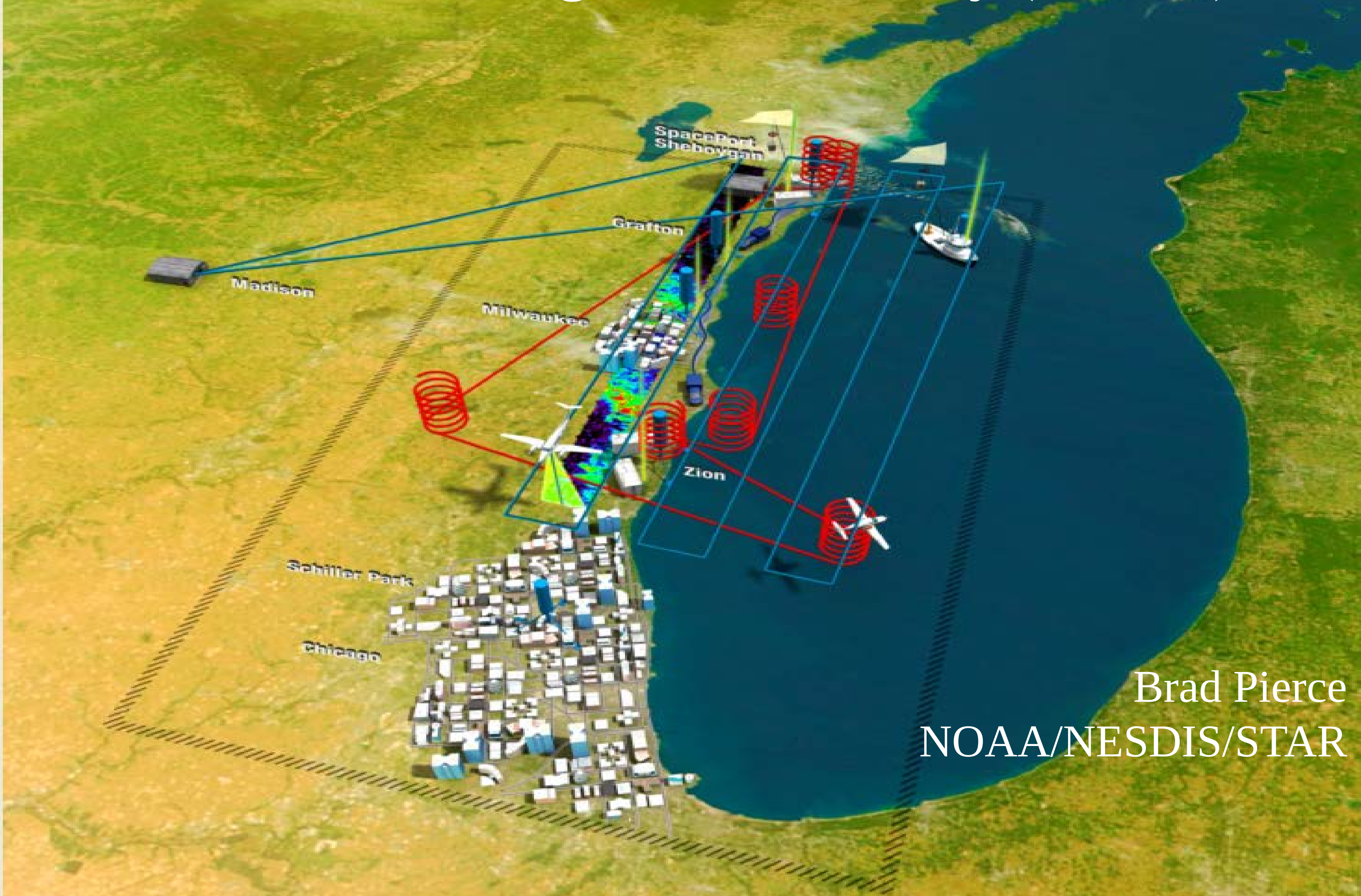
2017 Lake Michigan Ozone Study (LMOS)



Brad Pierce
NOAA/NESDIS/STAR

Sheboygan County Chamber of Commerce First Friday Forum, Sheboygan WI, August 3, 2018

2017 Lake Michigan Ozone Study (LMOS)

<u>What are the potential outcomes/benefits of LMOS 2017?</u>

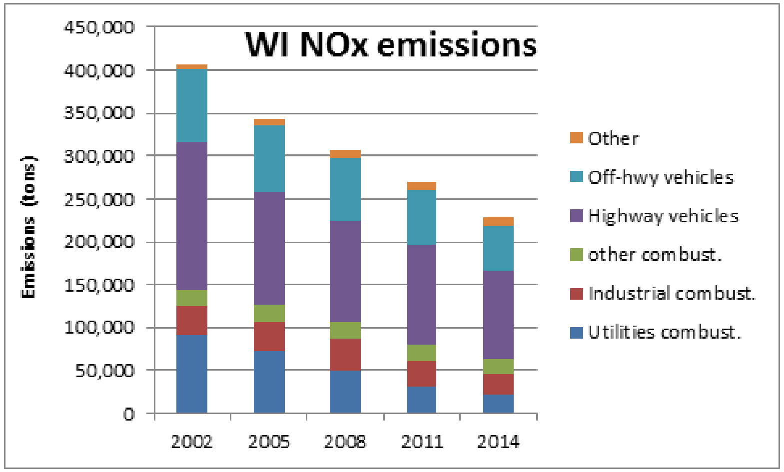
LMOS 2017 measurements provide critical observations for evaluating a new generation of air quality models attempting to better simulate ozone episodes in the region. Over the long term, the information collected is expected to result in:

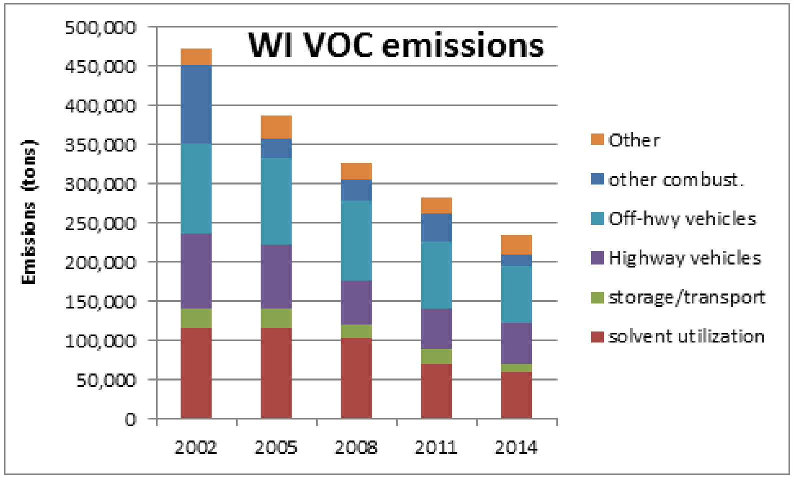
- Improved modeled ozone forecasts for this region, which states and EPA use to meet state and federal Clean Air Act requirements.
- Better understanding of the lakeshore gradient in ozone concentrations, which could influence how EPA addresses future regional ozone issues.
- Improved knowledge of how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

<u>What institutions are involved in LMOS 2017?</u>

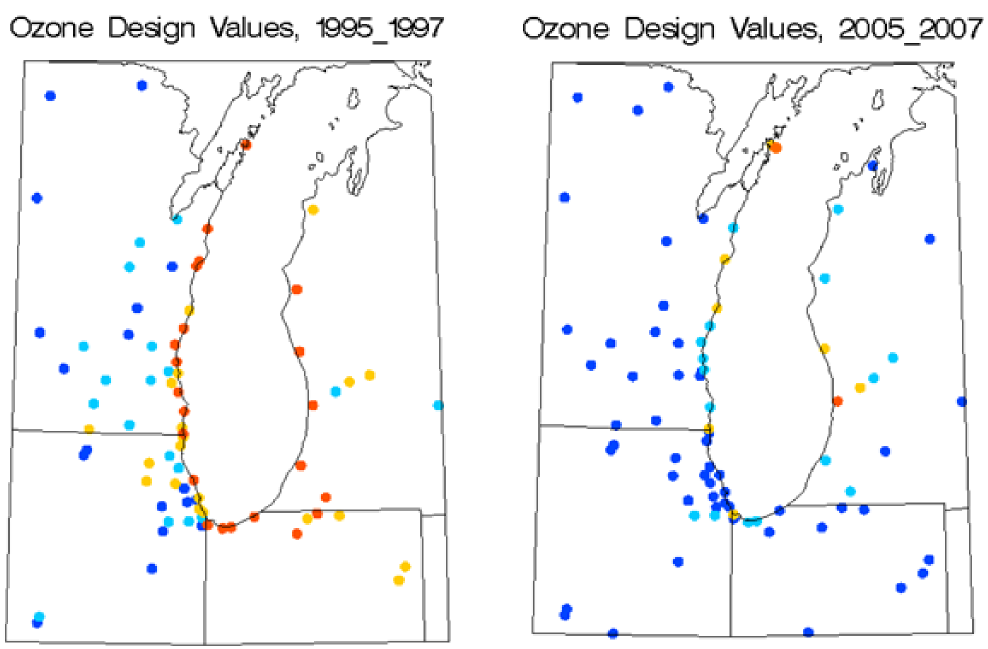
- Researcher institutions: NOAA, NASA, U.S. EPA, University of Wisconsin, University of Iowa, University of Minnesota, University of Northern Iowa, University of Maryland Baltimore County, Scientific Aviation.
- Air quality management agencies: Lake Michigan Air Directors Consortium (LADCO), Wisconsin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

Wisconsin emissions are declining and ozone is improving





NOx= NO+NO2 (nitrogen oxides) VOC=Volatile Organic Compounds, both are ozone precursors



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

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).**

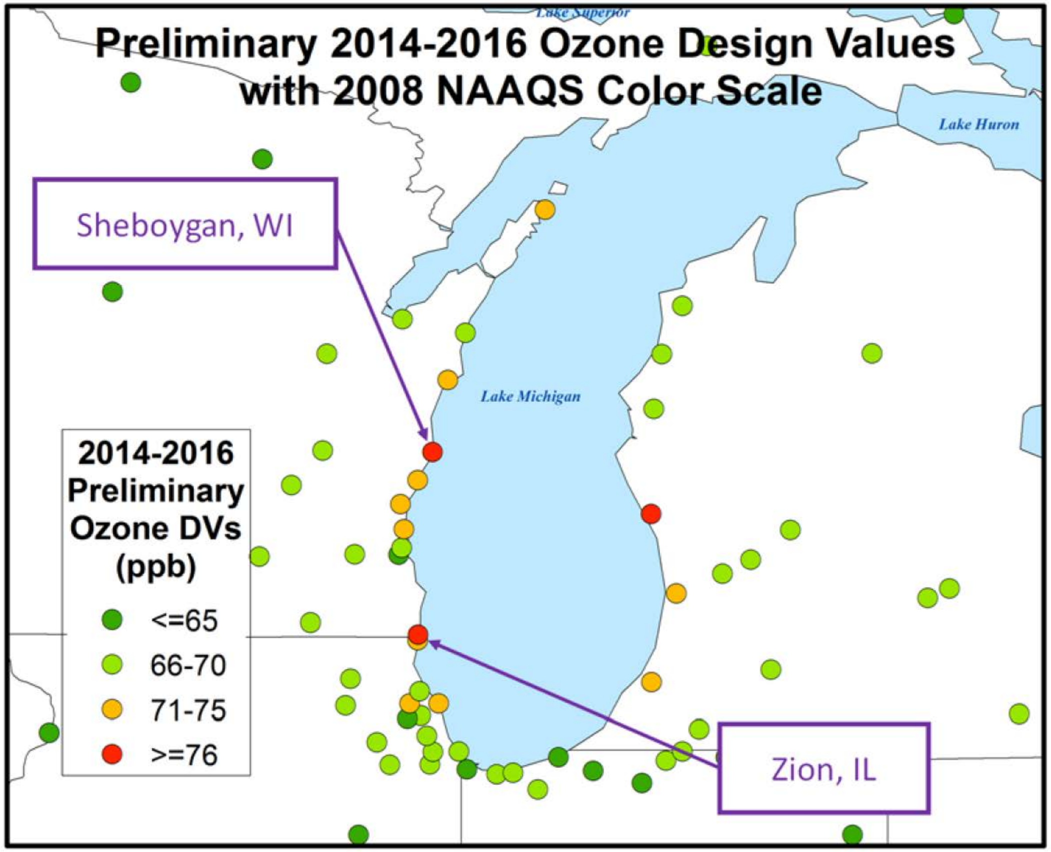
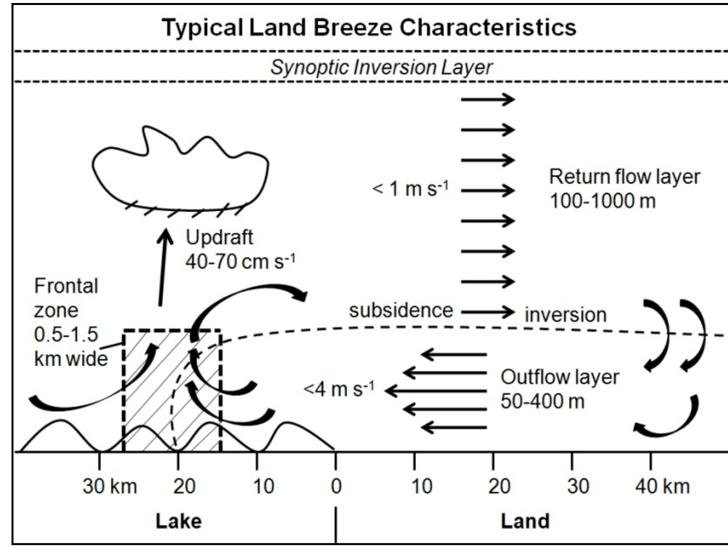


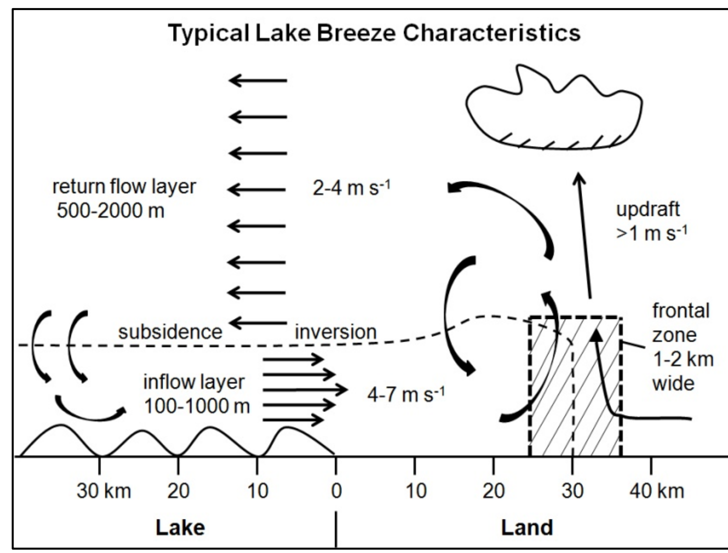
Figure 1. Ground sites hosting measurements for LMOS 2017

2017 Lake Michigan Ozone Study White Paper: http://www.ladco.org/

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.



