

# 2017 Lake Michigan Ozone Study (LMOS)



Brad Pierce  
NOAA/NESDIS/STAR

# 2017 Lake Michigan Ozone Study (LMOS)

## What are the potential outcomes/benefits of LMOS 2017?

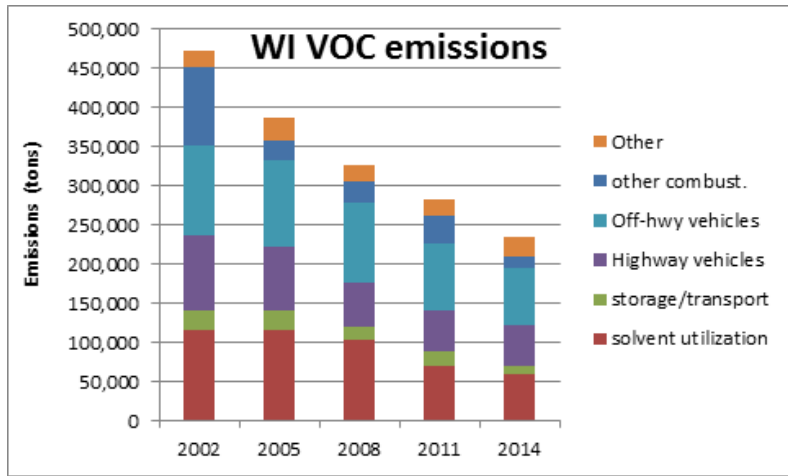
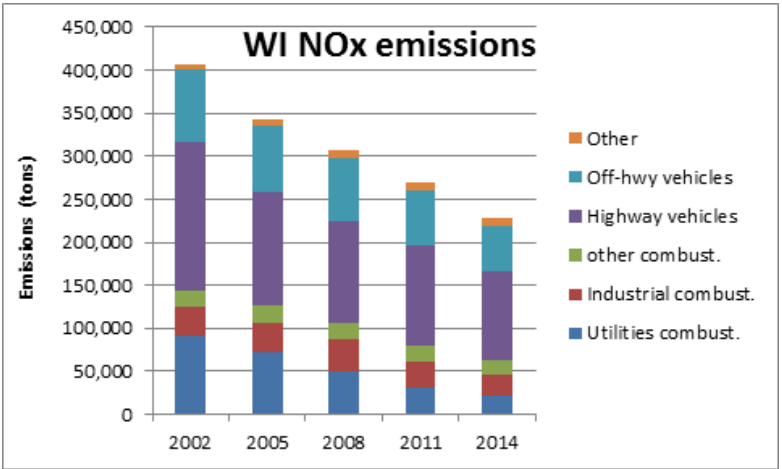
LMOS 2017 measurements provide critical observations for evaluating a new generation of air quality models attempting to better simulate ozone episodes in the region. Over the long term, the information collected is expected to result in:

- Improved modeled ozone forecasts for this region, which states and EPA use to meet state and federal Clean Air Act requirements.
- Better understanding of the lakeshore gradient in ozone concentrations, which could influence how EPA addresses future regional ozone issues.
- Improved knowledge of how emissions influence ozone formation in the region.

## What institutions are involved in LMOS 2017?

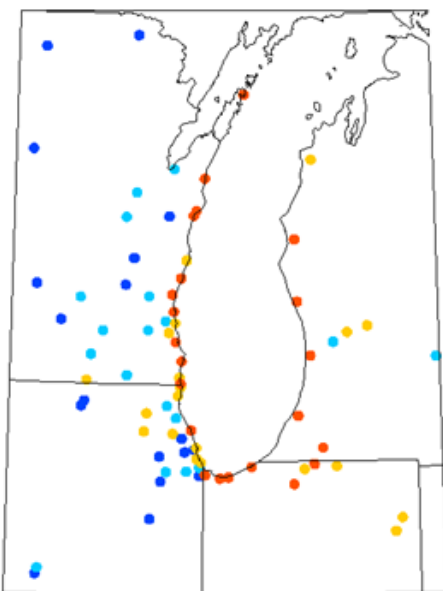
- Researcher institutions: NOAA, NASA, U.S. EPA, University of Wisconsin, University of Iowa, University of Minnesota, University of Northern Iowa, University of Maryland Baltimore County, Scientific Aviation.
- Air quality management agencies: Lake Michigan Air Directors Consortium (LADCO), Wisconsin DNR, Illinois EPA, Indiana DEM.
- Nonprofit organizations: Electric Power Research Institute (EPRI)
- Commercial Services: Scientific Aviation

# Wisconsin emissions are declining and ozone is improving

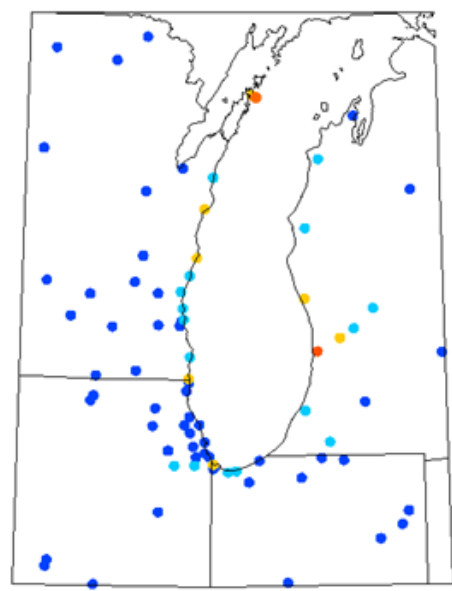


NO<sub>x</sub>= NO+NO<sub>2</sub> (nitrogen oxides) VOC=Volatile Organic Compounds, both are ozone precursors

Ozone Design Values, 1995\_1997



Ozone Design Values, 2005\_2007

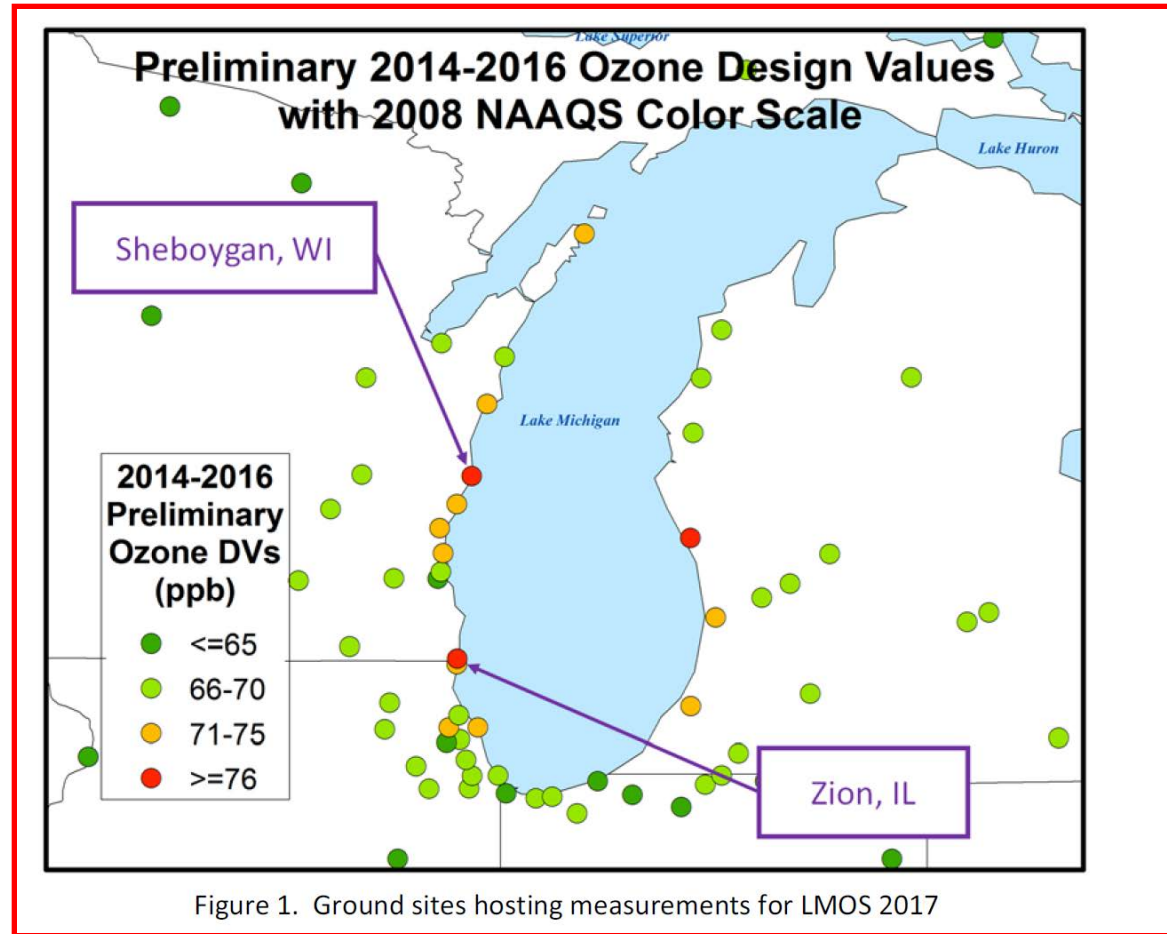


Provided by Angie Dickens (WDNR) and Donna Kenski (LADCO)

DV, in ppb  
 90+  
 85-89  
 80-84  
 <80

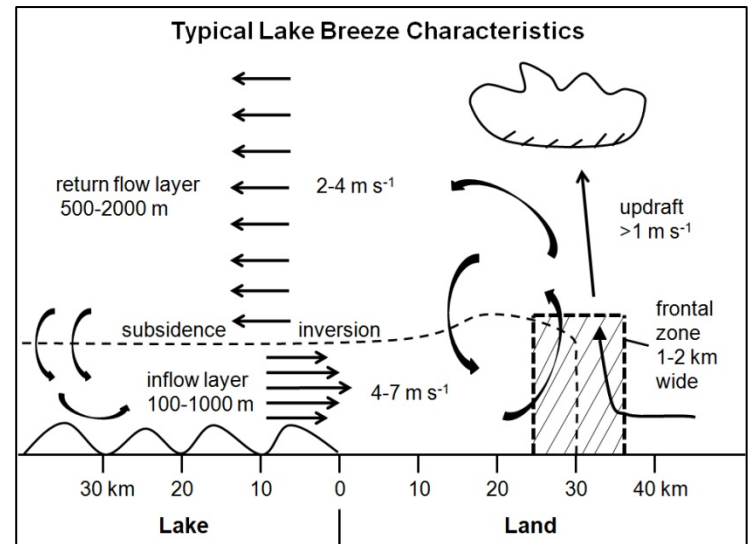
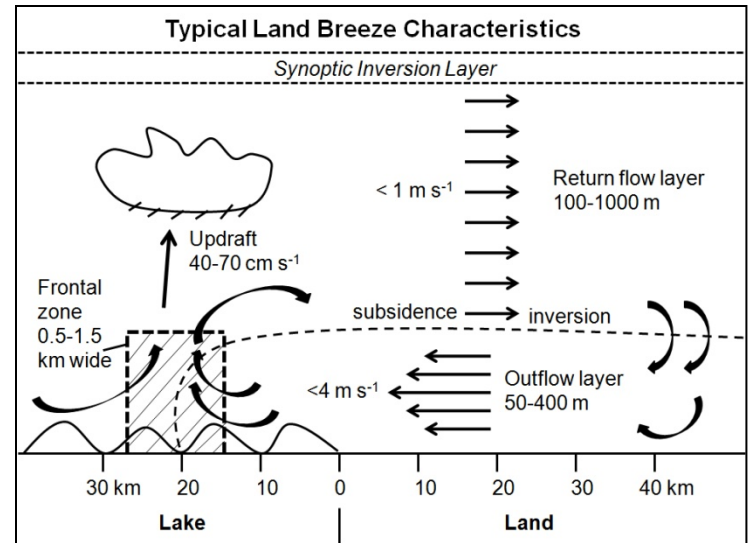
# But there are still coastal sites which are above the new ozone standard (70ppbv)

- Anticipated new non-attainment areas with new, lower ozone standard and persistent exceedances of the old (2008) ozone standard.
- Impact of high ozone on public health in high density urban areas (Chicago, Milwaukee).



# Lake Michigan and Ozone Formation

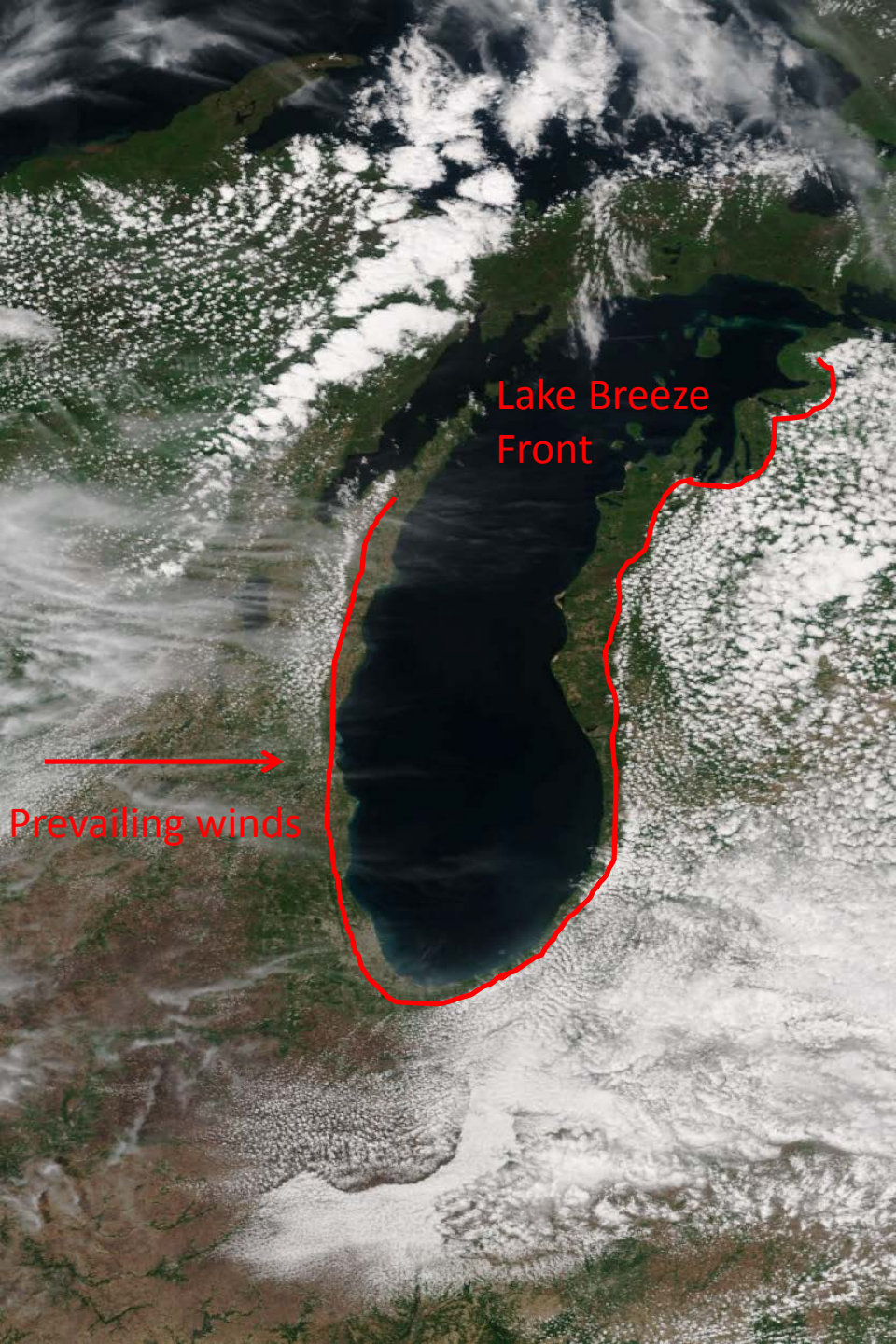
- *Land breeze* blows ozone precursor compounds from rush hour over lake.
- The boundary layer height is low due to cold water chilling the air above.
- The pollutants are concentrated near the surface where ozone forms.
- An afternoon *lake breeze* transports the ozone back onto land.





