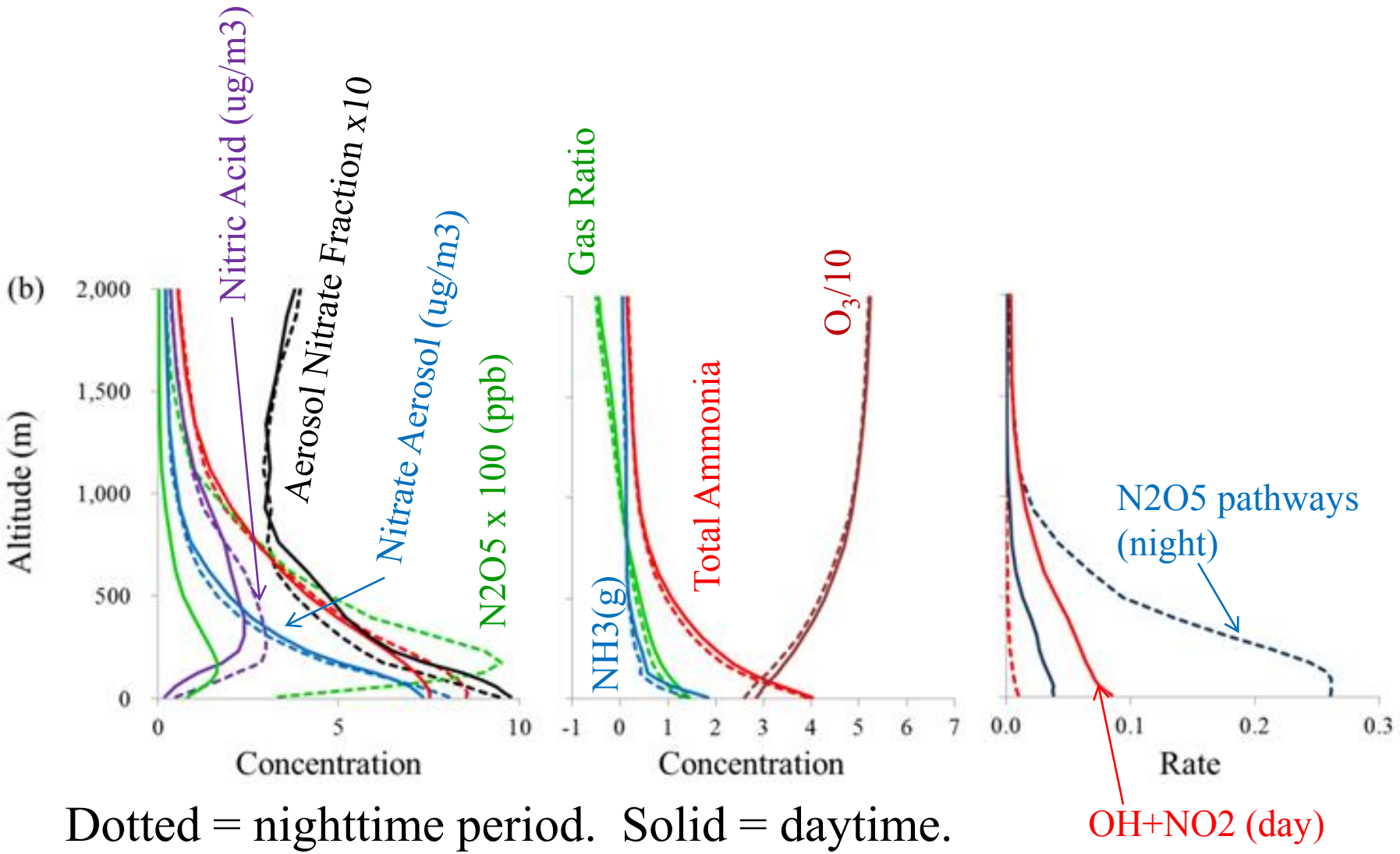
Notice the different scales



Elevated daytime production, mainly at the surface, in high NOx locations

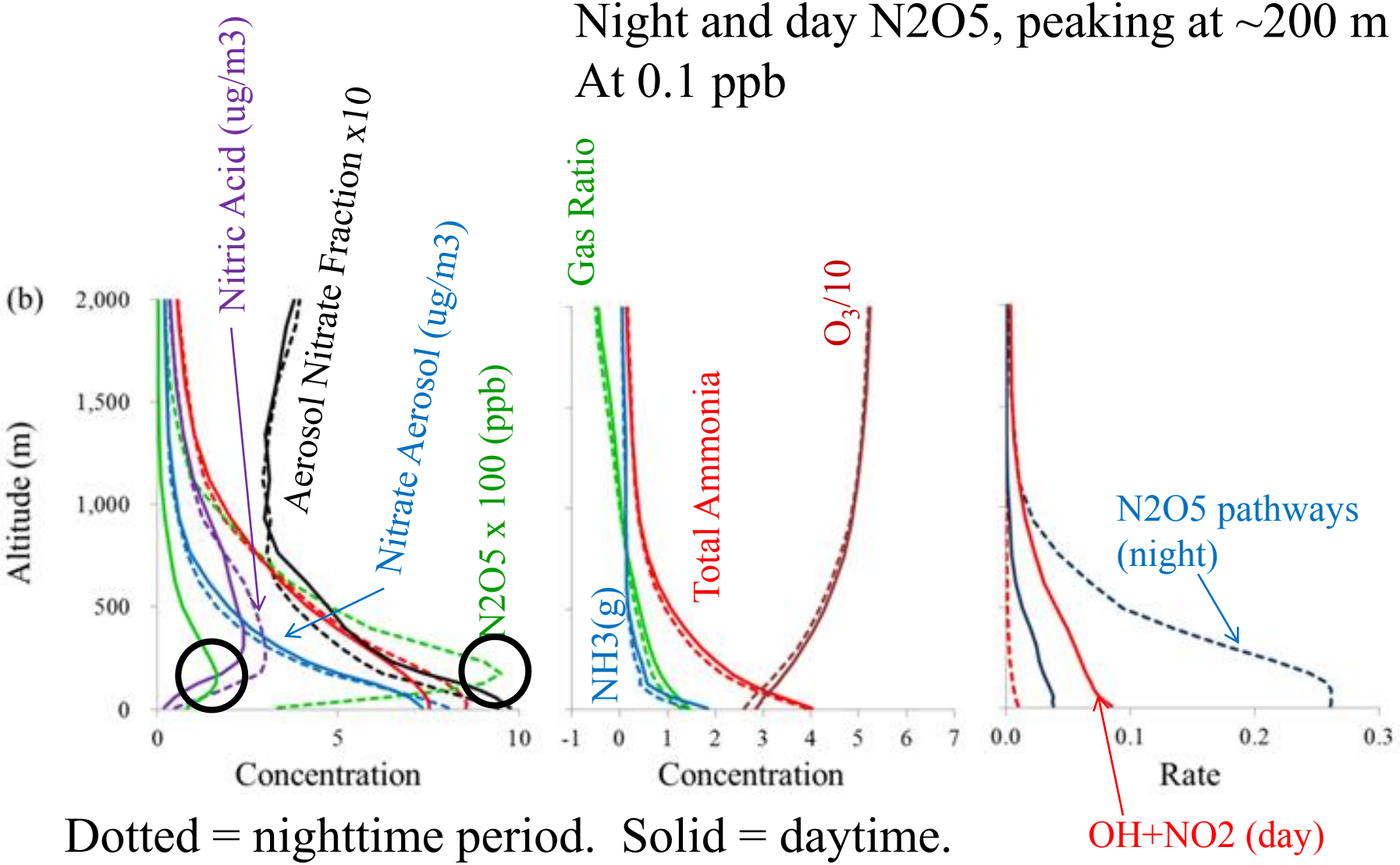


Decrease in the nighttime fraction in some (but not all) cities



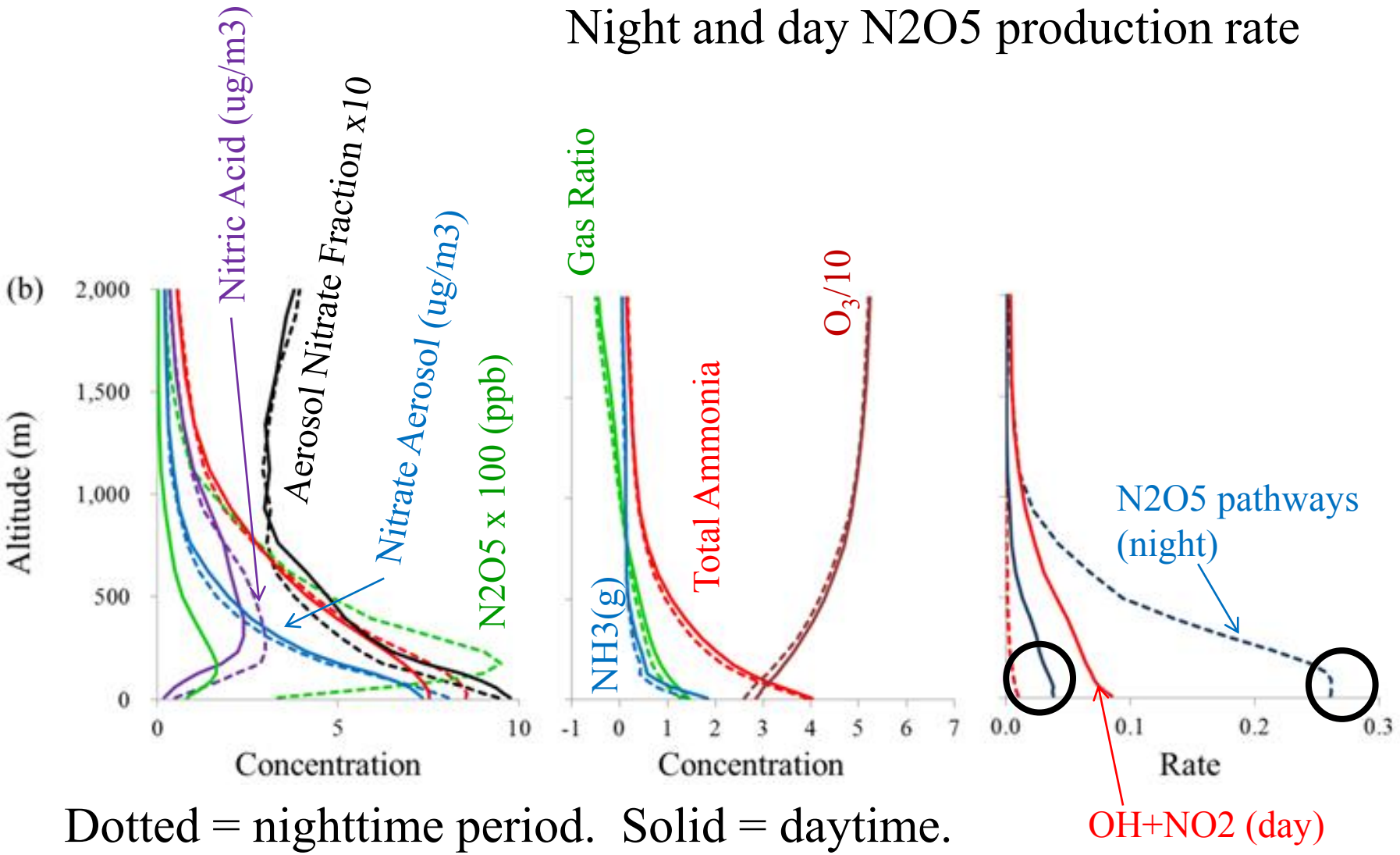
Dotted = nighttime period. Solid = daytime.
Mayville episode buildup periods

Night and day N2O5, peaking at ~200 m
At 0.1 ppb



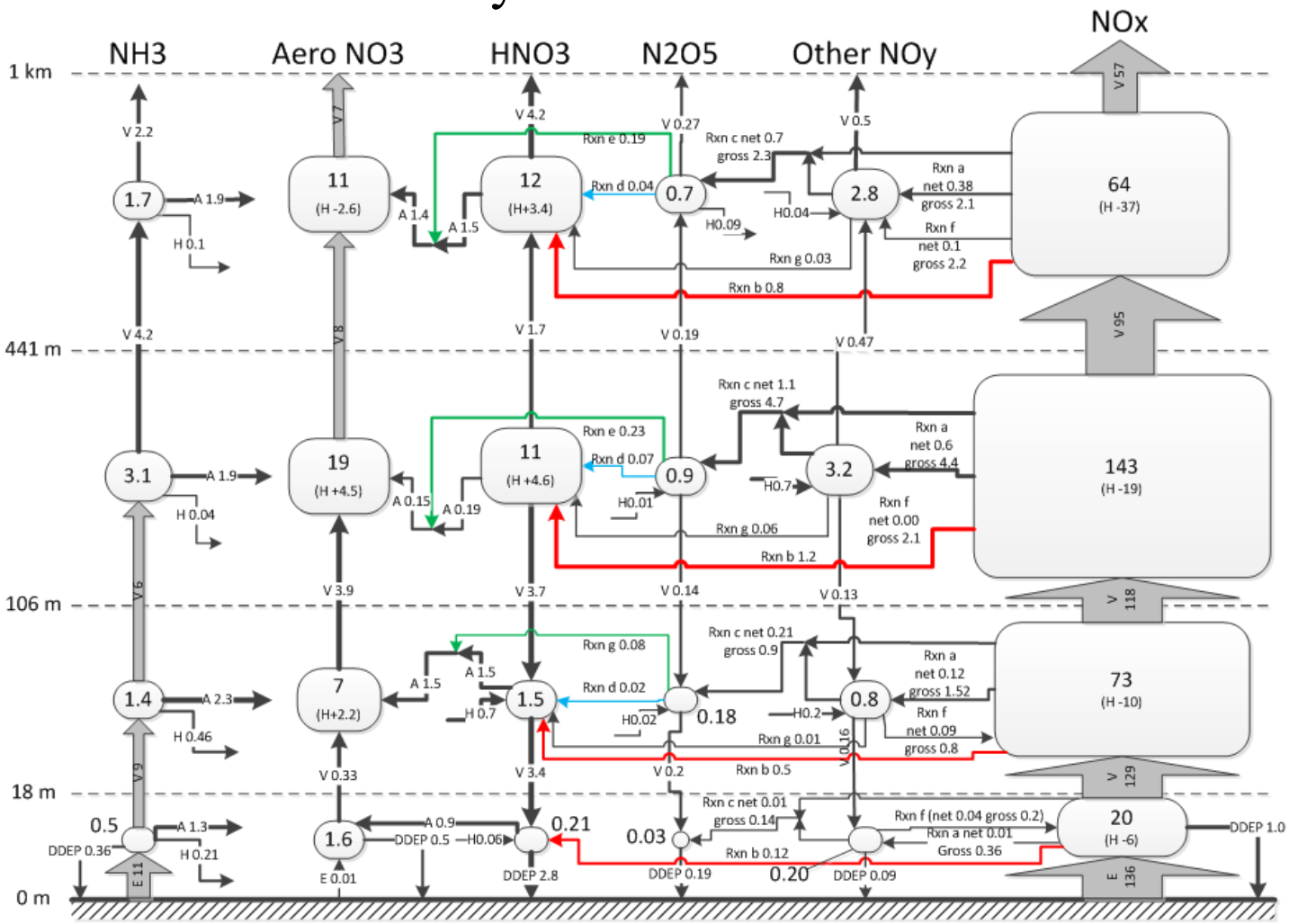
Dotted = nighttime period. Solid = daytime.
Mayville episode buildup periods

Night and day N2O5 production rate



Dotted = nighttime period. Solid = daytime.
Mayville episode buildup periods

Milwaukee Day



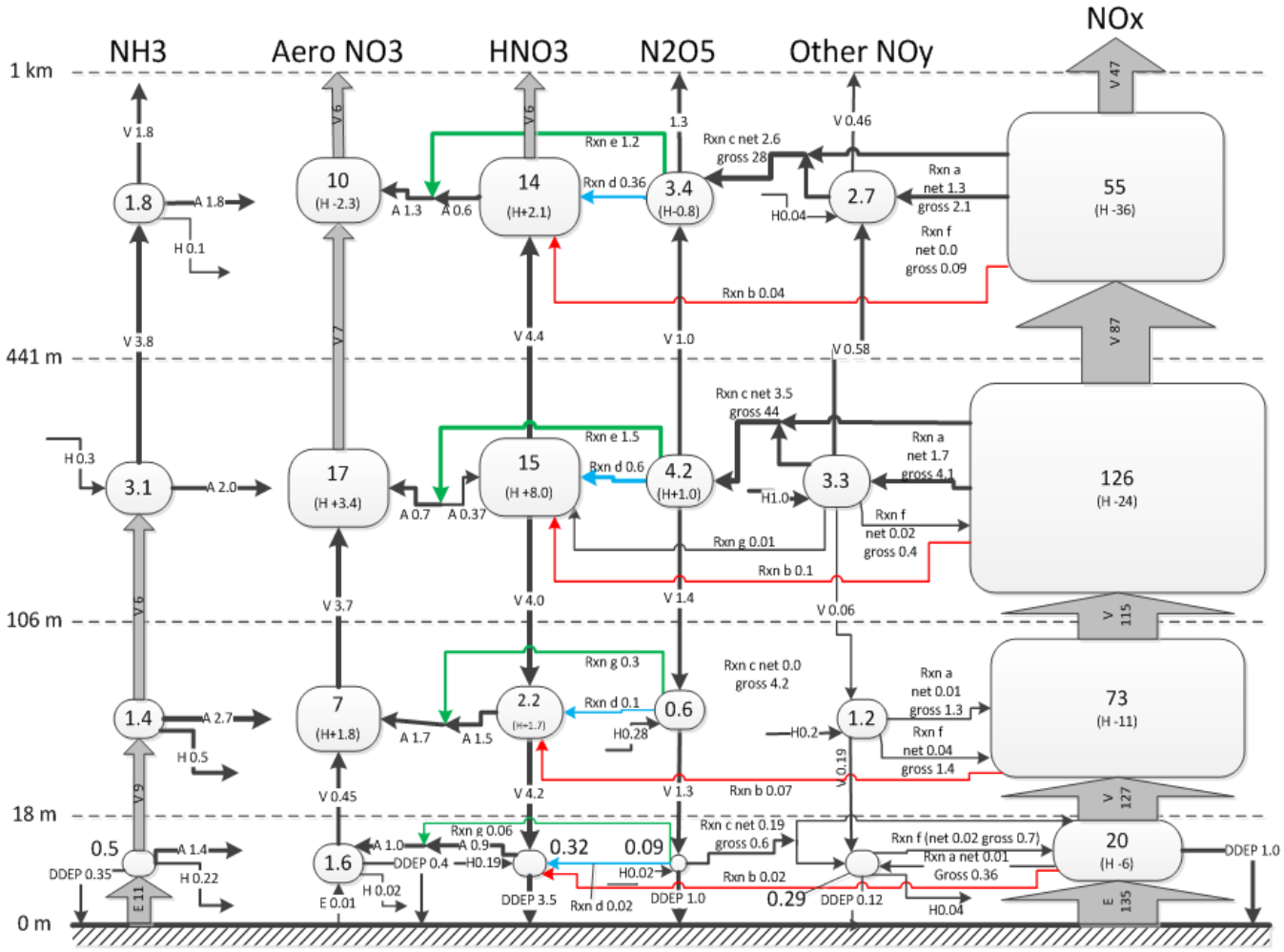
Reservoir in µmole N / m^2.
Fluxes are in µmole N / m^2-hr.