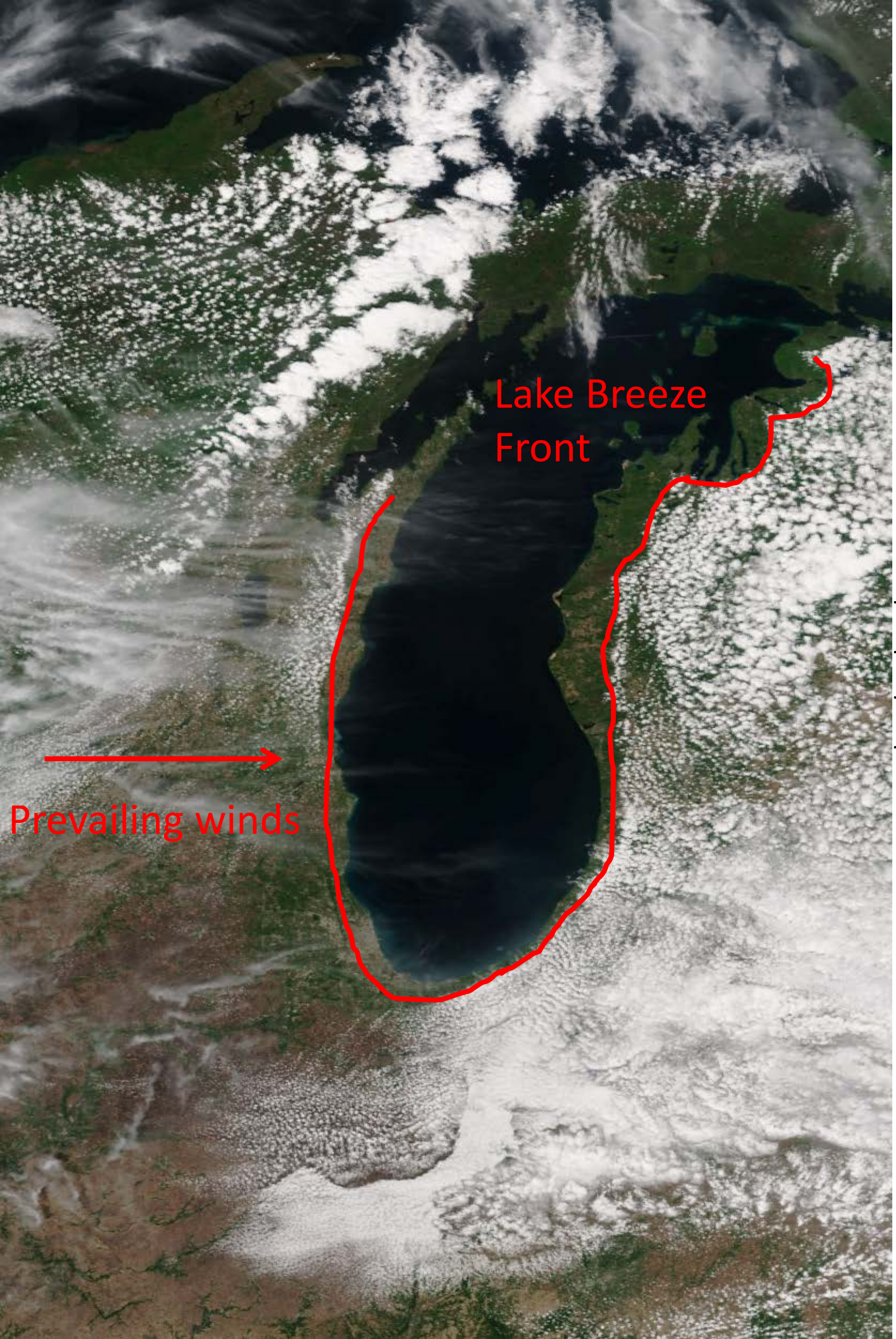


White Paper: http://www.ladco.org/

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

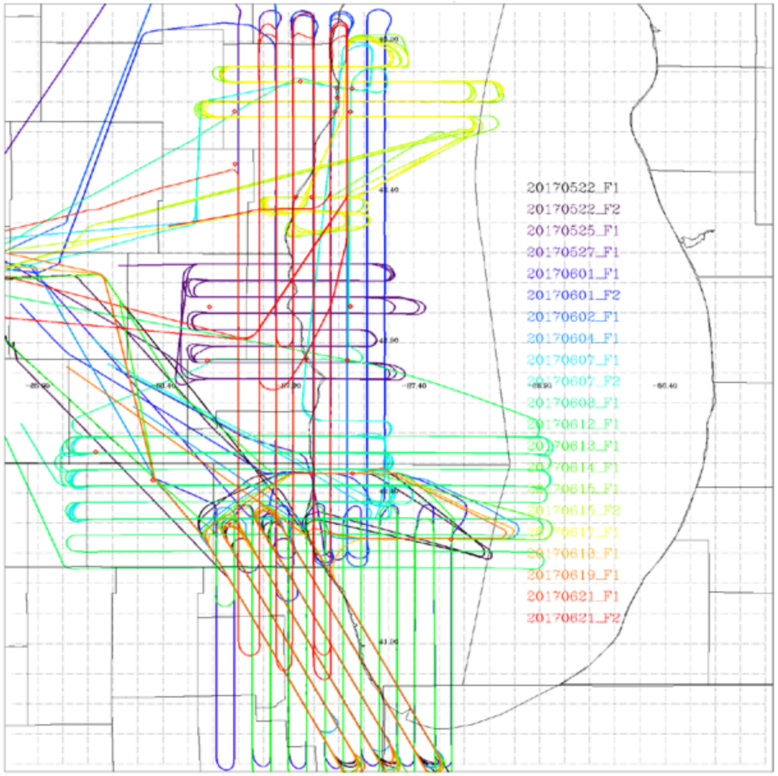
Summary of measurements made during the LMOS 2017 field campaign

Location	Measurement*	Research Institution*
Ground Sites		
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†	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
Airborne Platforms		
Lakeshore region	Airborne remote sensing of NO_2 (GeoTASO)	NASA
	Airborne remote sensing of clouds (AirHARP)	Univ. Maryland, Baltimore County
	Airborne in situ profiling of pollutants and meteorology	Scientific Aviation
Shipboard Platform		
Lake Michigan	In situ measurements of pollutants	U.S. EPA ORD
	Remote sensing of pollutants and boundary later height	U.S. EPA ORD
Mobile Platforms		
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

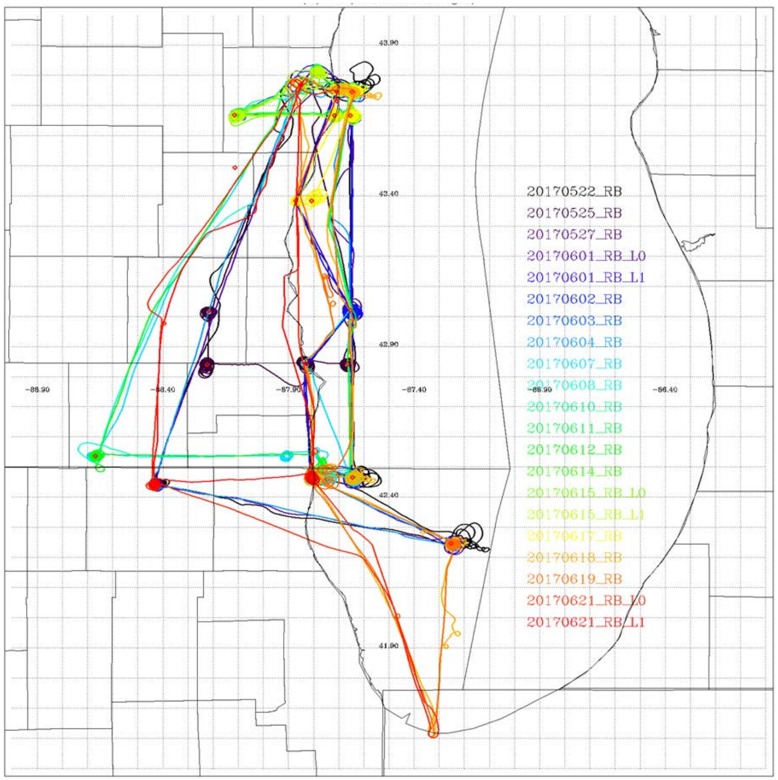
GeoTASO = Geostationary Trace gas and Aerosol Sensor Optimization instrument
AirHARP = Airborne Hyper Angular Rainbow Polarimeter
GMAP = Geospatial Mapping of Pollutants
† These measurements were made at Spaceport Sheboygan, Zion, two Wisconsin DNR monitoring locations (Grafton and Milwaukee SER) and one Illinois EPA monitoring location (Schiller Park).

LMOS 2017 Aircraft Measurements

NASA GeoTASO remote sensing Flights



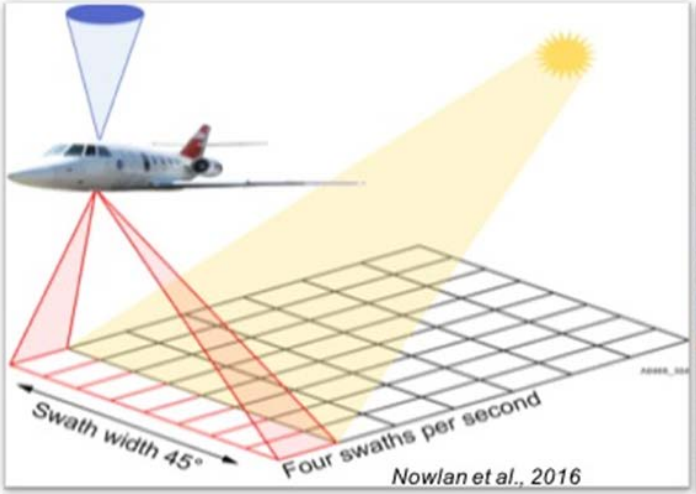
Scientific Aviation insitu sampling Flights



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

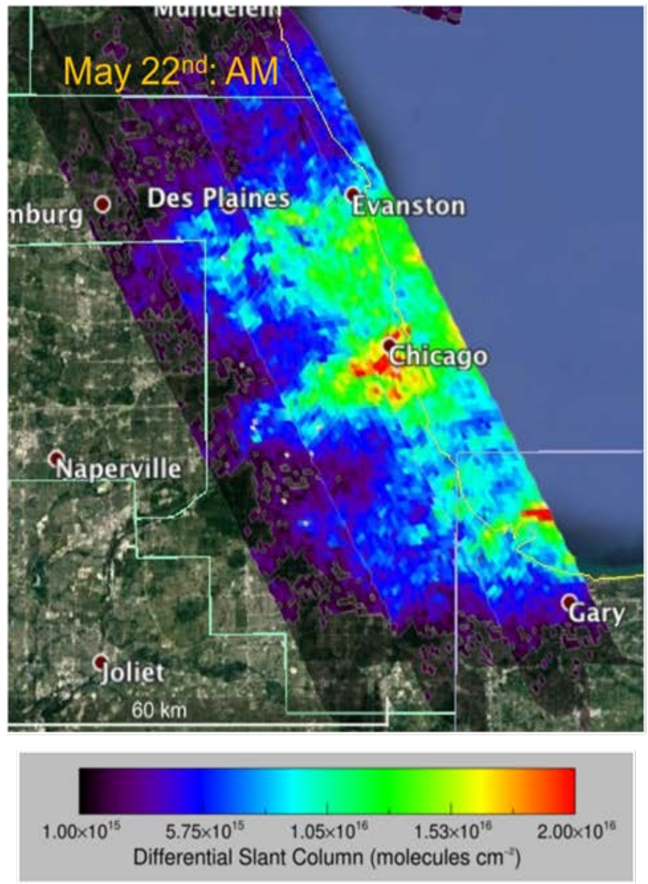
The Electric Power Research Institute (EPRI) provided funding for Scientific Aviation Flights during LMOS

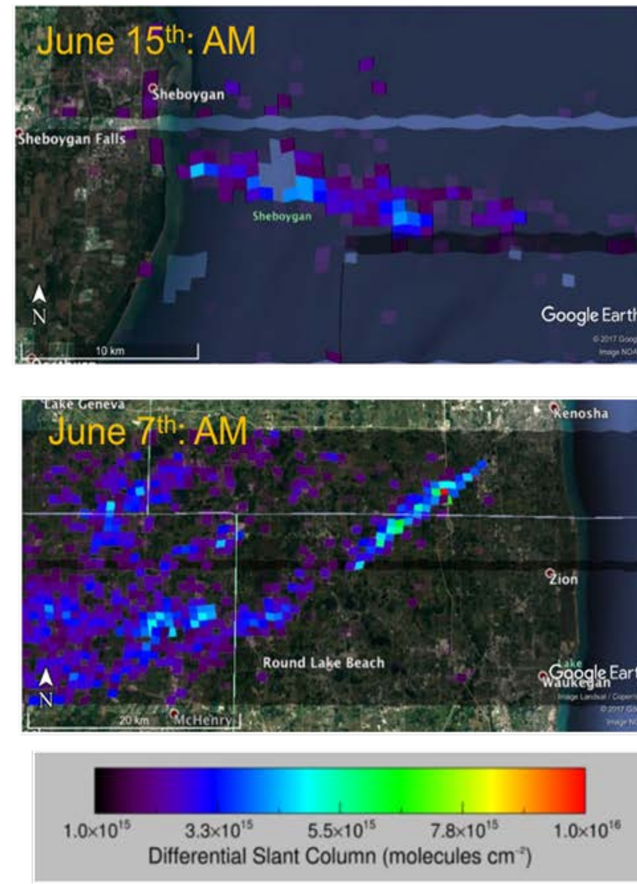
NASA GeoTASO remote sensing Flights



NO_2 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.

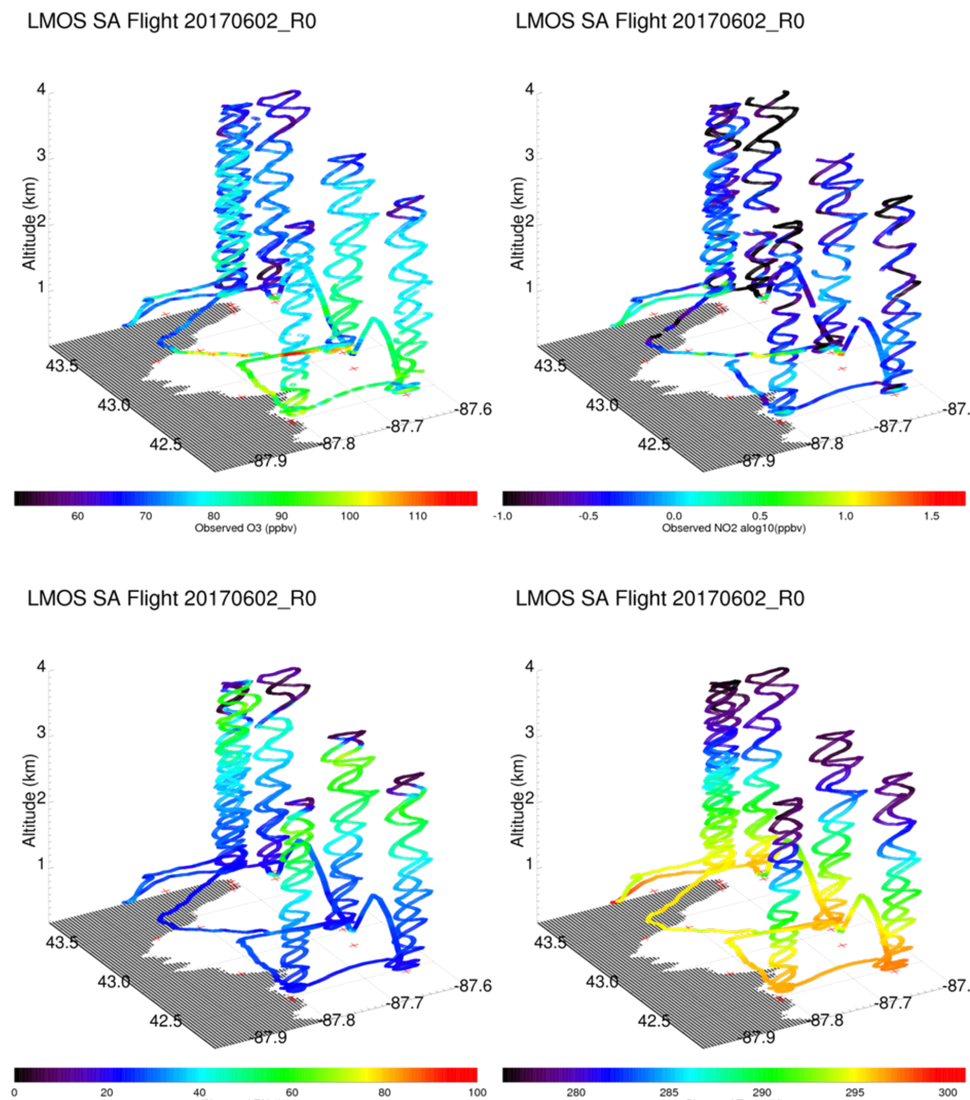




Scientific Aviation in situ profiling Flights

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.

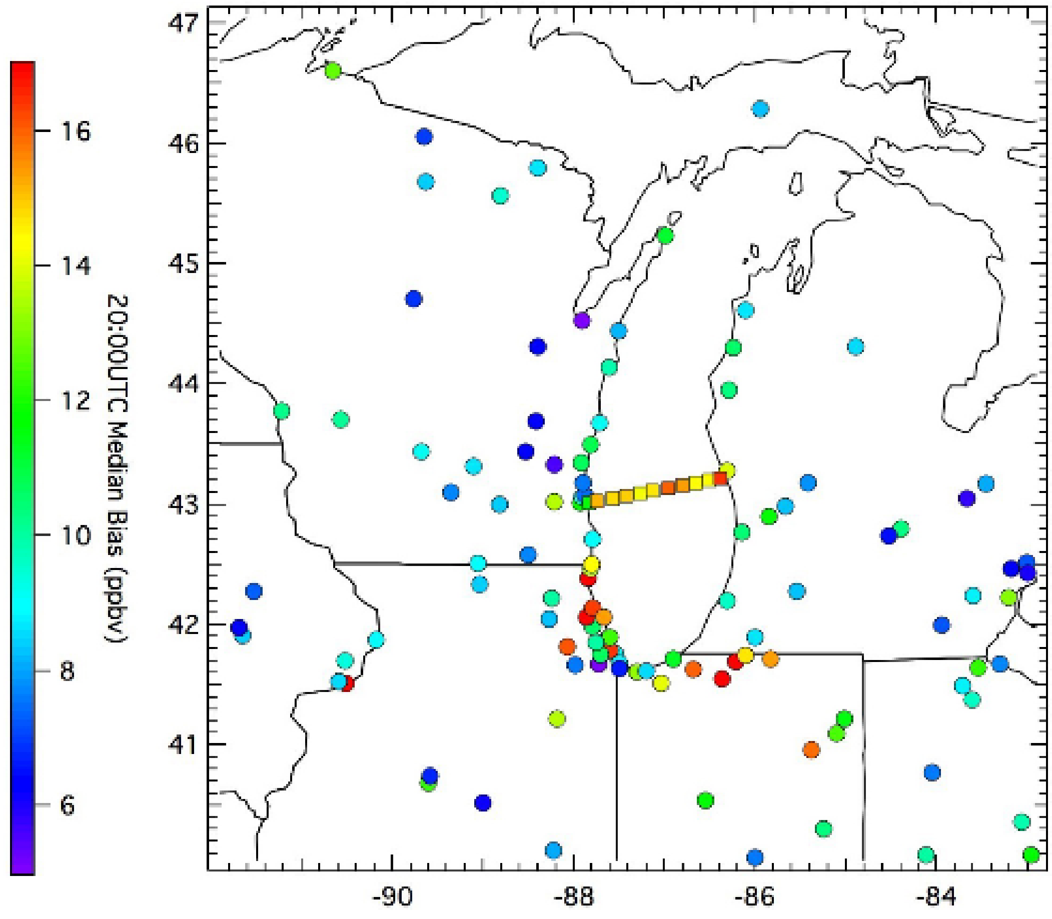
SA flights provided vertical profiles over and offshore from selected ground sites (Sheboygan and Zion), offshore profiles east of Milwaukee and Chicago.



