Elevated Ozone Along the Shoreline of Lake Michigan

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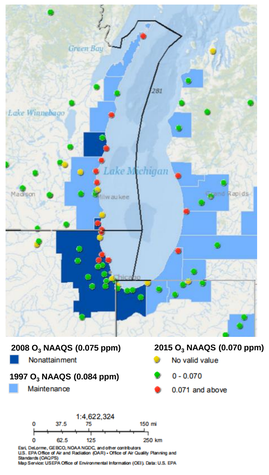
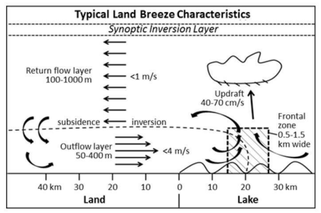
Ozone Nonattainment Around Lake Michigan & Lake Breeze Meteorology

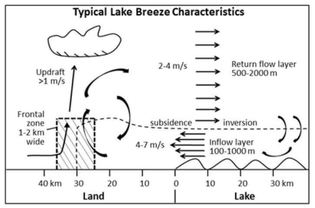


Observations of elevated ozone along the shoreline of Lake Michigan relative to areas farther inland expressed as 2014-2016 design values. The "design value" for ozone is the 3-year average of the annual 4th highest daily 8-hour average ozone concentration.



Land Breeze

The morning land breeze can transport local precursor emissions over the lake.



Lake Breeze

The afternoon lake breeze can bring local emissions back on shore after they have had time to photochemically react to form ozone in the shallow inversion layer over the lake.

Figures from White Paper: Lake Michigan Ozone Study 2017 (LMOS 2017) Peirce et al. 2016

Impact on Production and Transport

The land/lake breeze is typically more localized than the prevailing (synoptic) winds. Studies indicate the land/lake breeze can trap, stratify, and recirculate offshore air. Daytime inversions over the lake create stable layers of urban plumes, which, on warm sunny days, are conducive to ozone formation. The afternoon lake breeze can carry photochemically aged, ozone-rich air toward the land where violations of the ozone standard can be measured at downwind locations along the shoreline. Additionally, large-scale, summertime, stagnant high-pressure systems centered to the southeast of the lake have been implicated in high ozone episodes, because they can produce southerly and southeasterly flows over Lake Michigan, which enhance the flow of photochemically aged air to downwind locations along the shoreline of Lake Michigan. The relative role of each (the land/land breeze and synoptic flow) is episode-specific and not fully understood. *[Cleary et al. 2015; Foley et al. 2011; Lennartson and Schwartz 1999; Dye et al. 1995]*

History

- **1987** Wisconsin and EPA agree to fund an ozone transport study (Wisconsin vs. Reilly, No. 87-C-0395)
- **1989** Lake Michigan Air Directors Consortium (**LADCO**) formed to manage the study
- **1991** Lake Michigan Ozone Study (**LMOS 1991**)
- **1994-2003** LADCO Aircraft Project (**LAP**)

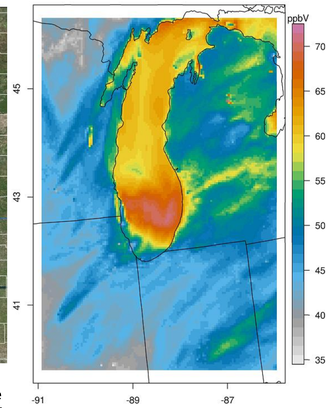
Overall Findings from LAP & LMOS 1991

Large-scale high-pressure anticyclonic flows can enhance the localized lake breeze flow of photochemically aged, ozone-rich air to downwind locations along the shoreline of Lake Michigan (Lennartson and Schwartz 1999, Hanna and Chang 1995, Dye et al. 1995, Foley et al. 2011)

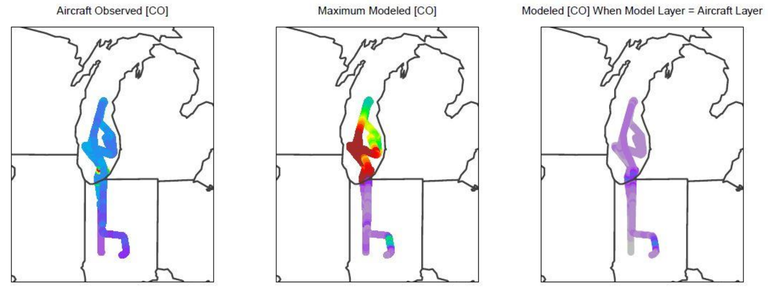
- **2017** Lake Michigan Ozone Study (**LMOS 2017**)