**VIIRS Image May 27, 2011**

Satellite image of Lake  
Michigan showing  
Lake Breeze Front



**VIIRS Image May 27, 2011**

Satellite image of Lake Michigan showing Lake Breeze Front

# Summary of measurements made during the LMOS 2017 field campaign

Location	Measurement*	Research Institution*
<b>Ground Sites</b>		
Spaceport Sheboygan	Remote sensing of meteorology (SPARC Trailer)	UW-Madison -SSEC
	In situ measurements of pollutants	U.S. EPA ORD
Zion, IL	Remote sensing of meteorology (Sodar/MW Radiometer)	Univ. Northern Iowa
	Detailed in situ chemical measurements	Univ. Iowa, UW-Madison, Univ. Minnesota
	Routine measurements of ozone	Illinois EPA
Various <sup>†</sup>	Remote sensing of pollutants and boundary layer height	U.S. EPA ORD
Sheboygan transect	In situ measurements of ozone at four locations	U.S. EPA ORD
<b>Airborne Platforms</b>		
Lakeshore region	Airborne remote sensing of NO <sub>2</sub> (GeoTASO)	NASA
	Airborne remote sensing of clouds (AirHARP)	Univ. Maryland, Baltimore County
	Airborne in situ profiling of pollutants and meteorology	Scientific Aviation
<b>Shipboard Platform</b>		
Lake Michigan	In situ measurements of pollutants	U.S. EPA ORD
	Remote sensing of pollutants and boundary later height	U.S. EPA ORD
<b>Mobile Platforms</b>		
Northeast IL and Southeast WI	In situ measurements of pollutants (GMAP)	U.S. EPA Region 5
Grafton to Sheboygan	In situ measurements of ozone and meteorology	UW-Eau Claire

**GeoTASO = Geostationary Trace gas and Aerosol Sensor Optimization instrument**

**AirHARP = Airborne Hyper Angular Rainbow Polarimeter**

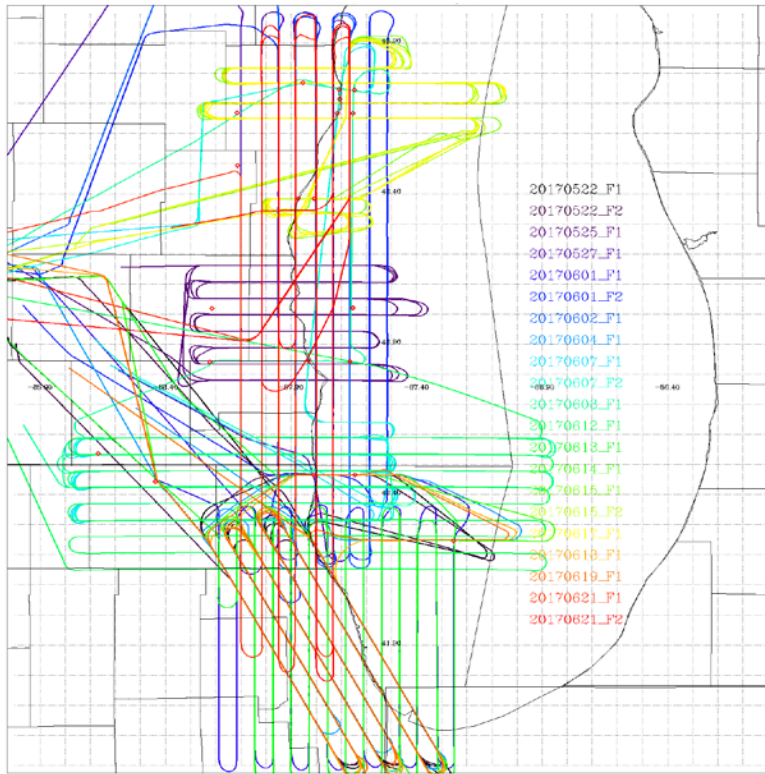
**GMAP = Geospatial Mapping of Pollutants**

**† These measurements were made at Spaceport Sheboygan, Zion, two Wisconsin DNR monitoring locations (Grafton and Milwaukee SER) and one Illinois EPA monitoring location (Schiller Park).**

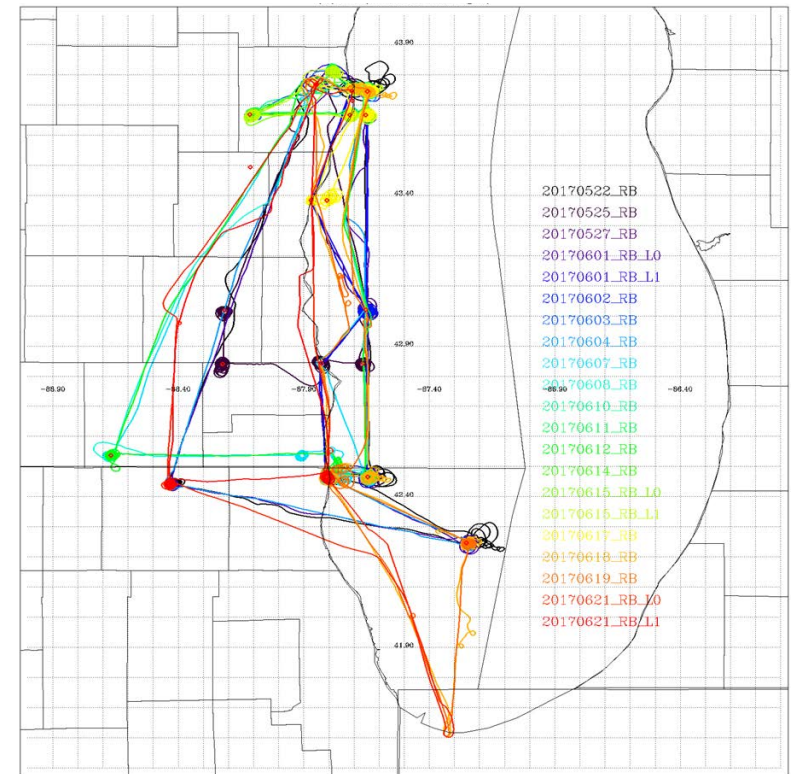


# LMOS 2017 Aircraft Measurements

## NASA GeoTASO remote sensing Flights



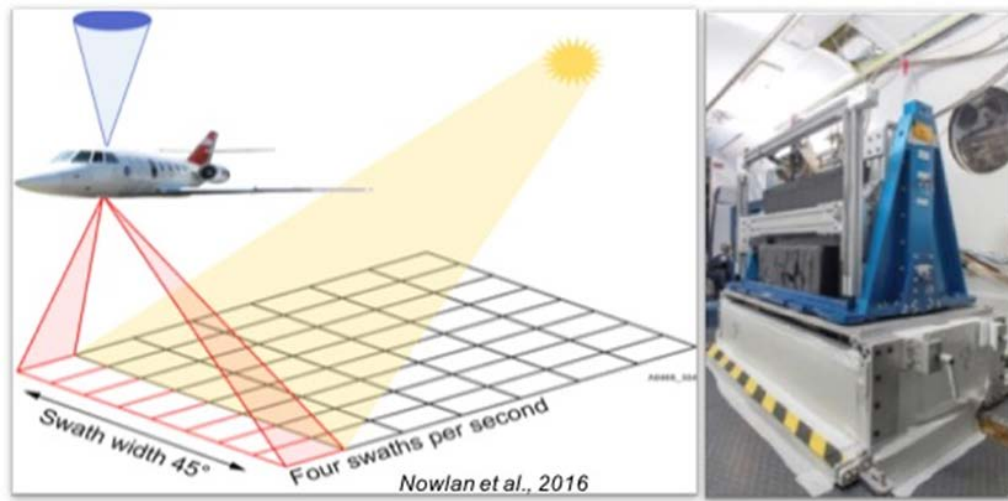
## Scientific Aviation insitu sampling Flights



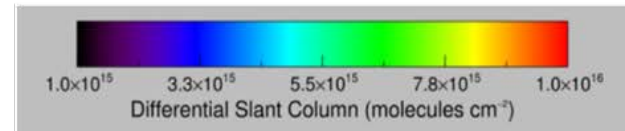
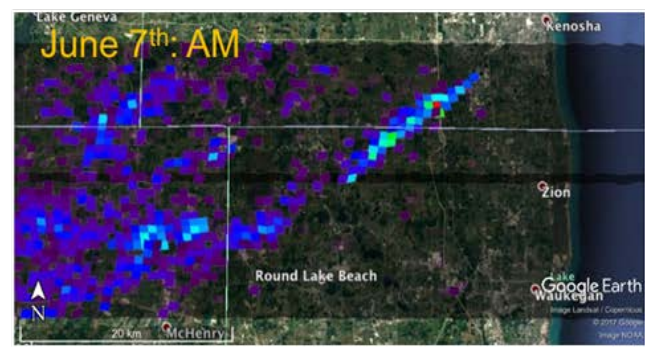
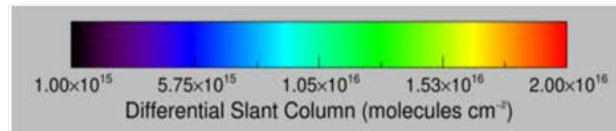
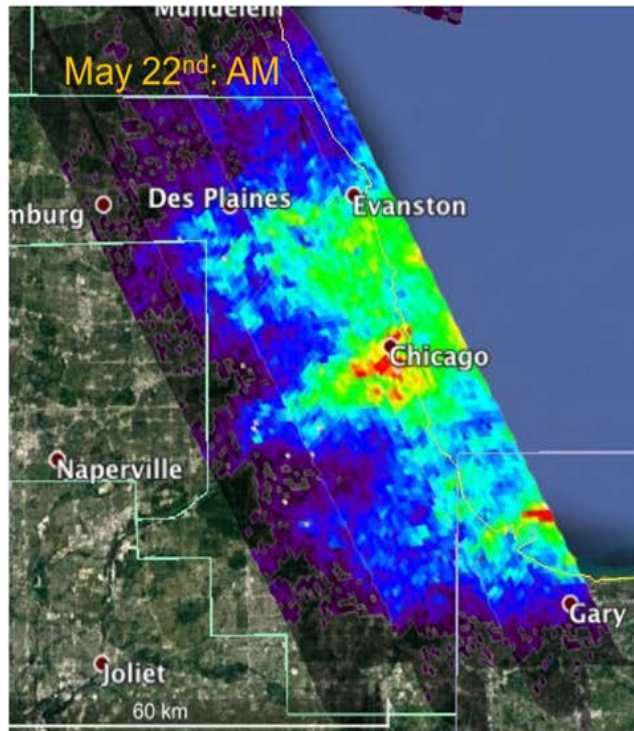
**GeoTASO (Geostationary Trace gas and Aerosol Sensor Optimization) is an airborne hyperspectral mapping instrument that is being used as an airborne testbed for future high-resolution trace-gas observations from geostationary sensors such as TEMPO**

**The Electric Power Research Institute (EPRI) provided funding for Scientific Aviation Flights during LMOS**

# NASA GeoTASO remote sensing Flights



NO<sub>2</sub> differential slant columns (DSCs) were retrieved from GeoTASO spectra via Differential Optical Absorption Spectroscopy (DOAS). The DOAS technique provides a column amount relative to a reference scene, which ideally is unpolluted and cloud-free.



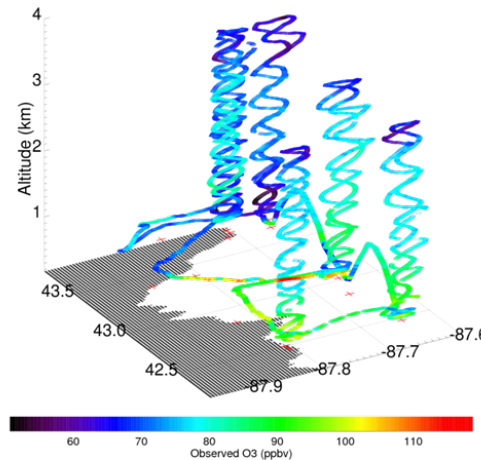
# Scientific Aviation in situ profiling Flights



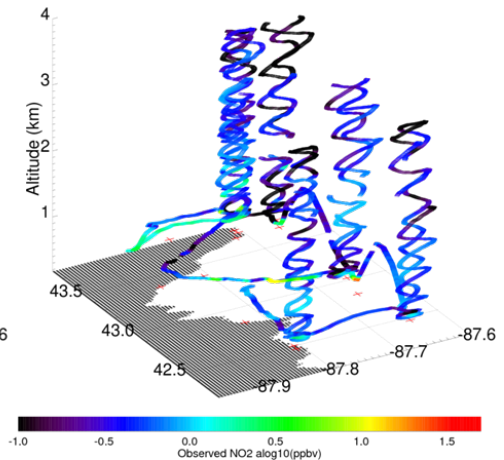
Scientific Aviation (SA) was contracted by the Electric Power Research Institute (EPRI) to participate in LMOS 2017 with airborne in situ profiling of  $O_3$ ,  $NO_2$ ,  $CO_2$ ,  $CH_4$ , altitude, T, RH, winds, and pressure.

SA flights provided vertical profiles over and offshore from selected ground sites (Sheboygan and Zion), offshore profiles east of Milwaukee and Chicago.

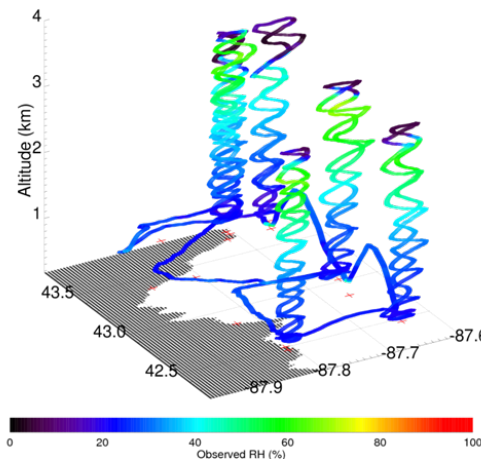
LMOS SA Flight 20170602\_R0



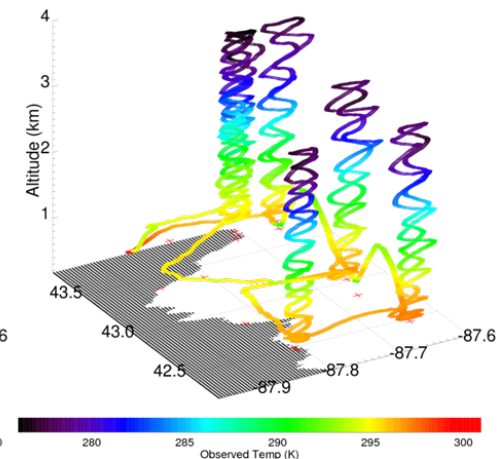
LMOS SA Flight 20170602\_R0



LMOS SA Flight 20170602\_R0



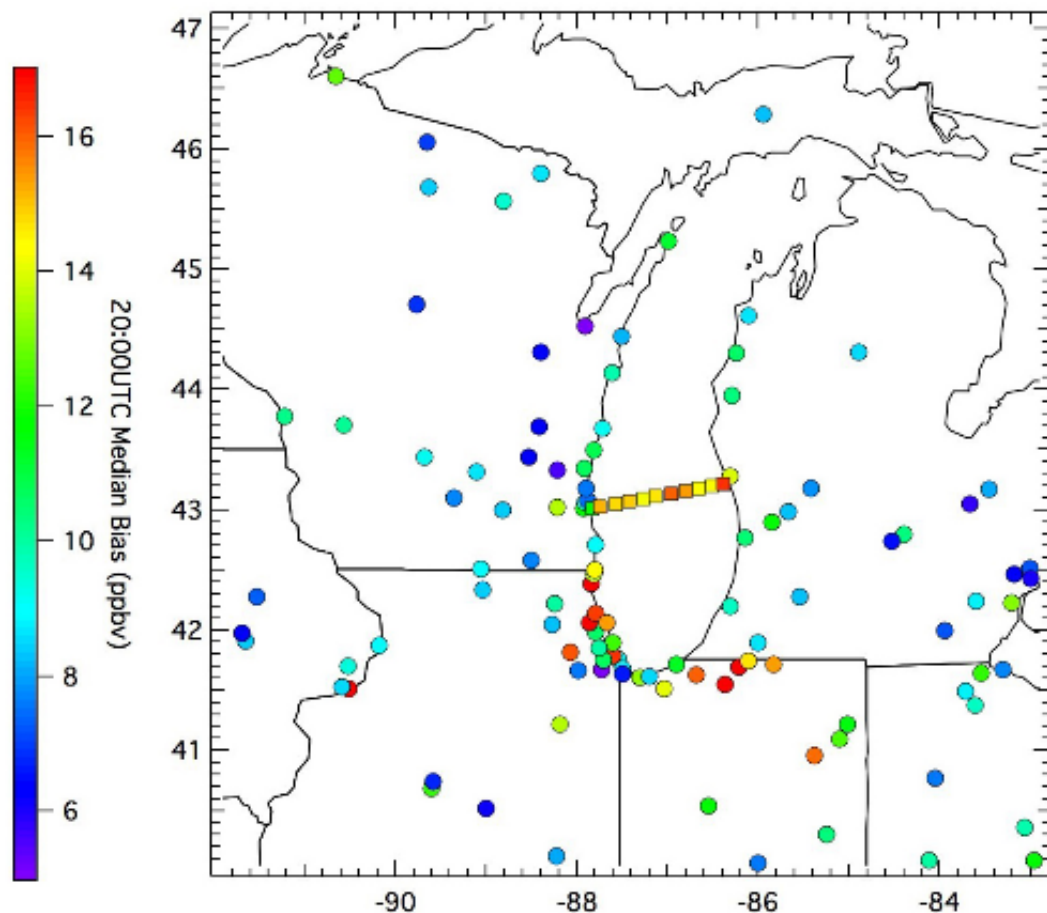
LMOS SA Flight 20170602\_R0



# NOAA National Weather Service (NWS) Air Quality Forecast

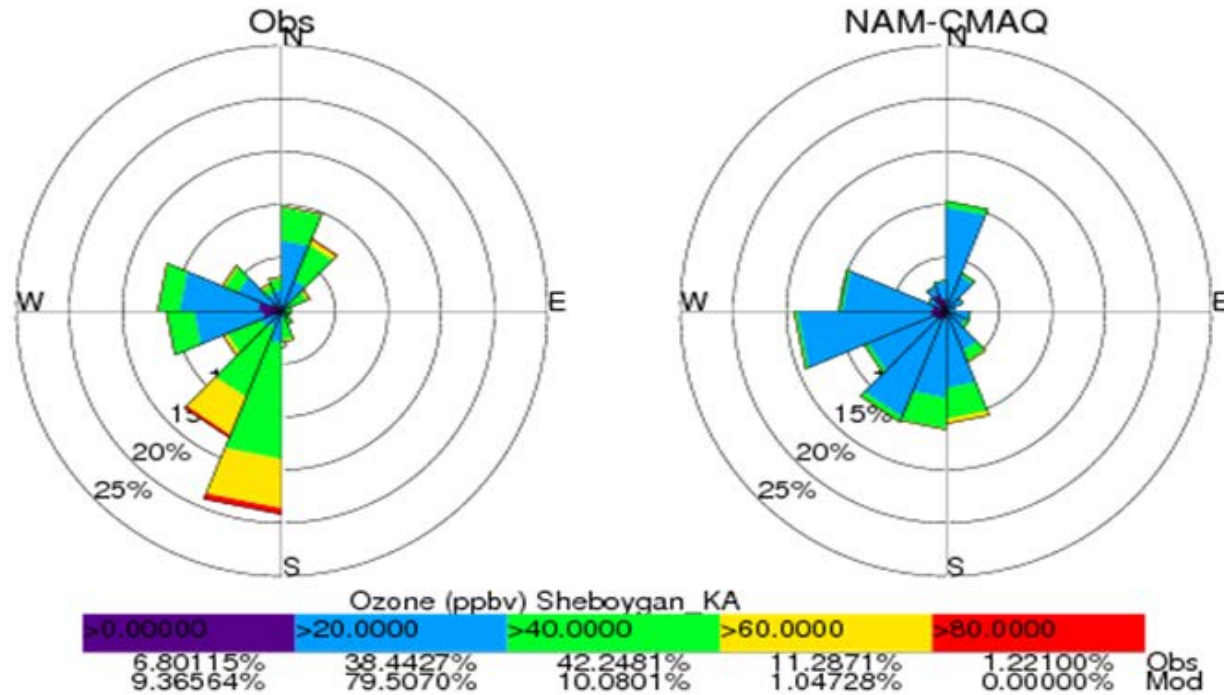
NWS air quality forecasts were evaluated during LMOS 2017