NOAA National Weather Service (NWS) Air Quality Forecast

NWS air quality forecasts were evaluated during LMOS 2017

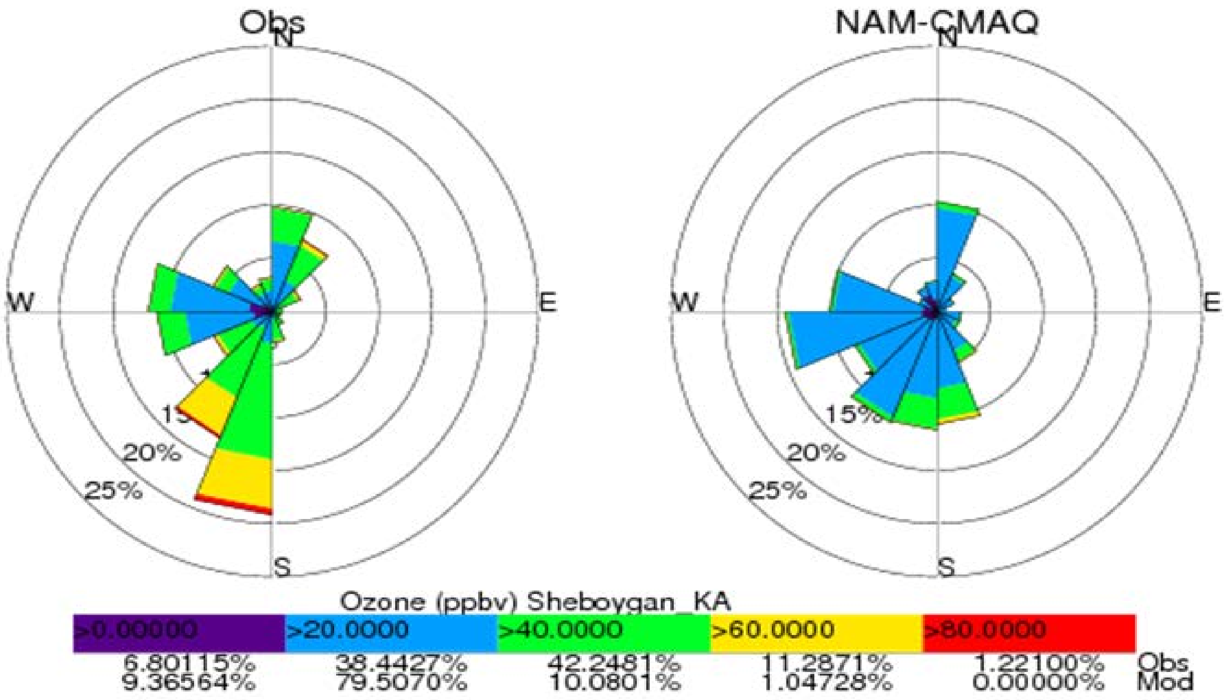
NWS operational air quality forecasts use the North American Model (NAM) meteorology to drive the EPA Community Multiscale Air Quality Model (CMAQ) to perform twice daily forecasts of air quality over the continental US (http://airquality.weather.gov/)



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)

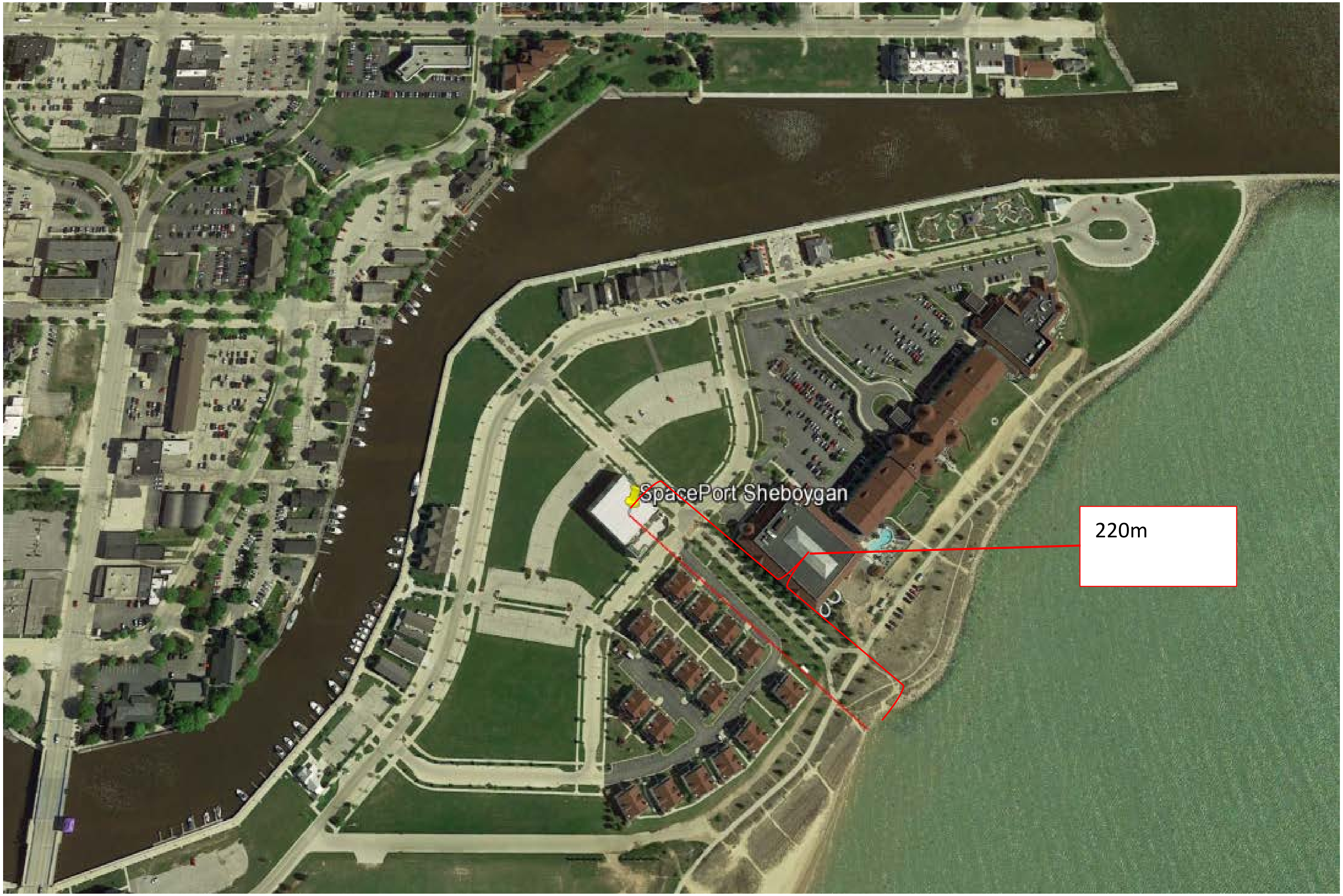
Cleary et al., 2015, Ozone distributions over southern Lake Michigan: comparisons between ferry-based observations, shoreline-based DOAS observations and model forecasts Atmos. Chem. Phys. (doi:10.5194/acp-15-5109-2015)

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

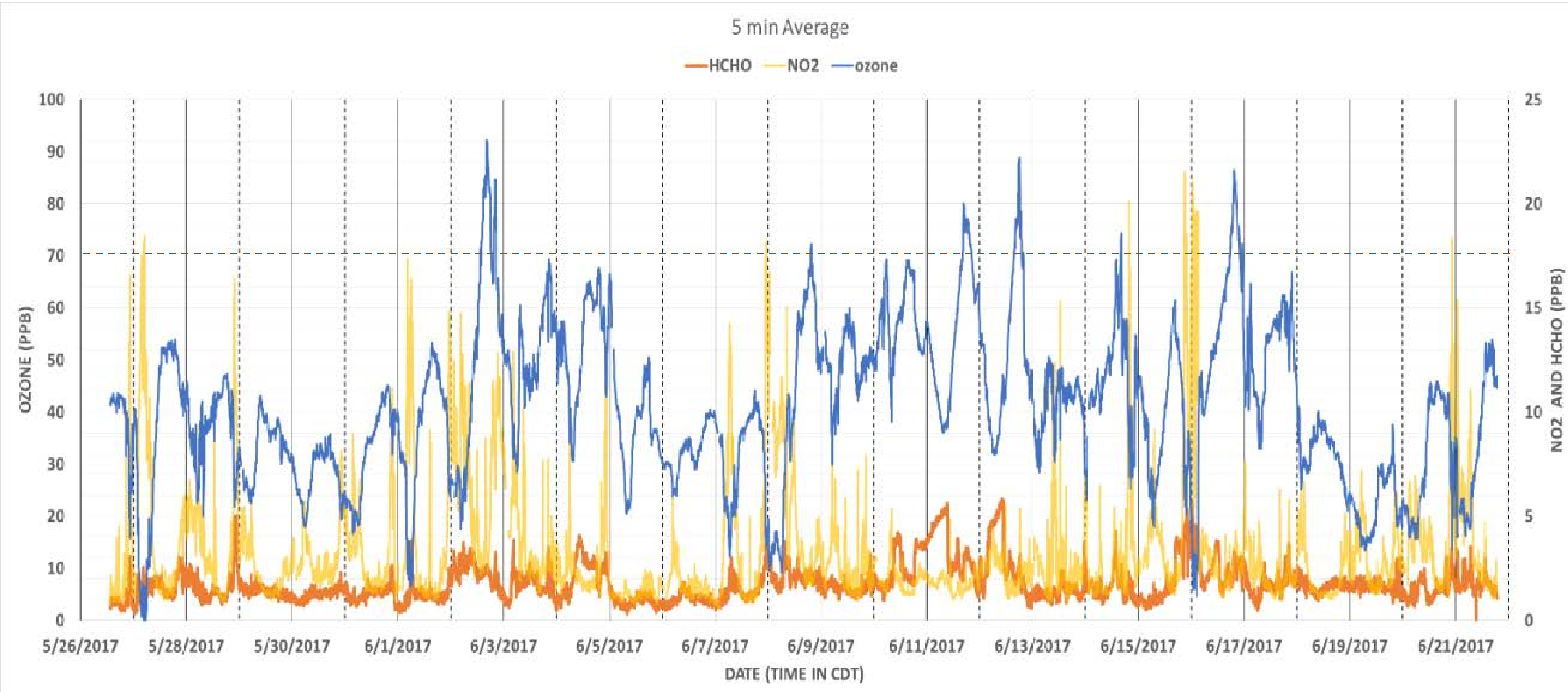
Location of the LMOS EPA measurements in Sheboygan, WI



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

Measurement	Measurement Principle	Model/Manufacturer	Time Resolution	Relevant Reference
O_3	Scrubberless Ultraviolet Photometric (SL-UV)	2B Technology M211*	10-seconds	EQOA-0514-215
	Ultraviolet Photometric	2B Personnel Ozone Monitors	1-minute	EQOA–0815–227.
$NO/NO_2/NOx$	Cavity attenuated phase shift spectroscopy (CAPS)	Teledyne T500U*	10-seconds	EQNA-0514-212
	O_3 Chemiluminescence with Molybdenum converter	Teledyne T200U	10-seconds	RFNA-1194-099
NOy	O_3 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
$O_3/NO_2/HCHO$ 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		

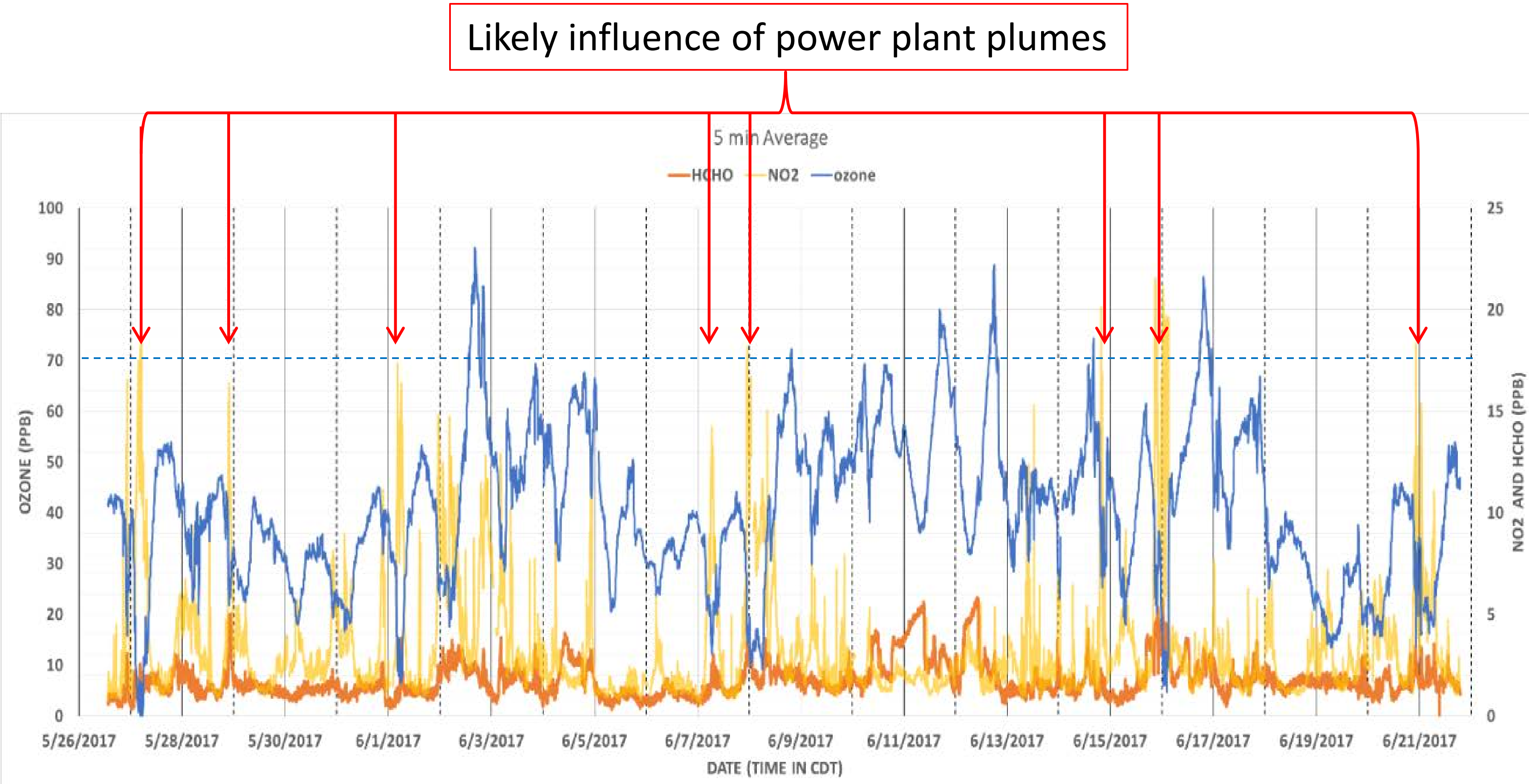
Time series of O3, NO2 and HCHO measurements at Spaceport Sheboygan



Formaldehyde (HCHO) and nitrogen dioxide (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

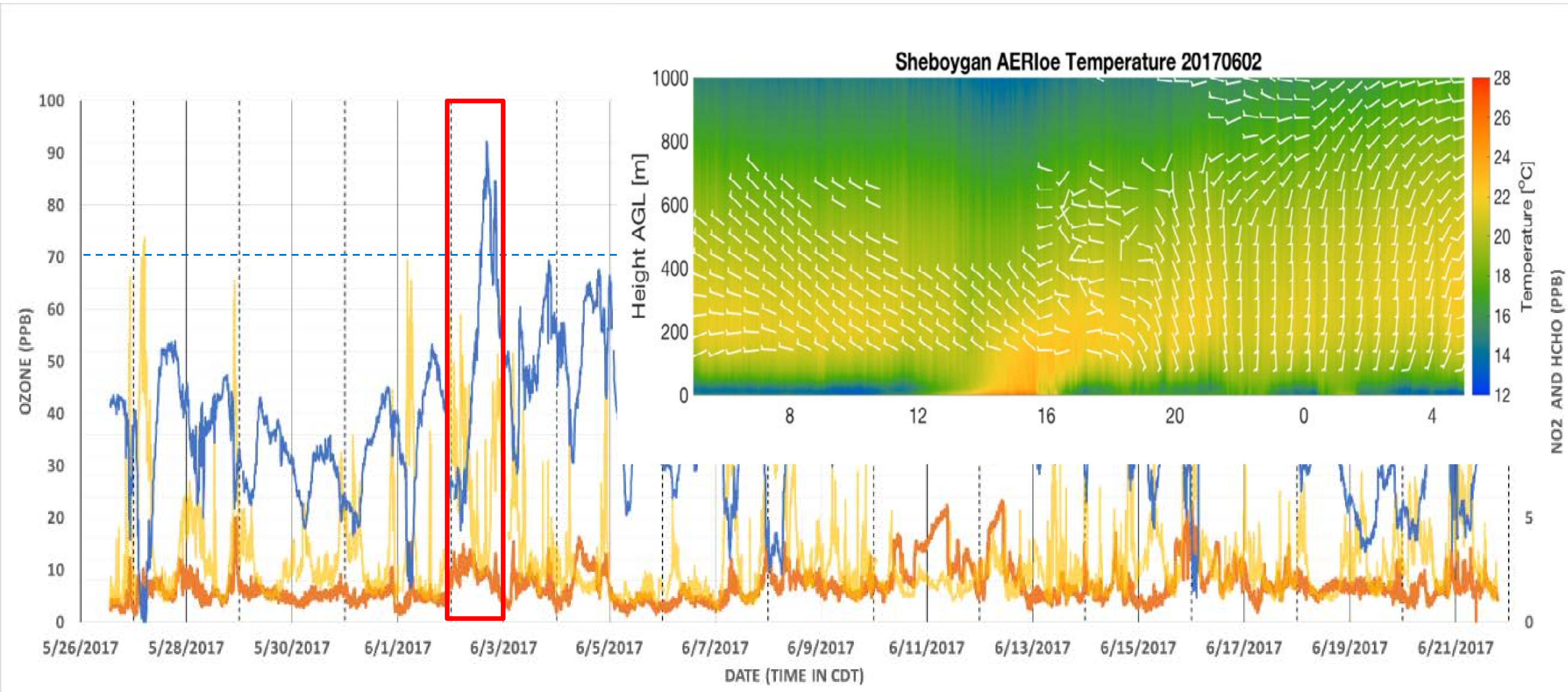


Formaldehyde (HCHO) and nitrogen dioxide (NO2) serve to indicate the chemical regime for ozone formation (i.e., NOx limited and volatile organic compound (VOC) limited) at Sheboygan.