Black lines
Aerosol process
Horizontal advection and diffusion
Vertical advection and diffusion
Emissions
DDEP

a: net NO_3 radical formation
c: net N_2O_5 formation
g: HNO_3 formation from the NO_3 radical

Colored lines
b: $NO_2 + OH \rightarrow HNO_3$
d: homogenous formation of HNO_3 from N_2O_5
Flux e: heterogeneous formation of HNO_3 from N_2O_5

Milwaukee Night



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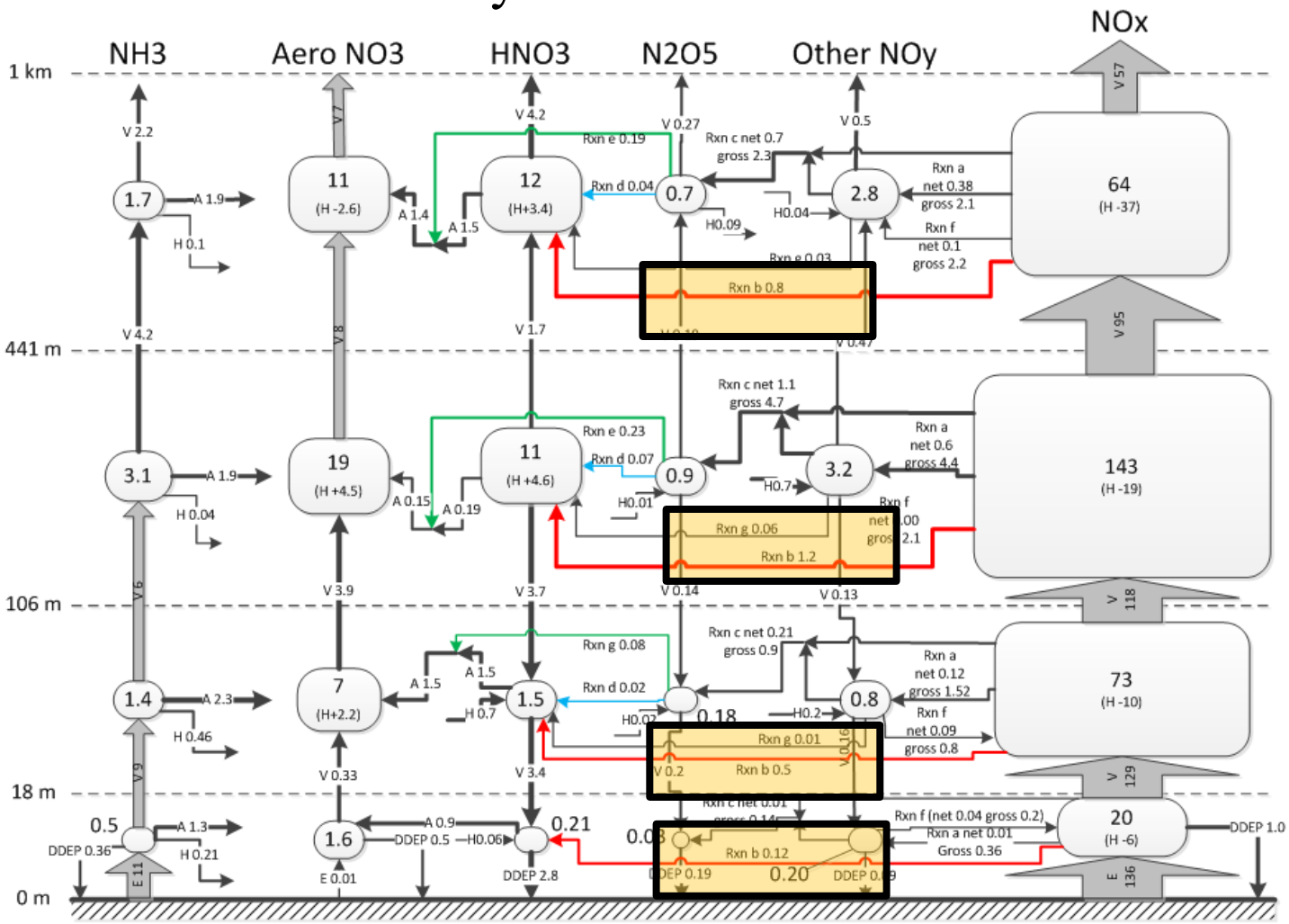
Milwaukee Day



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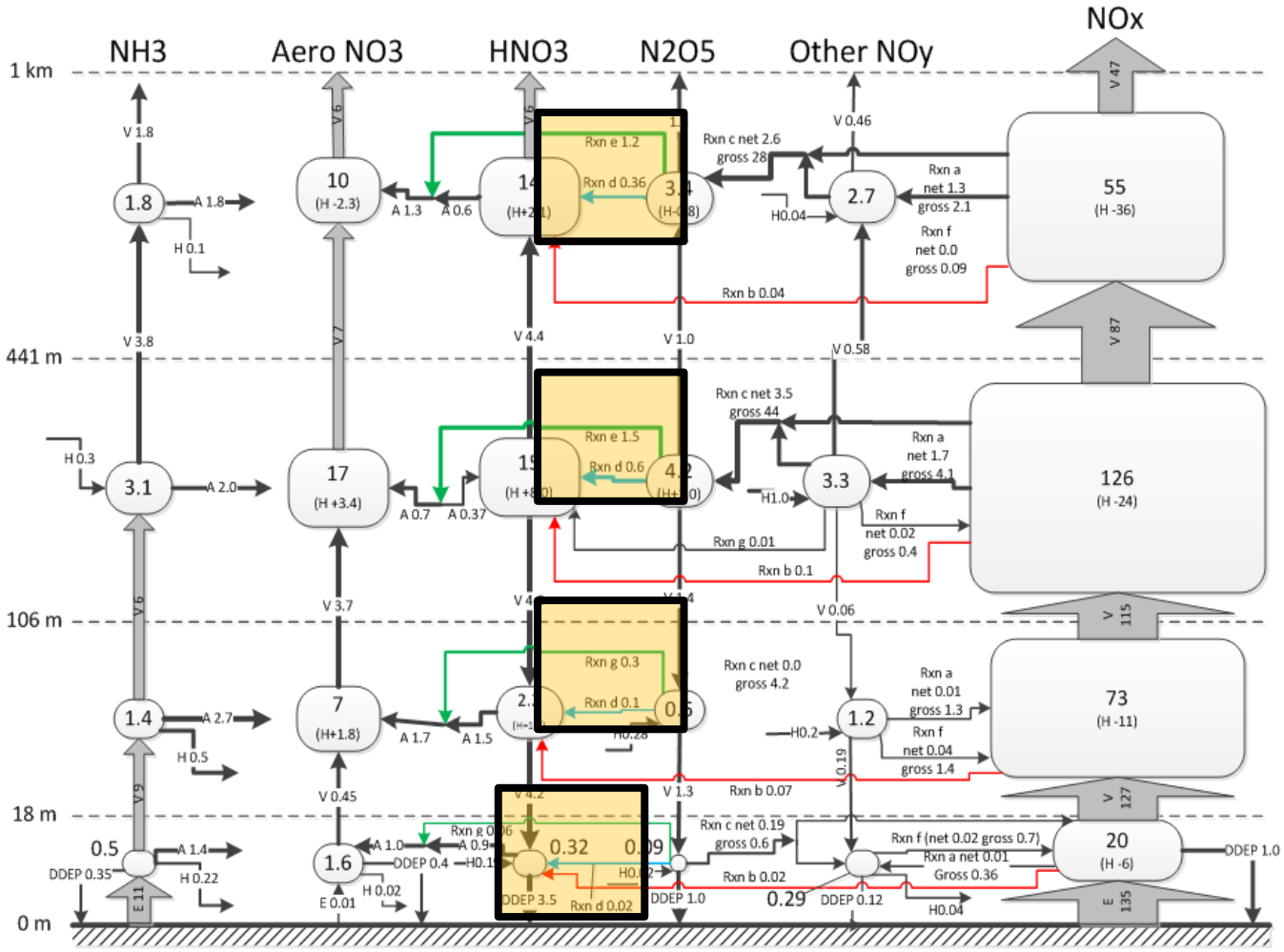
2.8 µmole N / m^2-hr for the daytime pathway

Milwaukee Night



Reservoir in µmole N / m^2.
Fluxes are in µmole N / m^2-hr.

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Horizontal advection and diffusion
Vertical advection and diffusion
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a: net NO_3 radical formation
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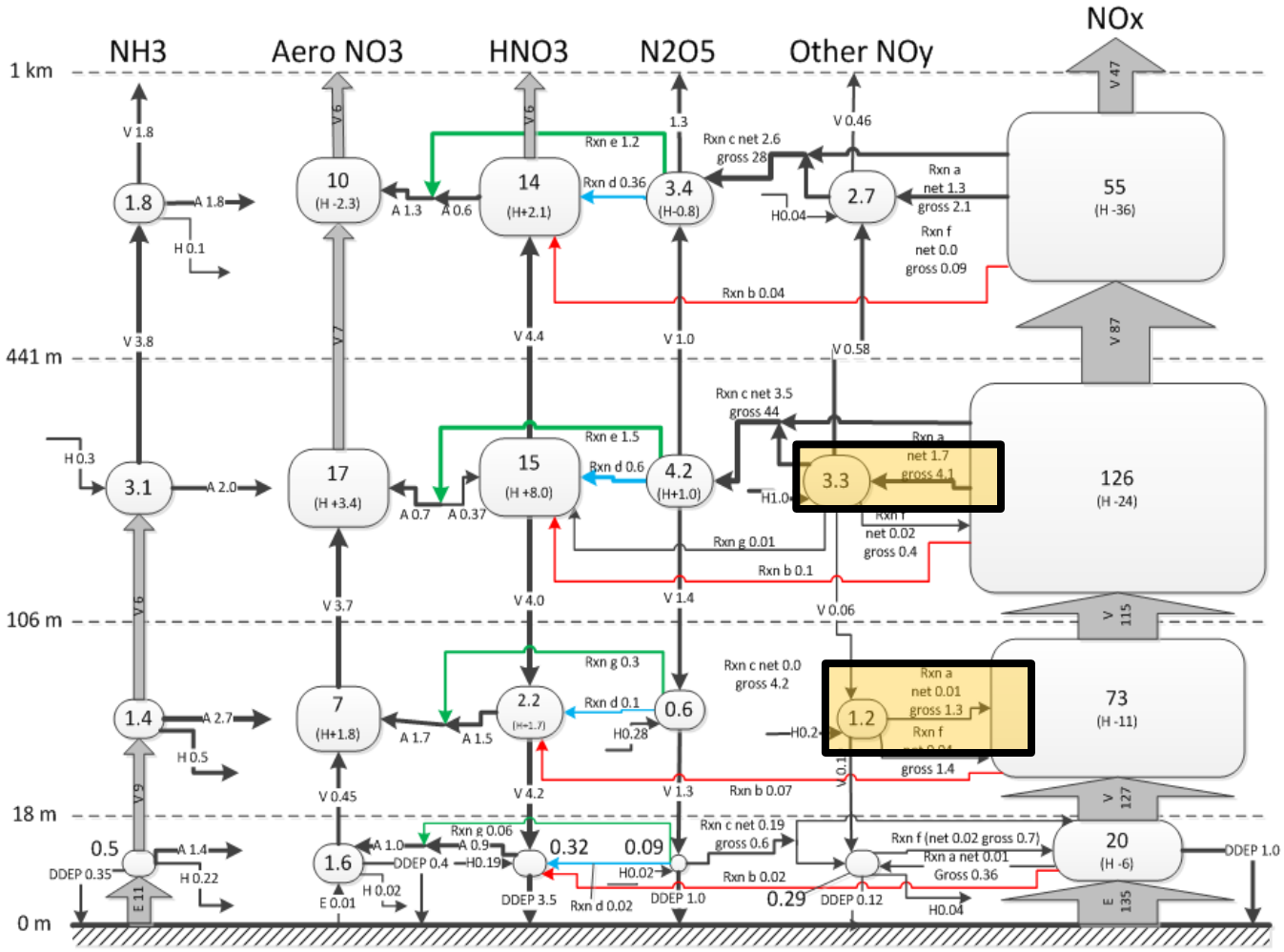
g: HNO_3 formation from the NO_3 radical

Colored lines
b: $NO_2 + OH \rightarrow HNO_3$
d: homogenous formation of HNO_3 from N_2O_5
Flux e: heterogeneous formation of HNO_3 from N_2O_5

4.4 µmole N / m^2-hr for the nighttime pathway

Milwaukee Night



Reservoir in µmole N / m^2.
Fluxes are in µmole N / m^2-hr.

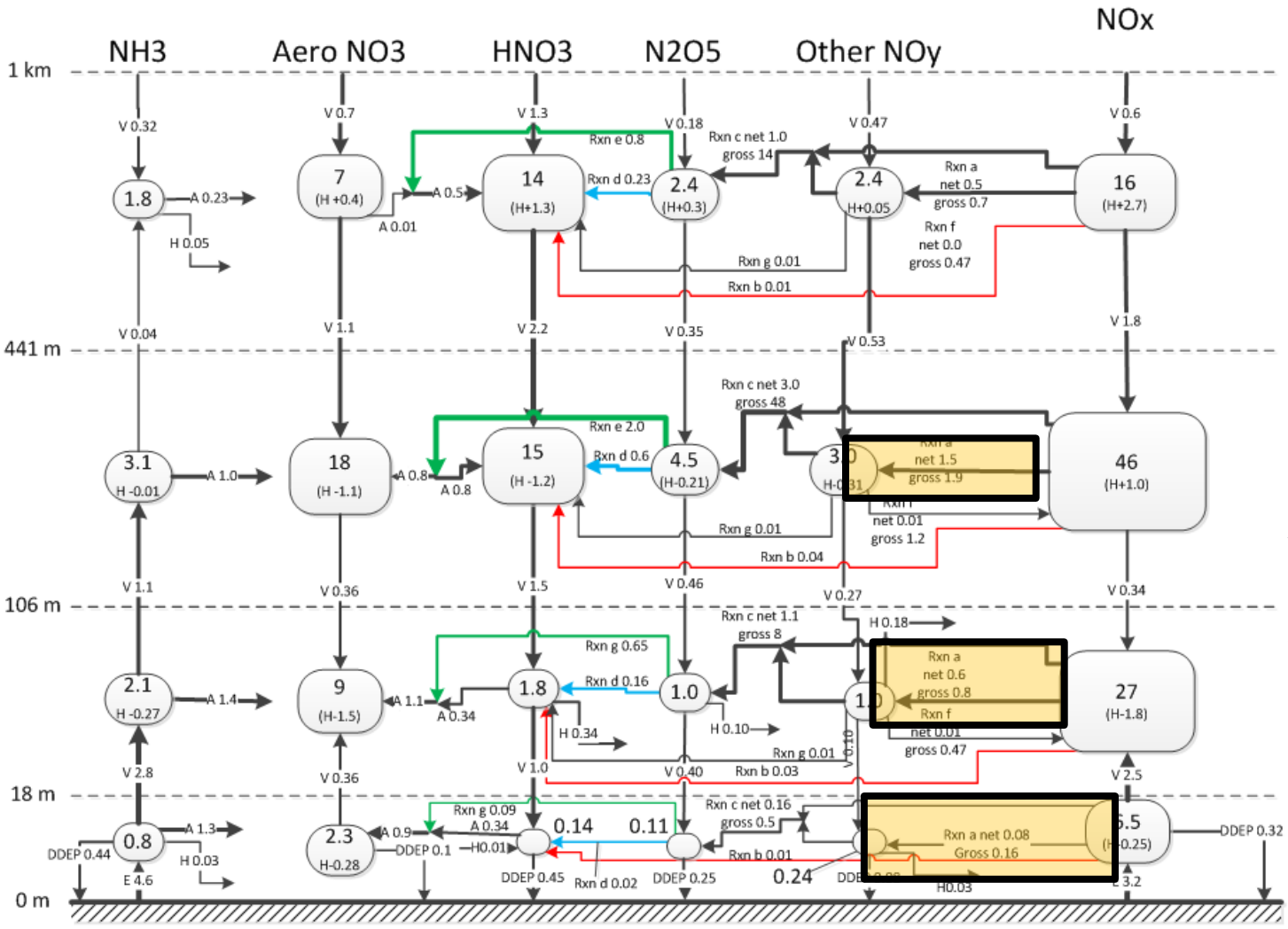
Black lines
Aerosol process
Horizontal advection and diffusion
Vertical advection and diffusion
Emissions
DDEP

a: net NO_3 radical formation
c: net N_2O_5 formation
g: HNO_3 formation from the NO_3 radical

Colored lines
b: $NO_2 + OH \rightarrow HNO_3$
d: homogenous formation of HNO_3 from N_2O_5
Flux e: heterogeneous formation of HNO_3 from N_2O_5

Urban nighttime titration of O3 by high NOx forces net NO3 decomposition at surface at night

Mayville Night



Reservoir in µmole N / m^2.
Fluxes are in µmole N / m^2-hr.