NWS operational air quality forecasts use the North American Model (NAM) meteorology to drive the EPA Community Multiscale Air Quality Model (CMAQ) to perform twice daily forecasts of air quality over the continental US (<http://airquality.weather.gov/>)



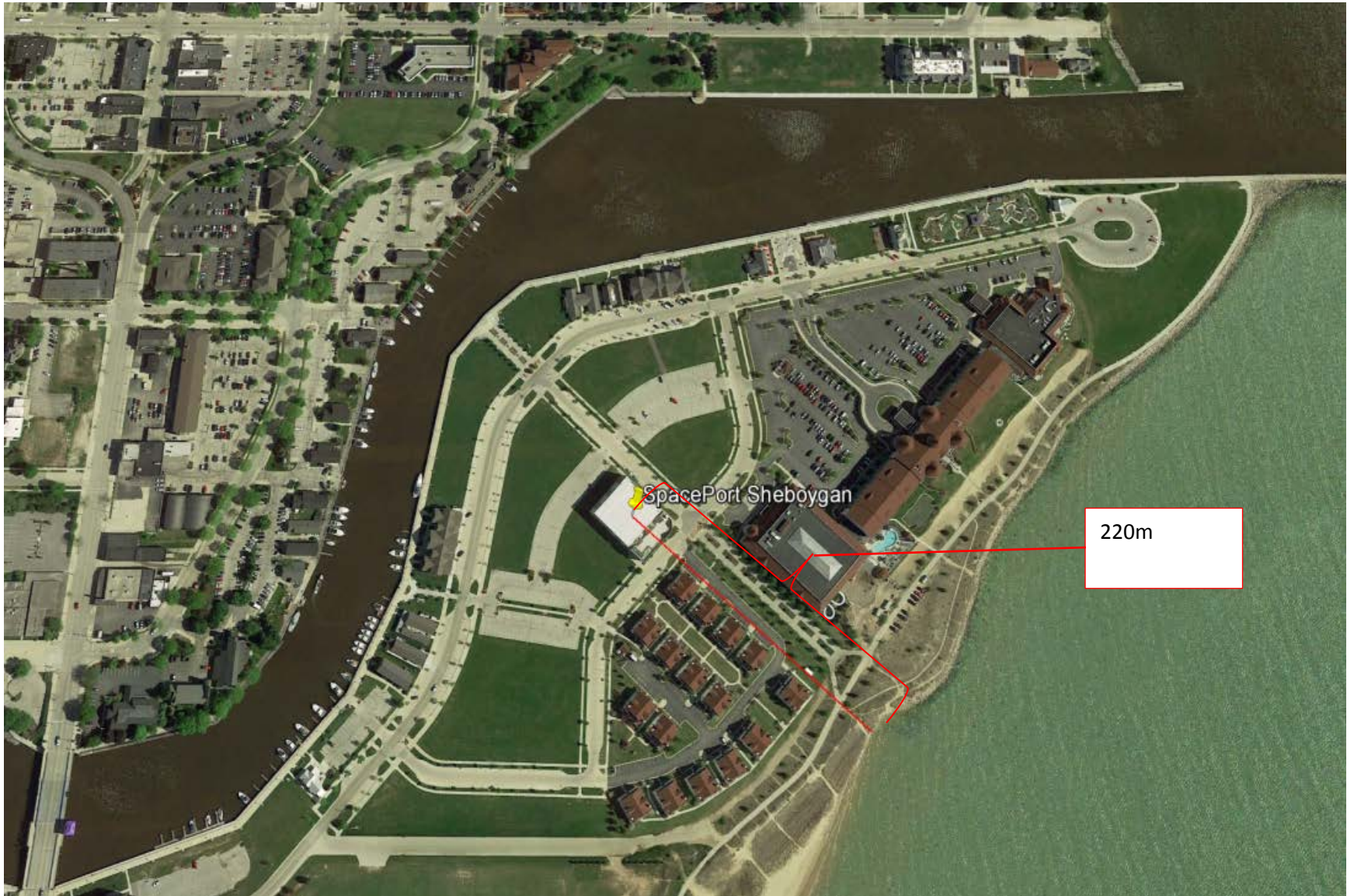
2008 to 2010 NWS NAM-CMAQ model bias for air quality EPA station monitors (circles) and Lake Express ferry (boxes) (From Cleary et al, 2015)

# NAM-CMAQ Comparison with Sheboygan KA Monitor during LMOS 2017



- Observations at Sheboygan KA monitor show that the highest ozone (>60ppbv) is associated with the prevailing SW winds
- NAM-CMAQ underestimates the frequency of the prevailing southerly winds and overestimates the frequency of westerly winds at Sheboygan KA
- NAM-CMAQ forecasts consistently underestimates ozone mixing ratios with nearly 88% of the NAM-CMAQ ozone forecasts predicting less than 40 ppbv at Sheboygan KA

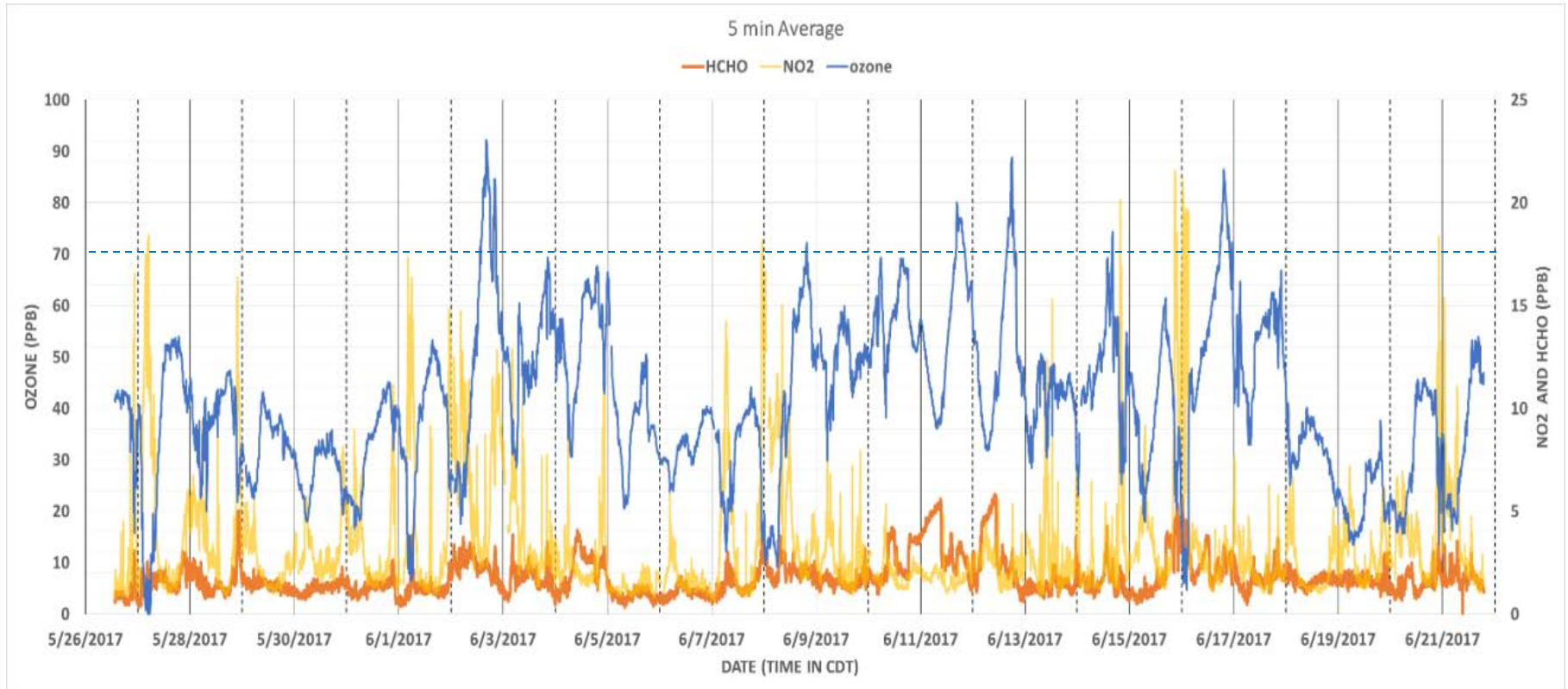
# Location of the LMOS EPA measurements in Sheboygan, WI



# Summary of EPA Measurements at Sheboygan, WI, during LMOS 2017

Measurement	Measurement Principle	Model/Manufacturer	Time Resolution	Relevant Reference
O <sub>3</sub>	Scrubberless Ultraviolet Photometric (SL-UV)	2B Technology M211*	10-seconds	EQOA-0514-215
	Ultraviolet Photometric	2B Personnel Ozone Monitors	1-minute	EQOA-0815-227.
NO/NO <sub>2</sub> /NO <sub>x</sub>	Cavity attenuated phase shift spectroscopy (CAPS)	Teledyne T500U*	10-seconds	EQNA-0514-212
	O <sub>3</sub> Chemiluminescence with Molybdenum converter	Teledyne T200U	10-seconds	RFNA-1194-099
NO <sub>y</sub>	O <sub>3</sub> Chemiluminescence with external Molybdenum converter at 10m	Teledyne T200U	10-seconds	NA
HCHO	Quantum Cascade Laster (1765 cm-1)	Aerodyne Research*	1- seconds	Herndon et al., 2007
O <sub>3</sub> /NO <sub>2</sub> /HCHO column densities	Sun-sky radiances 280-525nm	NASA Goddard Pandora Spectrometer	Total columns every 80-s	Herman et al., 2009
*WS, WD, T, RH, BP, Prec.	Various	Vaisala WXT520 with ultrasonic wind sensors		

# Time series of O3, NO2 and HCHO measurements at Spaceport Sheboygan



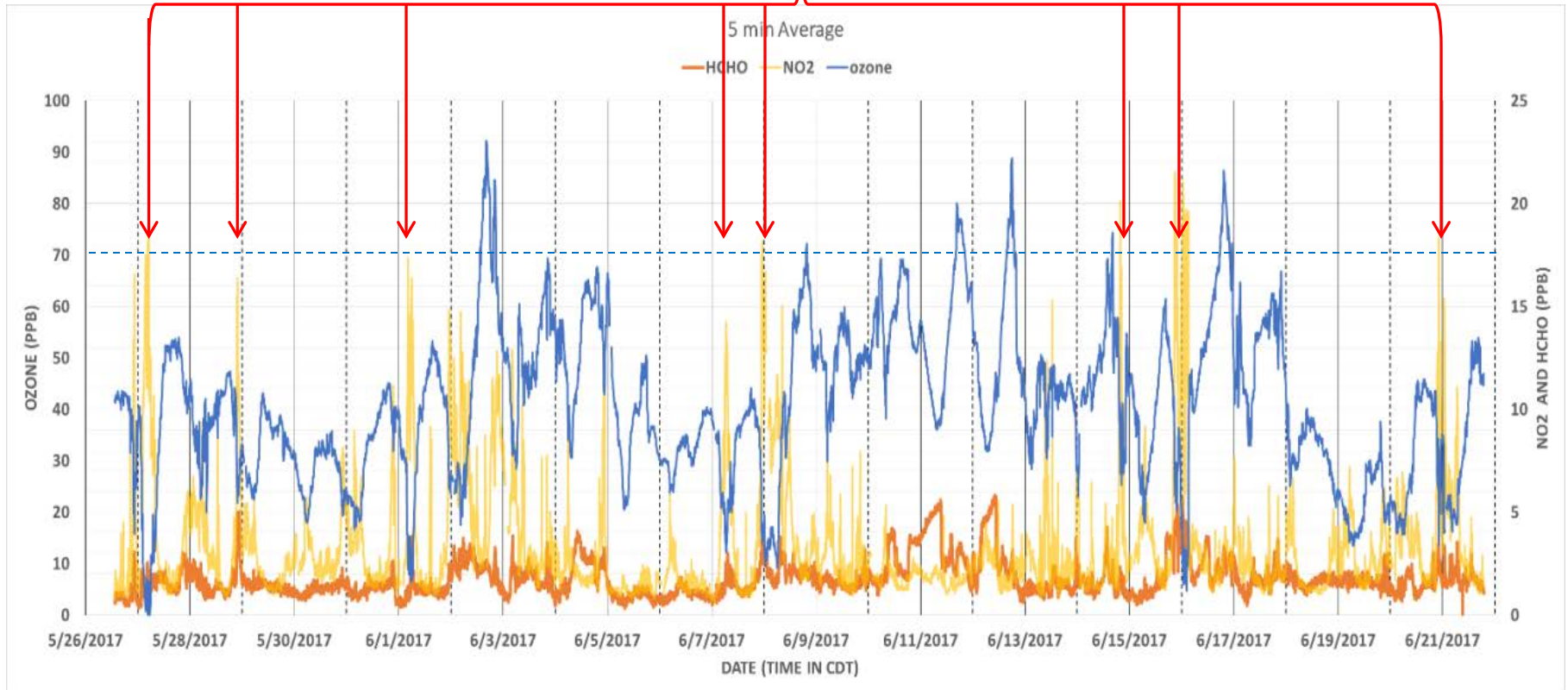
Formaldehyde (HCHO) and nitrogen dioxide (NO<sub>2</sub>) serve to indicate the chemical regime for ozone formation (i.e., NO<sub>x</sub> limited and volatile organic compound (VOC) limited) at Sheboygan.