(Jim Szykman, EPA)

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

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

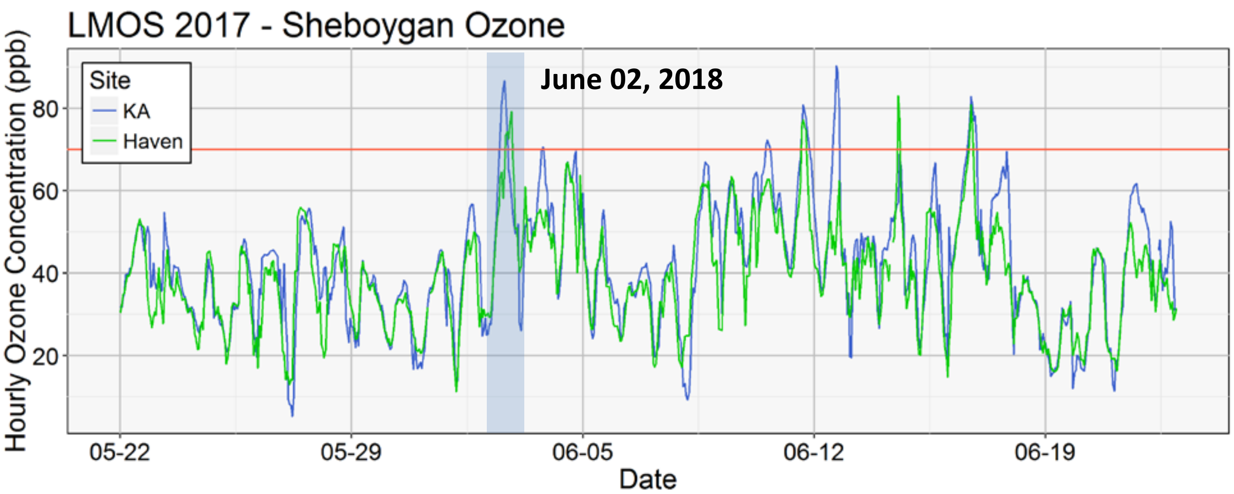


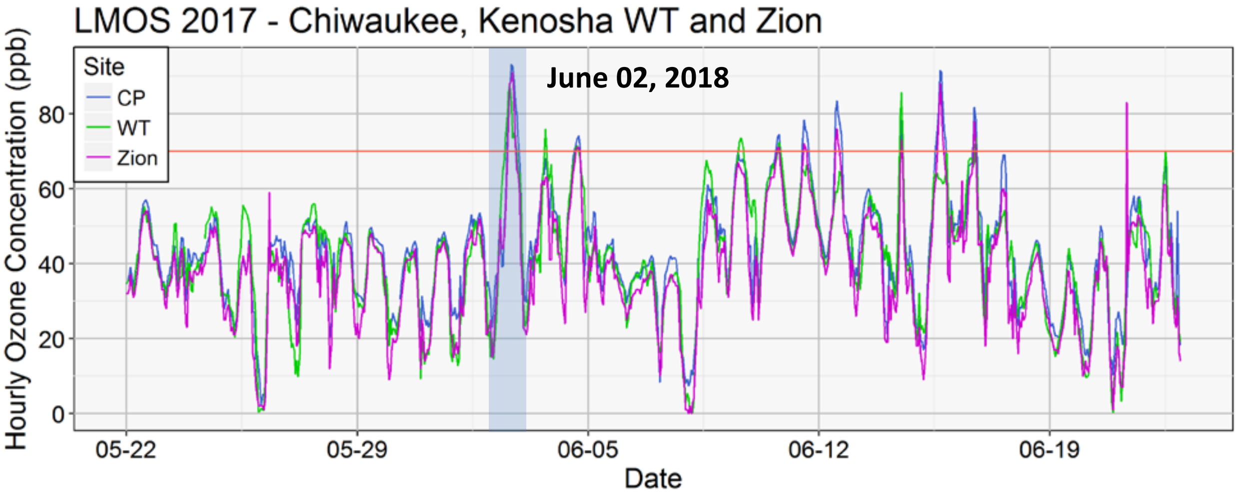
Formaldehyde (HCHO) and nitrogen dioxide (NO2) serve to indicate the chemical regime for ozone formation (i.e., NOx limited and volatile organic compound (VOC) limited) at Sheboygan.

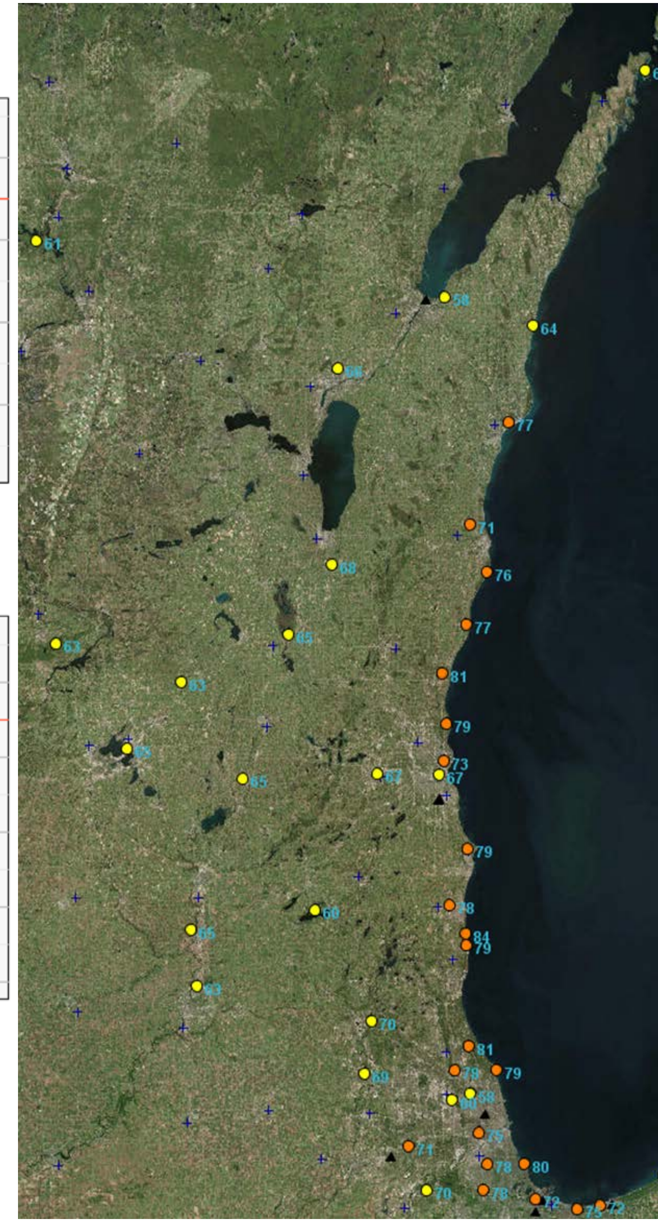
(Tim Wagner, UW-Madison/SSEC)

Lakeshore ozone during LMOS 2017

June 02, 2017 MDA8







MDA8=Maximum Daily 8 hour Average

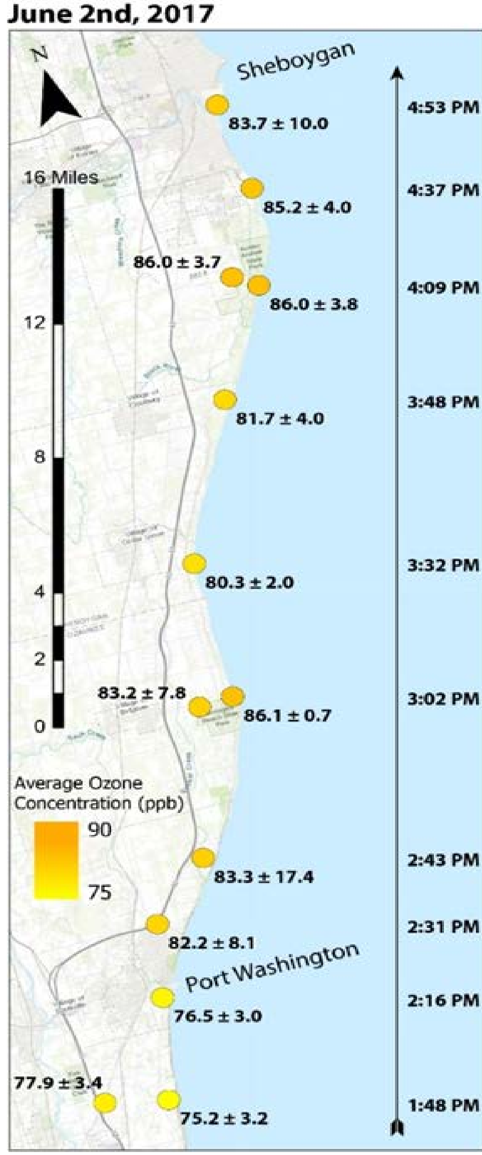
(Angie Dickens , WDNR)

Along shore O3 gradients

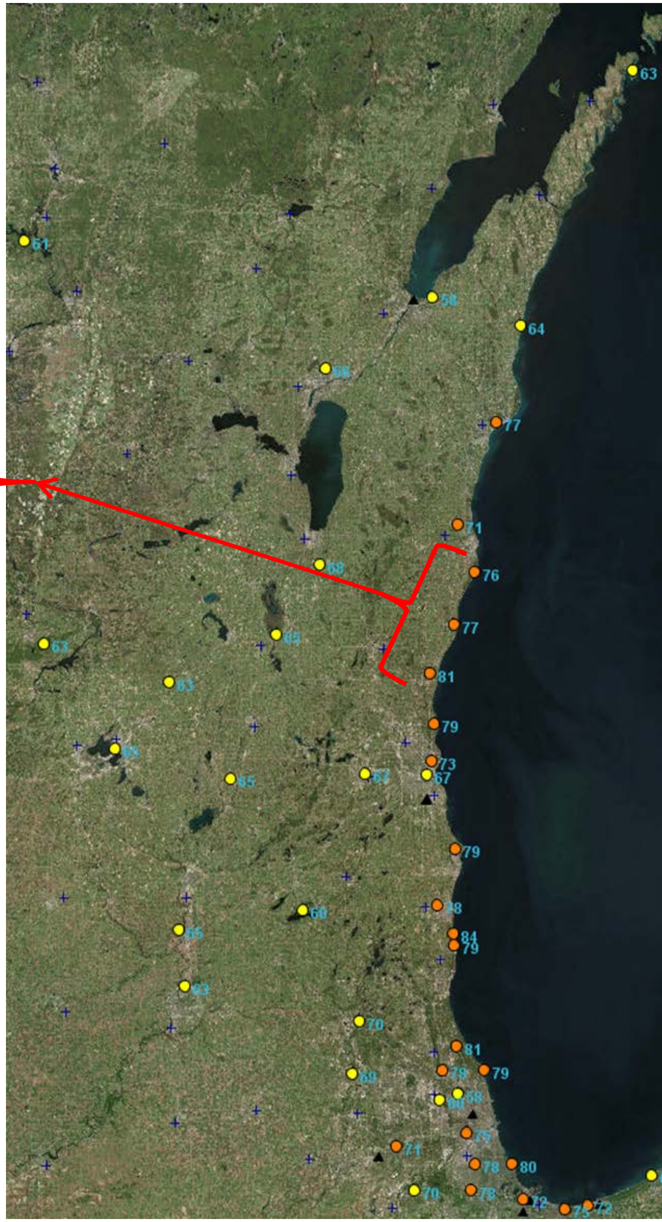
Kohler-Andrae Dunes

Harrington Beach Park

Grafton



June 02, 2017 MDA8

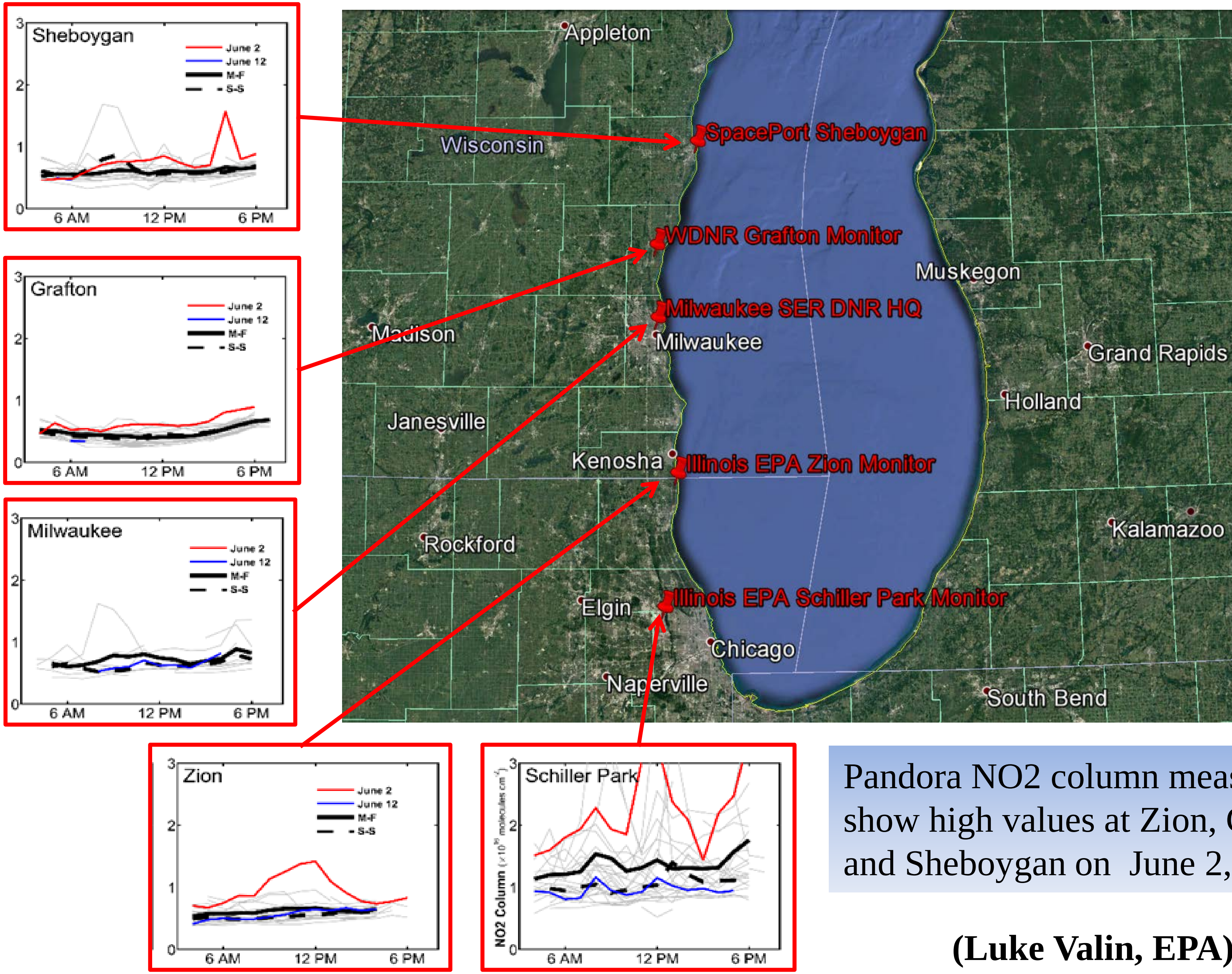


UW-Eau Claire automobile platform ozone measurements show increasing coastal ozone concentrations through the afternoon of June 2, 2017