Black lines
Aerosol process
Horizontal advection and diffusion
Vertical advection and diffusion
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DDEP

a: net NO_3 radical formation
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g: HNO_3 formation from the NO_3 radical

Colored lines
b: $NO_2 + OH \rightarrow HNO_3$
d: homogenous formation of HNO_3 from N_2O_5
Flux e: heterogeneous formation of HNO_3 from N_2O_5

NO3 formation continues at night at all layers in the rural cell (less NOx, O3 remains higher)

Emissions Sensitivity Methods

- Direct Sensitivity

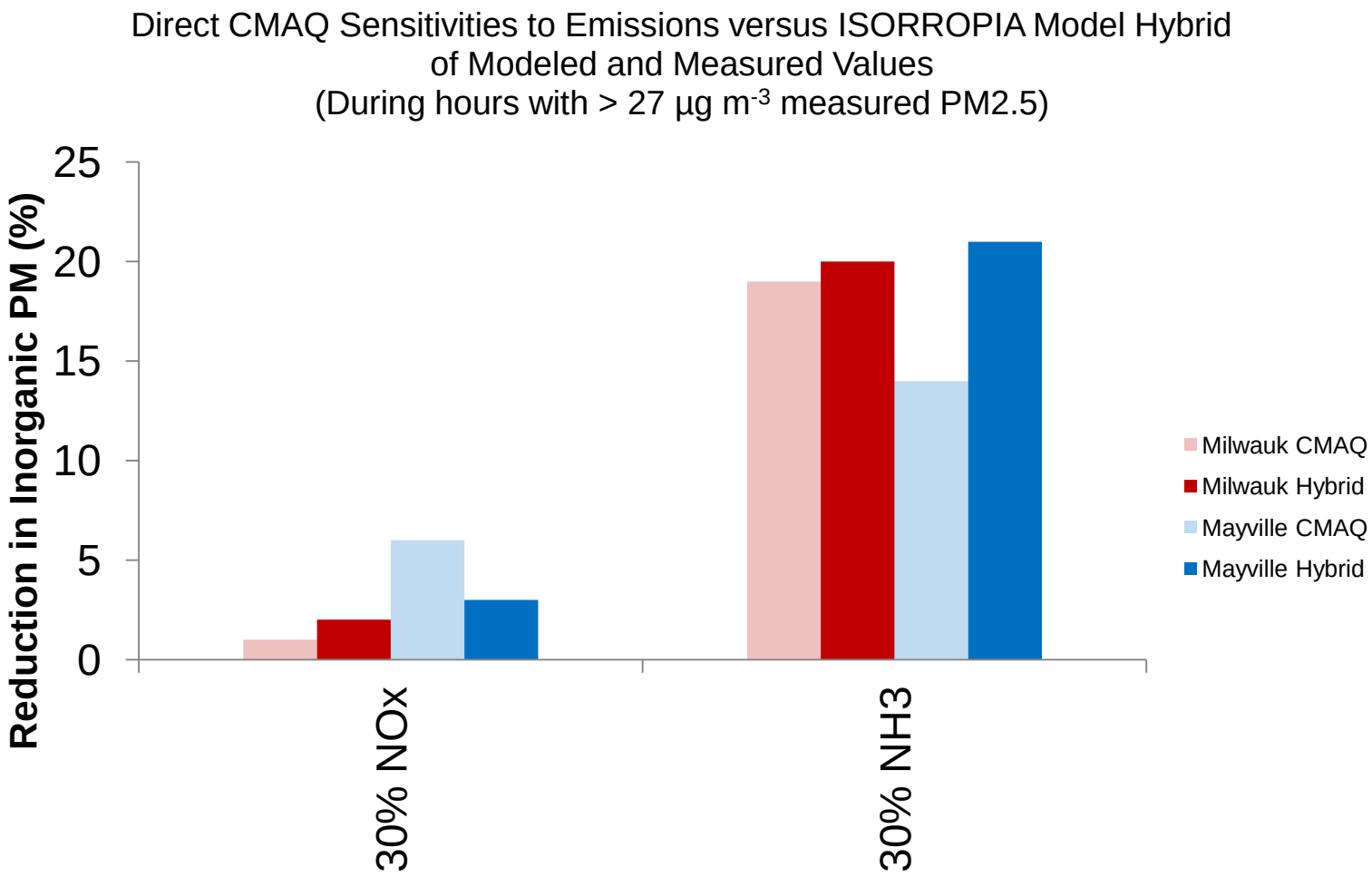
$$\frac{Inorganic\ PM_{2.5}\ in\ sensitivity\ CMAQ\ run}{Inorganic\ PM_{2.5}\ \ in\ base\ CMAQ\ run}$$

- Hybrid Box Model Sensitivity

$$\frac{Sensitivity\ case\ inorganic\ PM_{2.5}\ in\ predicted\ by\ ISORROPIA}{Inorganic\ PM_{2.5}\ \ from\ ISORROPIA\ with\ all\ measured\ inputs}$$

  - Input to sensitivity case box model?
  - Measured T and RH
  - Measured total sulfate, ammonia, and nitrate x fractional reduction in these species predicted by CMAQ model

Thermodynamic Sensitivity / Model Skill



Take Home Points

- LADCO Winter Nitrate Study Combined 3 months of observations with CMAQ and CAMx model runs
- Rural / Urban Patterns Identified and Quantified
- Raw Data, 2 Reports, and 2 Pubs Available
- Model Improvements?
  - Urban Locations
    - Boundary layer meteorology > NO_y chemistry, emissions, deposition > Organic aerosols
  - Rural Locations
    - NO_y chemistry, emissions, deposition > Organic aerosols ~ Sulfate aerosols
- Negative model bias for ammonia
- 72% of nitrate formation can be attributed to the nighttime pathway.
- Model treatment of heterogeneous nitrate should be a key factor in model-model differences.

Review of Take Home Points

- The NO_y system: large NO_x reservoir, resistant to depositional removal, that undergoes gradual transformation into nitrate, often (but not always) passing through the reactive intermediate forms of the NO_3 radical, N_2O_5, and other forms of NO_y such as HONO and PAN.
- Nitrate production is mainly a regional phenomenon, with rates greater than 100 µmole/m^2-day for most of the domain.
- Urban enhancements in the daytime formation pathway are balanced by urban deficiencies in nighttime pathway leading to minimal urban / rural contrast in nitrate production.
- High concentrations of nitric acid extend spatially over a broad region with a peak near the Ohio River Valley. The southern Great Lakes and the Ohio River Valley have the most intense nitrate formation rates according to the model.
- In Wisconsin, emissions sensitivity to NH_3 is greater than sensitivity to NO_x

Some thoughts on future questions

- Deposition velocities over the Great Lakes are important
- Deposition velocities over open water, ice, and snow-covered ice may need to be considered
- N_2O_5→nitrate rates presented here may be upper limit, as $N_2O_5 \rightarrow ClNO_2$ may consume a fraction of the N_2O_5, and organic coatings will depress the heterogeneous reaction rate

Co-authors and Acknowledgements

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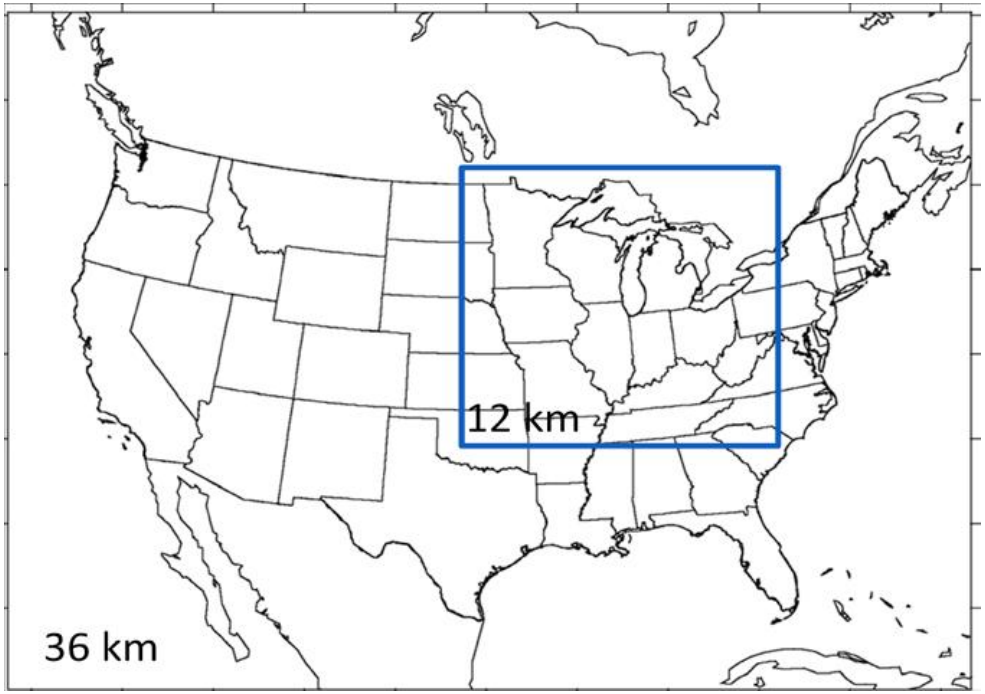
  - Michael Majewski
  - Bill Adamski
- Funding
  - LADCO
  - Electric Power Research Institute

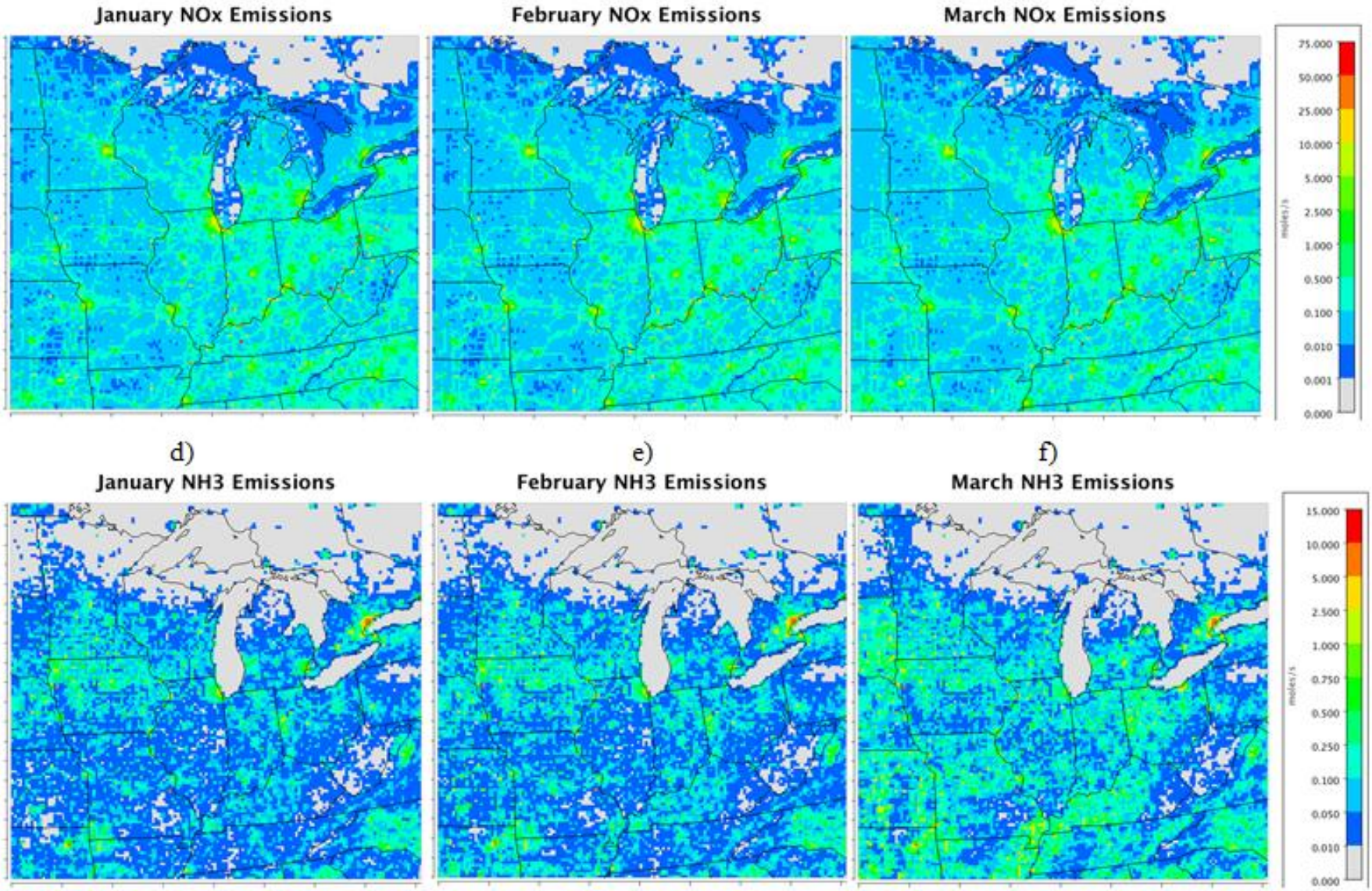
Additional slides

Model Configuration U of Iowa

- Community Multiscale Air Quality Model (CMAQ) v4.7.1
  - CB05 gas phase / AERO5 aerosol module
  - ACM2 PBL closure
  - Mass-conserving advection
  - 35 vertical layers
- LADCO's 12 km regional modeling grid
  - Hourly boundary conditions from a 36 km simulation (with the same configuration) covering the continental United States.
- Meteorology
  - WRF 3.1.1 with the RPO configuration selected by Iowa DNR, SESARM, and LADCO
  - ACM2 PBL closure
  - Pleim-Xu land surface module
  - RRTM radiation
  - Morrison microphysics
  - Kain-Fritsch cumulus
  - NARR 3-hourly met for initial and boundaries
  - Analysis nudging on NARR above the PBL, horizontal winds used for observational nudging in the PBL
- Emissions
  - LADCO's 2007 emissions inventory used for 12km domain.
  - Day-specific biomass burning emissions from MODIS fire detection products.