**(Jim Szykman, EPA)**



# Time series of O3, NO2 and HCHO measurements at Spaceport Sheboygan

Likely influence of power plant plumes

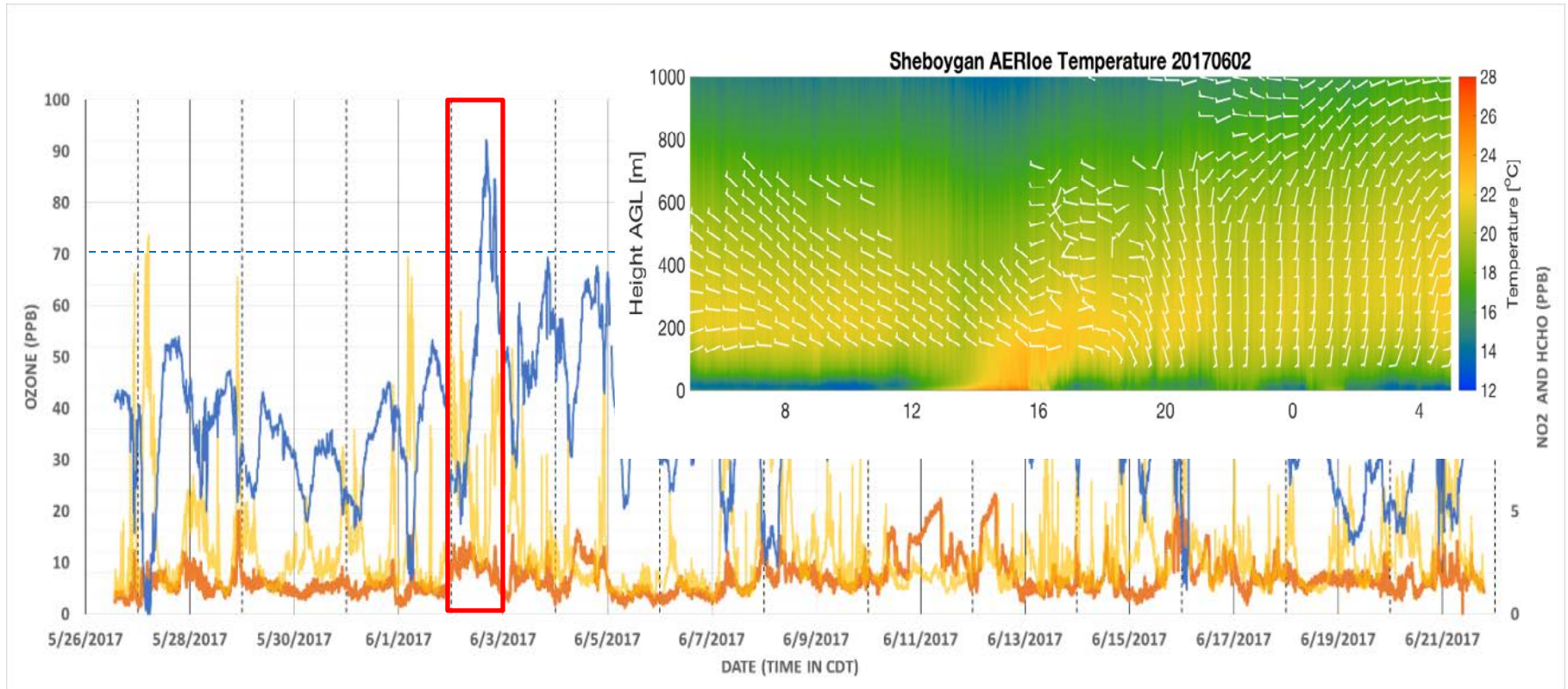


Formaldehyde (HCHO) and nitrogen dioxide (NO2) serve to indicate the chemical regime for ozone formation (i.e., NOx limited and volatile organic compound (VOC) limited) at Sheboygan.

**(Jim Szykman, EPA)**

# Time series of O3, NO2 and HCHO measurements at Spaceport Sheboygan

Ozone Exceedance Day: June 02, 2017 (wind and temperature profiles)

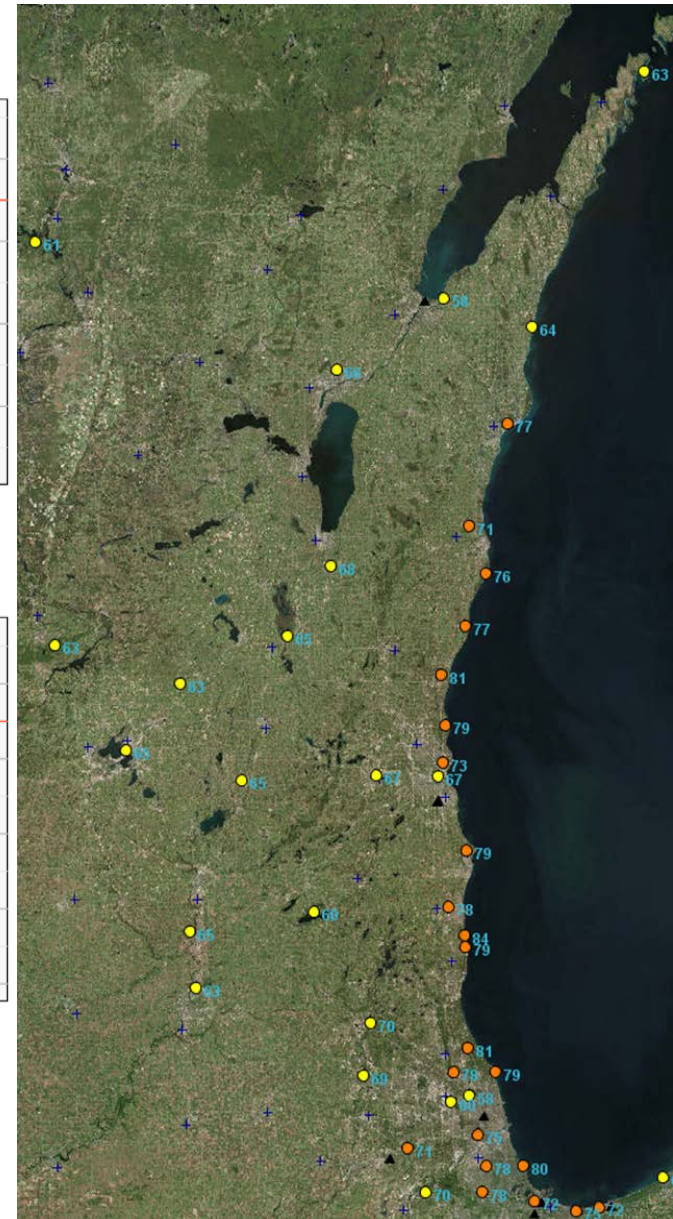
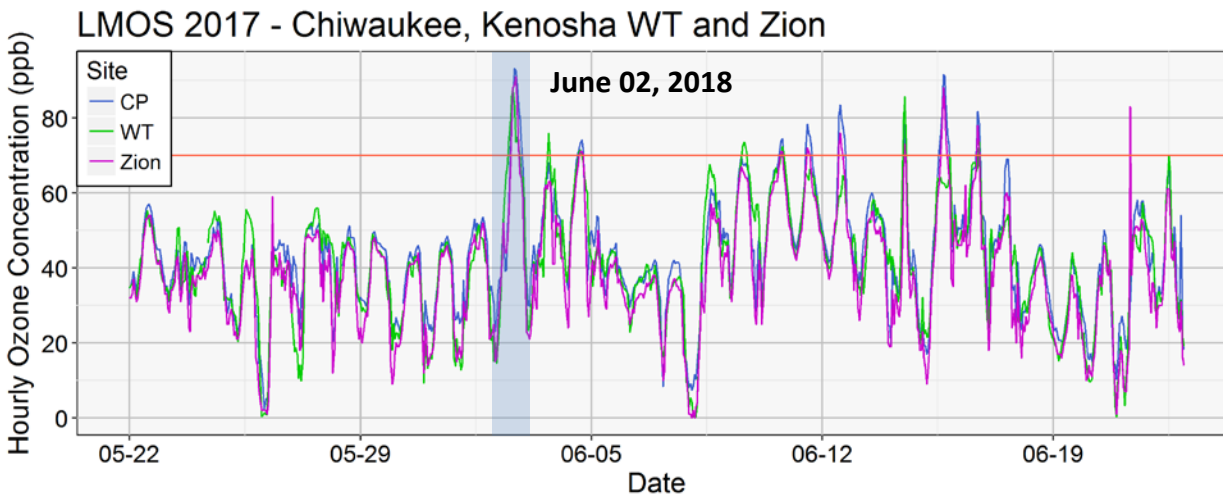
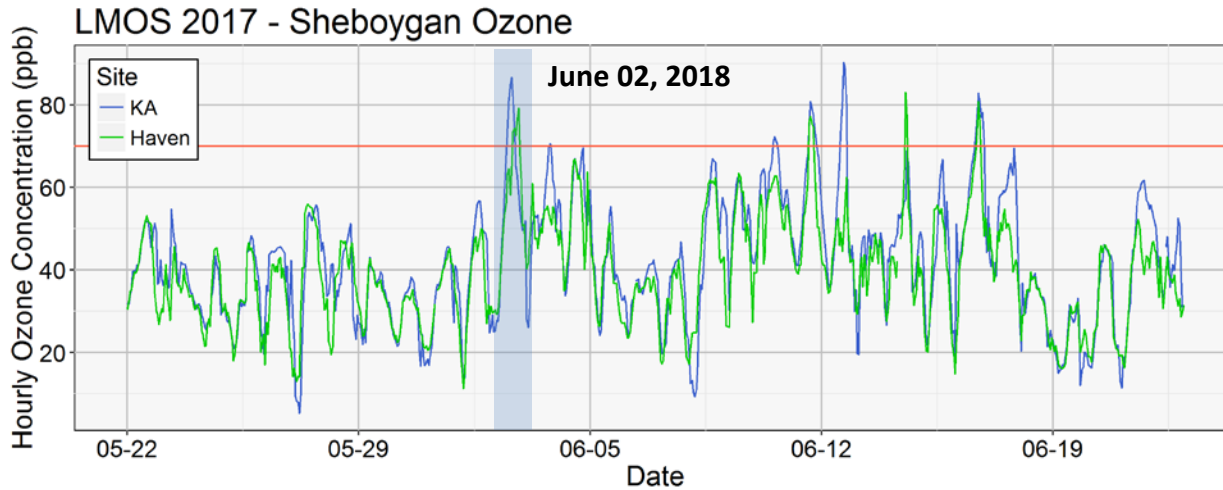


Formaldehyde (HCHO) and nitrogen dioxide (NO<sub>2</sub>) serve to indicate the chemical regime for ozone formation (i.e., NO<sub>x</sub> limited and volatile organic compound (VOC) limited) at Sheboygan.

(Tim Wagner, UW-Madison/SSEC)

# Lakeshore ozone during LMOS 2017

June 02, 2017 MDA8



(Angie Dickens , WDNR)

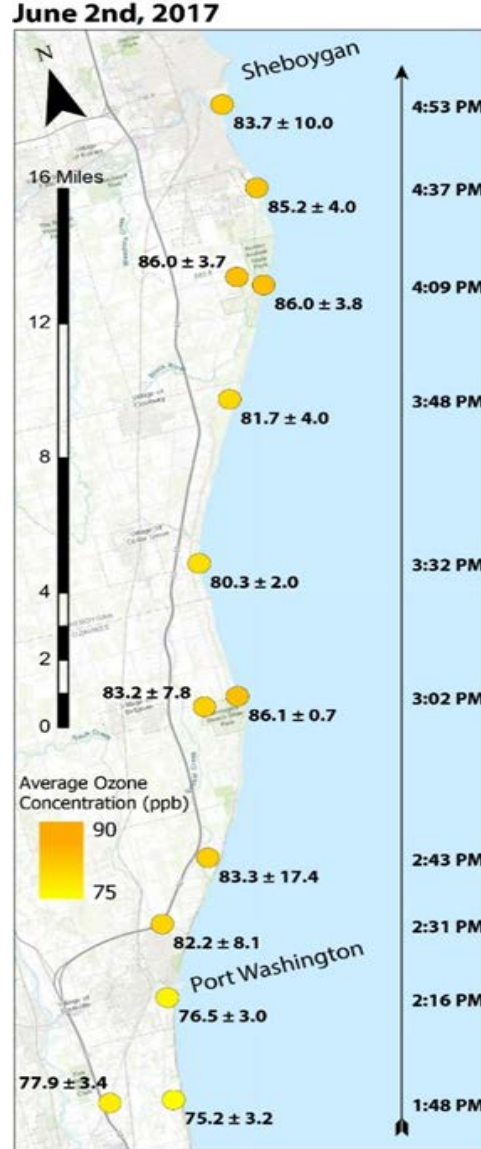
MDA8=Maximum Daily 8 hour Average

# Along shore O3 gradients

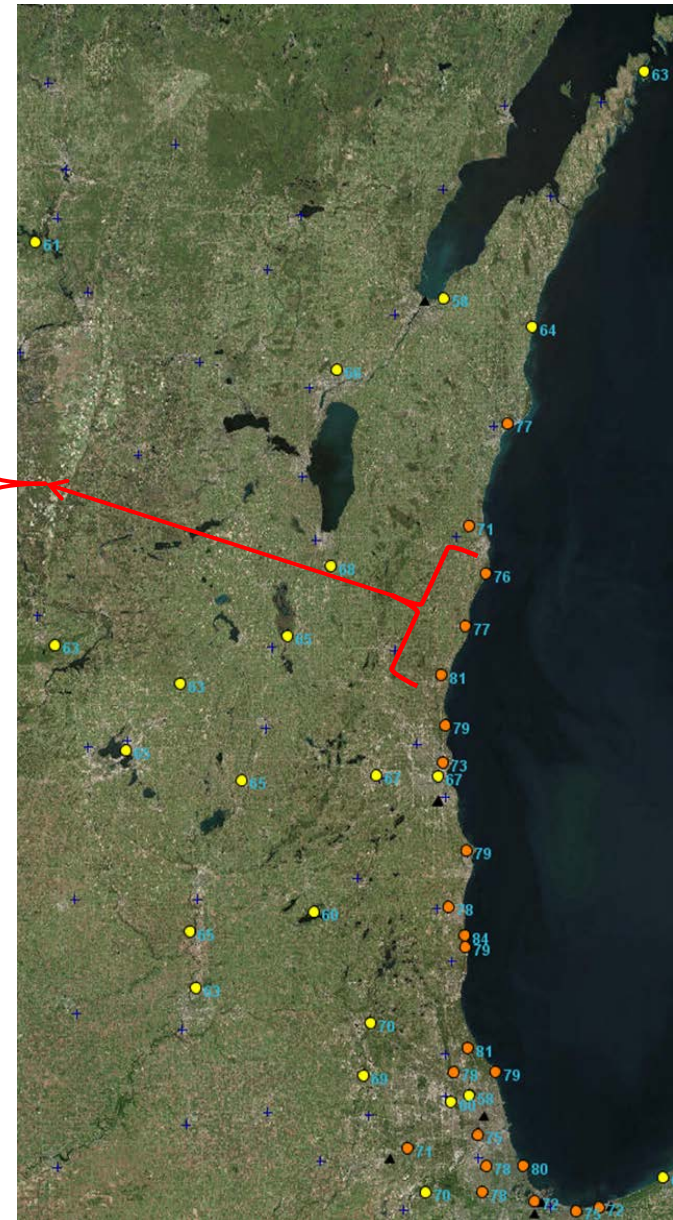
Kohler-Andrae Dunes

Harrington Beach Park

Grafton



# June 02, 2017 MDA8

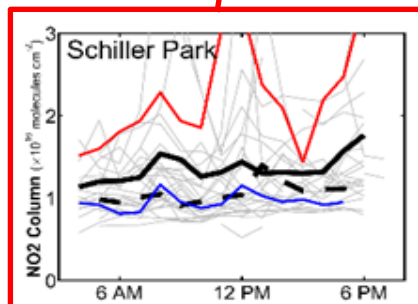
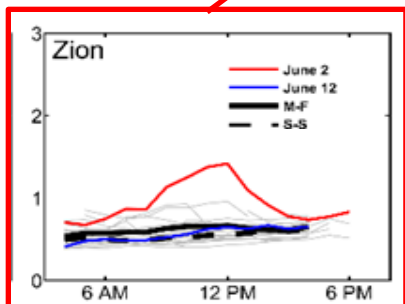
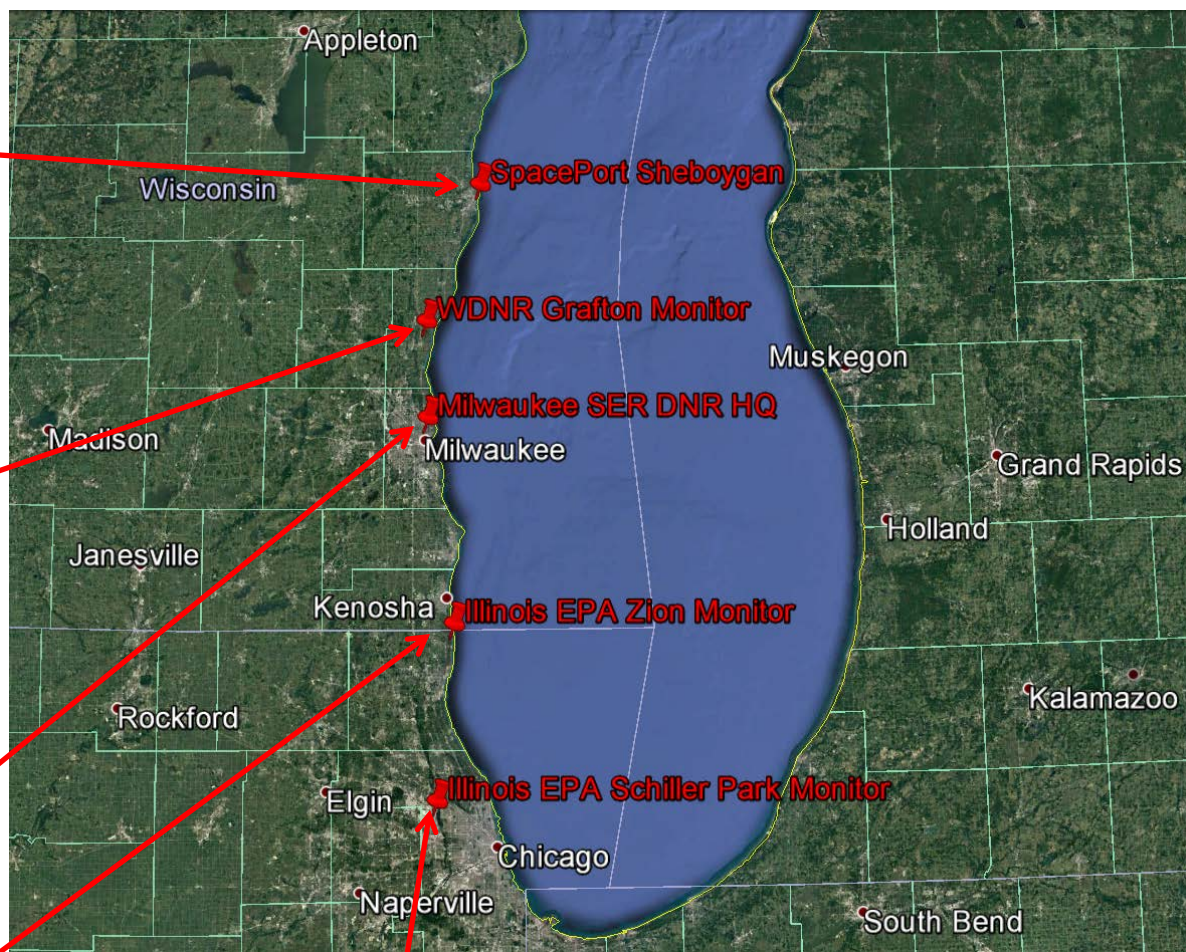
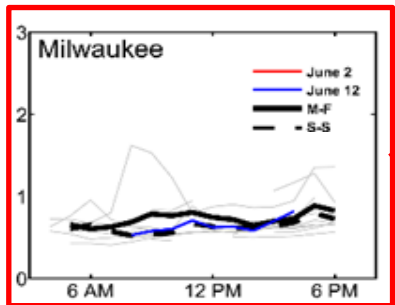
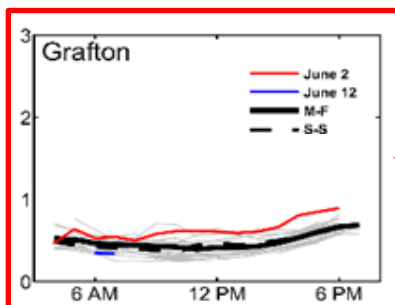
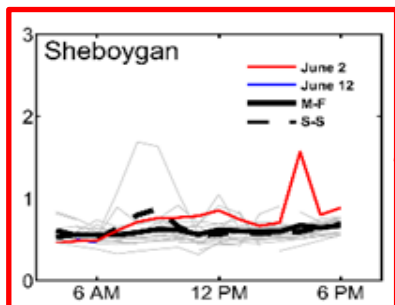