(Patricia Cleary, UW-Eau Claire)

MDA8=Maximum Daily 8 hour Average

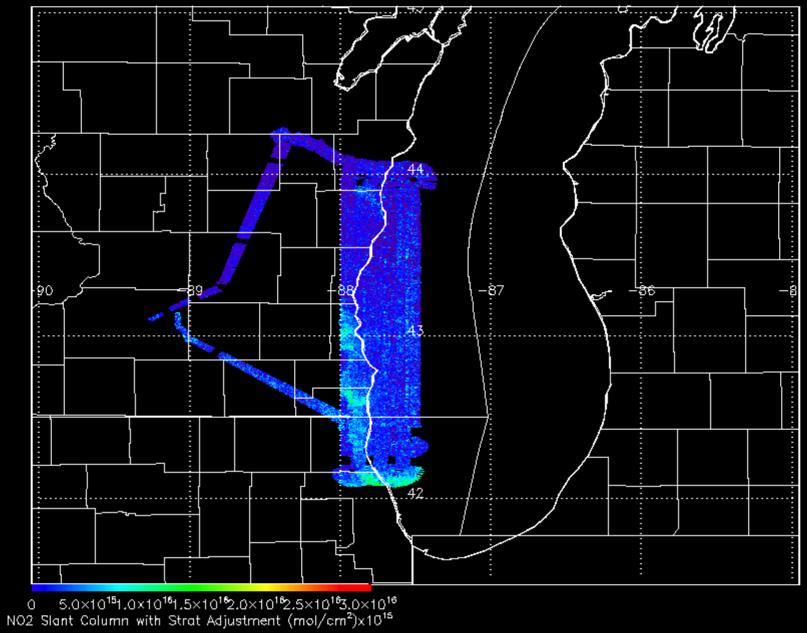
Ground based UV/visible grating spectrometers (Pandoras) column NO2 measurements during LMOS 2017



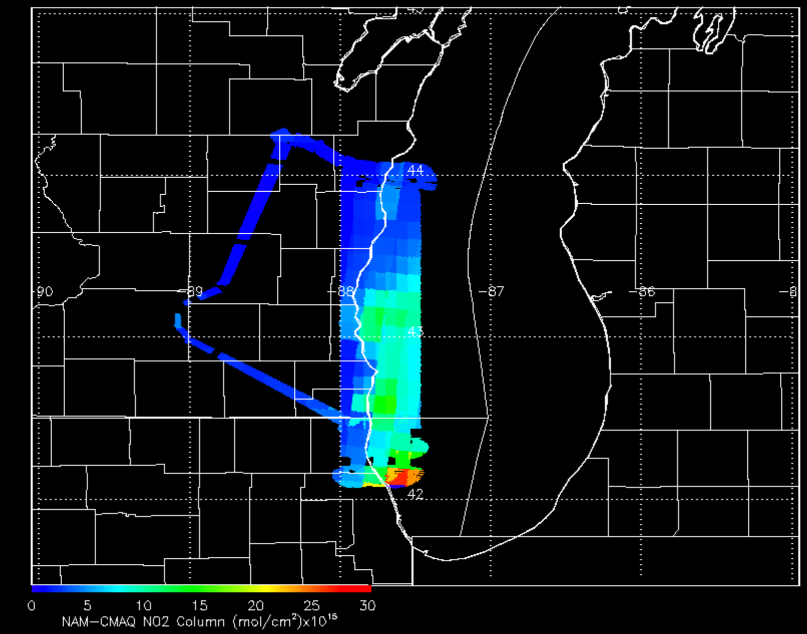
Pandora NO2 column measurements show high values at Zion, Grafton, and Sheboygan on June 2, 2017

(Luke Valin, EPA)

GeoTASO NO2 Slant Column June 02, 2017

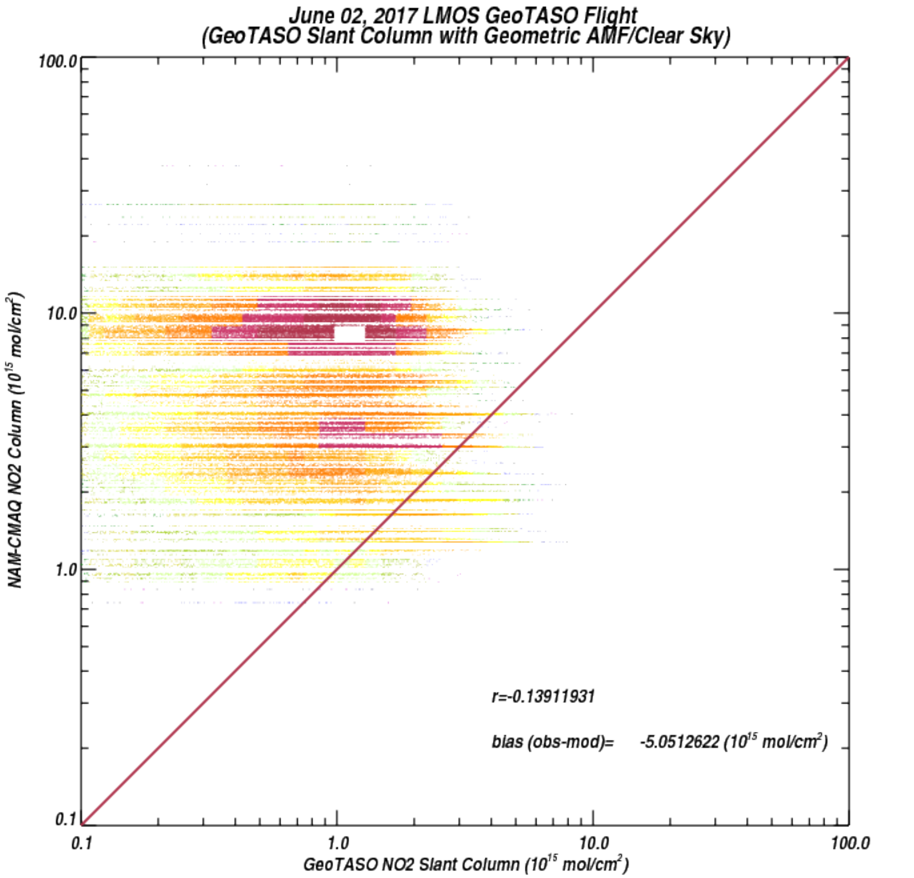


NAM-CMAQ NO2 Column June 02, 2017

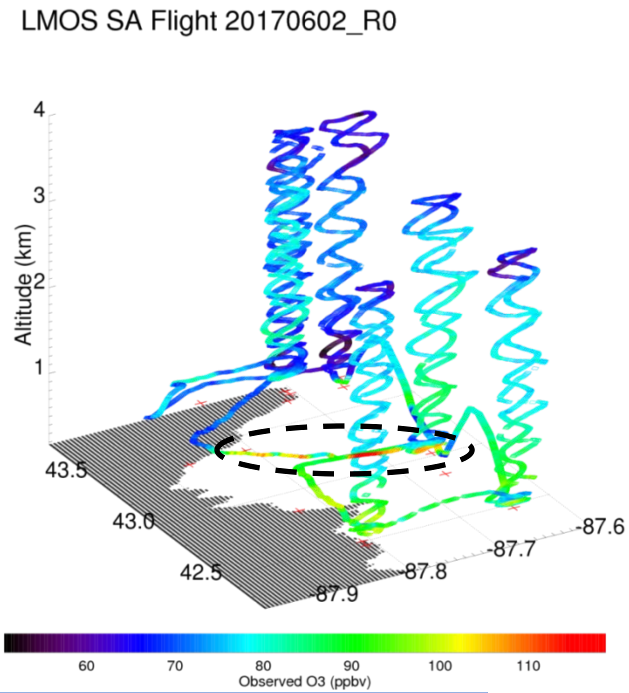


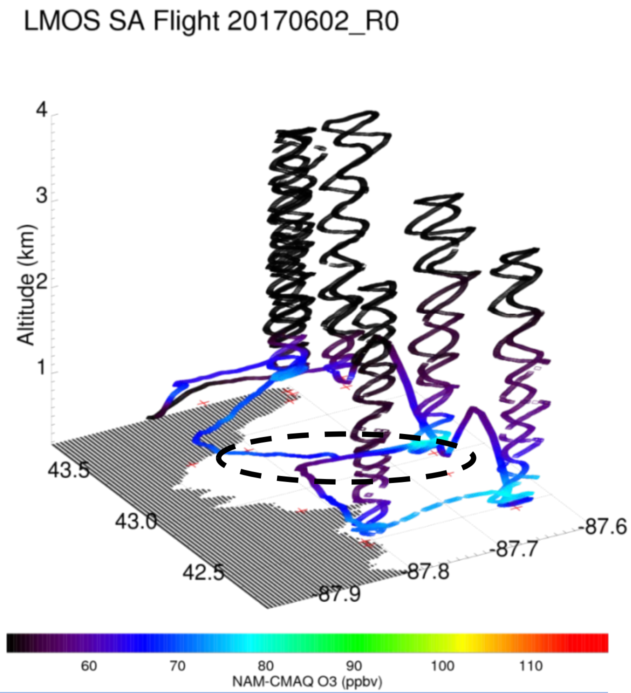
GeoTASO Coastal Survey Flight June 02, 2017

NWS NAM-CMAQ significantly overestimates observed NO2 column



Coastal Ozone Exceedance Day

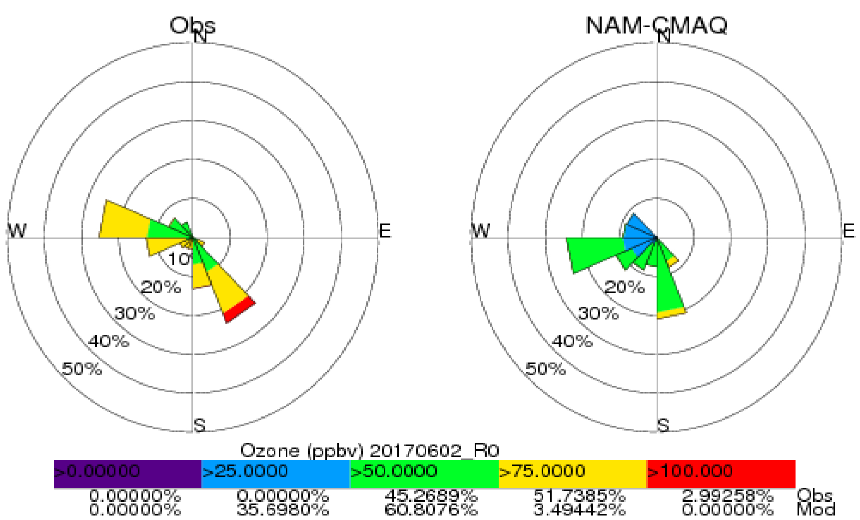


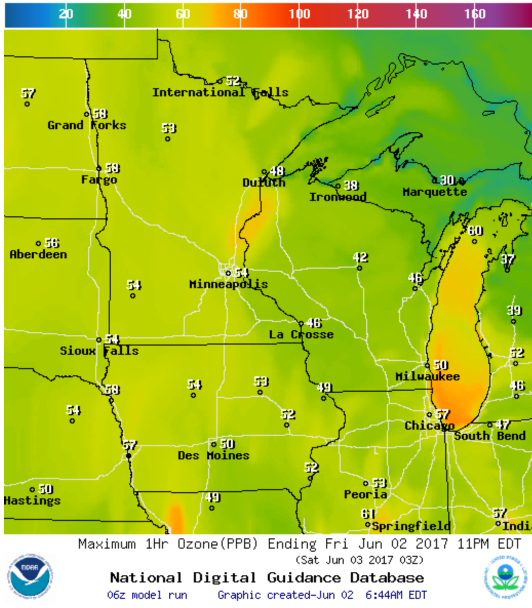


NWS NAM-CMAQ significantly underestimates ozone concentrations within the marine boundary layer

Max Observed O3 > 110ppbv

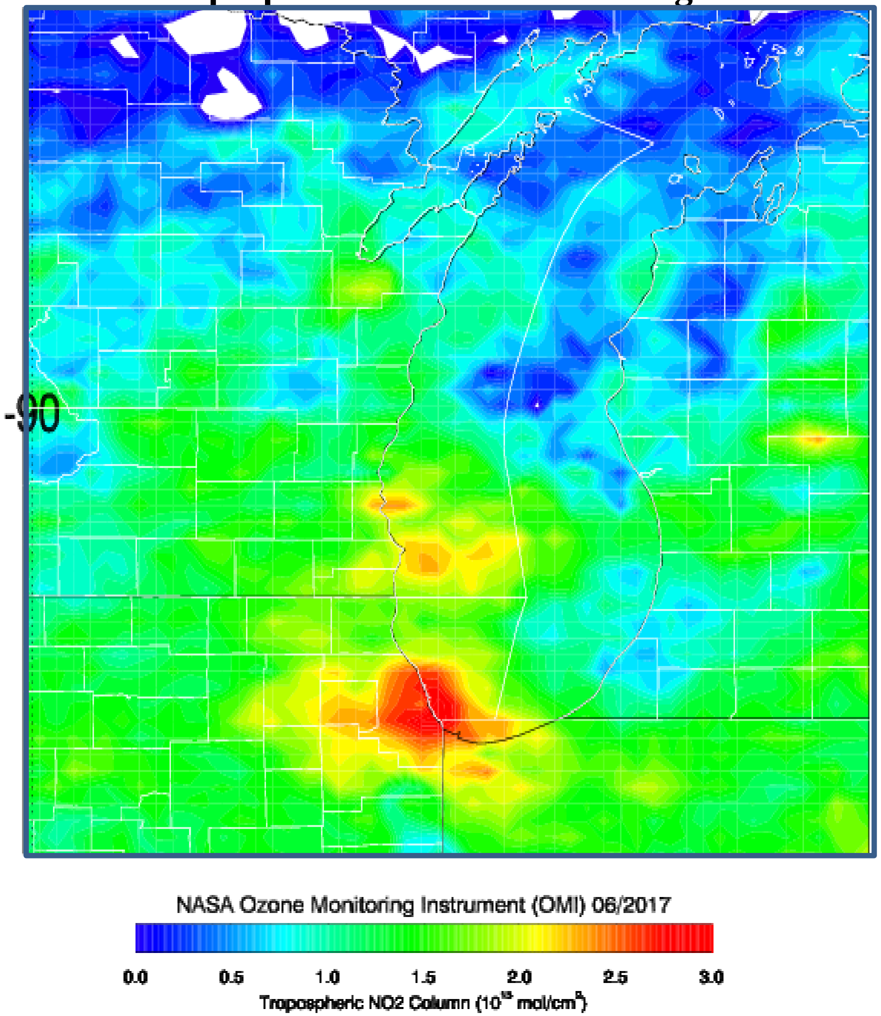
Max NAM-CMAQ O3 < 80ppbv





Aura Ozone Monitoring Instrument (OMI) Tropospheric NO2 column Data Assimilation

OMI Tropospheric NO2 column during June 2017



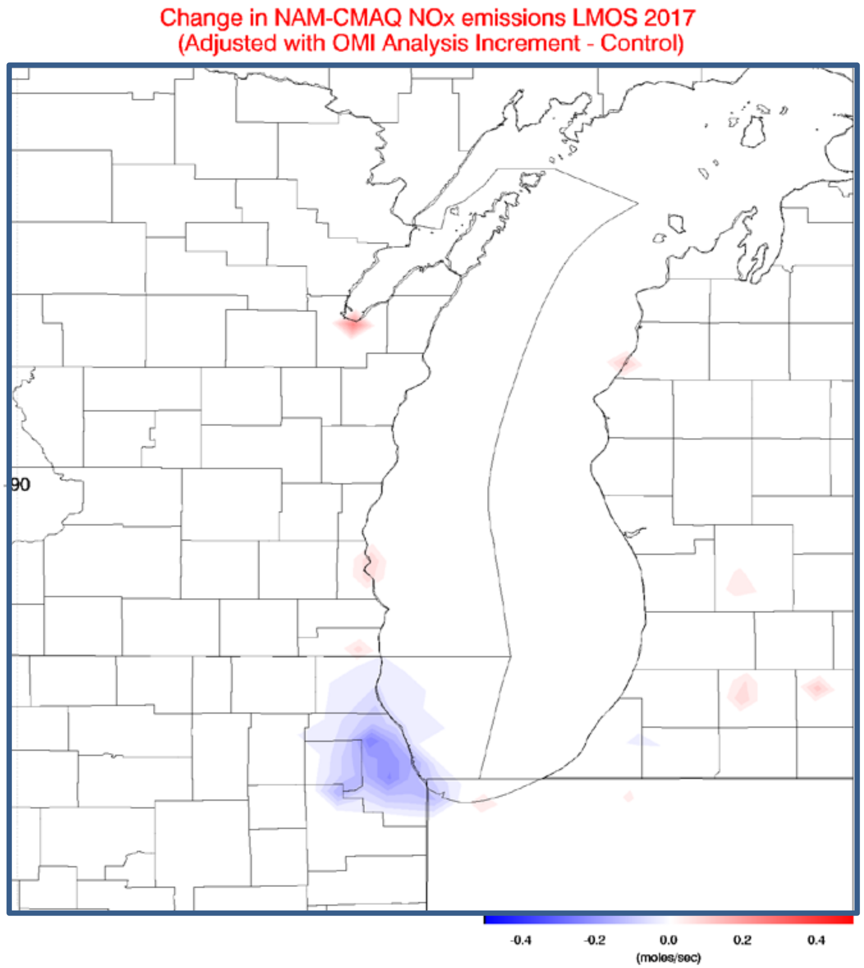
$$\frac{\Delta E}{E} = \beta \times \frac{\Delta \Omega}{\Omega}.$$

NOx emissions adjustments (ΔE) are constrained using OMI tropospheric NO2 column analysis increments (ΔΩ)

β accounts for the sensitivity of the NO2 column to changes in NOx emissions following Lamsal et al 2011.