- Process Analysis
  - Chemical and process rates stored for all layers up to 550 m, with focus on NOy processing and N2O5 heterogeneous chemistry


January NOx Emissions
February NOx Emissions
March NOx Emissions
75.000
50.000
25.000
10.000
5.000
2.500
1.000
0.500
0.100
0.010
0.001
0.000
moles/s
d)
e)
f)
January NH3 Emissions
February NH3 Emissions
March NH3 Emissions
15.000
10.000
5.000
2.500
1.000
0.750
0.500
0.250
0.100
0.050
0.010
0.000
moles/s

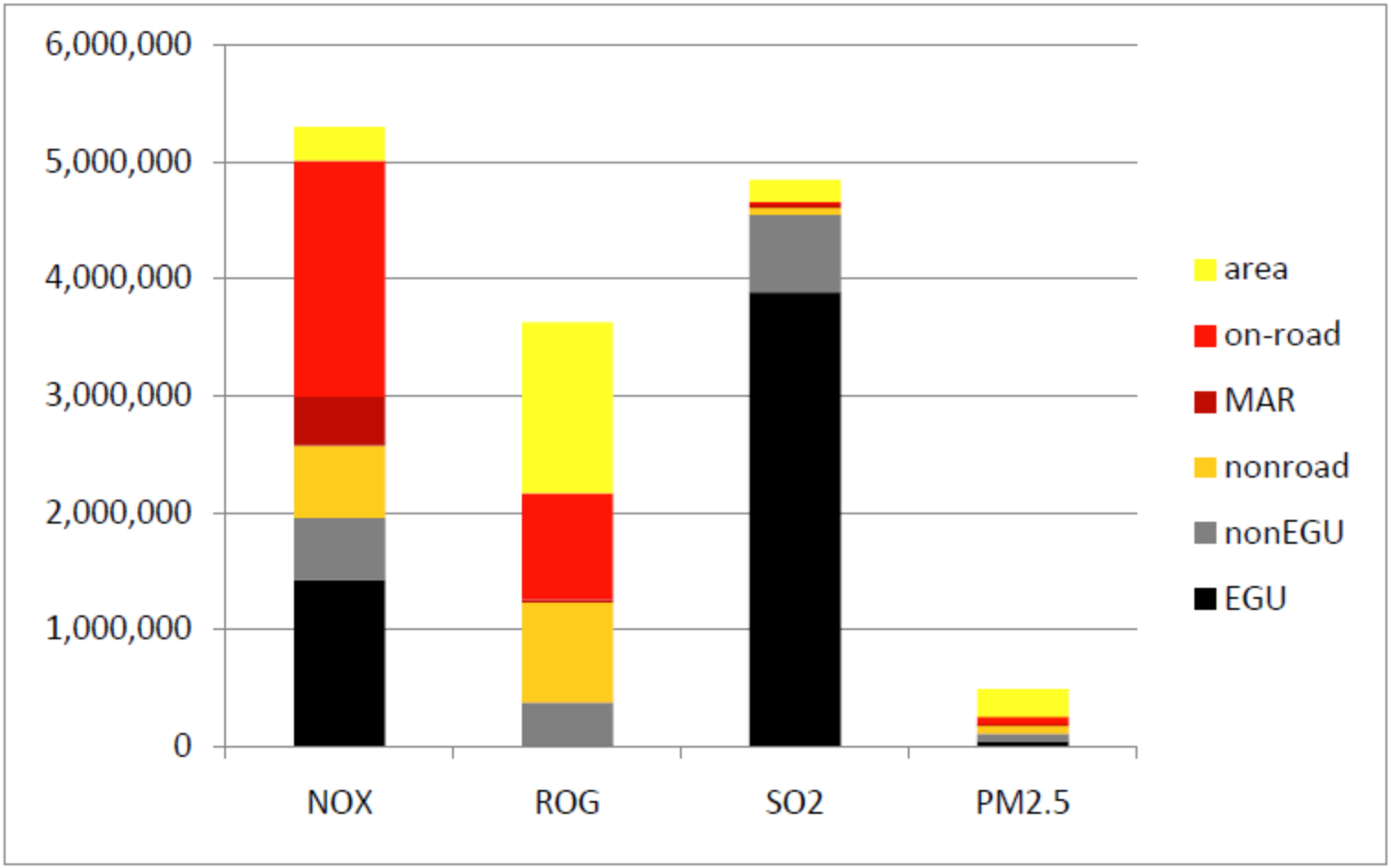
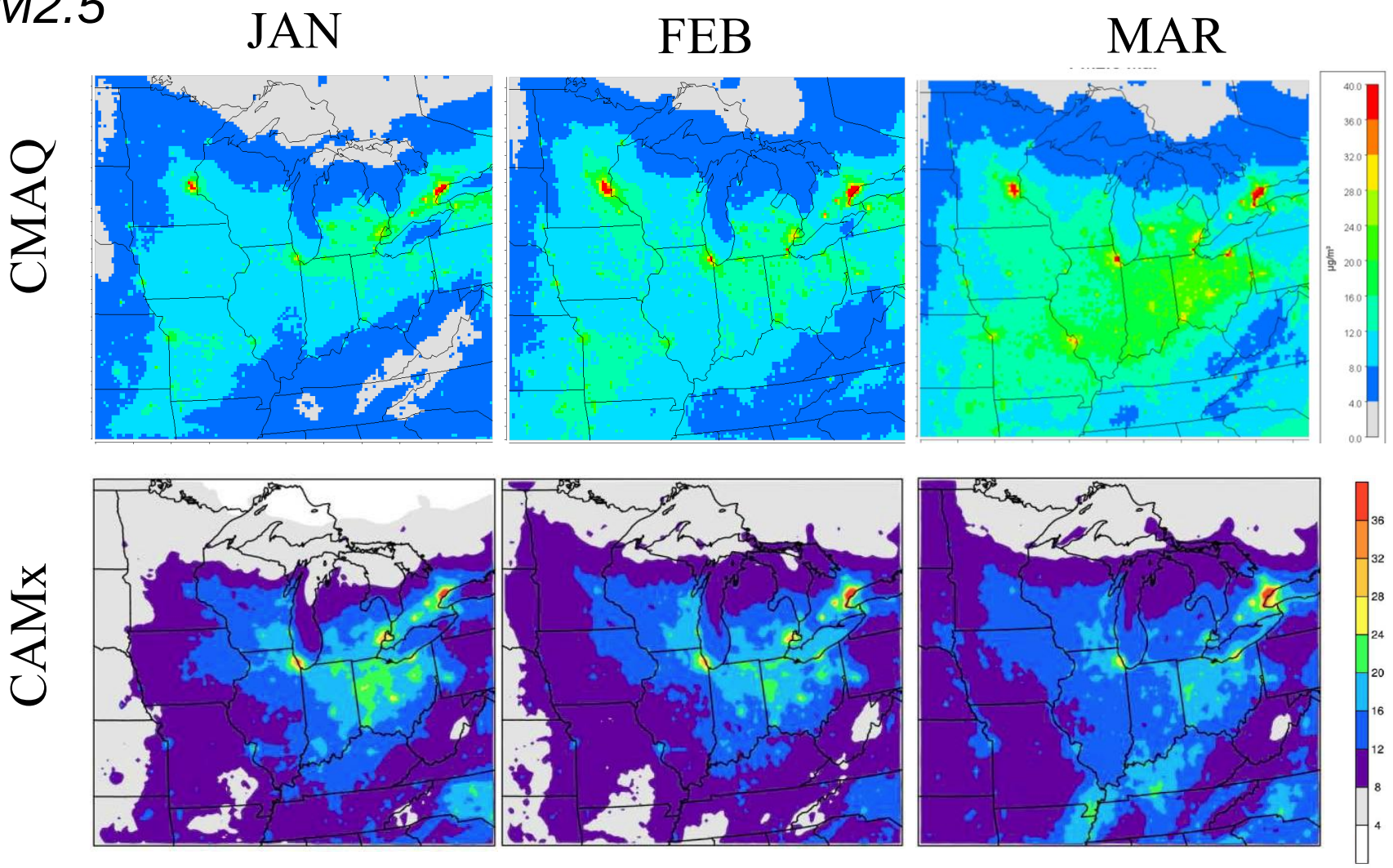


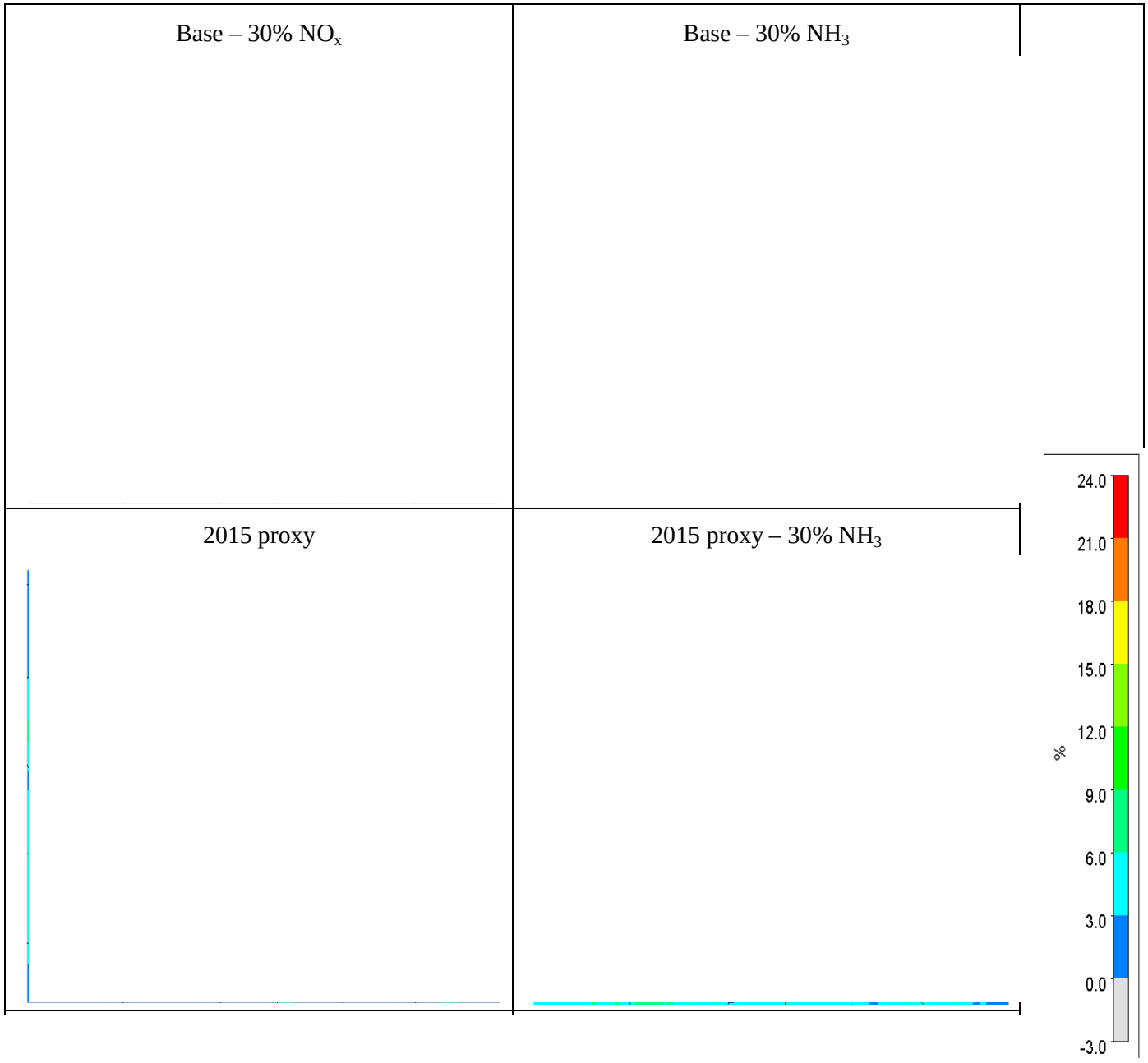
Figure 4. 2007 annual emissions by pollutant and source sector (LADCO States)

Emissions Details

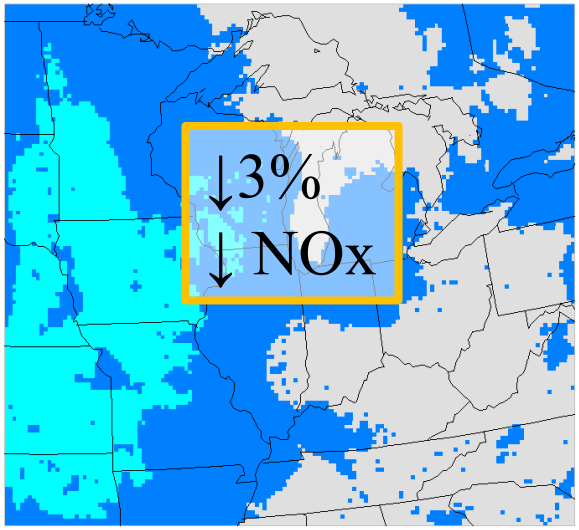
- Emissions represent 2007/2008 conditions, although 2009 was modeled.
- Emissions were based on the May 2011 version of the **LADCO 2007/2008 Base C anthropogenic inventory** (*LADCO*, 2010), resolving monthly average emissions and their diurnal profiles for each emissions sector.
  - Upper Midwest, which comprise a large part of the 12 km modeling domain, LADCO's 2007 emissions data were used for EGU point, non-road, and on-road sources, and 2008 emissions data were used for non-EGU point and area sources.
  - For other states in the modeling domain, data representing 2005 conditions were provided by RPOs.
- The 2007/2008 inventories for on-road, off-road, and ammonia, emissions were estimated using a range of emission models. EPA's new MOVES2010a model was used with national default inputs to produce on-road emissions for the country.
- EPA's NMIM2008 model was used to produce emissions for most off-road sources. The emissions for three other off-road categories (commercial marine, aircraft, and rail) were developed separately.
- Agricultural ammonia emissions were based on Carnegie Mellon University's Ammonia Emission Inventory for the Continental United States. Specifically, the CMU annual emissions for 2002 were first grown to reflect 2007 conditions.
  - A new process-based ammonia emissions model developed for LADCO (*Zhang, et al.*, 2005; *Mansell et al.*, 2005) was then used to develop monthly and hourly temporal allocation factors.
- The Upper Midwest 2007/2008 inventory for area and point sources was based on data supplied by states. 2007 emissions were supplied for EGU point sources, while 2008 data were supplied for area and non-EGU point sources.
- Emissions for Canada were based on the 2005 Canadian National Pollutant Release Inventory, Version 1.0 (NPRI). A subset of the NPRI data (emissions and stack parameters) relevant to air quality modeling were reformatted and used in the regional modeling. Canadian area sources were allocated from provincial totals to the modeling grid using population as the primary spatial surrogate, which leads to artifacts in agricultural and non-road emissions
- Hourly biogenic emissions from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) version 2.04 (*Guenther et al.*, 2004), were processed to both grids from 1 km resolution input fields and hourly WRF meteorology, and speciated for CB05 as in *Wilkerson* (2006).
- Daily gridcell-specific point fire emissions were taken from the 1 km x 1 km resolution Fire INventory from NCAR (FINN; *Wiedinmyer et al.*, 2011), based on MODIS fire detection retrievals. Emissions were processed for CMAQ by estimating hourly rates and vertical plume rise using a local fire size and intensity clustering technique (*WRAP*, 2005) as applied to a prior version of this inventory by *Tai et al.* (2008). Speciated VOC emissions rates for the CB05 mechanism were allocated from total VOC emissions as in *Tai et al.* (2008).

PM2.5


JAN
FEB
MAR
CMAQ
CAMx
40.0
36.0
32.0
28.0
24.0
20.0
16.0
12.0
8.0
4.0
0.0
µg/m³
36
32
28
24
20
16
12
8
4


Base – 30% NO_x
Base – 30% NH_3
2015 proxy
2015 proxy – 30% NH_3
24.0
21.0
18.0
15.0
12.0
9.0
6.0
3.0
0.0
-3.0
%

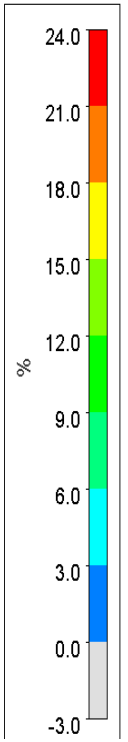
Base – 30% NO_x



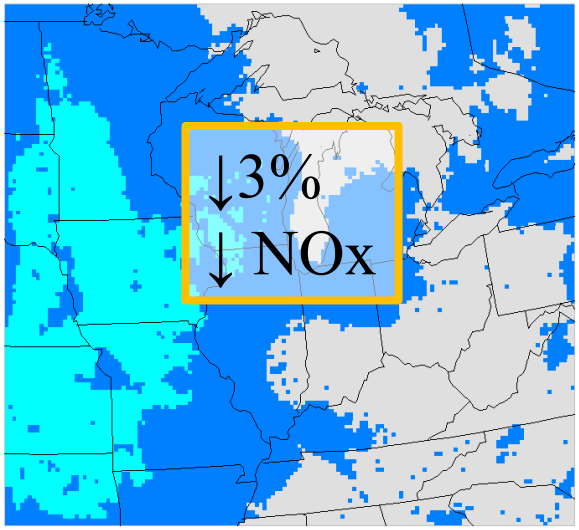
Base – 30% NH_3

2015 proxy

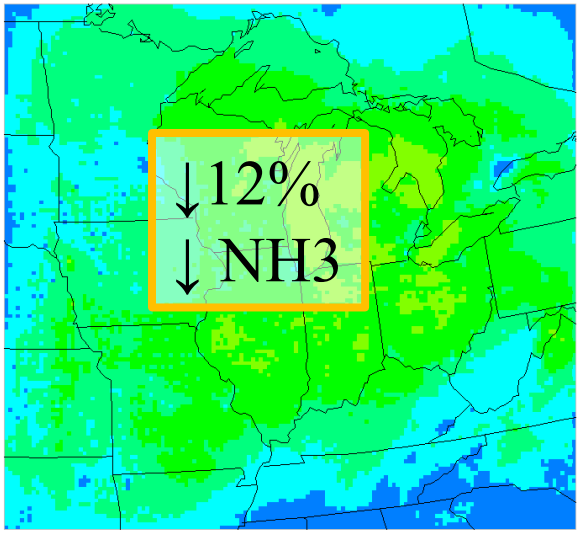
2015 proxy – 30% NH_3



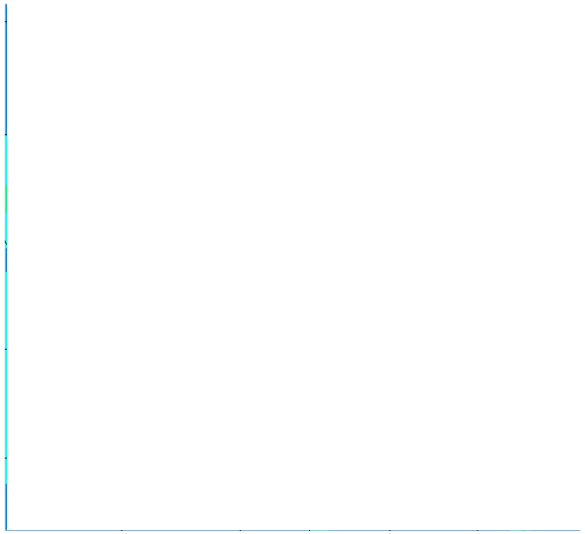
Base – 30% NO_x



Base – 30% NH_3



2015 proxy



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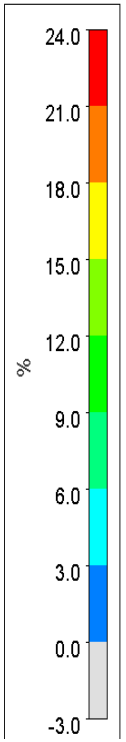