UW-Eau Claire automobile platform ozone measurements show increasing coastal ozone concentrations through the afternoon of June 2, 2017

(Patricia Cleary, UW-Eau Claire)

MDA8=Maximum Daily 8 hour Average

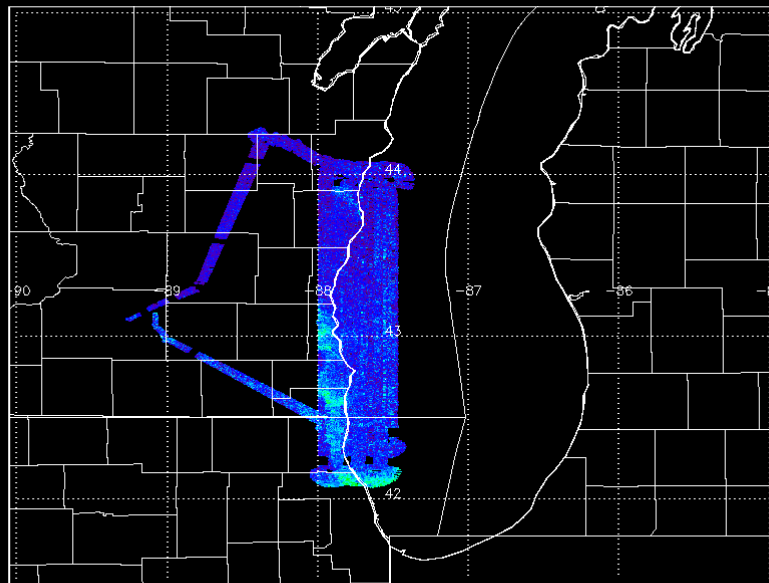
# Ground based UV/visible grating spectrometers (Pandoras) column NO<sub>2</sub> measurements during LMOS 2017



Pandora NO<sub>2</sub> column measurements show high values at Zion, Grafton, and Sheboygan on June 2, 2017

(Luke Valin, EPA)

# GeoTASO NO2 Slant Column June 02, 2017

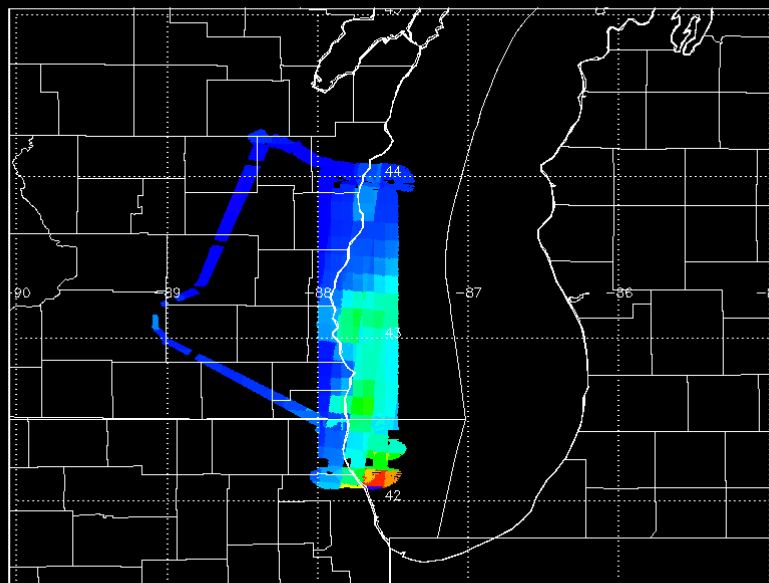


0 5.0x10<sup>14</sup> 1.0x10<sup>15</sup> 1.5x10<sup>15</sup> 2.0x10<sup>15</sup> 2.5x10<sup>15</sup> 3.0x10<sup>15</sup>  
NO2 Slant Column with Strat Adjustment (mol/cm<sup>2</sup>)x10<sup>15</sup>

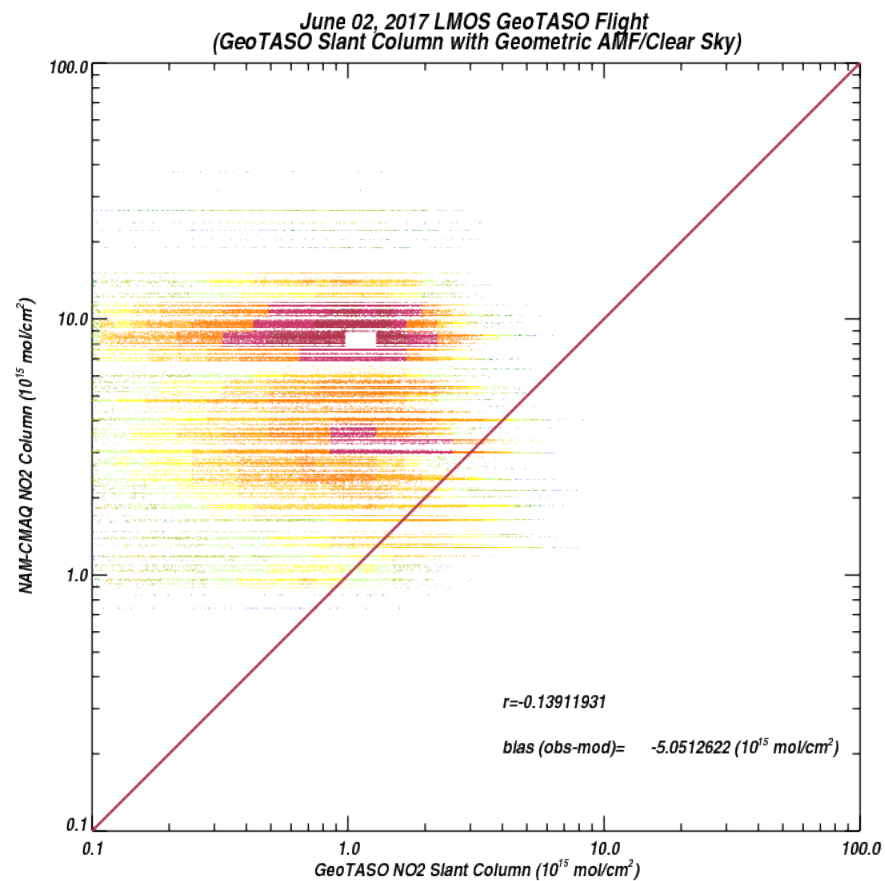
# GeoTASO Coastal Survey Flight June 02, 2017

**NWS NAM-CMAQ significantly overestimates observed NO2 column**

# NAM-CMAQ NO2 Column June 02, 2017



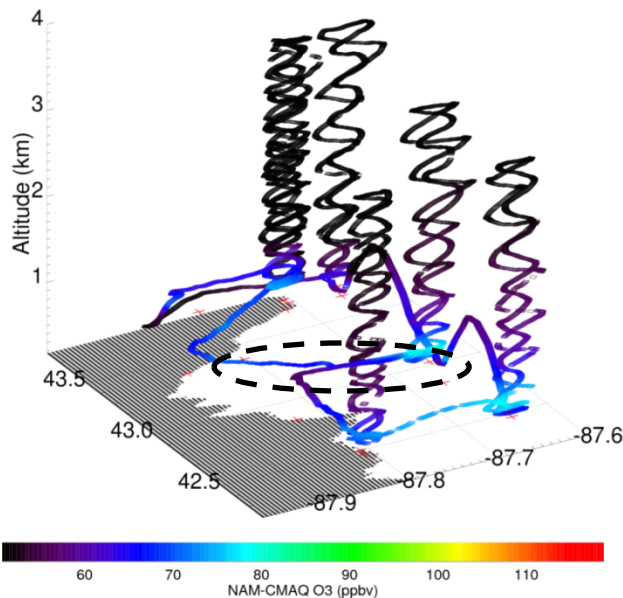
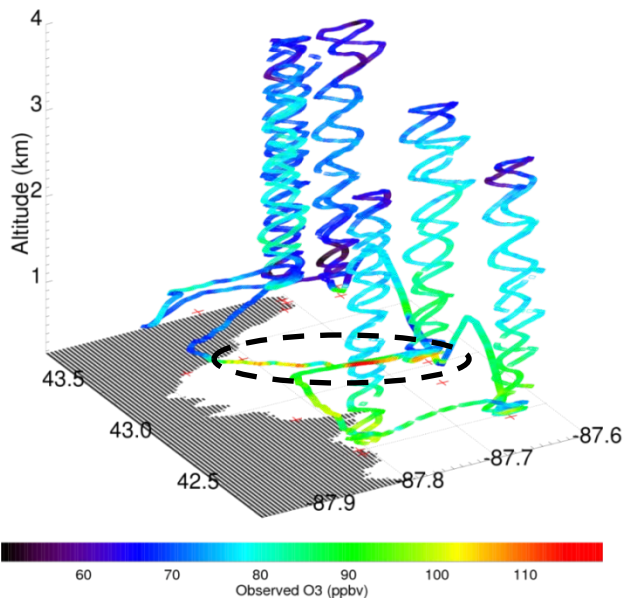
0 5 10 15 20 25 30  
NAM-CMAQ NO2 Column (mol/cm<sup>2</sup>)x10<sup>15</sup>



# Coastal Ozone Exceedance Day

LMOS SA Flight 20170602\_R0

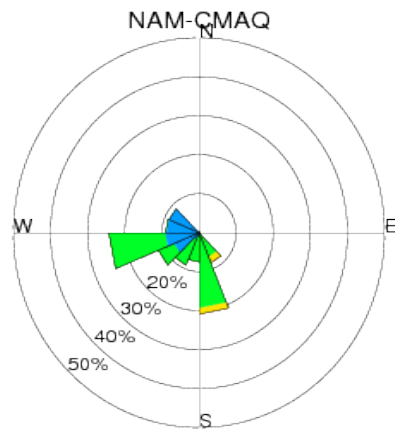
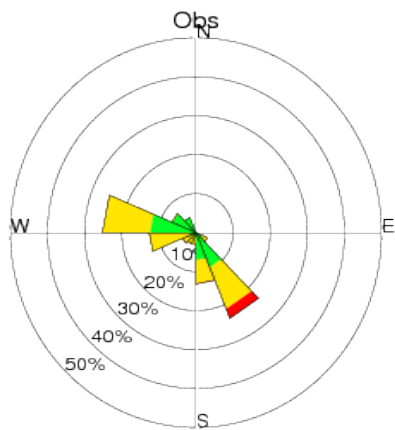
LMOS SA Flight 20170602\_R0



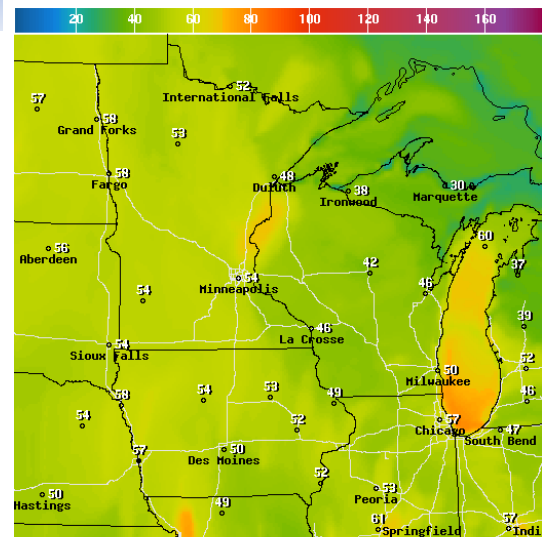
**NWS NAM-CMAQ significantly underestimates ozone concentrations within the marine boundary layer**

**Max Observed O3 > 110ppbv**

**Max NAM-CMAQ O3 < 80ppbv**



Ozone (ppbv) 20170602_R0				
<0.00000	>25.0000	>50.0000	>75.0000	>100.000
0.00000%	0.00000%	45.2689%	51.7385%	2.99258%
0.00000%	35.6980%	60.8076%	3.49442%	0.00000%
				Obs Mod



Maximum 1hr Ozone(PPB) Ending Fri Jun 02 2017 11PM EDT (Sat Jun 03 2017 03Z)

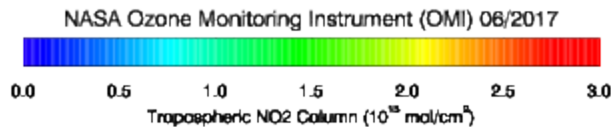
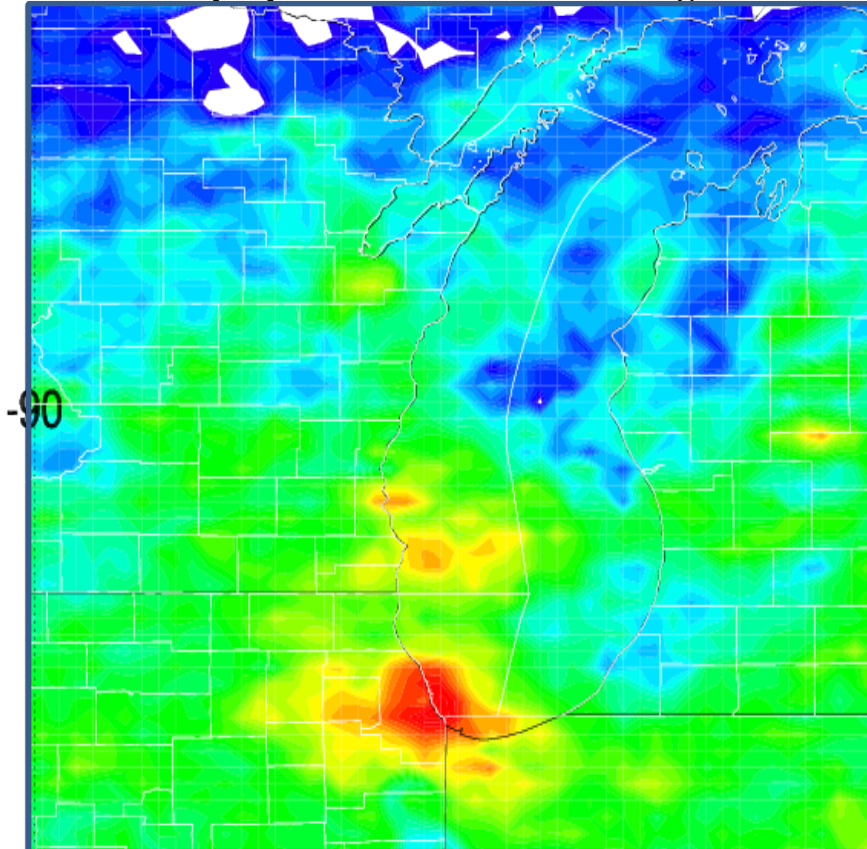