Lamsal, L. N., et al. (2011), Application of satellite observations for timely updates to global anthropogenic NOx emission inventories, Geophys. Res. Lett., 38, L05810, doi:10.1029/2010GL046476.

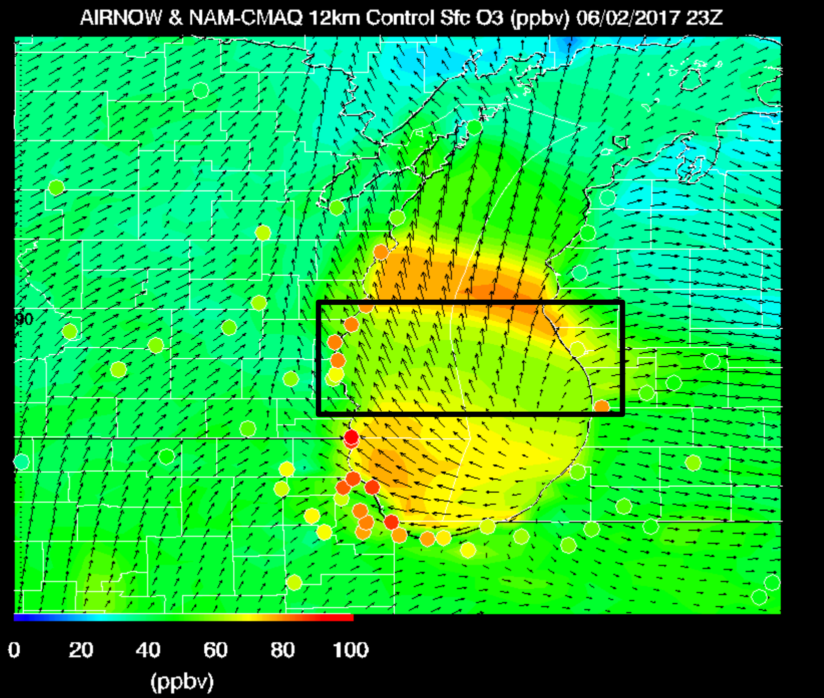
Aura Ozone Monitoring Instrument (OMI) Tropospheric NO2 column Data Assimilation

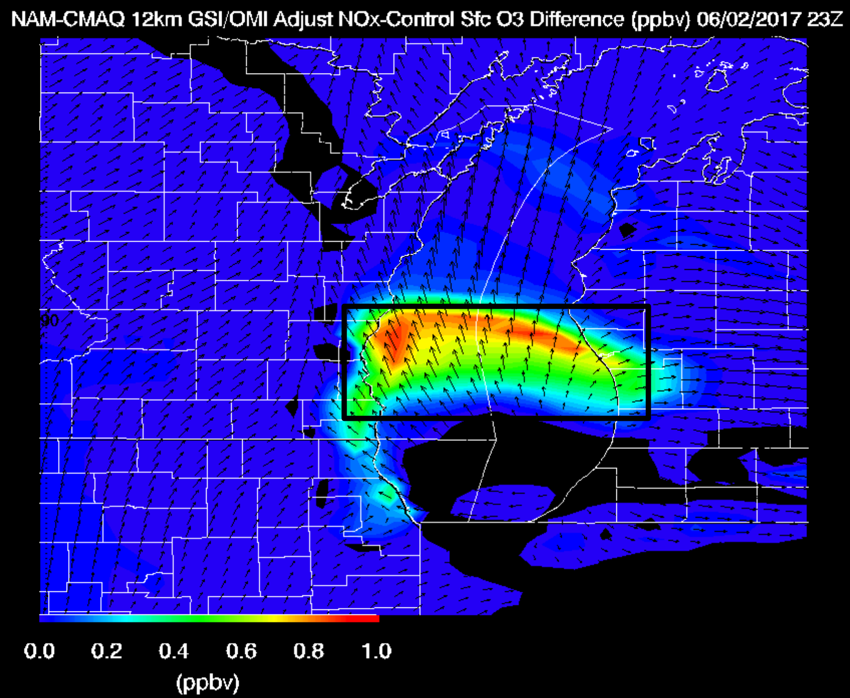


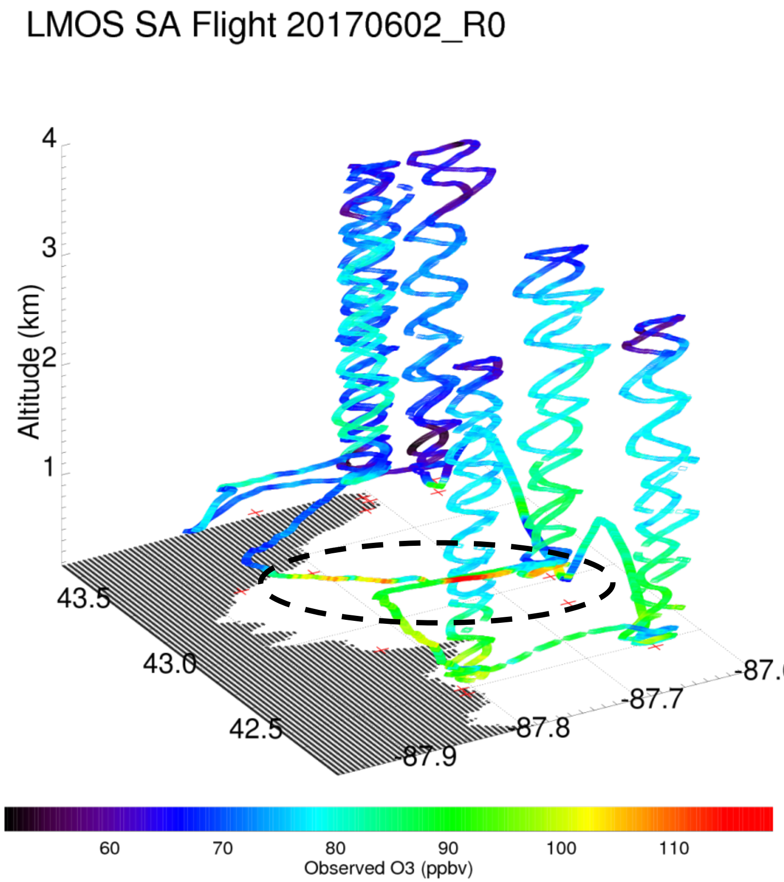
$$\frac{\Delta E}{E} = \beta \times \frac{\Delta \Omega}{\Omega}.$$

Assimilation of OMI NO2 results in small (~4%) reductions in NOx emissions over Chicago

Lamsal, L. N., et al. (2011), Application of satellite observations for timely updates to global anthropogenic NOx emission inventories, Geophys. Res. Lett., 38, L05810, doi:10.1029/2010GL046476.





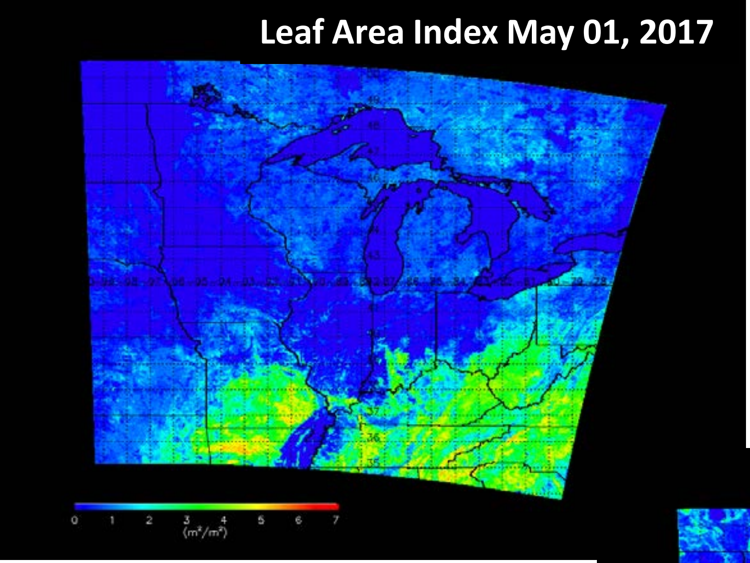


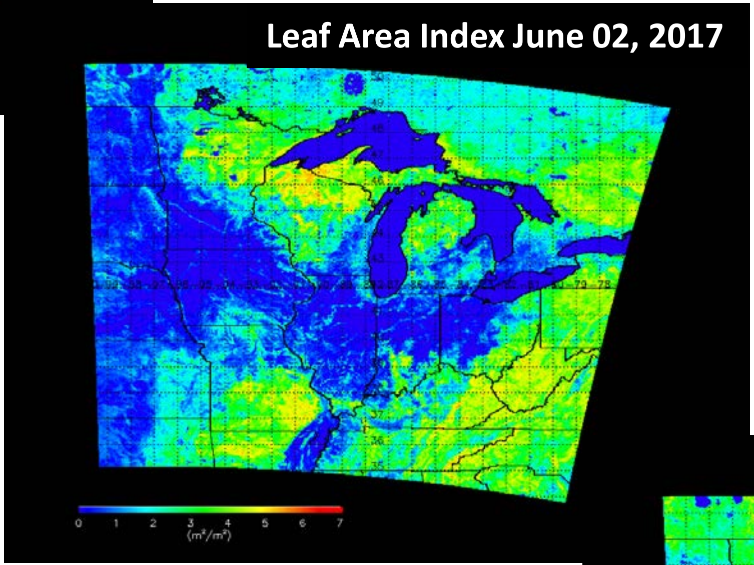
Max Observed O3 > 110ppbv

Reductions in NOx emissions on high ozone day leads to slight (~1ppbv) increases in surface ozone

Biogenic VOC Sensitivity Studies

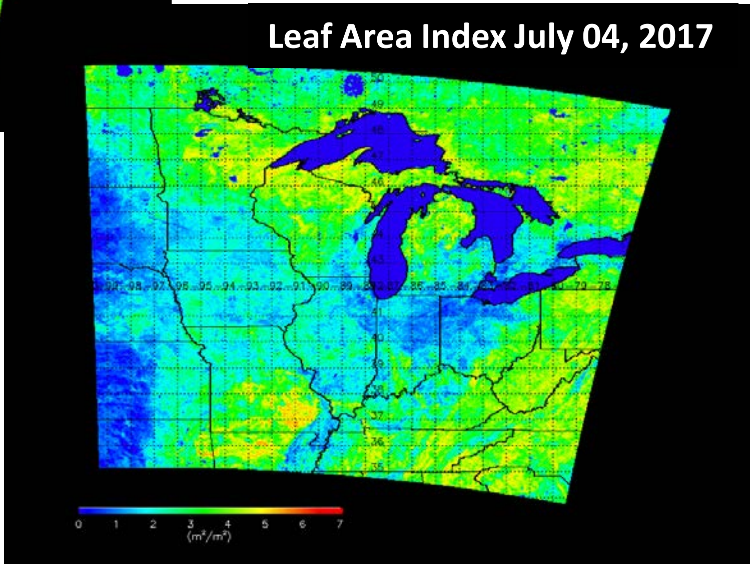
NAM-CMAQ 2x Biogenic emission Experiment
May 22 – June 13, 2018

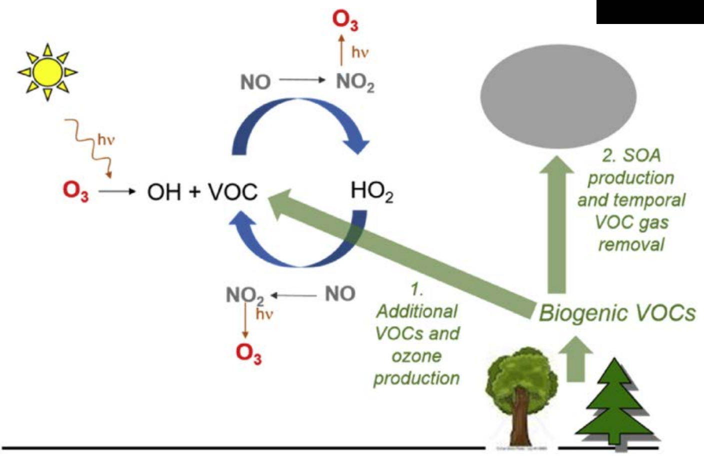


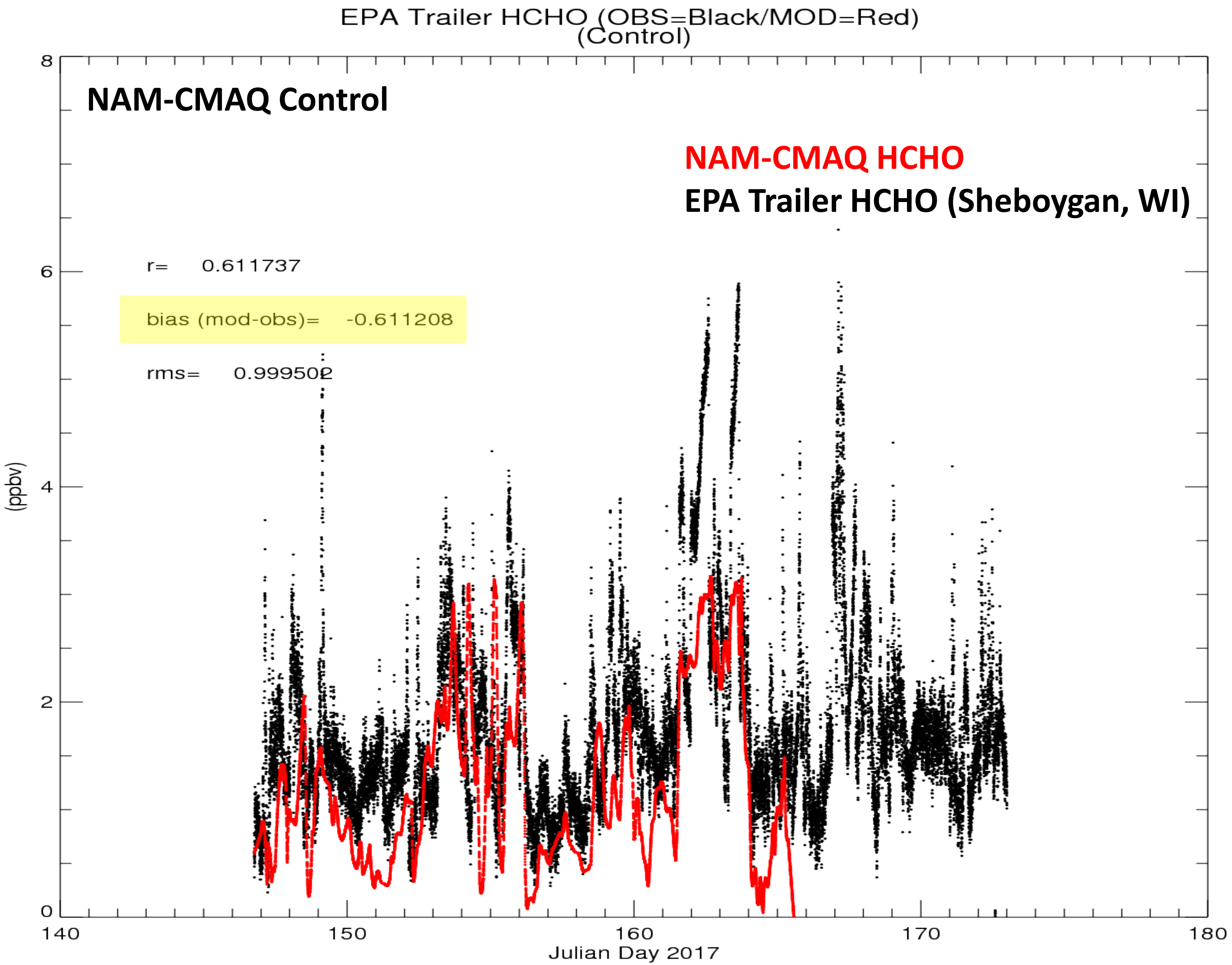


Isoprene (biogenic VOC) emissions increase with leaf area (leaf out)