CMAQv5.2 Model Simulation Coincident with Ground and Aircraft Observations on July 7, 2013

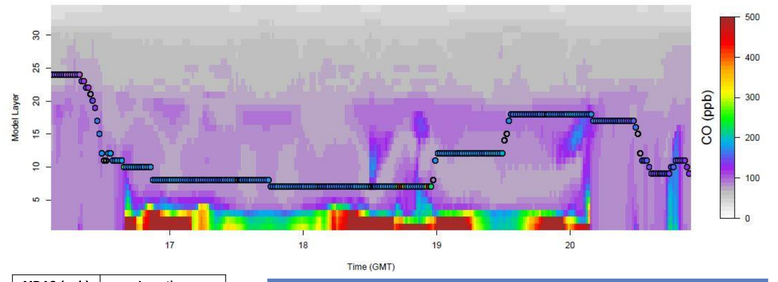
NOMADSS Research Flight RF15
NSF/NCAR C-130 flew over Lake Michigan on July 7, 2013, as part of the Southeast Atmosphere Study (SAS)
which is the umbrella for The Nitrogen, Oxidants, Mercury and Aerosol Distributions, Sources and Sinks (NOMADSS) project.

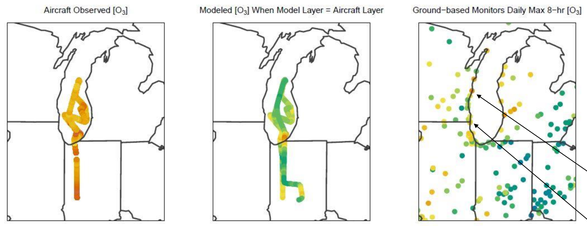


Modeled maximum daily 8-hour average ozone (MDA8) for July 7, 2013, using CMAQv5.2 with CB6r3 at a 4-km resolution. The model was applied with 35 vertical layers extending from the surface to 50 mb.



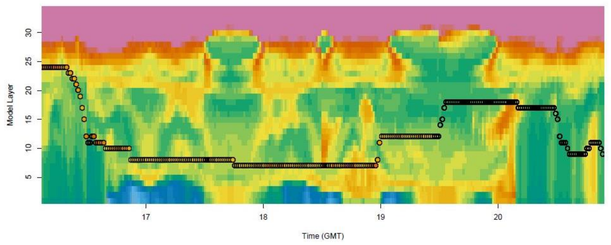
Carbon Monoxide: ***Top panels from left to right*** show the aircraft CO measurements, the maximum modeled CO regardless of the layer in which it occurred, and the modeled CO when the model layer is equal to the aircraft layer for July 7, 2013.
Bottom panel shows the modeled CO mixing ratios in ppb for all 35 vertical layers modeled and the circles show the aircraft CO measurements on the same ppb scale. **The 2017 LMOS study will be a valuable opportunity to evaluate both upper air and surface level chemical species to better understand the complicated chemical-meteorological interactions in this area.**





Ozone: ***Top panels from left to right*** show the aircraft ozone measurements, the modeled ozone when the model layer is equal to the aircraft layer, and modeled MDA8 for July 7, 2013, at the ground-based ozone monitors in the modeling domain.
Bottom panel shows the modeled ozone mixing ratios in ppb for all 35 vertical layers modeled and the circles show the aircraft ozone measurements on the same ppb scale.

MDA8 (ppb)	Location
71 (modeled 56)	**Sheboygan Nonattainment Area** Kohler Andrae Monitor: 55-117-0006
63 (modeled 43)	**Chicago Nonattainment Area** Chiwaukee Prairie Monitor: 55-059-0019



The modeling system predicts both ozone formation and destruction over Lake Michigan. Aircraft observations tend to be higher than the surface mixing layer in the model making evaluation problematic using these data, which emphasizes the need for more data (**e.g., 2017 LMOS study**) to better constrain and understand model predictions.

Summary

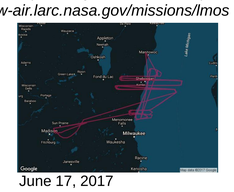
- Ozone measurements are generally greater near the shoreline than father inland. While it is well-known that the lake can influence ozone formation, the relative role of lake breeze (local) and synoptic (regional-scale) meteorology on ozone production and transport is episode-specific and not fully understood.
- Routine ozone measurements are collected over the land, but not over the water (Lake Michigan). The July 7, 2013 aircraft measurements over Lake Michigan provided an opportunity for model evaluation of ozone data collected over the lake.