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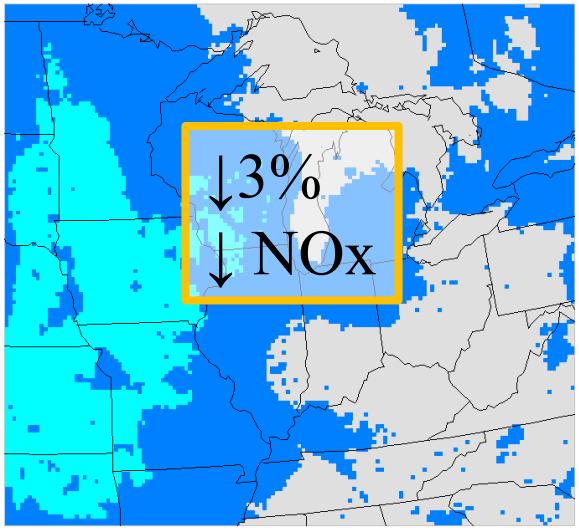

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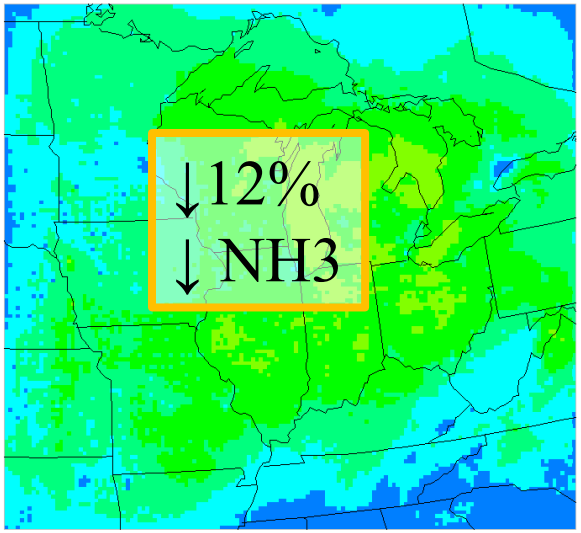

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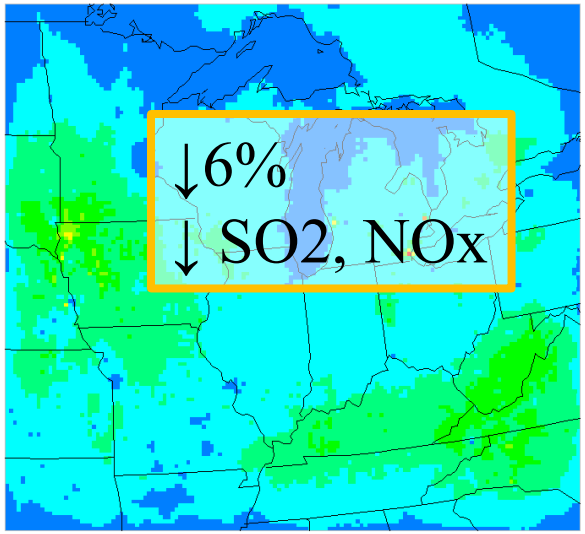

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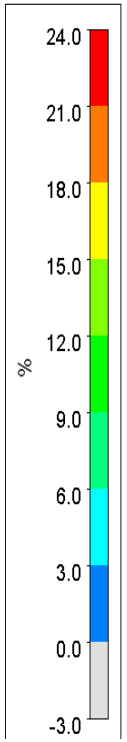

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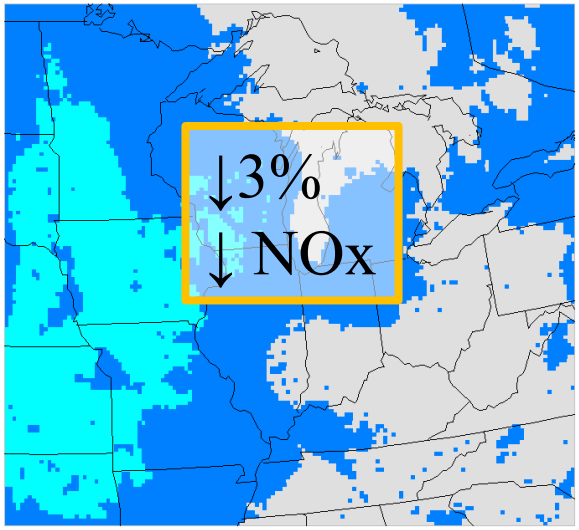

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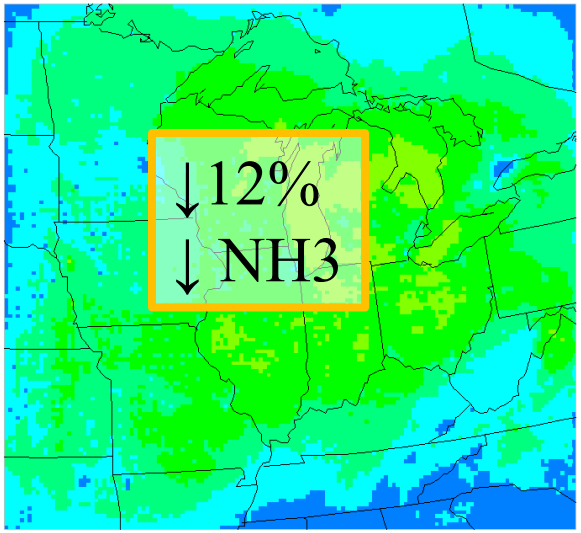

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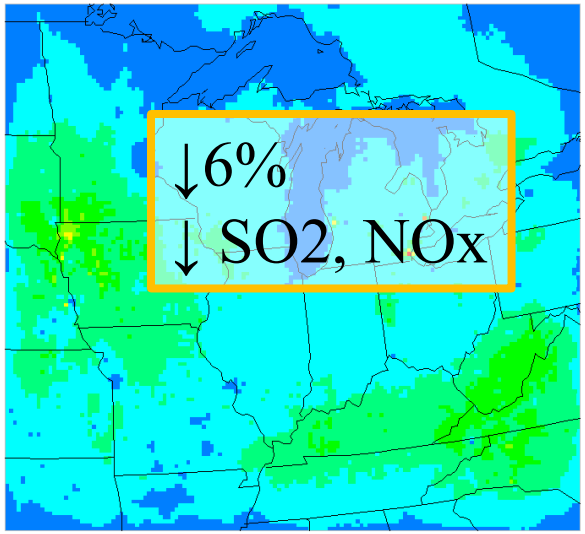

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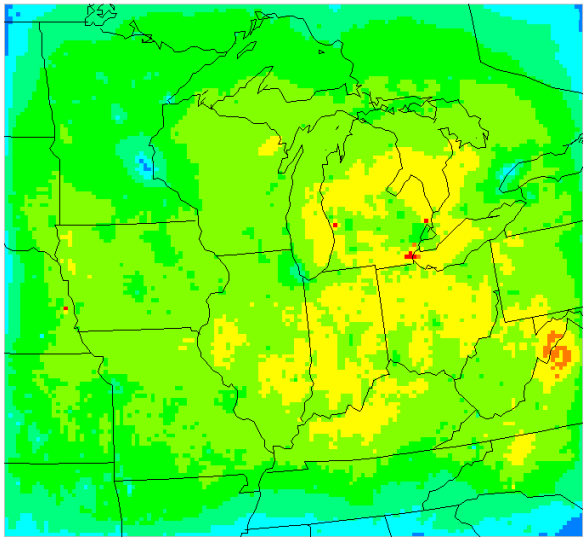

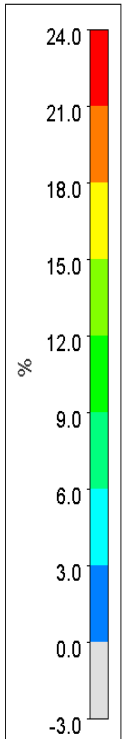

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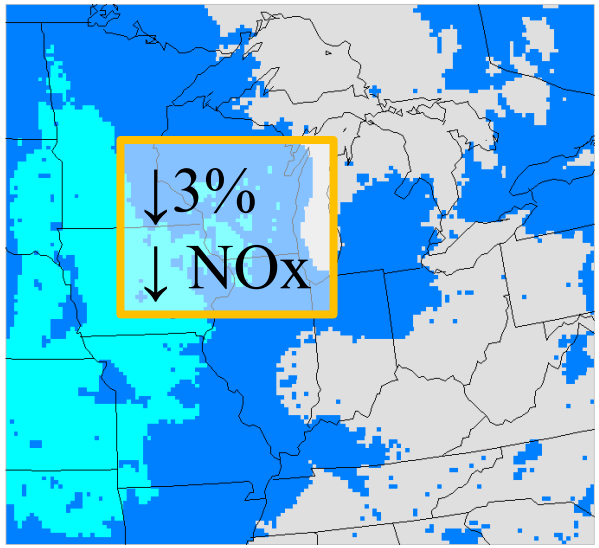

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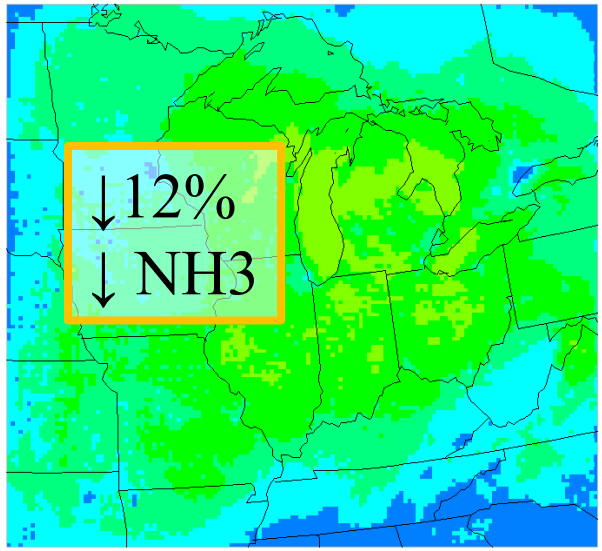
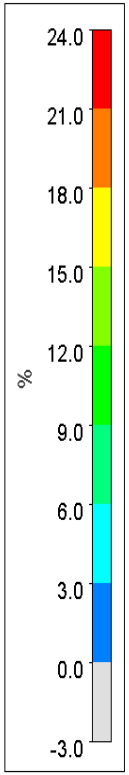


Base – 30% NO_x (250 km)

Base – 30% NH_3 (250 km)



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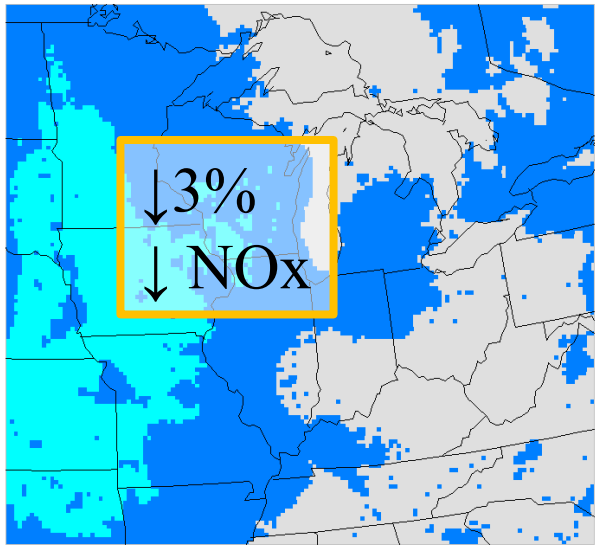

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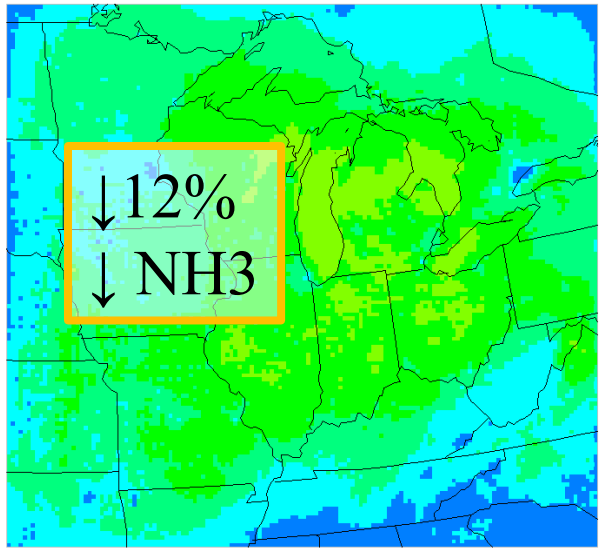

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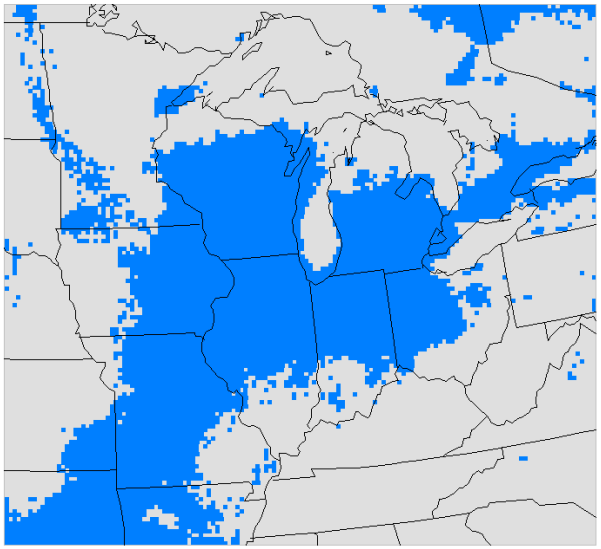

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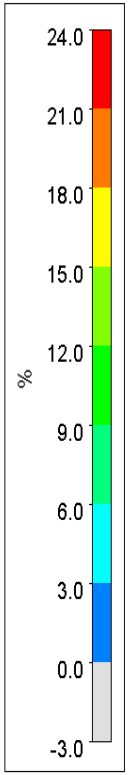

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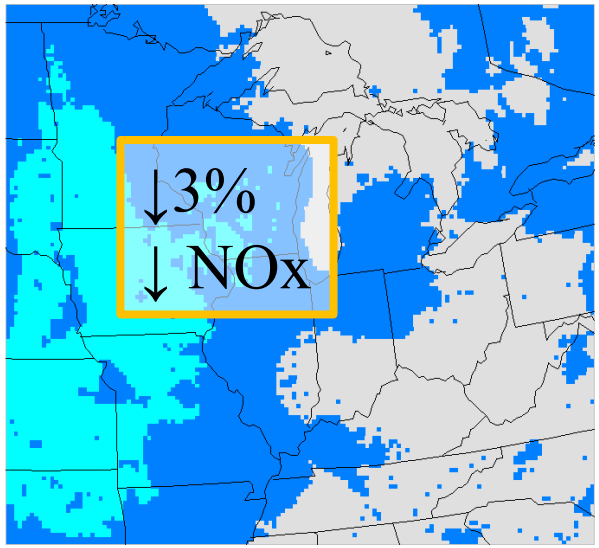

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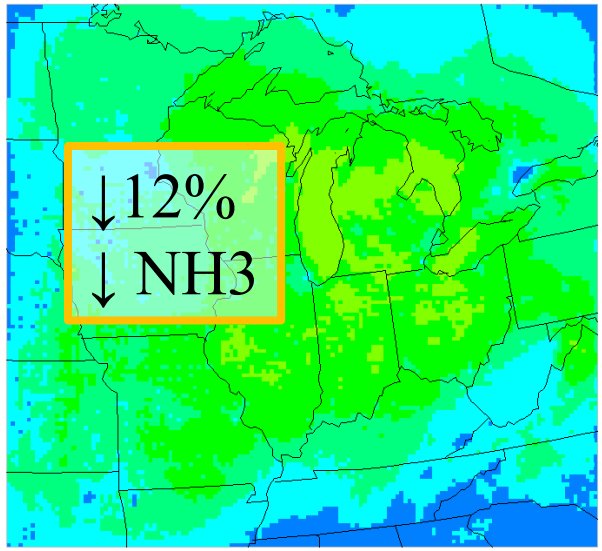