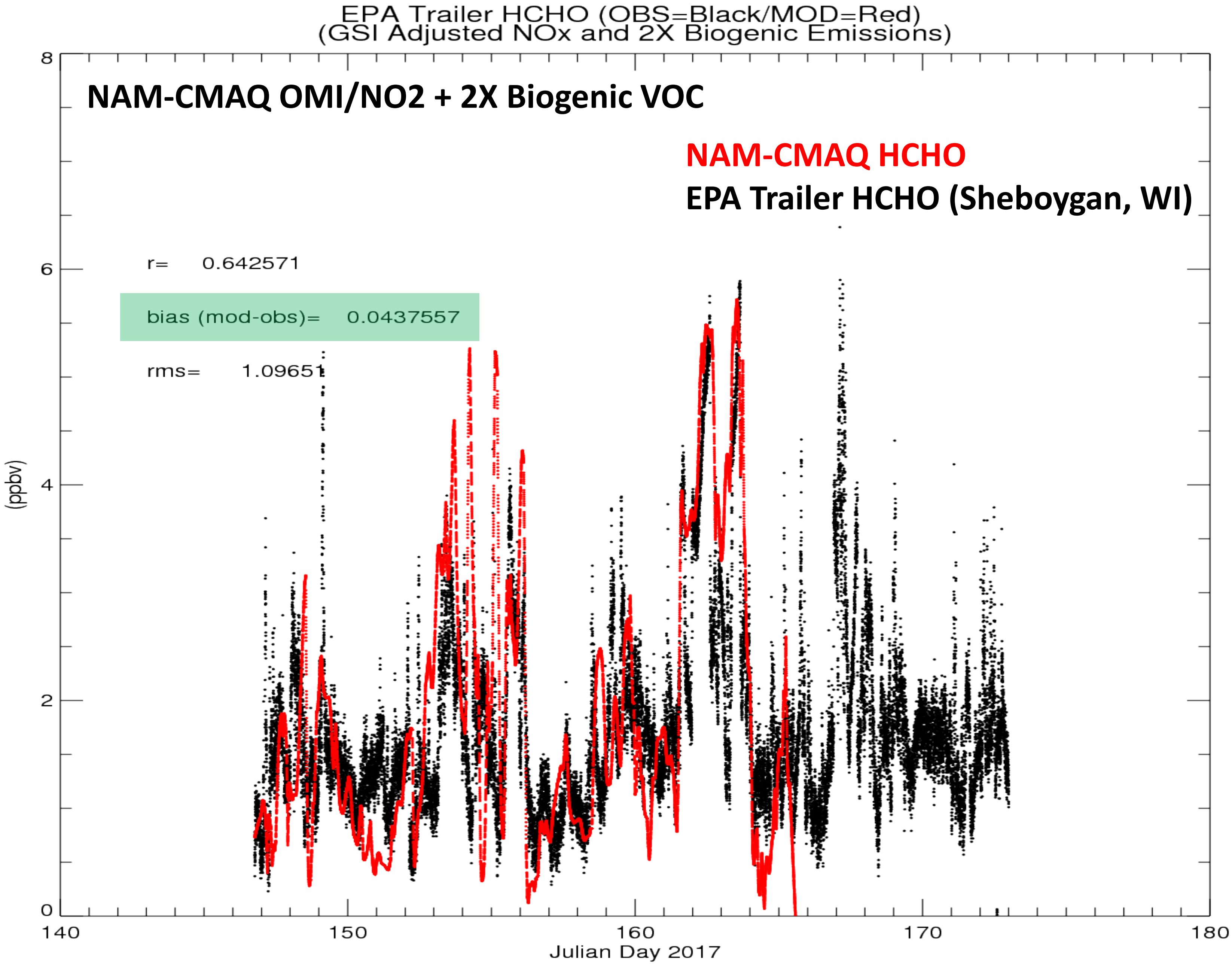
Increased biogenic VOCs can enhance ozone production in urban plumes







Insitu HCHO provided by Jim Szykman (EPA)



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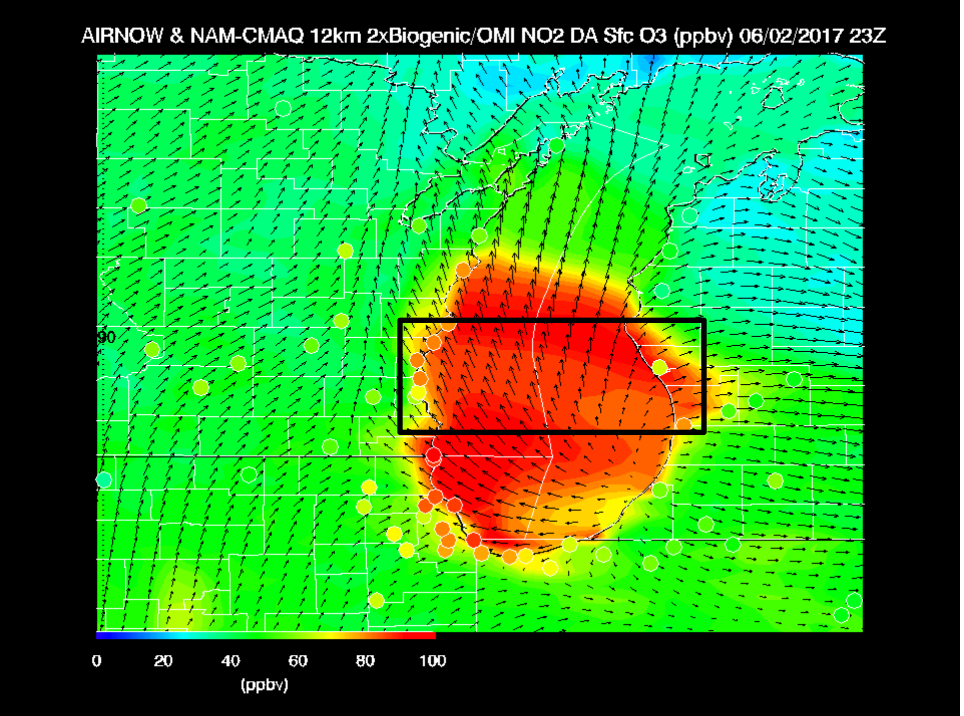
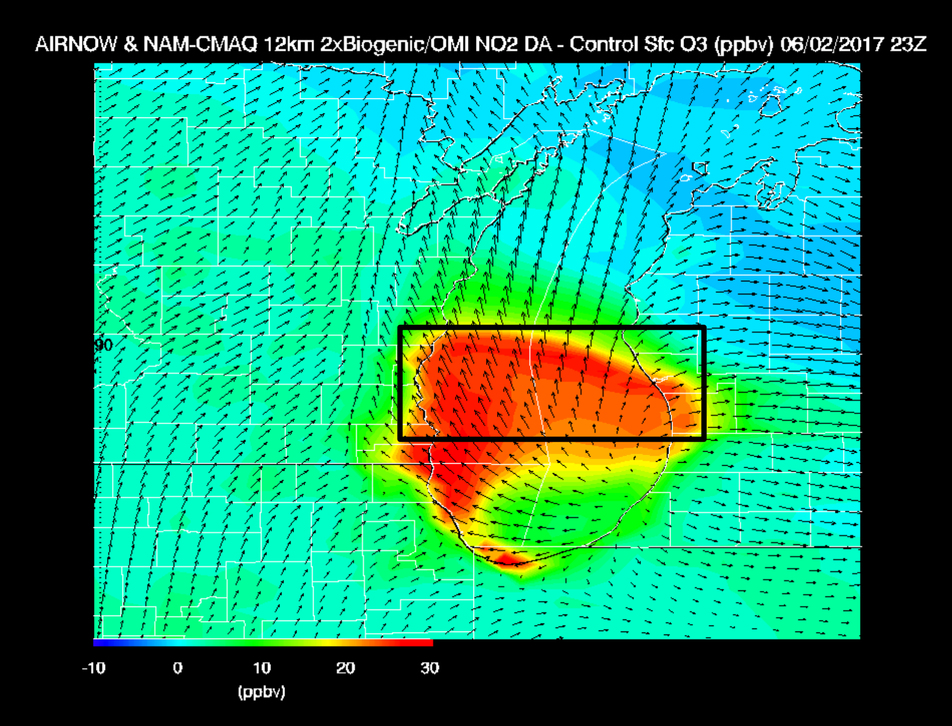
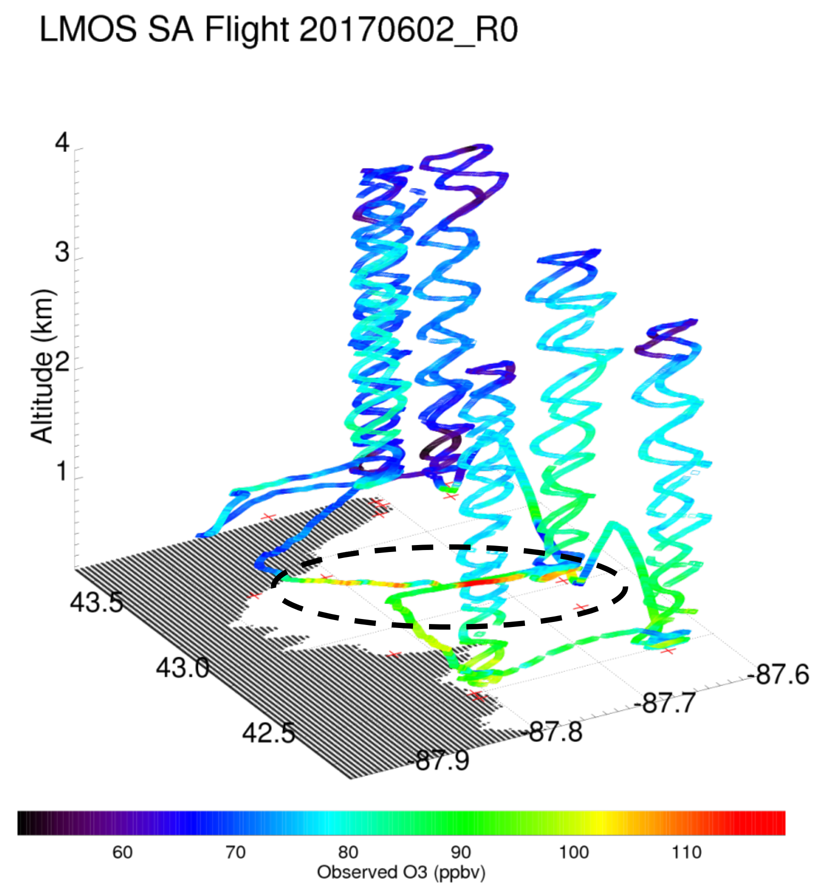


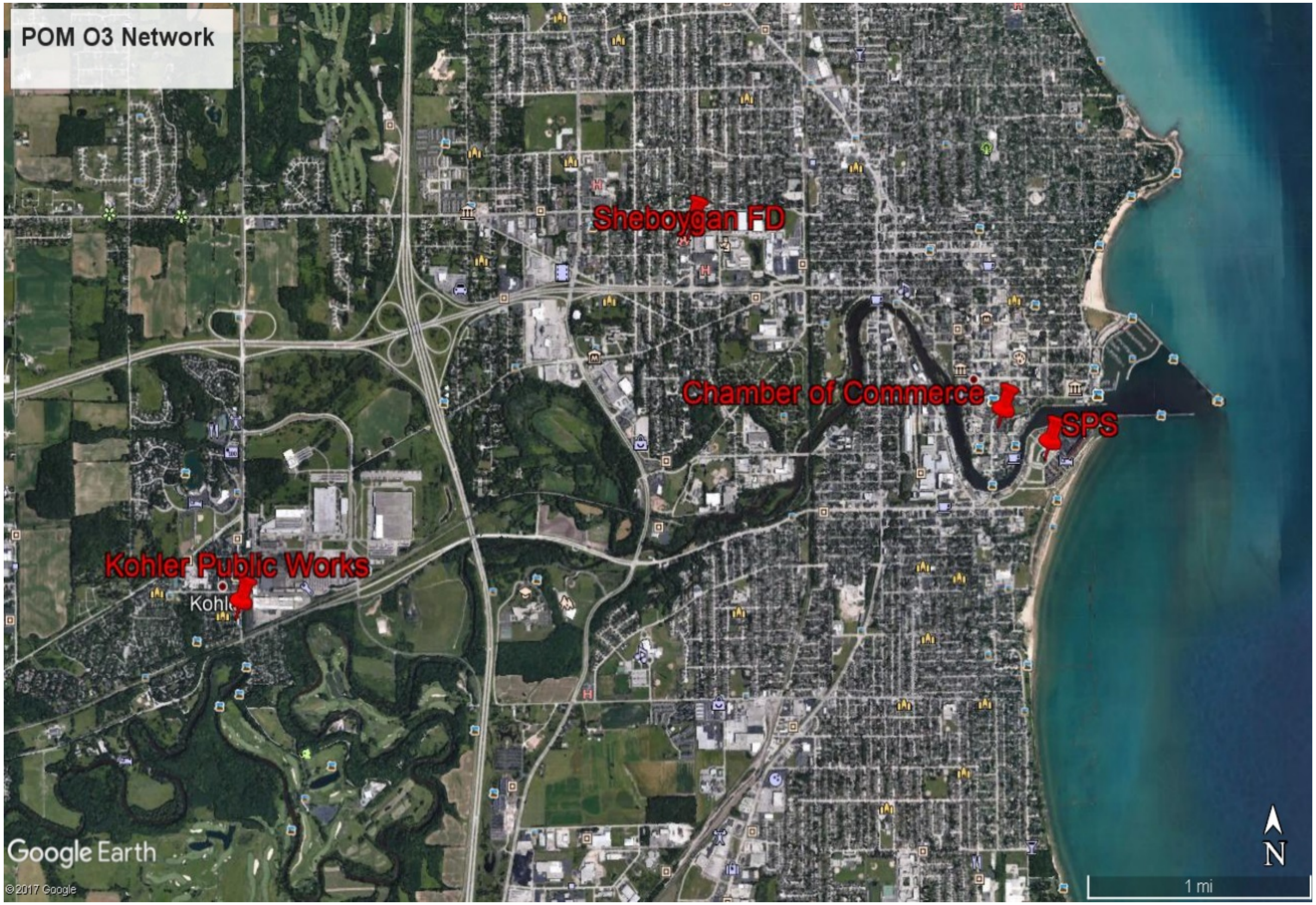




Max Observed O3 > 110ppbv

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

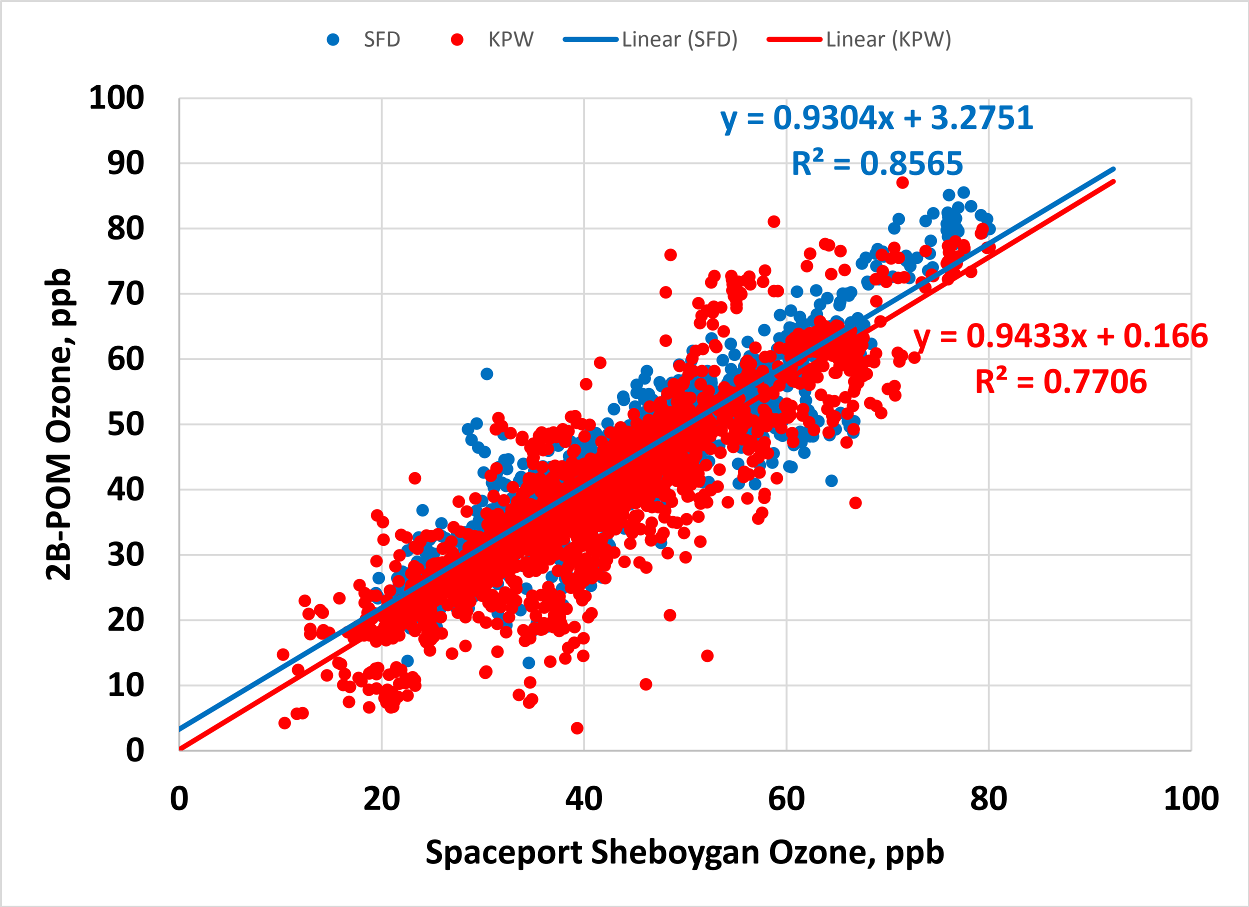
Locations of the 2B-Personal Ozone Monitors for inland gradient study



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 NO2 concentrations during ozone exceedance events during LMOS 2017.**

  - ✓ **NAM-CMAQ sensitivity studies show that reductions in anthropogenic NOx 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.