National Digital Guidance Database  
06z model run Graphic created-Jun 02 6:44AM EDT



# Aura Ozone Monitoring Instrument (OMI) Tropospheric NO<sub>2</sub> column Data Assimilation

OMI Tropospheric NO<sub>2</sub> column during June 2017



$$\frac{\Delta E}{E} = \beta \times \frac{\Delta \Omega}{\Omega}$$

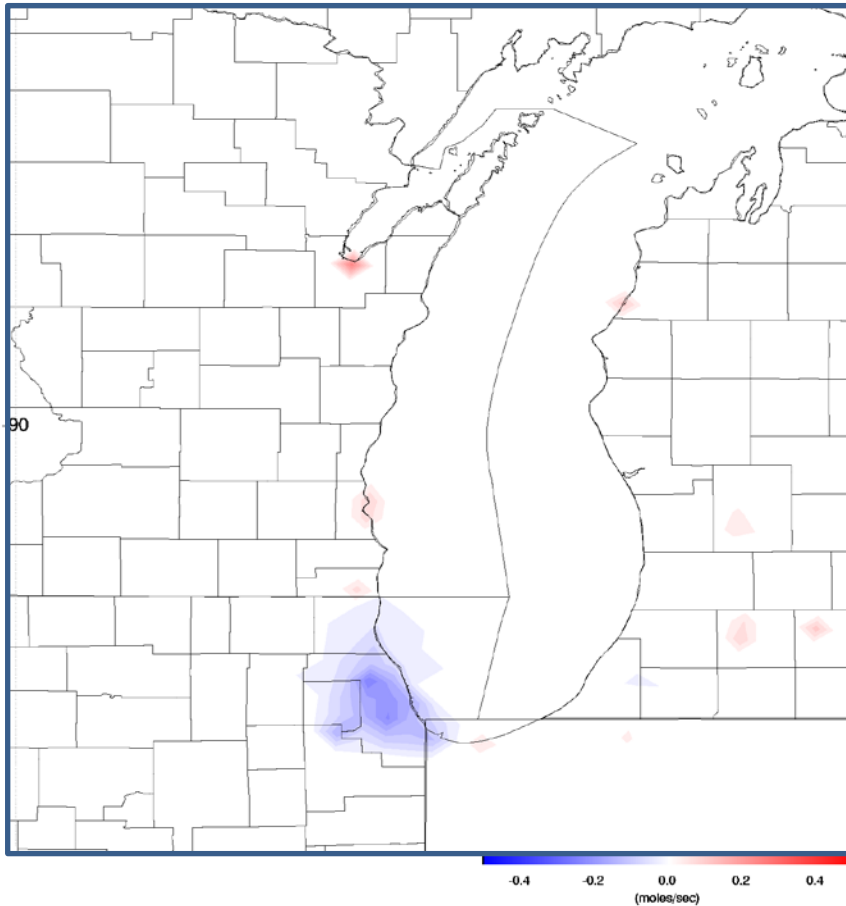
**NO<sub>x</sub> emissions adjustments ( $\Delta E$ ) are constrained using OMI tropospheric NO<sub>2</sub> column analysis increments ( $\Delta \Omega$ )**

**$\beta$  accounts for the sensitivity of the NO<sub>2</sub> column to changes in NO<sub>x</sub> emissions following Lamsal et al 2011.**



# Aura Ozone Monitoring Instrument (OMI) Tropospheric NO<sub>2</sub> column Data Assimilation

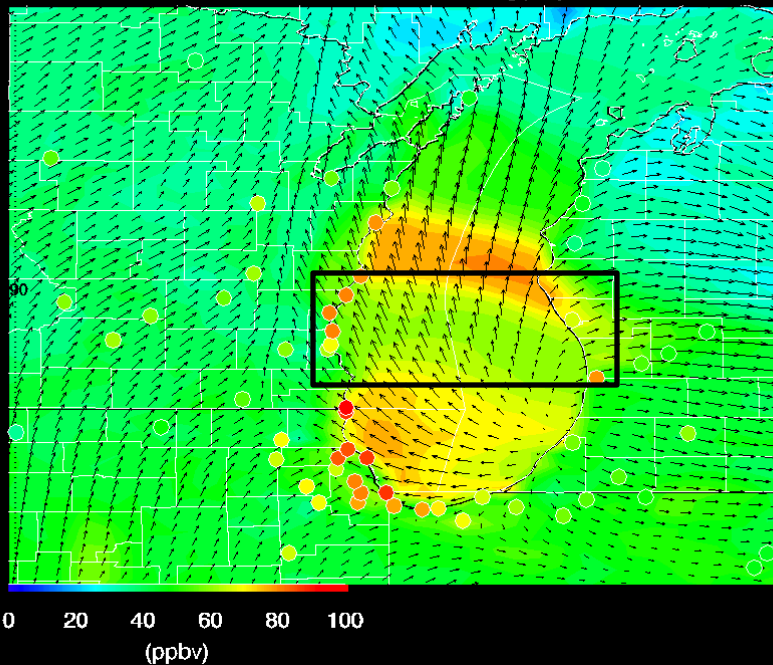
Change in NAM-CMAQ NO<sub>x</sub> emissions LMOS 2017  
(Adjusted with OMI Analysis Increment - Control)



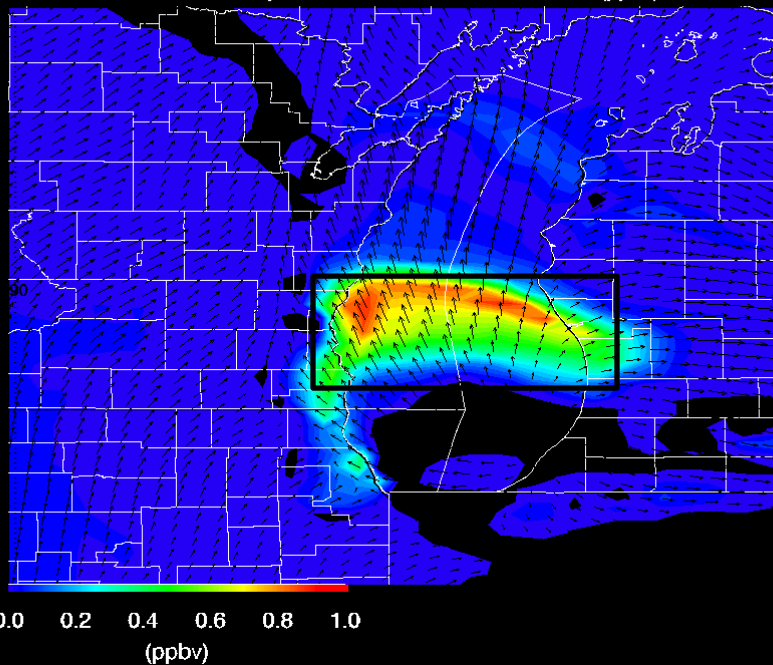
$$\frac{\Delta E}{E} = \beta \times \frac{\Delta \Omega}{\Omega}$$

**Assimilation of OMI NO<sub>2</sub> results in small (~4%) reductions in NO<sub>x</sub> emissions over Chicago**

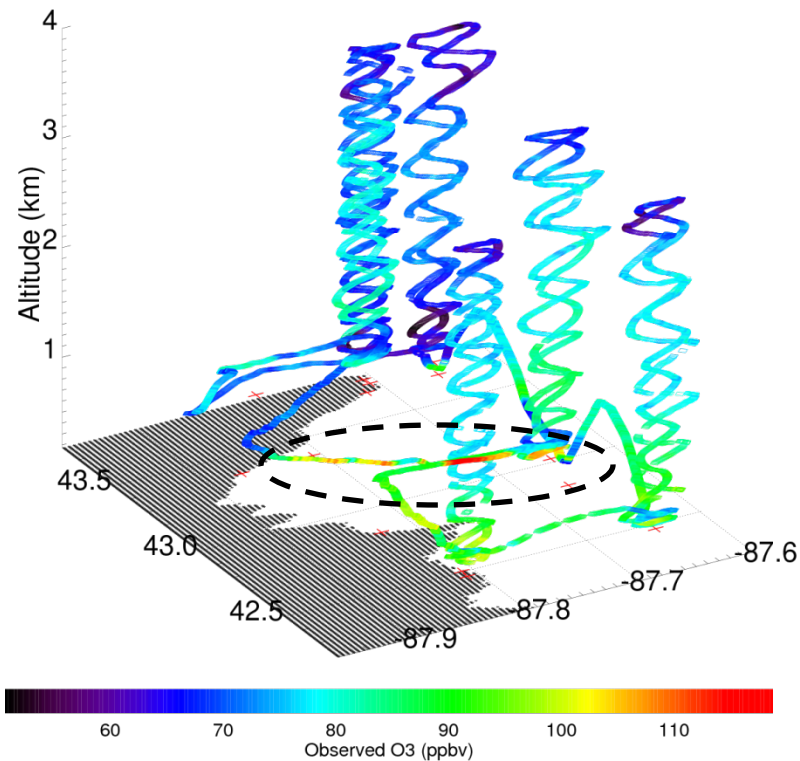
AIRNOW & NAM-CMAQ 12km Control Sfc O3 (ppbv) 06/02/2017 23Z



NAM-CMAQ 12km GSI/OMI Adjust NOx-Control Sfc O3 Difference (ppbv) 06/02/2017 23Z



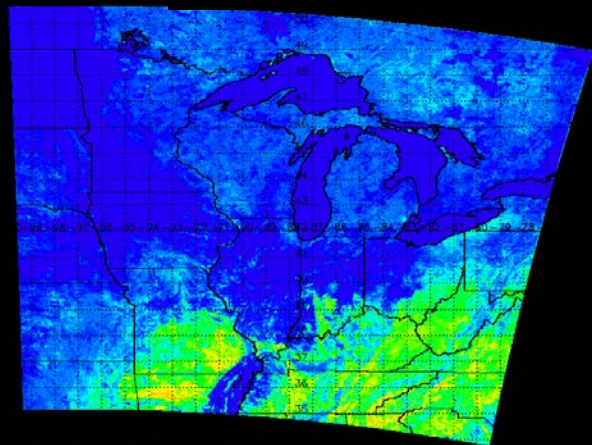
LMOS SA Flight 20170602\_R0



**Max Observed O3 > 110ppbv**

**Reductions in NO<sub>x</sub> emissions on high ozone day leads to slight (~1ppbv) increases in surface ozone**

Leaf Area Index May 01, 2017



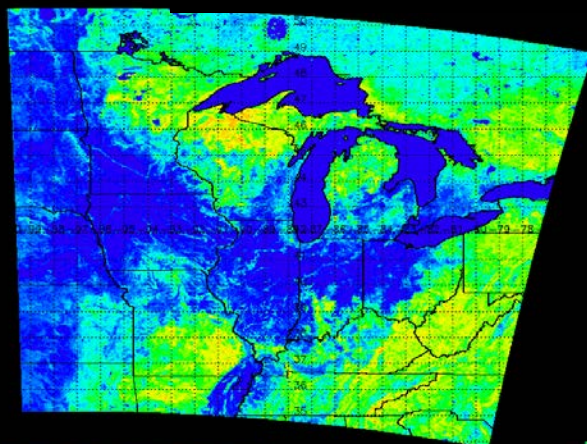
0 1 2 3 4 5 6 7 (m²/m²)

Increased biogenic VOCs can enhance ozone production in urban plumes

# Biogenic VOC Sensitivity Studies

## NAM-CMAQ 2x Biogenic emission Experiment May 22 – June 13, 2018

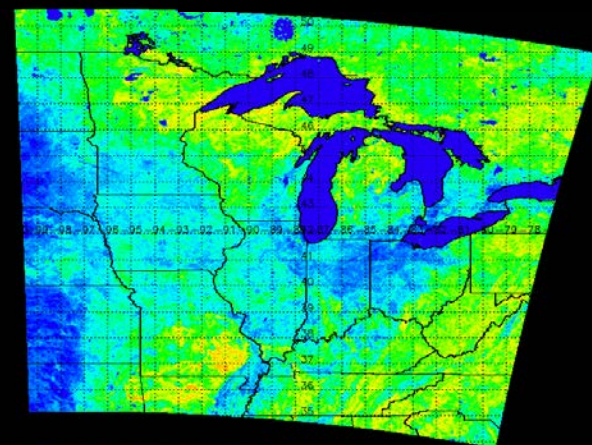
Leaf Area Index June 02, 2017



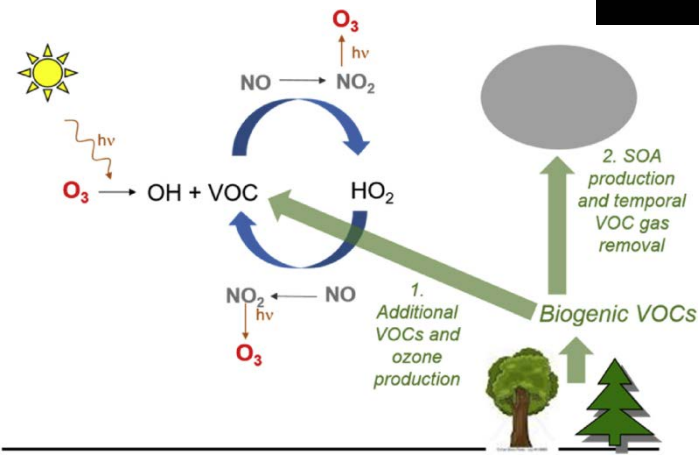
0 1 2 3 4 5 6 7 (m²/m²)

Isoprene (biogenic VOC) emissions increase with leaf area (leaf out)

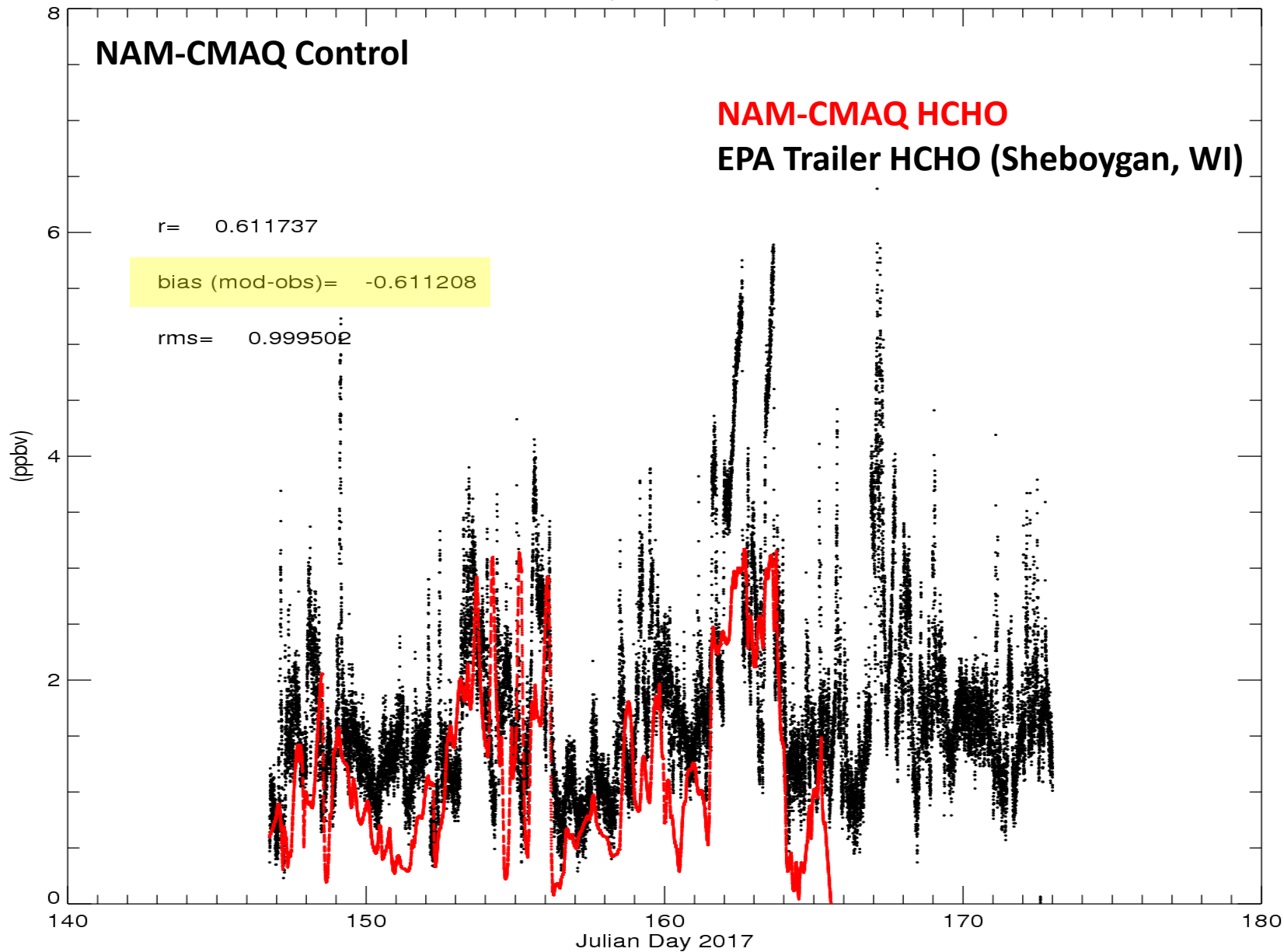
Leaf Area Index July 04, 2017



0 1 2 3 4 5 6 7 (m²/m²)