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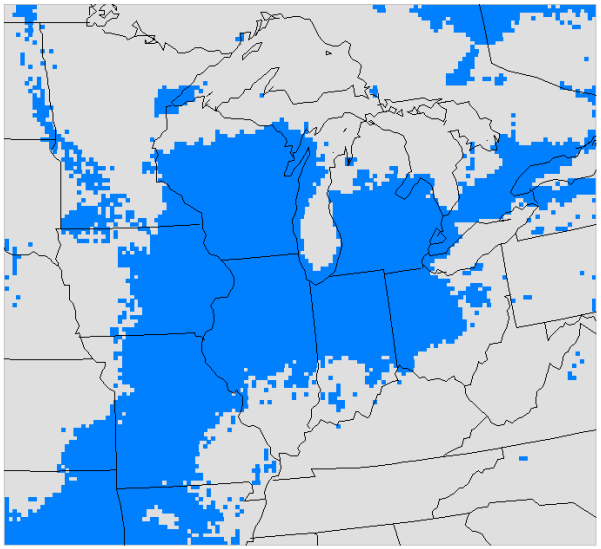
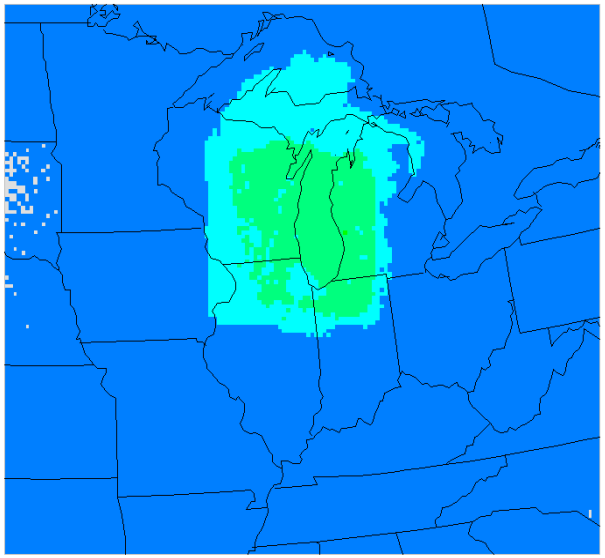
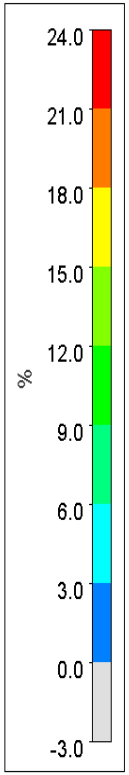
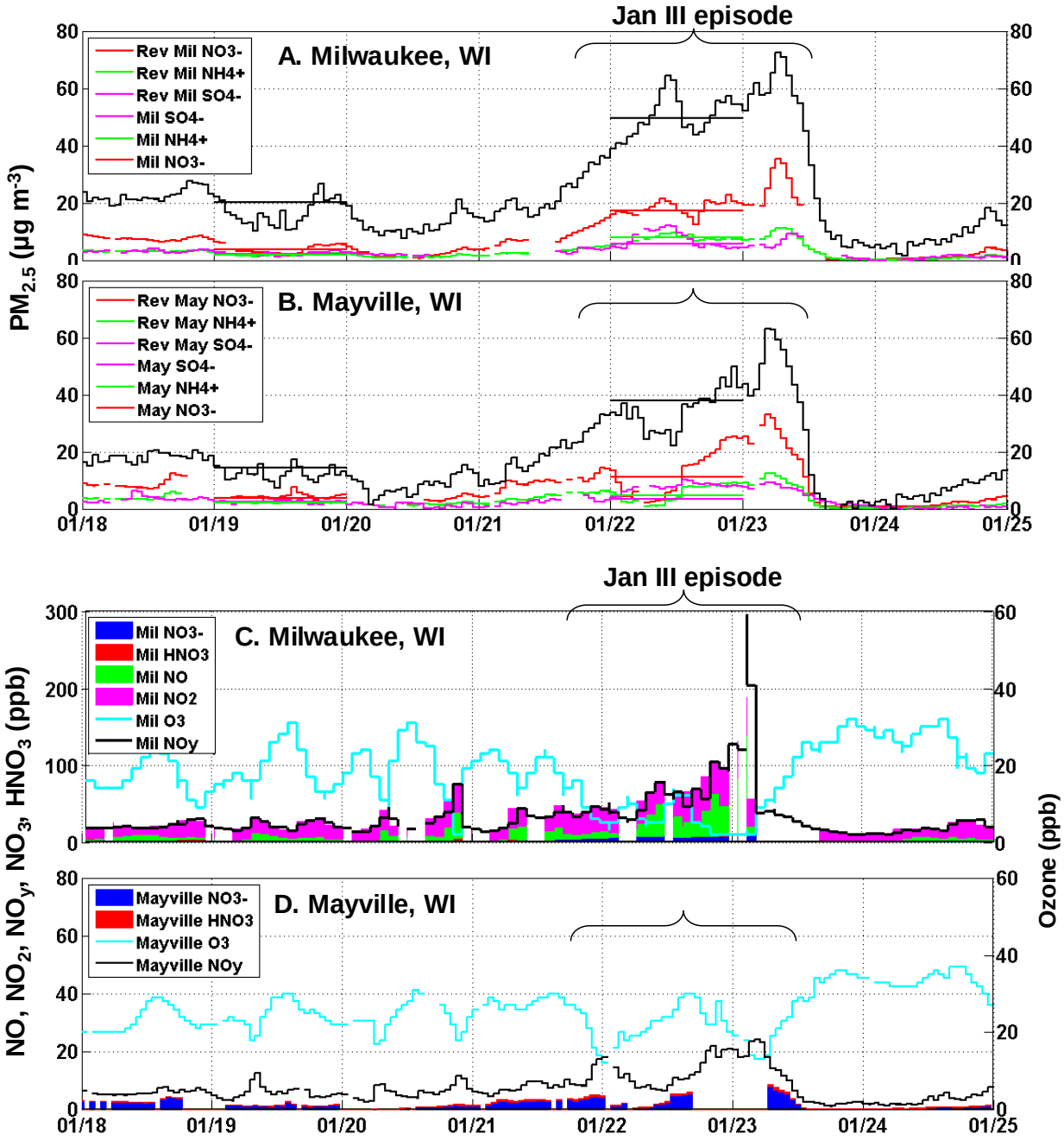


Base – 30% NH_3 (250 km)

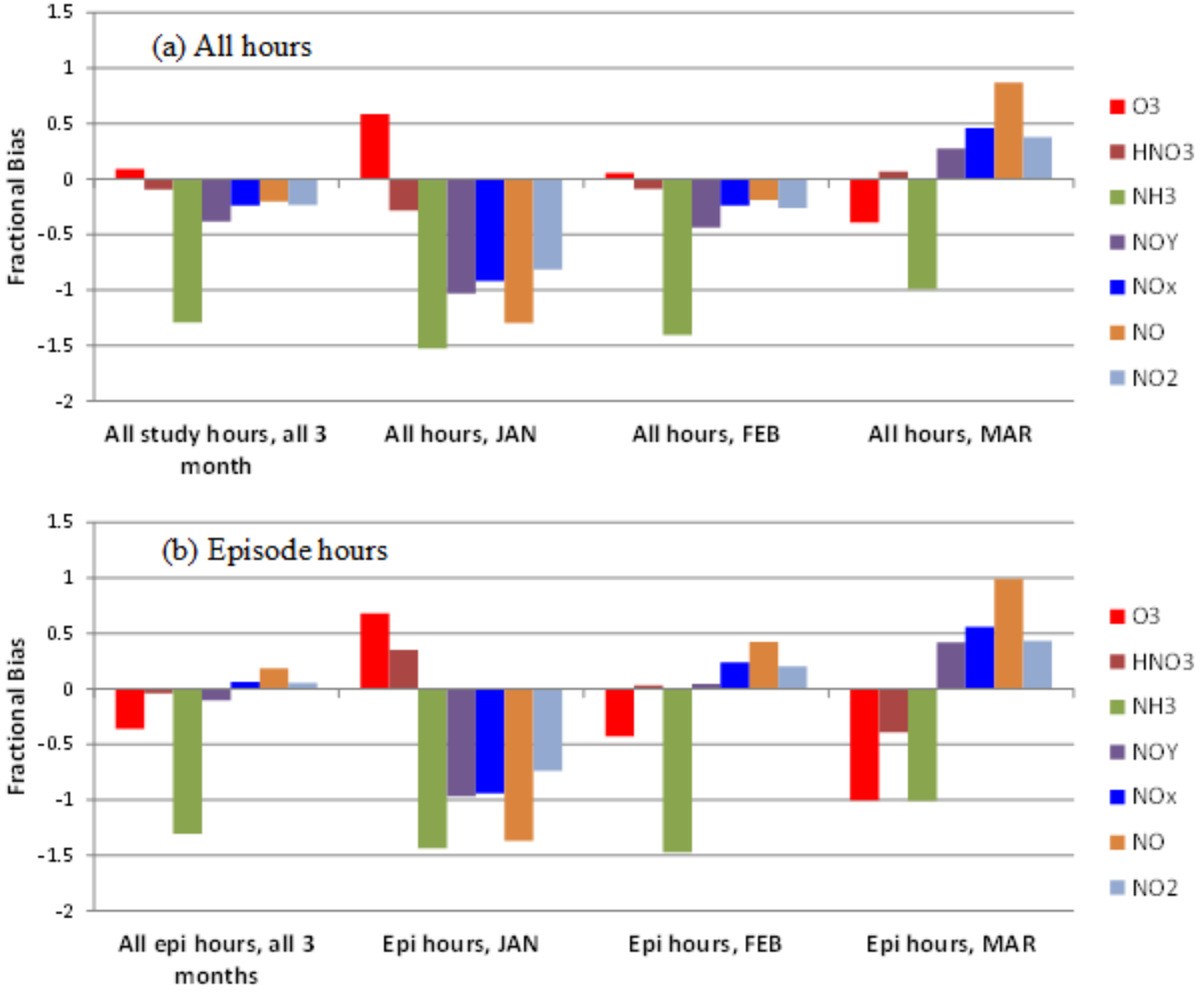


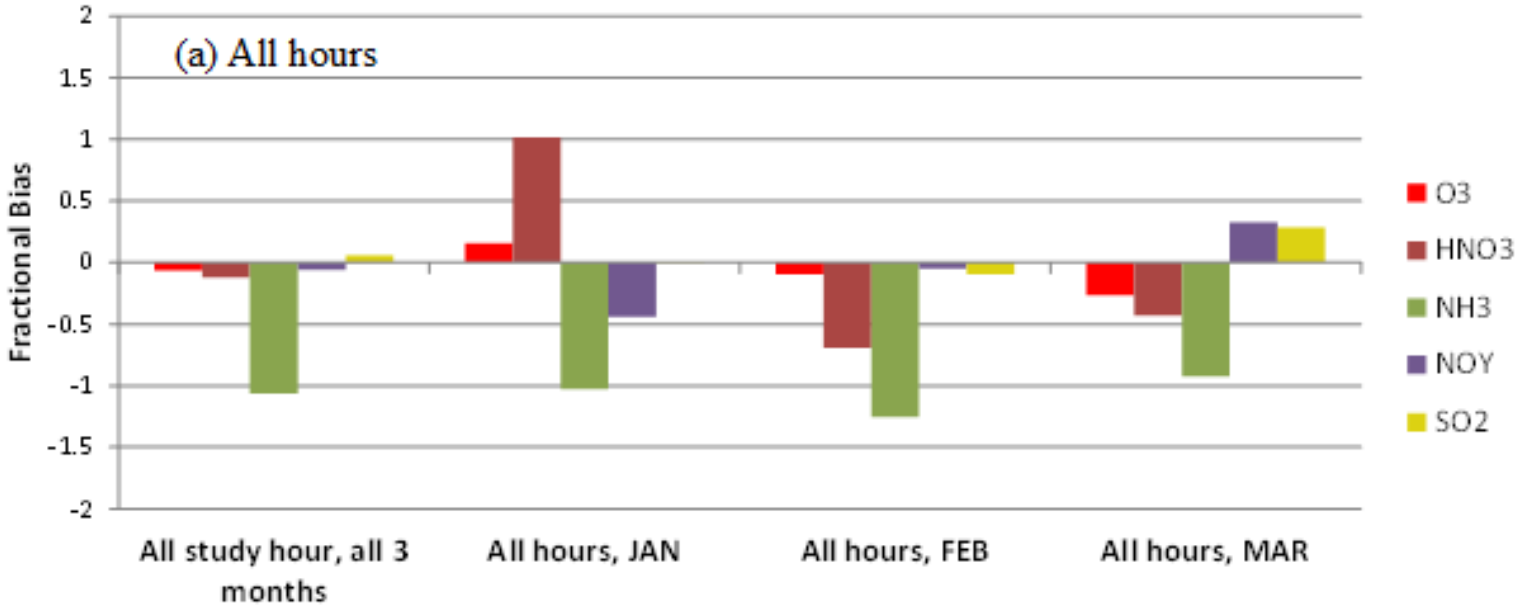


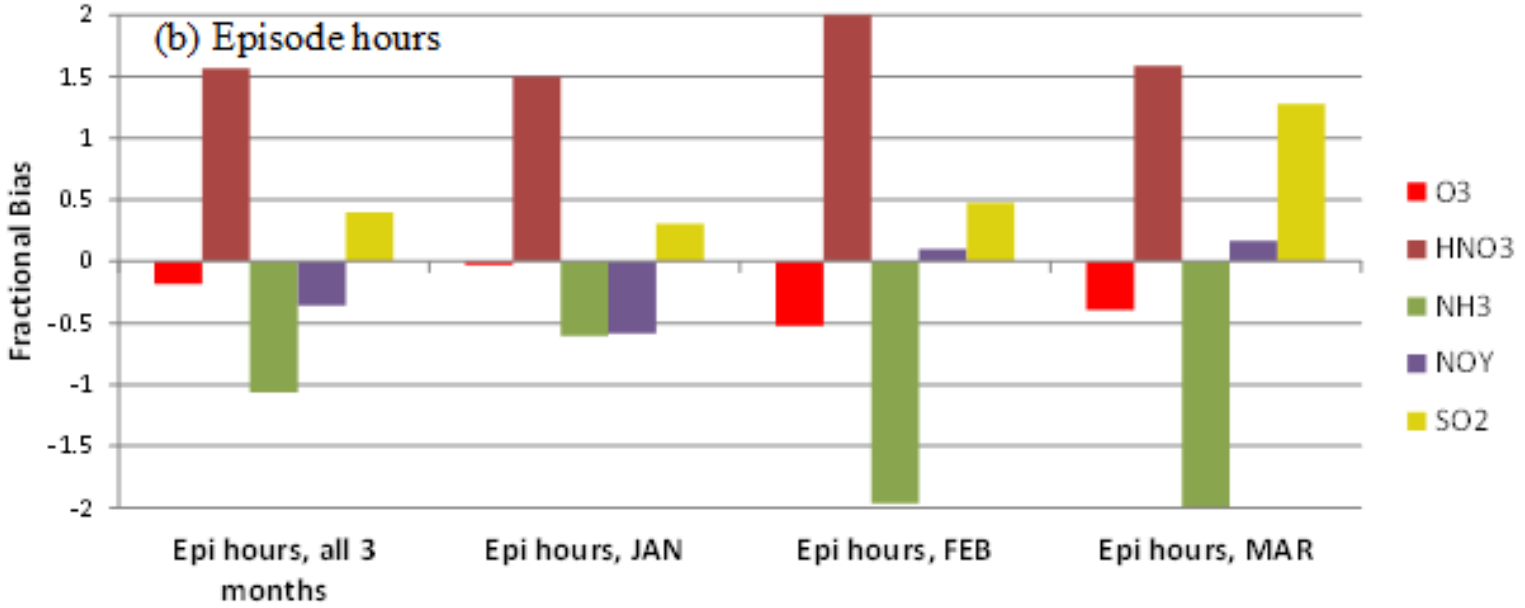


Detailed view of an episode

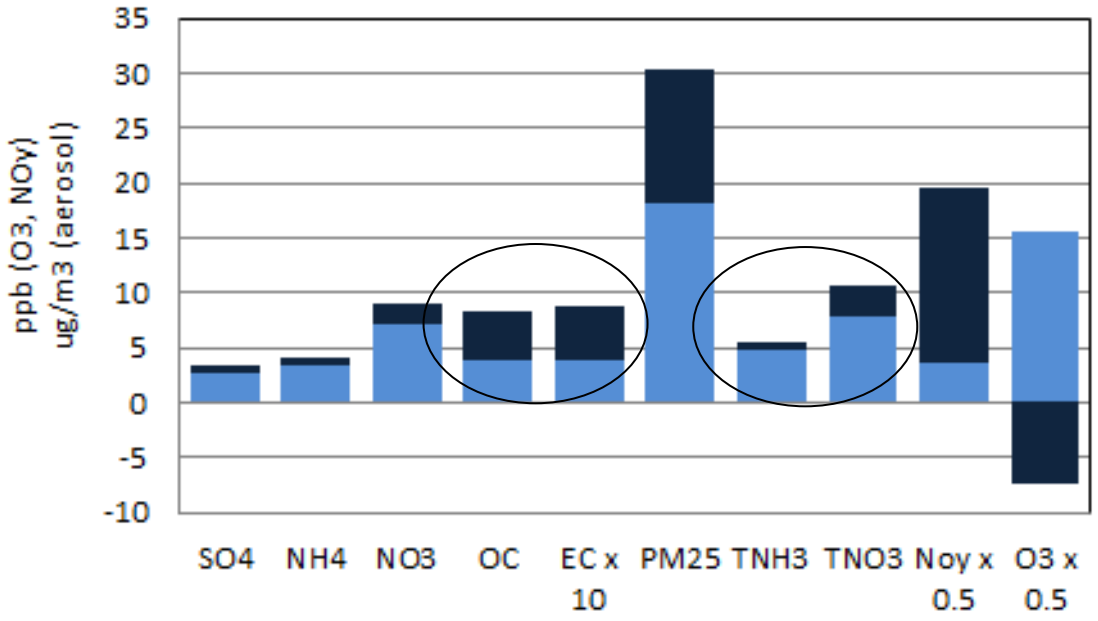
Agreement between multiple independent measurements