Opportunities for Future Investigation

The **2017** Lake Michigan Ozone Study (**LMOS 2017**) provides a new opportunity for model evaluation. The study included contributions from NASA, NOAA, LADCO, Wisconsin DNR, UW-Madison, University of Iowa, University of Minnesota, EPA Office of Research and Development (ORD), EPA Region 5, and other groups.

The field study included aircraft, ship, and ground-based supersite measurements collected in the summer of 2017. *https://www-air.larc.nasa.gov/missions/lmos*

LaRC UC-12B (N528NA)



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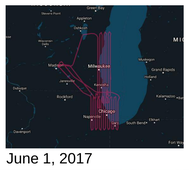

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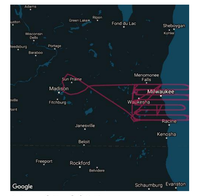

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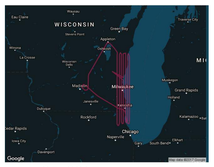
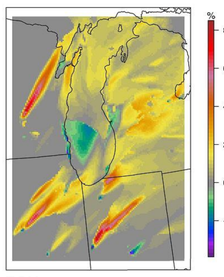


May 27, 2017

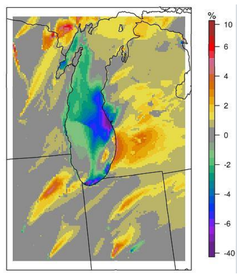
https://airbornescience.nasa.gov/tracker

Zero-Out Modeling

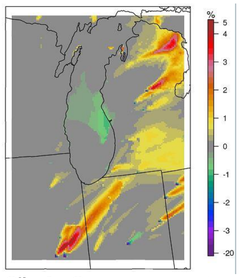
Zero-out modeling showing emission source sector contributions to the MDA8 on the day the aircraft flew over the lake, July 7, 2013.



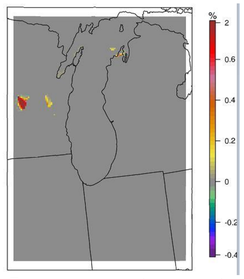
EGU source sector percent contribution to MDA8 on 7/7/13
Max: 8.3% (3.85 ppb)



Non-EGU source sector percent contribution to MDA8 on 7/7/13
Max: 6.9% (2.84 ppb)



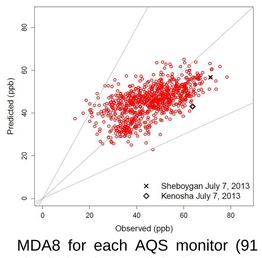
Oil & Gas source sector percent contribution to MDA8 on 7/7/13
Max: 4.4% (2.19 ppb)



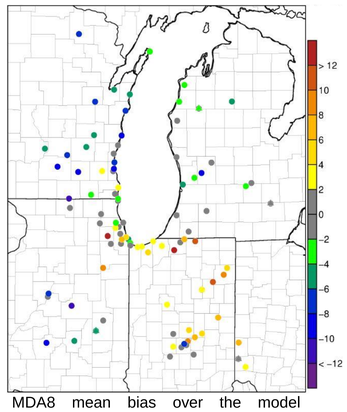
Fires source sector percent contribution to MDA8 on 7/7/13
Max: 1.7% (0.765 ppb)

Model Performance

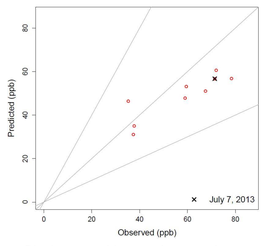
While there is a reasonable correlation between the modeled and observed MDA8 during the simulation period (July 1-9, 2013), the model tends to overestimate the lowest observed values and underestimate the highest observations.



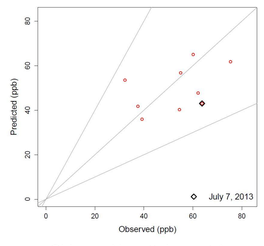
MDA8 for each AQS monitor (91 sites) in the model domain for each day over the model simulation period (7/1-7/9/13). The MDA8 at the Sheboygan and Chicago monitors, respectively, is shown for the day on which the C-130 flew over Lake Michigan (July 7, 2013). The lines on either side of the 1:1 line represent 0.5 and 2.



MDA8 mean bias over the model simulation period (7/1-7/9/13)



Sheboygan Nonattainment Area
Predicted vs. Observed MDA8 (7/1-7/9/13)



Chicago Nonattainment Area
Predicted vs. Observed MDA8 (7/1-7/9/13)

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Acknowledgements

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Disclaimer: Although this work was reviewed by EPA and approved for presentation, it may not necessarily reflect official Agency policy.