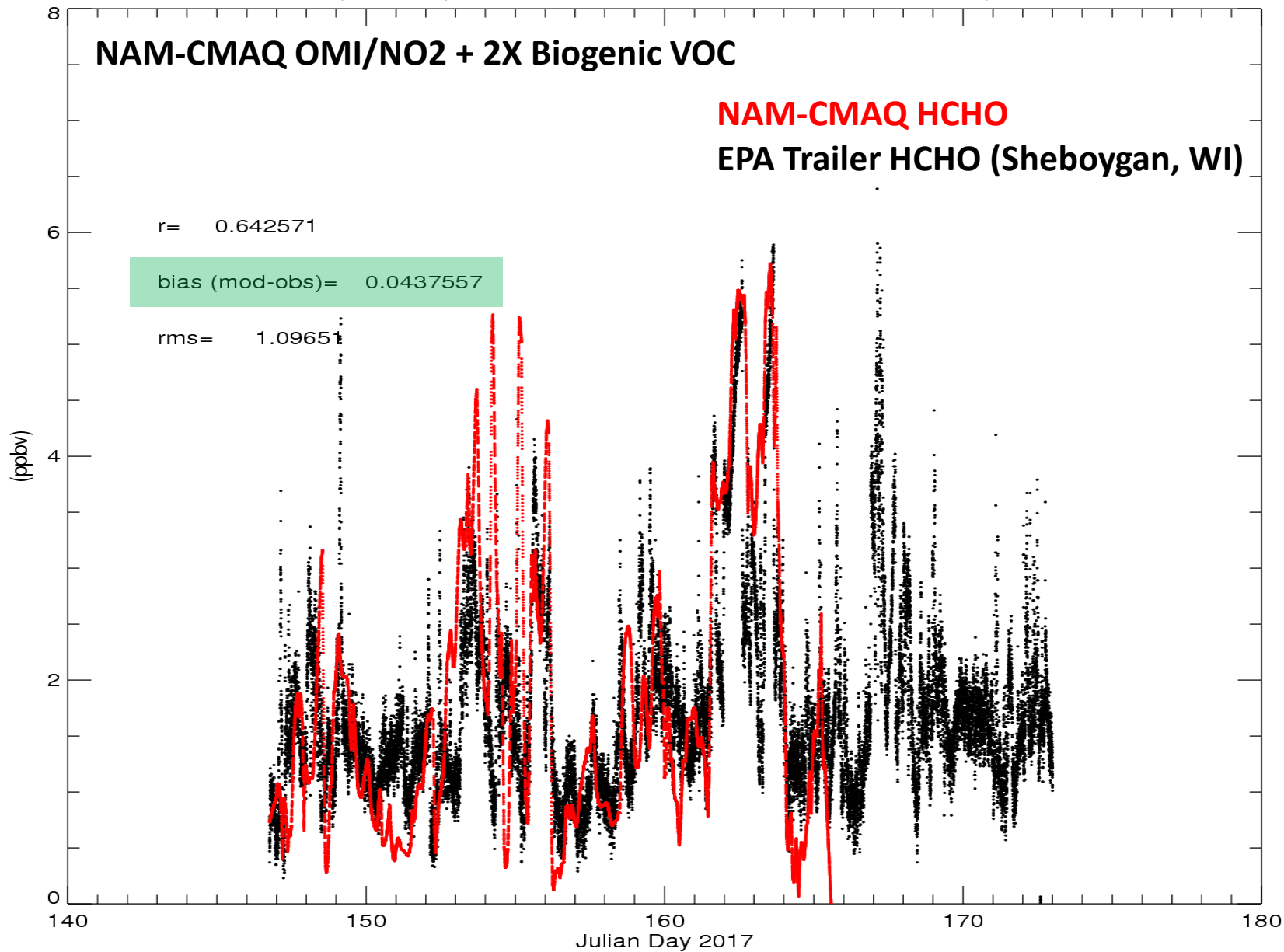


EPA Trailer HCHO (OBS=Black/MOD=Red)  
(Control)



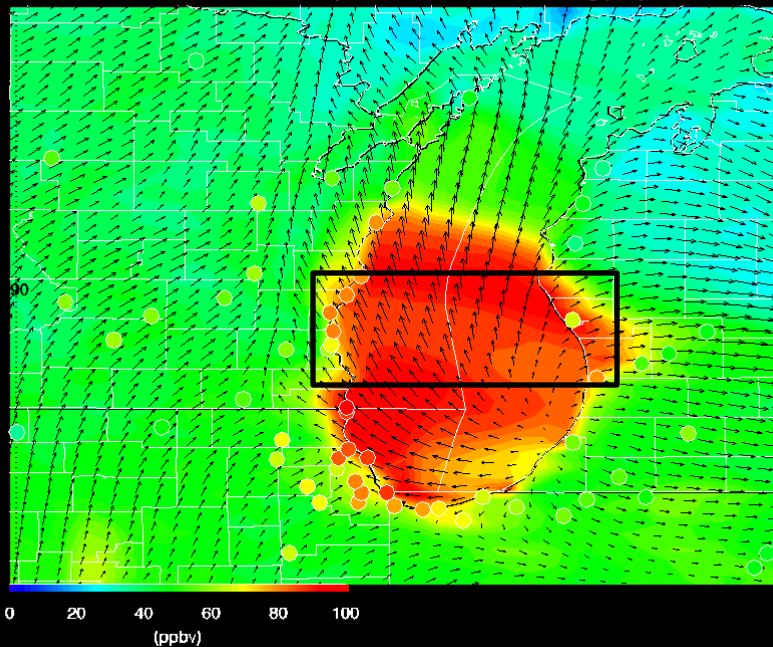
**In situ HCHO provided by Jim Szykman (EPA)**

EPA Trailer HCHO (OBS=Black/MOD=Red)  
(GSI Adjusted NOx and 2X Biogenic Emissions)

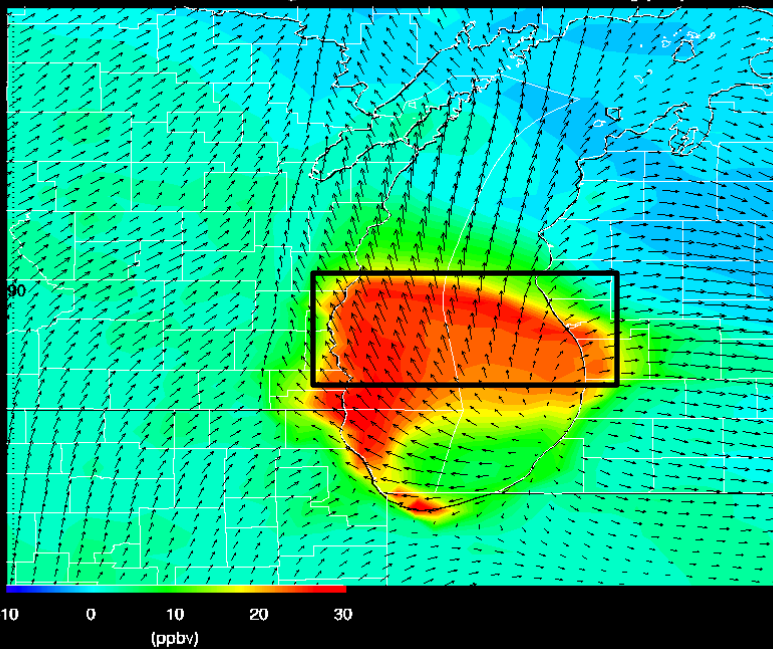


**In situ HCHO provided by Jim Szykman (EPA)**

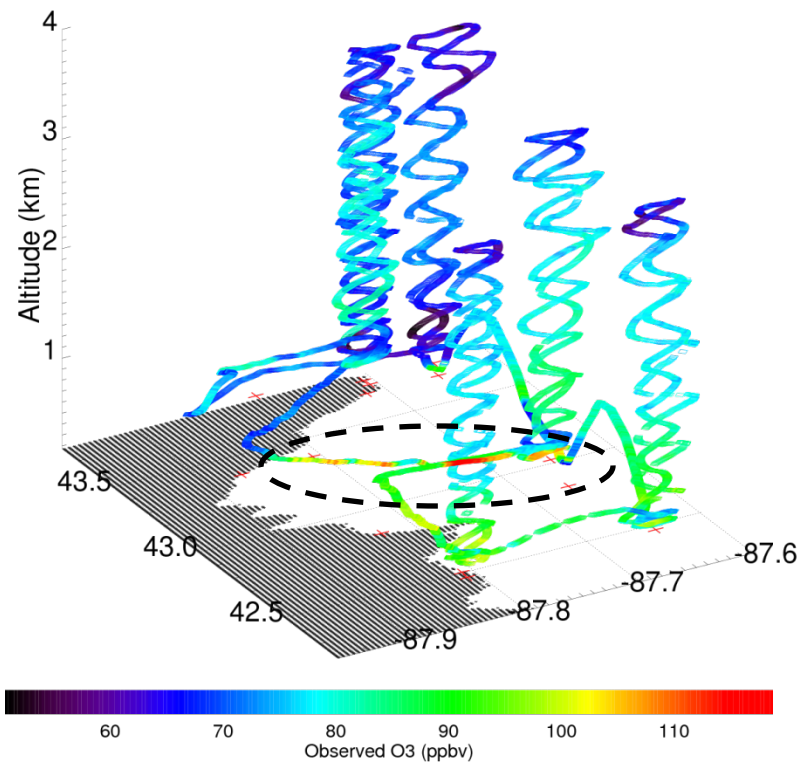
AIRNOW & NAM-CMAQ 12km 2xBiogenic/OMI NO2 DA Sfc O3 (ppbv) 06/02/2017 23Z



AIRNOW & NAM-CMAQ 12km 2xBiogenic/OMI NO2 DA - Control Sfc O3 (ppbv) 06/02/2017 23Z



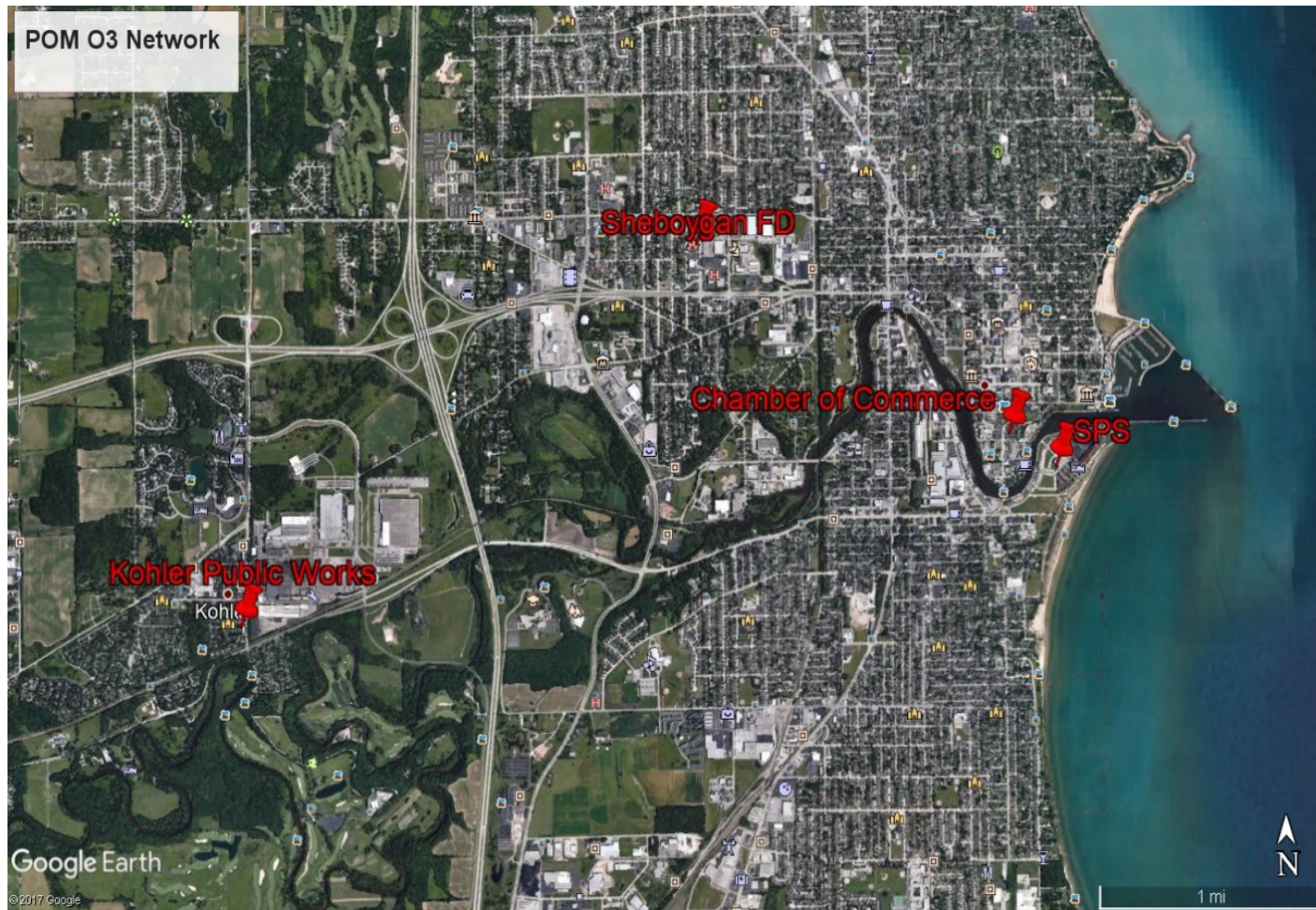
LMOS SA Flight 20170602\_R0



**Max Observed O3 > 110ppbv**

**2X Biogenic emissions on high ozone day leads to large (~30ppbv) increases in surface ozone**

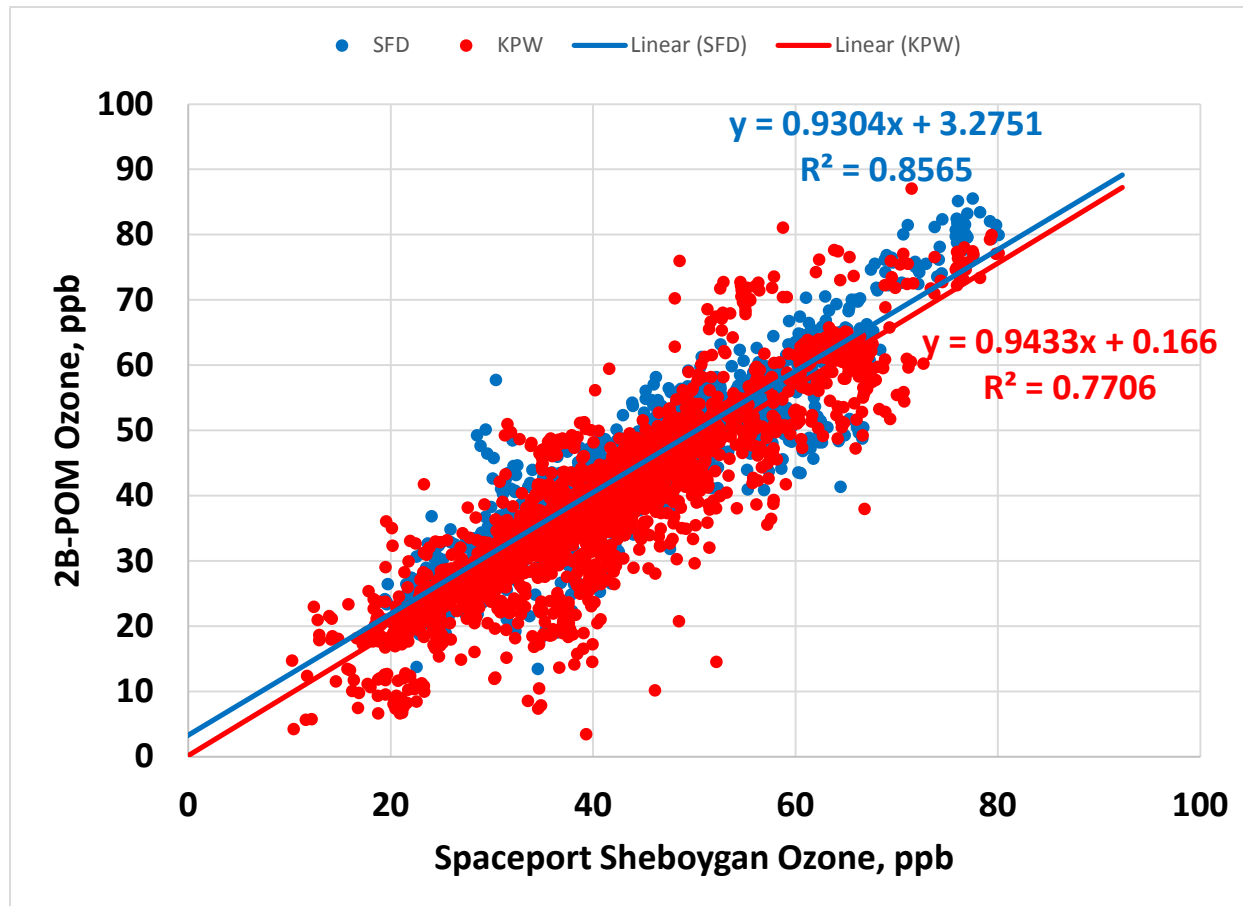
## Locations of the 2B-Personal Ozone Monitors for inland gradient study



Intermittent data capture issues were experienced with all of the 2B-POM instruments. The data capture rate was 95.8% at Spaceport Sheboygan (SPS), 22.2% at Sheboygan Chamber of Commerce, 27.3% at Sheboygan Fire Department, and 27.3% at Kohler Public Works.