(a) All hours
Fractional Bias
1.5
1
0.5
0
-0.5
-1
-1.5
-2
All study hours, all 3 month
All hours, JAN
All hours, FEB
All hours, MAR
O3
HNO3
NH3
NOY
NOx
NO
NO2
(b) Episode hours
Fractional Bias
All epi hours, all 3 months
Epi hours, JAN
Epi hours, FEB
Epi hours, MAR
O3
HNO3
NH3
NOY
NOx
NO
NO2


(a) All hours
Fractional Bias
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
All study hour, all 3 months
All hours, JAN
All hours, FEB
All hours, MAR
O3
HNO3
NH3
NOY
SO2


(b) Episode hours
Fractional Bias
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Epi hours, all 3 months
Epi hours, JAN
Epi hours, FEB
Epi hours, MAR
O3
HNO3
NH3
NOY
SO2

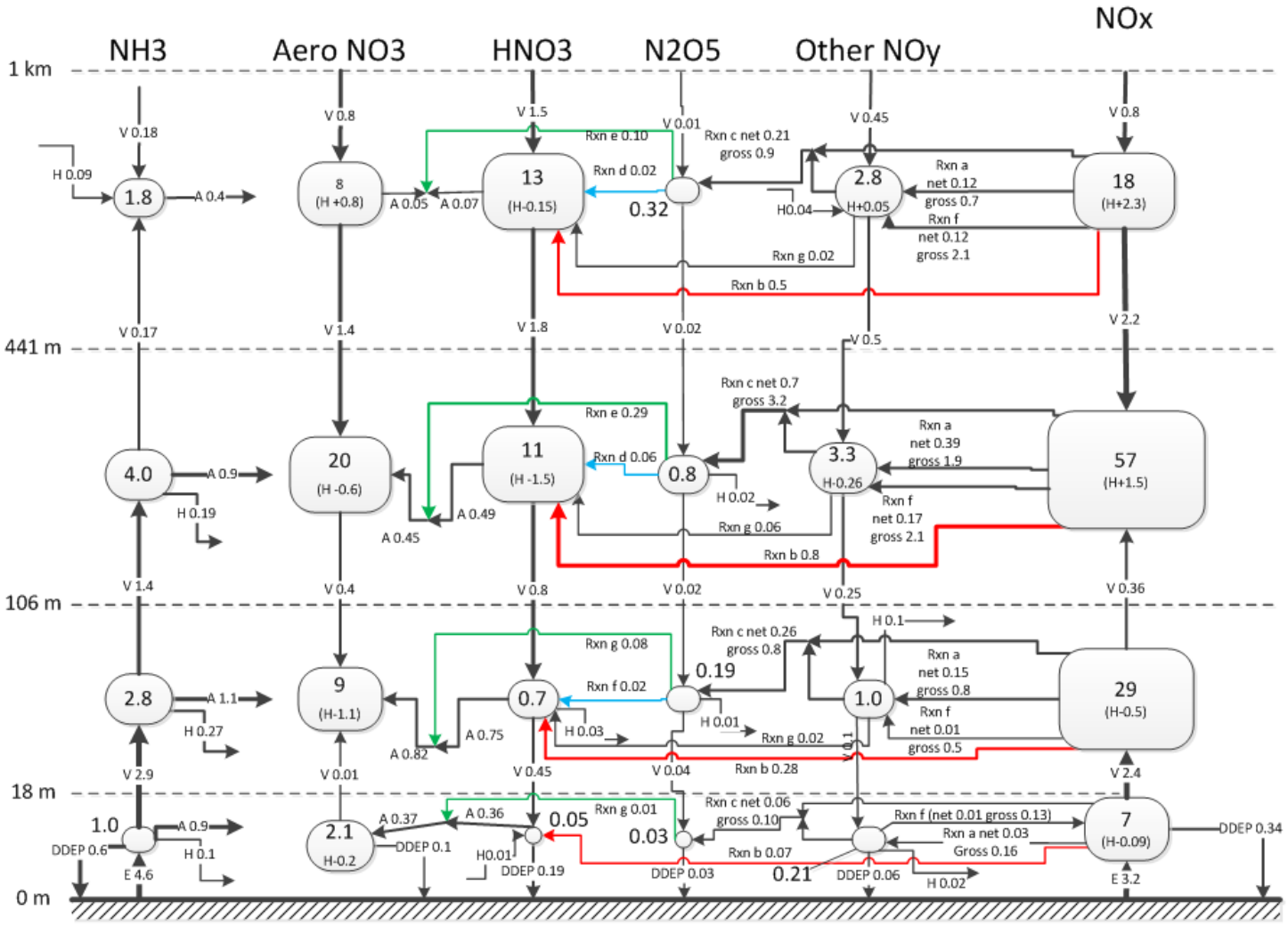
Urban-Rural Contrast During Episodes



Secondary species mainly regional (small urban excess)

OC, EC, and NOy have strong urban excess.

Mayville Day



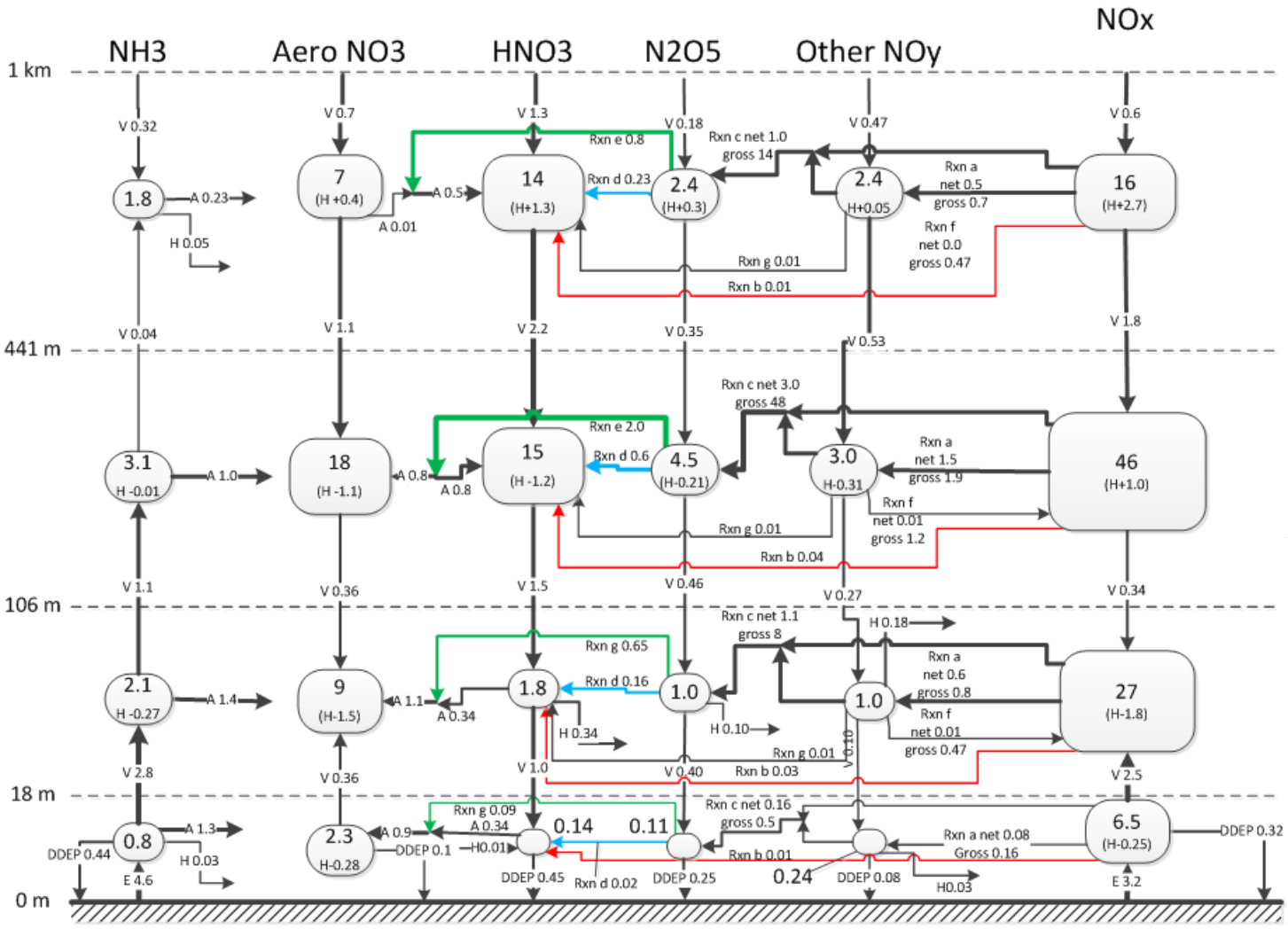
Reservoir in µmole N / m^2.
Fluxes are in µmole N / m^2-hr.

Black lines
Aerosol process
Horizontal advection and diffusion
Vertical advection and diffusion
Emissions
DDEP

a: net NO_3 radical formation
c: net N_2O_5 formation
g: HNO_3 formation from the NO_3 radical

Colored lines
b: $NO_2 + OH \rightarrow HNO_3$
d: homogenous formation of HNO_3 from N_2O_5
Flux e: heterogeneous formation of HNO_3 from N_2O_5

Mayville Night



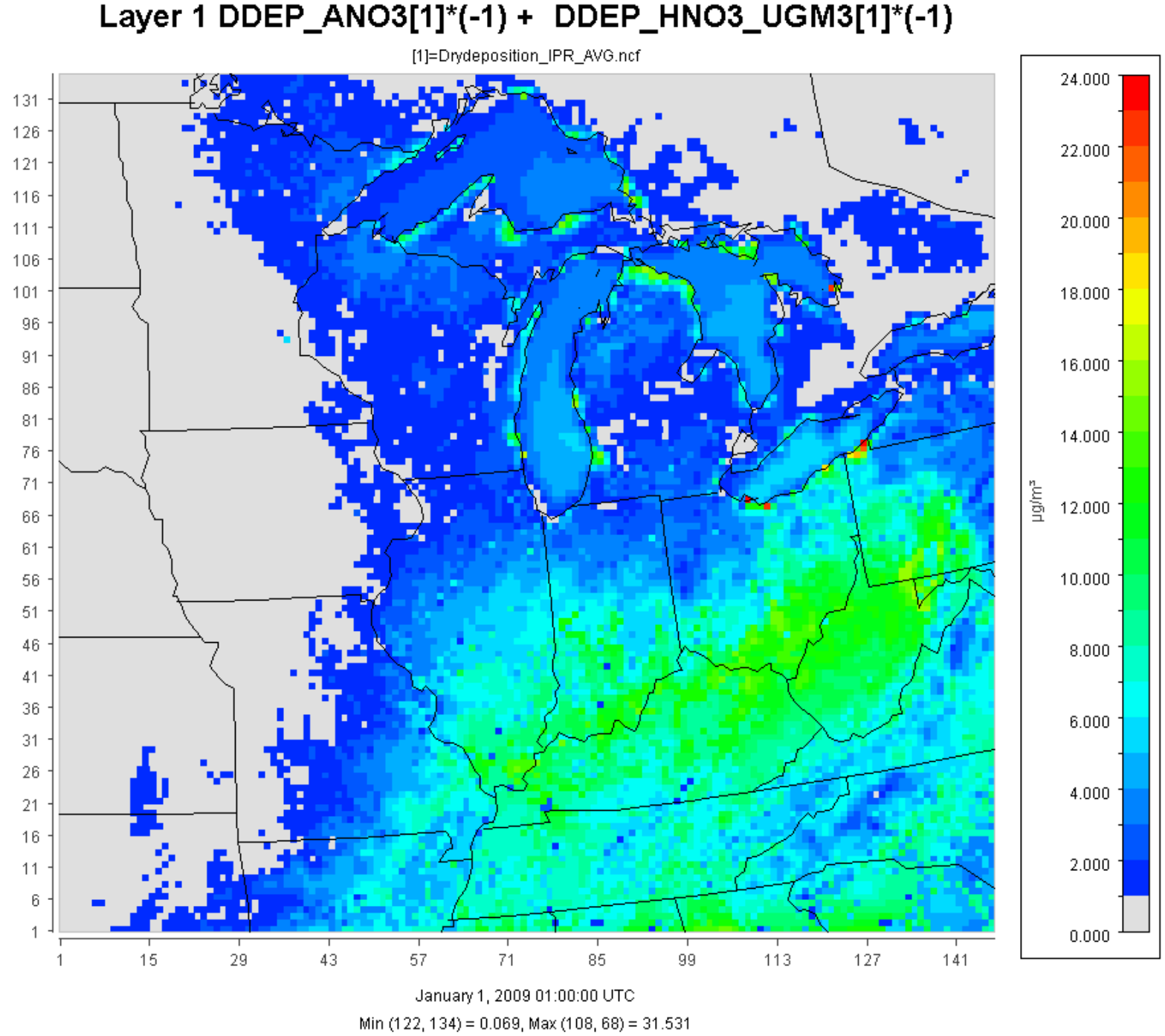
Reservoir in µmole N / m^2.
Fluxes are in µmole N / m^2-hr.

Black lines
Aerosol process
Horizontal advection and diffusion
Vertical advection and diffusion
Emissions
DDEP

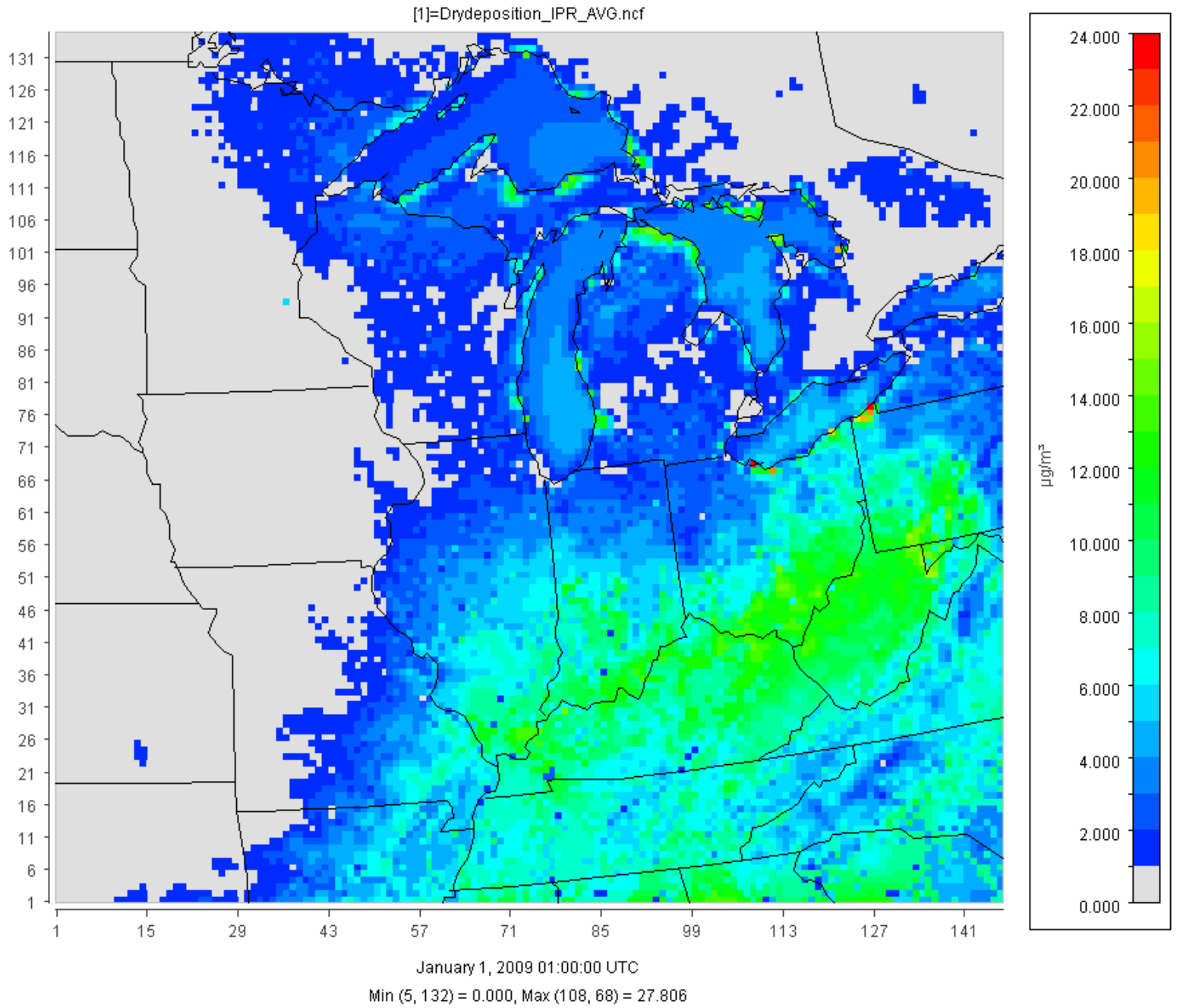
a: net NO_3 radical formation
c: net N_2O_5 formation
g: HNO_3 formation from the NO_3 radical