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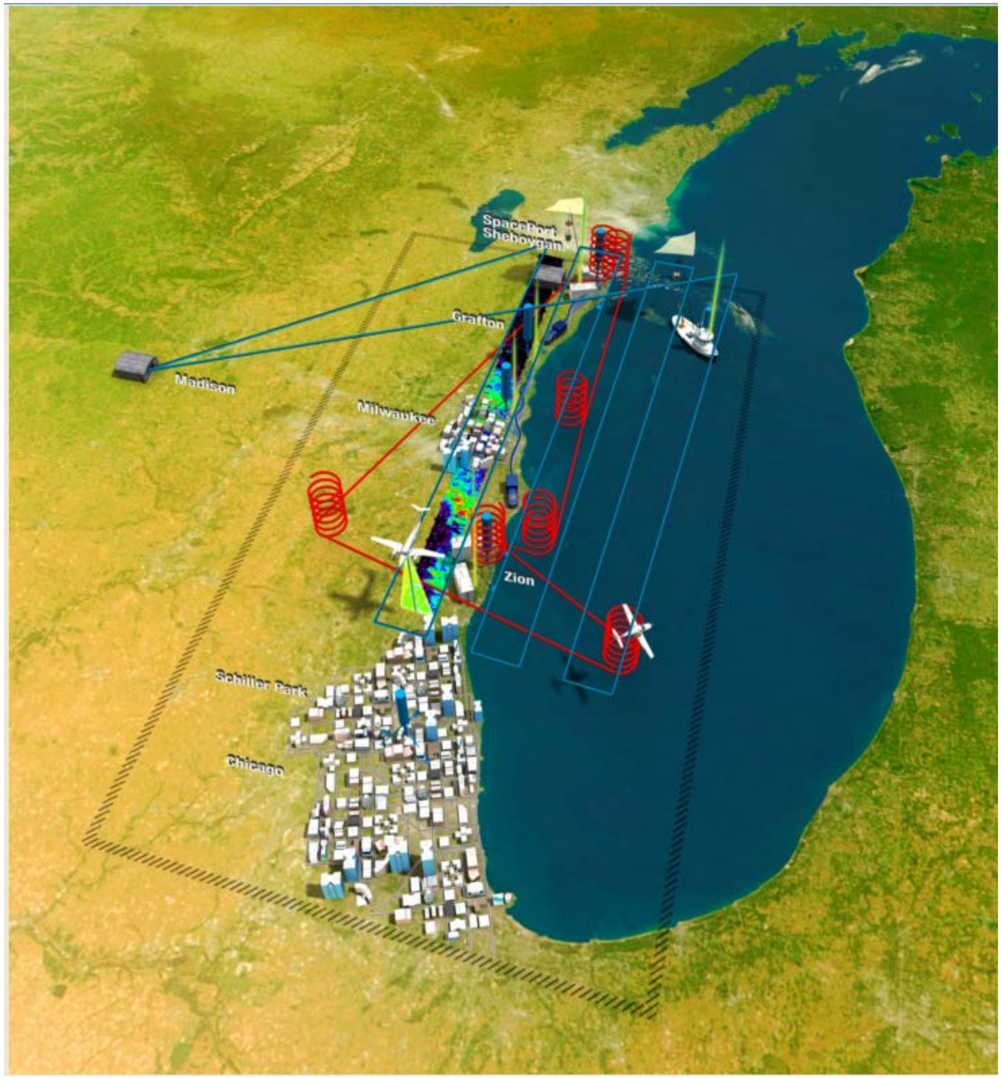
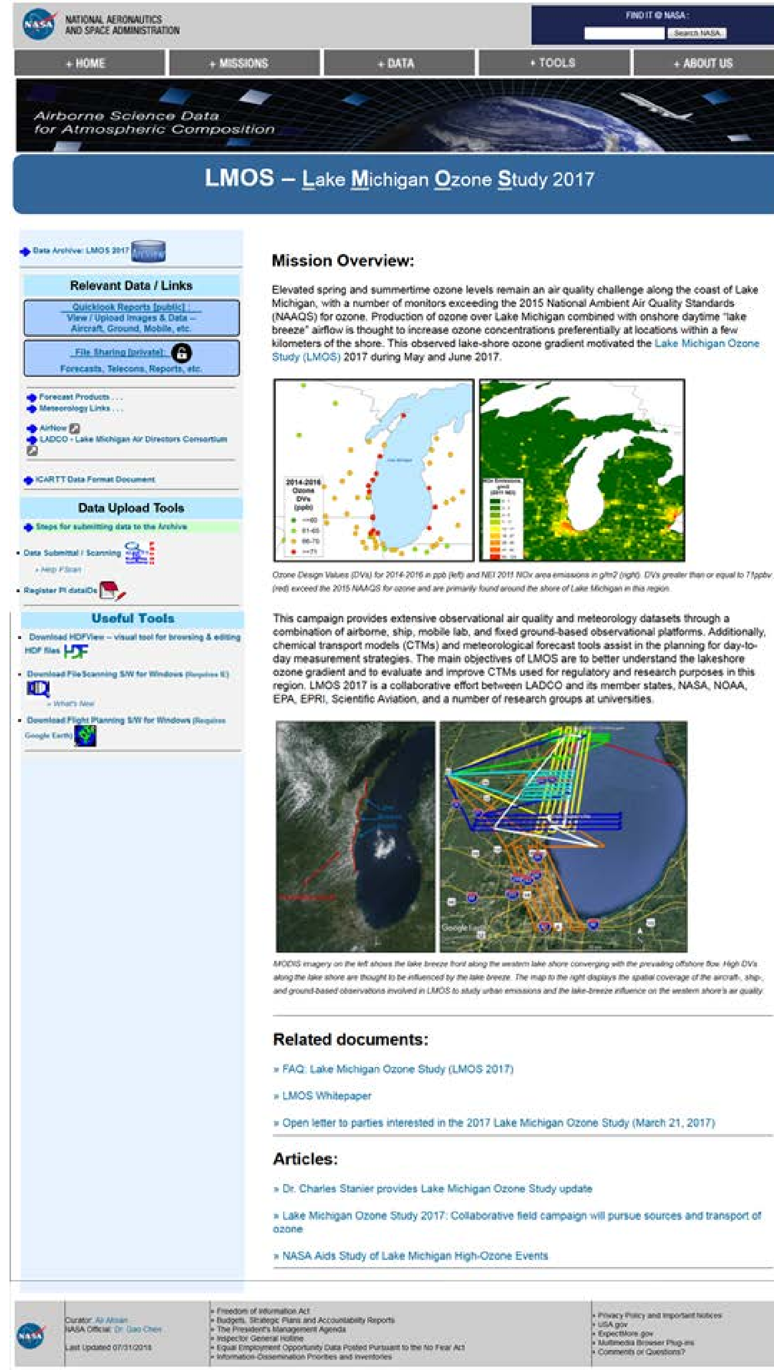
LMOS 2017 Data Archive

(Became publically available 8/2/2018)

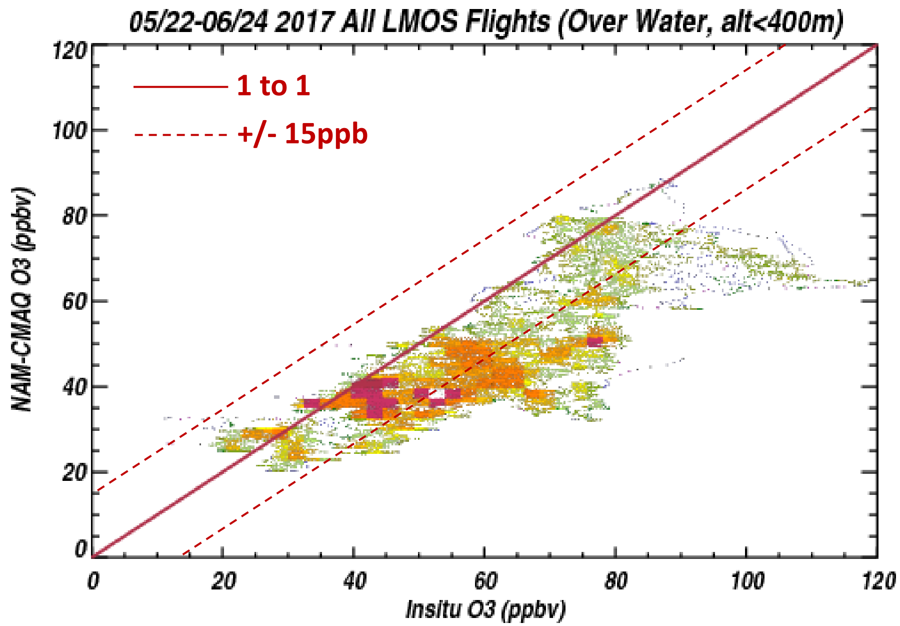


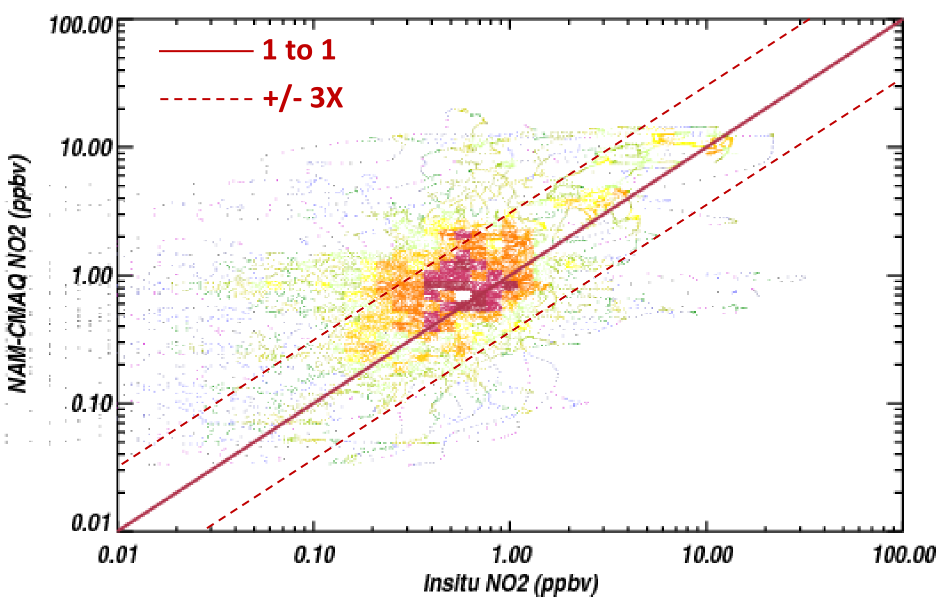


https://www-air.larc.nasa.gov/missions/lmos/index.html

Extra Slides

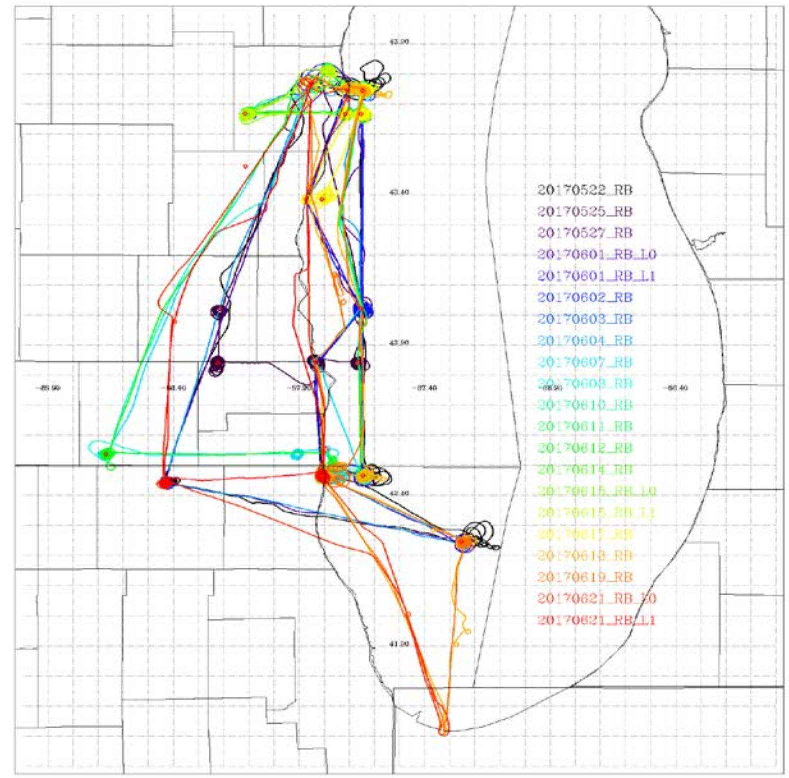
NAM-CMAQ vs Scientific Aviation (Over Water, Altitude <400m)





Steve Conley (Scientific Aviation PI)

All Scientific Aviation Flights

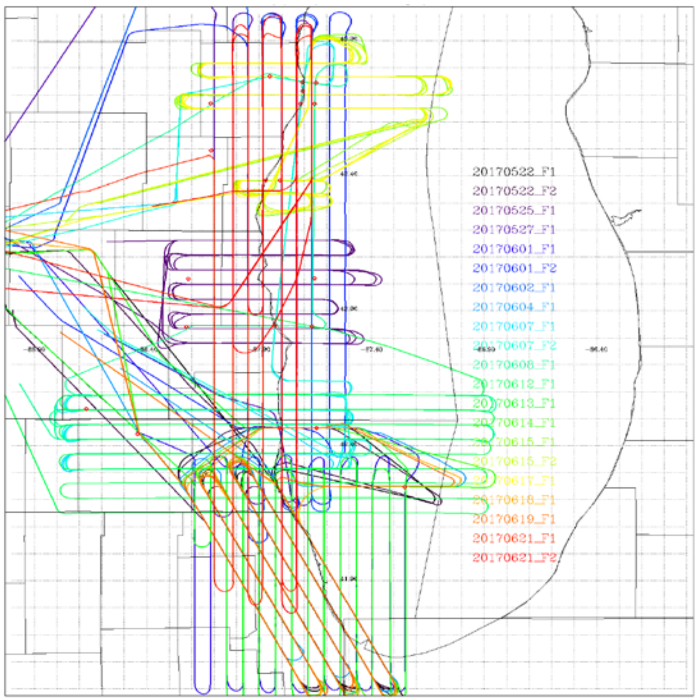


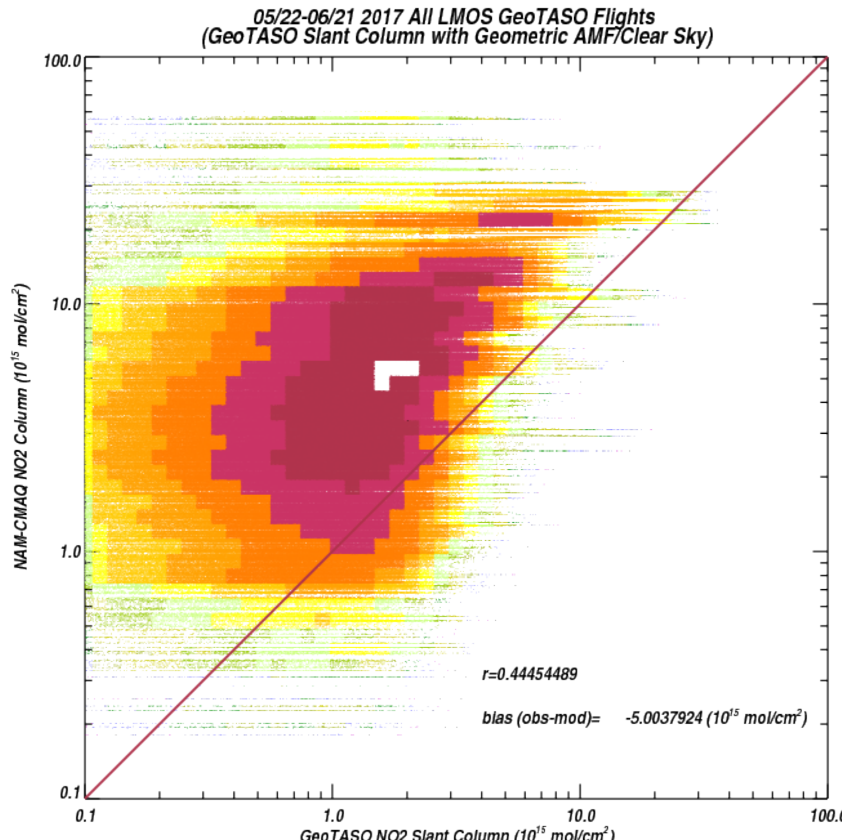
NAM-CMAQ underestimates O3 and overestimates NO2 over Lake Michigan

LMOS May 22 through June 21, 2017

NAM-CMAQ vs GeoTASO Differential Slant Column

All GeoTASO Flights





NAM-CMAQ overestimates NO2 columns compared to GeoTASO differential slant columns (currently not accounting for instrument sensitivity to NO2 profile)