**(Jim Szykman, EPA)**

# Regression of the inland 2B-POMs against the Spaceport Sheboygan data



The regressions indicate that the furthest site inland from the lakeshore (Kohler Public Works, KPW) experiences ozone values 5-6% lower than the lakeshore site (Spaceport Sheboygan).

(Jim Szykman, EPA)



# Summary and Conclusions

- **Significant ozone events occurred during LMOS 2017, with exceedances of the 70 ppb 8-hr ozone threshold on June 2, June 11-12, and June 14-16. The LMOS 2017 aircraft observed polluted layers with rapid ozone formation occurring in a shallow layer near the Lake Michigan surface.**
- **Modeling and observations show that this polluted layer over the lake is an important factor in coastal ozone exceedance events, but that meteorological and photochemical model skill in forecasting these needs improvement.**
  - ✓ **Comparisons between NAM-CMAQ forecasts, ground based monitors, in situ, and remote airborne measurements showed that NAM-CMAQ underestimated peak ozone concentrations and overestimated NO<sub>2</sub> concentrations during ozone exceedance events during LMOS 2017.**
  - ✓ **NAM-CMAQ sensitivity studies show that reductions in anthropogenic NO<sub>x</sub> emissions and increases in biogenic volatile organic compounds (VOCs) emissions are necessary to increase the predicted surface ozone during high ozone events during LMOS 2017.**
- **An experimental network of lower cost ozone monitors (2B-POM monitors) was deployed over a 6 km area of Sheboygan to measure differences in concentrations with respect to distance from the lake.**
  - ✓ **Inland ozone values were found to be 5-6% lower than the lakeshore site. However, intermittent data capture from these devices limits the drawing of detailed conclusions regarding spatial gradients.**

# Disclaimer

*Any opinions, findings, and conclusions or recommendations expressed in this presentation are those of the author and do not necessarily reflect the views of the National Science Foundation nor should they be construed as an official National Oceanic and Atmospheric Administration or U.S. Government position, policy, or decision.*

*The United States Environmental Protection Agency's Office of Research and Development partially performed and funded the research described within this presentation. This presentation has not undergone a full EPA review. As such, the results presented are not approved for external publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.*

# Acknowledgments

*The LMOS 2017 Science Team acknowledges the NASA Airborne Science Program and the NASA GEOstationary Coastal and Air Pollution Events (GEO-CAPE) Mission Pre-formulation Science Working Group for supporting the airborne remote sensing instruments, NSF (award number 1712909) and NOAA GOES-R Program Office for supporting the measurements at the Zion ground site, EPA and NOAA GOES-R program office for supporting the measurements at the Sheboygan ground site, and the Electric Power Research Institute (EPRI) for supporting the Scientific Aviation airborne in situ measurements.*

# LMOS 2017 Data Archive

(Became publically available 8/2/2018)



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SEARCH NASA

+ HOME + MISSIONS + DATA + TOOLS + ABOUT US

Airborne Science Data for Atmospheric Composition

LMOS – Lake Michigan Ozone Study 2017

Data Archive: LMOS 2017

**Relevant Data / Links**

- Quicklook Reports (public)
- View / Upload Images & Data – Aircraft, Ground, Mobile, etc.
- File Sharing (private)
- Forecasts, Telecons, Reports, etc.

Forecast Products ...

Meteorology Links ...

Airflow

LADCO - Lake Michigan Air Directors Consortium

ICARTT Data Format Document

**Data Upload Tools**

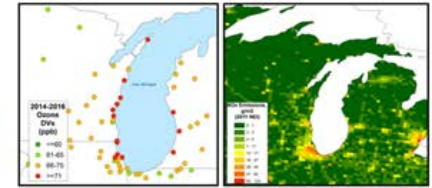
- Steps for submitting data to the Archive
- Data Submittal / Scanning
- Help / Start
- Register PI data

**Useful Tools**

- Download HDFView – visual tool for browsing & editing HDF files
- Download File Scanning SW for Windows (requires .NET)
- What's New
- Download Flight Planning SW for Windows (requires Google Earth)

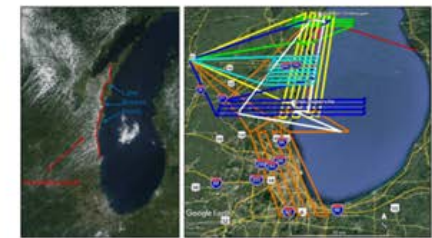
**Mission Overview:**

Elevated spring and summertime ozone levels remain an air quality challenge along the coast of Lake Michigan, with a number of monitors exceeding the 2015 National Ambient Air Quality Standards (NAAQS) for ozone. Production of ozone over Lake Michigan combined with onshore daytime 'lake breeze' airflow is thought to increase ozone concentrations preferentially at locations within a few kilometers of the shore. This observed lake-shore ozone gradient motivated the Lake Michigan Ozone Study (LMOS) 2017 during May and June 2017.



Ozone Design Values (DV) for 2014 2016 in ppb (left) and NEI 2011 MDC area emissions in ghr2 (right). DVs greater than or equal to 7 Tgpyr (red) exceed the 2015 NAAQS for ozone and are primarily found around the shore of Lake Michigan in this region.

This campaign provides extensive observational air quality and meteorology datasets through a combination of airborne, ship, mobile lab, and fixed ground-based observational platforms. Additionally, chemical transport models (CTMs) and meteorological forecast tools assist in the planning for day-to-day measurement strategies. The main objectives of LMOS are to better understand the lakeshore ozone gradient and to evaluate and improve CTMs used for regulatory and research purposes in this region. LMOS 2017 is a collaborative effort between LADCO and its member states, NASA, NOAA, EPA, EPRI, Scientific Aviation, and a number of research groups at universities.



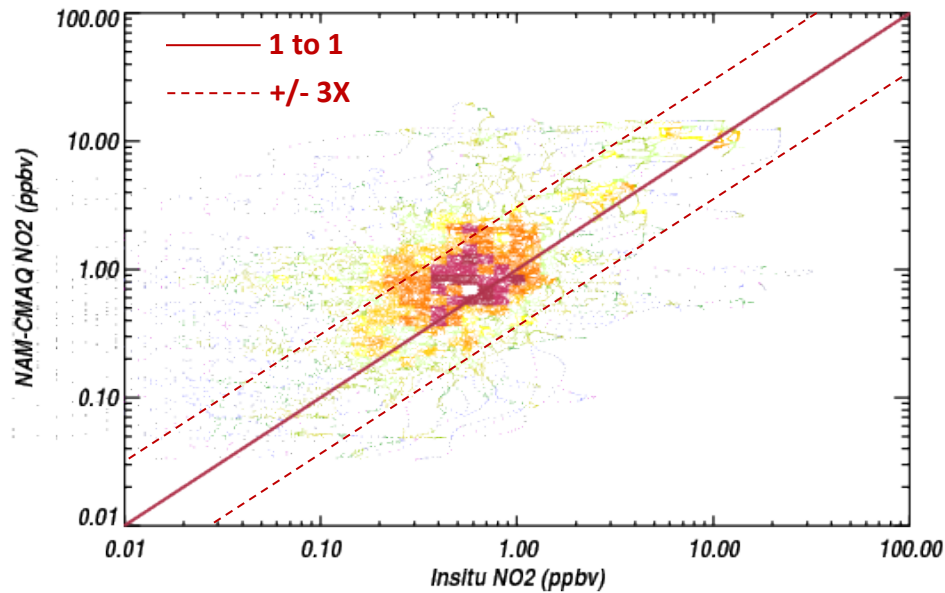
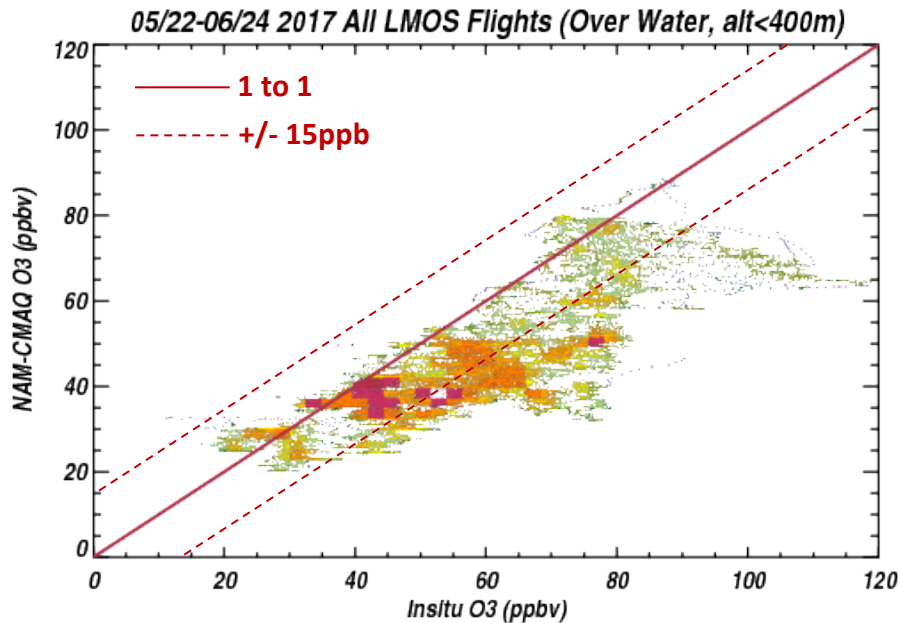
MDC imagery on the left shows the lake breeze front along the western lake shore converging with the prevailing offshore flow. High DVs along the lake shore are thought to be influenced by the lake breeze. The map to the right displays the spatial coverage of the aircraft, ship, and ground-based observations involved in LMOS to study urban emissions and the lake-breeze influence on the western shore's air quality.

- Related documents:**
- FAQ: Lake Michigan Ozone Study (LMOS 2017)
  - LMOS Whitepaper
  - Open letter to parties interested in the 2017 Lake Michigan Ozone Study (March 21, 2017)
- Articles:**
- Dr. Charles Stanier provides Lake Michigan Ozone Study update
  - Lake Michigan Ozone Study 2017: Collaborative field campaign will pursue sources and transport of ozone
  - NASA Aids Study of Lake Michigan High-Ozone Events

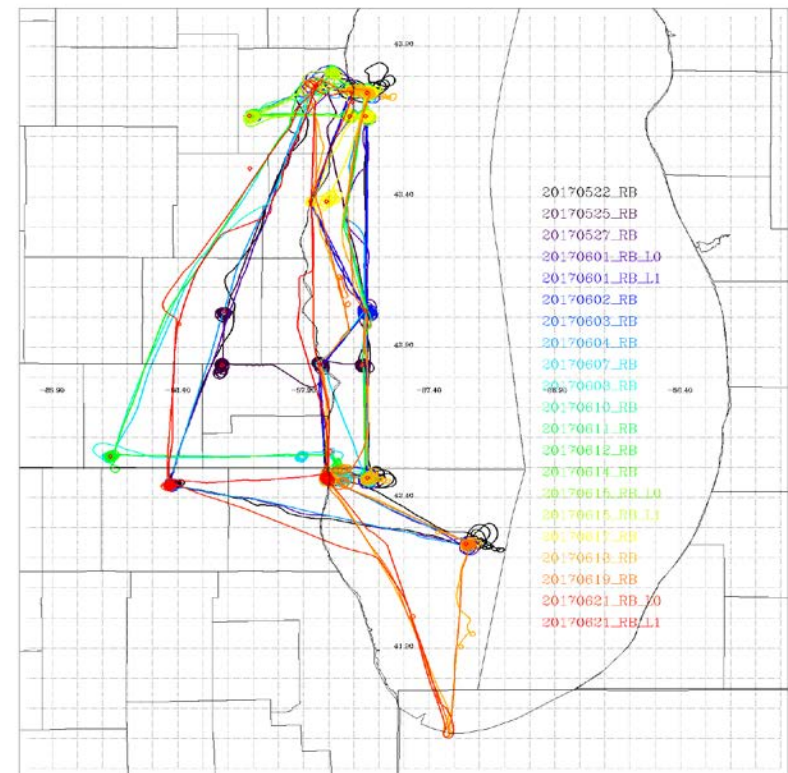
<https://www-air.larc.nasa.gov/missions/lmos/index.html>

# **Extra Slides**

# NAM-CMAQ vs Scientific Aviation (Over Water, Altitude <400m)



## All Scientific Aviation Flights



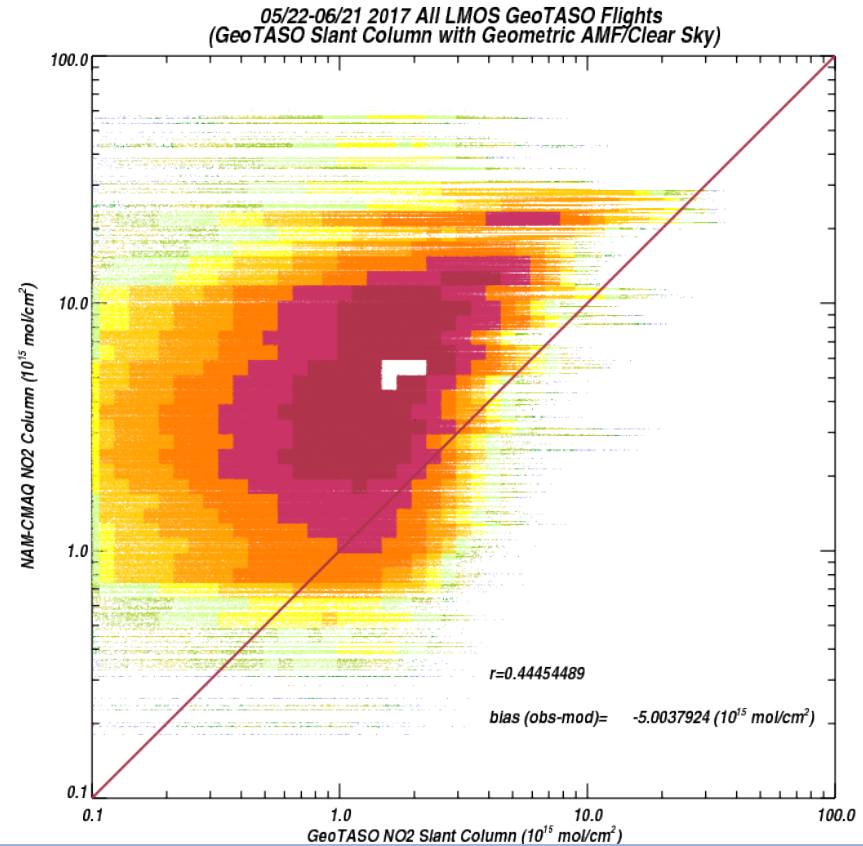
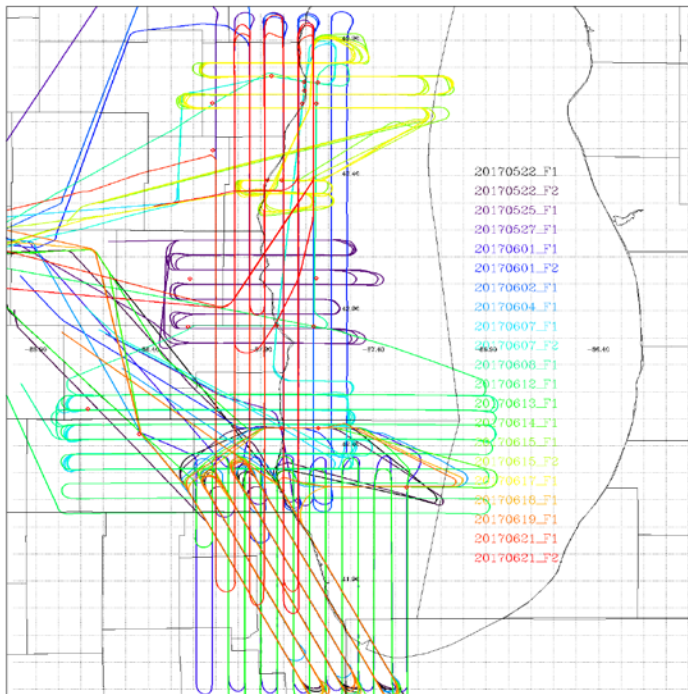
NAM-CMAQ underestimates O3  
and overestimates NO2 over Lake  
Michigan

Steve Conley (Scientific Aviation PI)

# LMOS May 22 through June 21, 2017

## NAM-CMAQ vs GeoTASO Differential Slant Column

### All GeoTASO Flights



NAM-CMAQ overestimates NO<sub>2</sub> columns compared to GeoTASO differential slant columns (currently not accounting for instrument sensitivity to NO<sub>2</sub> profile)