Colored lines
b: $NO_2 + OH \rightarrow HNO_3$
d: homogenous formation of HNO_3 from N_2O_5
Flux e: heterogeneous formation of HNO_3 from N_2O_5

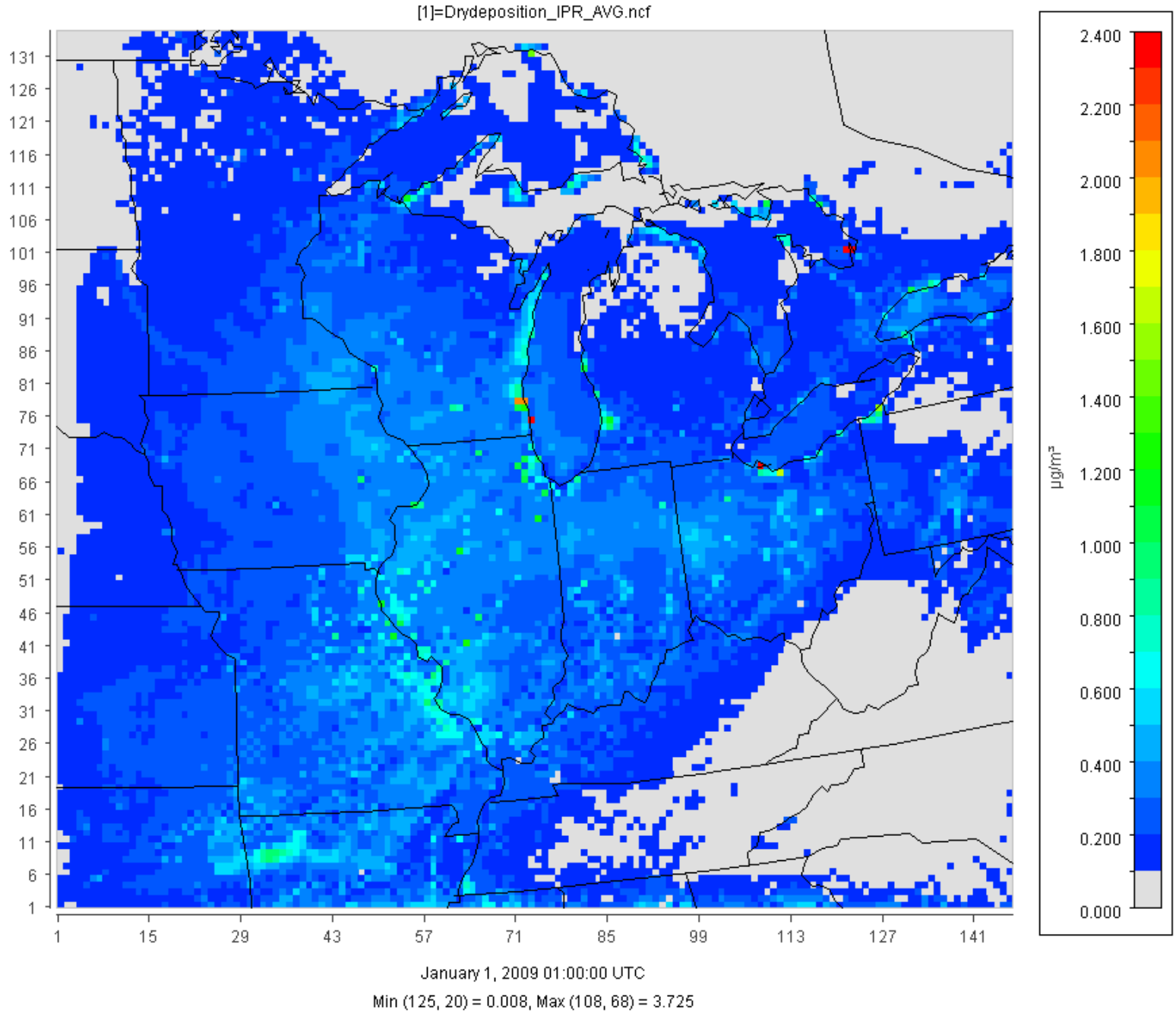
Dry Deposition Rate, Total Nitrate (ug/m3 per hour)



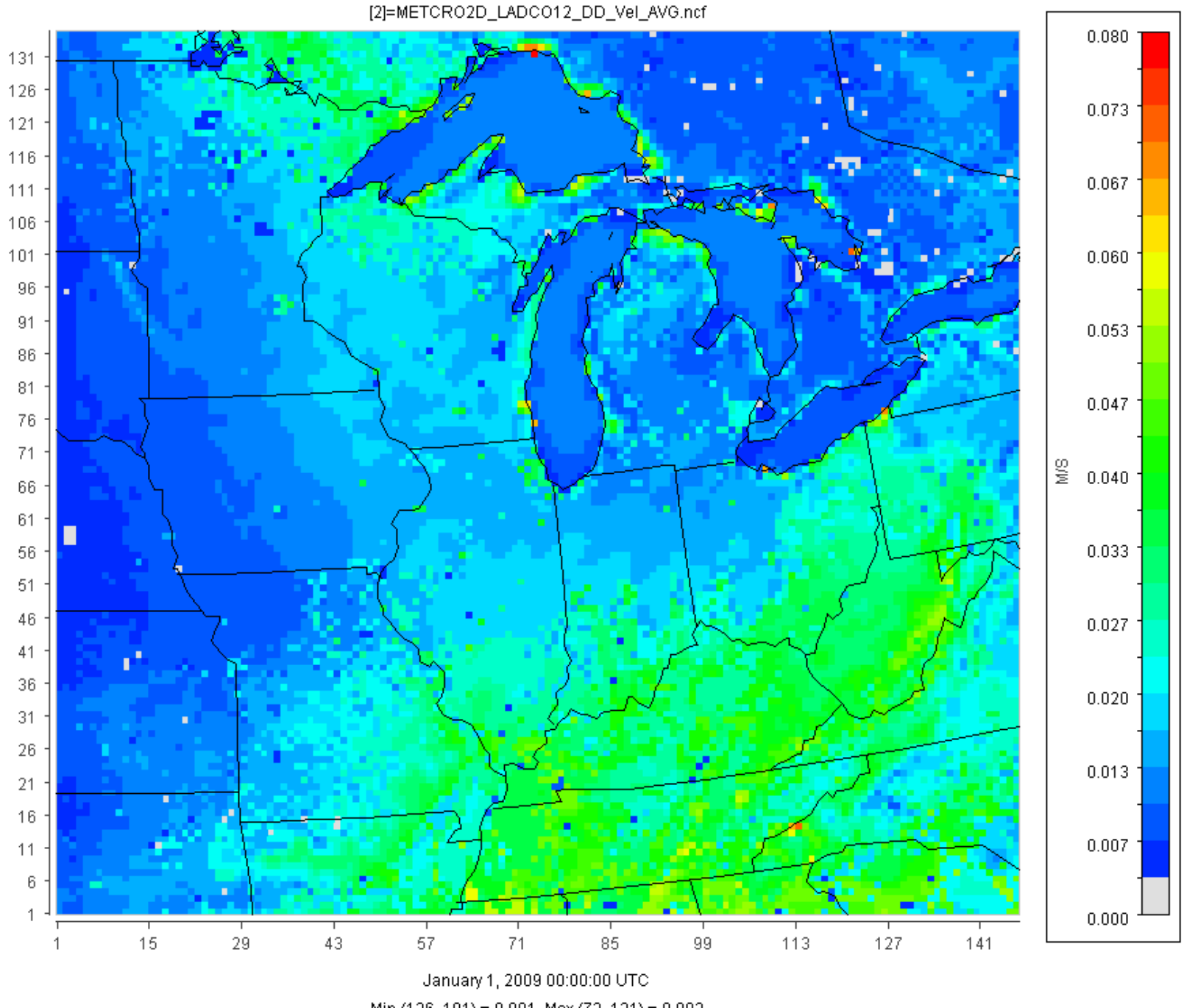
Dry Deposition Nitric Acid (ug/m3 per hour)



Dry Deposition Nitrate (ug/m3 per hour)



HNO3 Deposition Velocity



Emissions Sensitivity: Emissions Scenarios

- 30% NO_x from base case
- 30% NH_3 from base case
- 2015 Proxy Case
  - Simulate near-term changes in mobile NO_x & simulate approximation of implementation of Cross State Air Pollution Rule (CSAPR) effect on coal-fired power plant NO_x & SO_x emissions

  -70% EGU SO_2

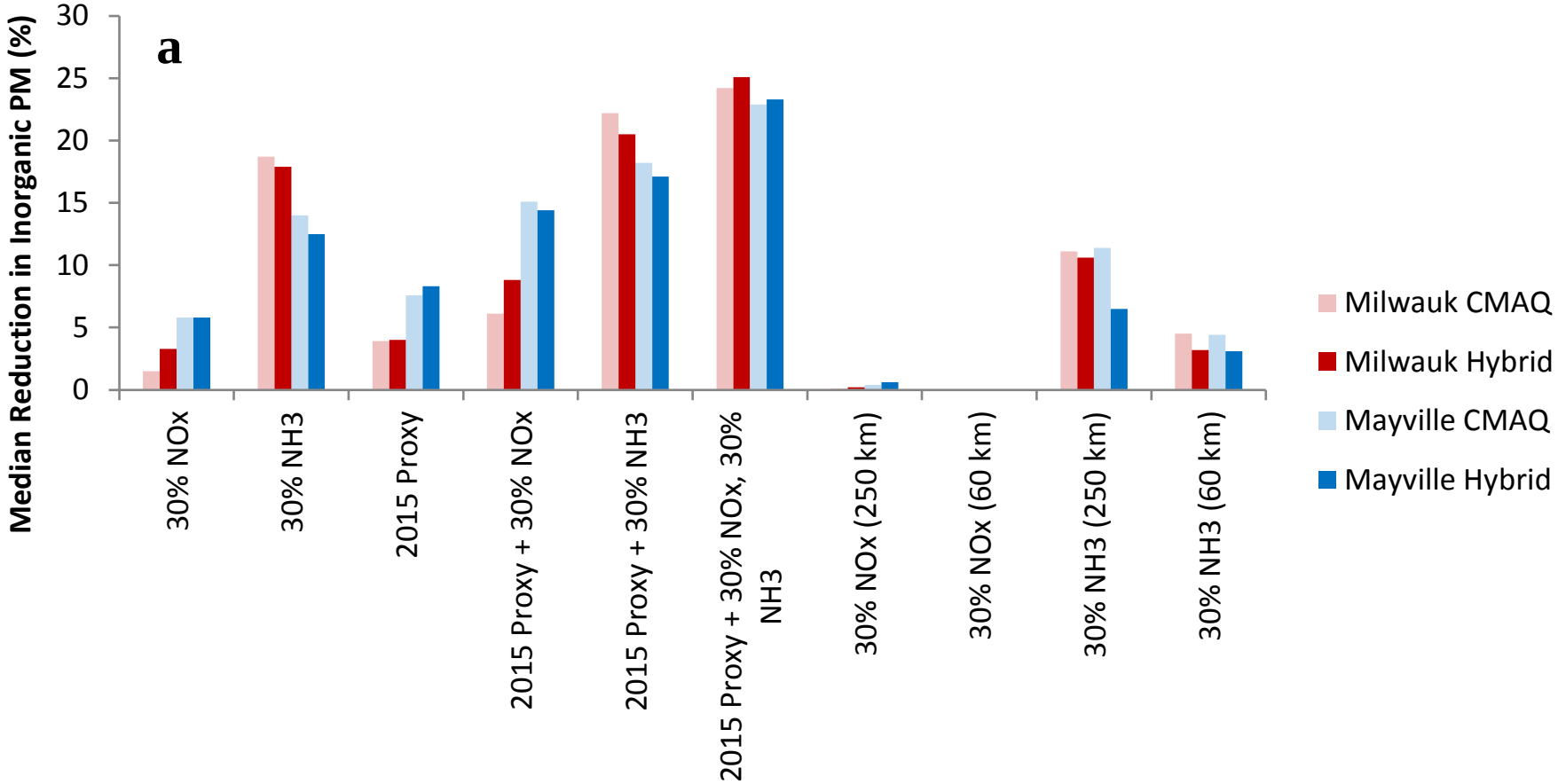
  -10% EGU NO_x

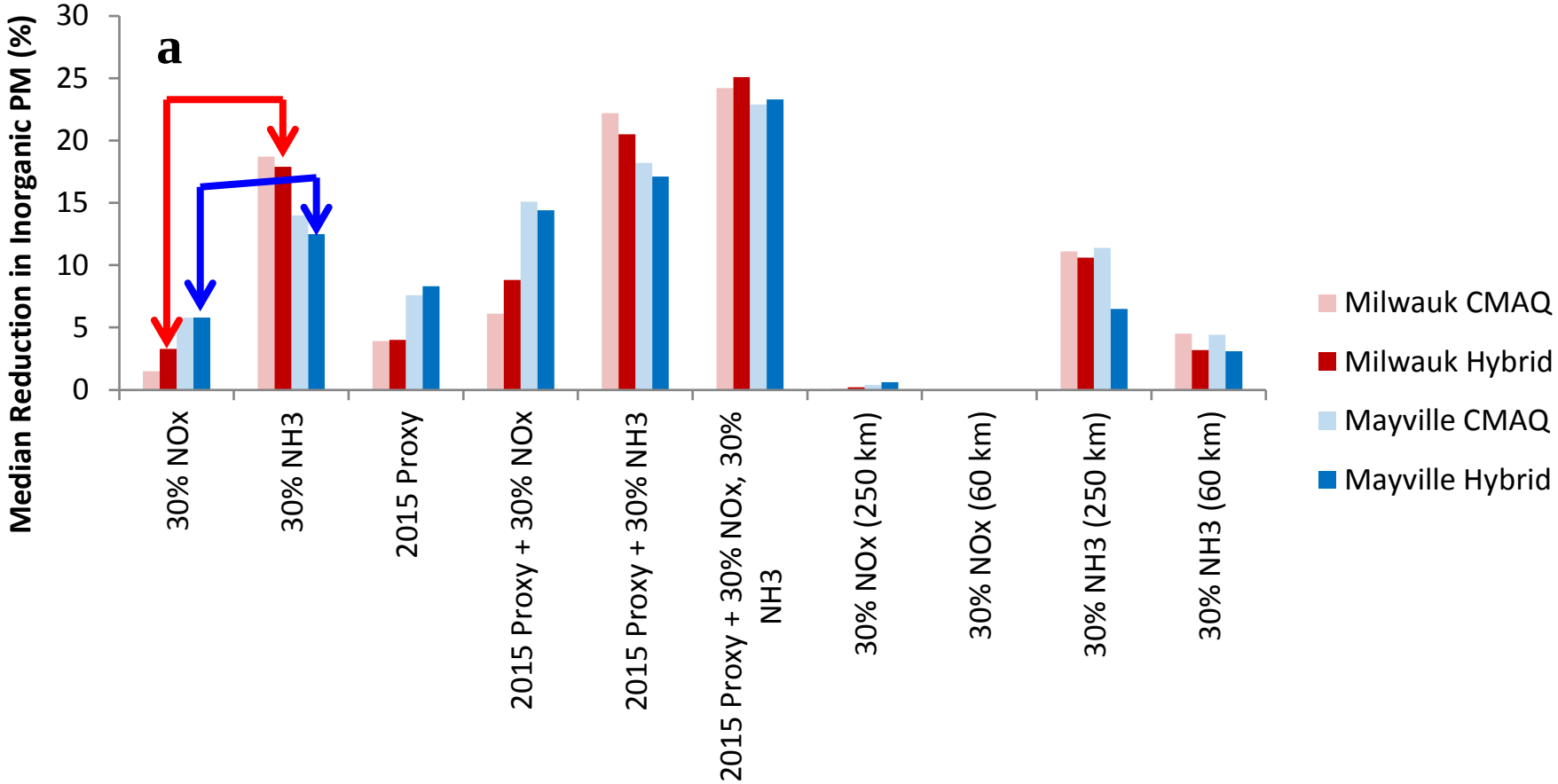
  -30% mobile NO_x
- Additional scenarios: add all-sector reductions to the 2015 Proxy Case

  - 30% NH_3

  - 30% NO_x

  - 30% NH_3 & - 30% NO_x


a
Median Reduction in Inorganic PM (%)
30
25
20
15
10
5
0
30% NOx
30% NH3
2015 Proxy
2015 Proxy + 30% NOx
2015 Proxy + 30% NH3
2015 Proxy + 30% NOx, 30% NH3
30% NOx (250 km)
30% NOx (60 km)
30% NH3 (250 km)
30% NH3 (60 km)
Milwauk CMAQ
Milwauk Hybrid
Mayville CMAQ
Mayville Hybrid


a
Median Reduction in Inorganic PM (%)
30
25
20
15
10
5
0
30% NOx
30% NH3
2015 Proxy
2015 Proxy + 30% NOx
2015 Proxy + 30% NH3
2015 Proxy + 30% NOx, 30% NH3
30% NOx (250 km)
30% NOx (60 km)
30% NH3 (250 km)
30% NH3 (60 km)
Milwauk CMAQ
Milwauk Hybrid
Mayville CMAQ
Mayville Hybrid