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Overview of the Lake Michigan Ozone Study 2017

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List of acronyms

AMF	Air mass factor
CAPS	Cavity attenuated phase shift
DMS	Dimethyl sulfide
EC	Elemental carbon
GCMS	Gas chromatograph mass spectrometer
IEPA	Illinois Environmental Protection Agency
Lidar	Laser detection and ranging
LPM	Liters per minute
MACR	Methacrolein
MVK	Methyl vinyl ketone
NERL	National Exposure Research Laboratory
NMVOC	Non-methane volatile organic compound
NO_x	Nitrogen oxides (NO + NO_2)
NO_y	Reactive nitrogen
OC	Organic carbon
PM	Particulate matter
RH	Relative humidity
$PM_{2.5}$	Fine particulate matter (smaller than 2.5 μm)
SODAR	Sonic detection and ranging
U	Zonal (east–west) wind velocity component
USEPA	United States Environmental Protection Agency
UWEC	University of Wisconsin–Eau Claire
V	Meridional (north–south) wind velocity component
WD	Wind direction
WS	Wind speed

Note for table ES1

The following sites are routine WDNR and IEPA sites where 1-min time resolution data were placed into the campaign repository. Normally, only 1-h data would be publicly available. Italics indicate locations in the table because instrumentation was added for the campaign. Other routine measurements may be available: please check USEPA AQS database; sites that are known to have other pollutants available (e.g., SO_2, PM_{10}, $PM_{2.5}$, speciated $PM_{2.5}$, NO_x) are marked with an asterisk.

With meteorology (temperature, wind speed, and wind direction)

- Chiwaukee Prairie 55-059-0019, ozone, NO_2, hourly $PM_{2.5}$
- Kohler Andrae 55-117-0006, ozone
- Sheboygan Haven 55-117-0009, ozone
- Kenosha Water Tower 55-059-0025, ozone
- Lake Geneva, 55-127-0005, ozone
- Manitowoc 55-071-0007, ozone*
- Newport Park 55-029-0004, ozone
- Harrington Beach 55-089-0009, ozone*
- *Grafton 55-089-0008, ozone*
- *Milwaukee WDNR SERS 55-079-0026, ozone, NO_x, NO, NO_2, NO_y, SO_2**

Air pollutants only

- Bayside 55-079-0085, ozone
- Kewaunee 55-061-0002, ozone
- Milwaukee, 16th St. 55-079-0010, ozone*

- Racine 55-101-0020, ozone
- Chicago CTA, NO_x
- Chicago Taft, NO_x
- Cicero, NO_x, ozone
- Evanston, ozone
- Northbrook, ozone, CO*
- Schiller Park, NO_x*

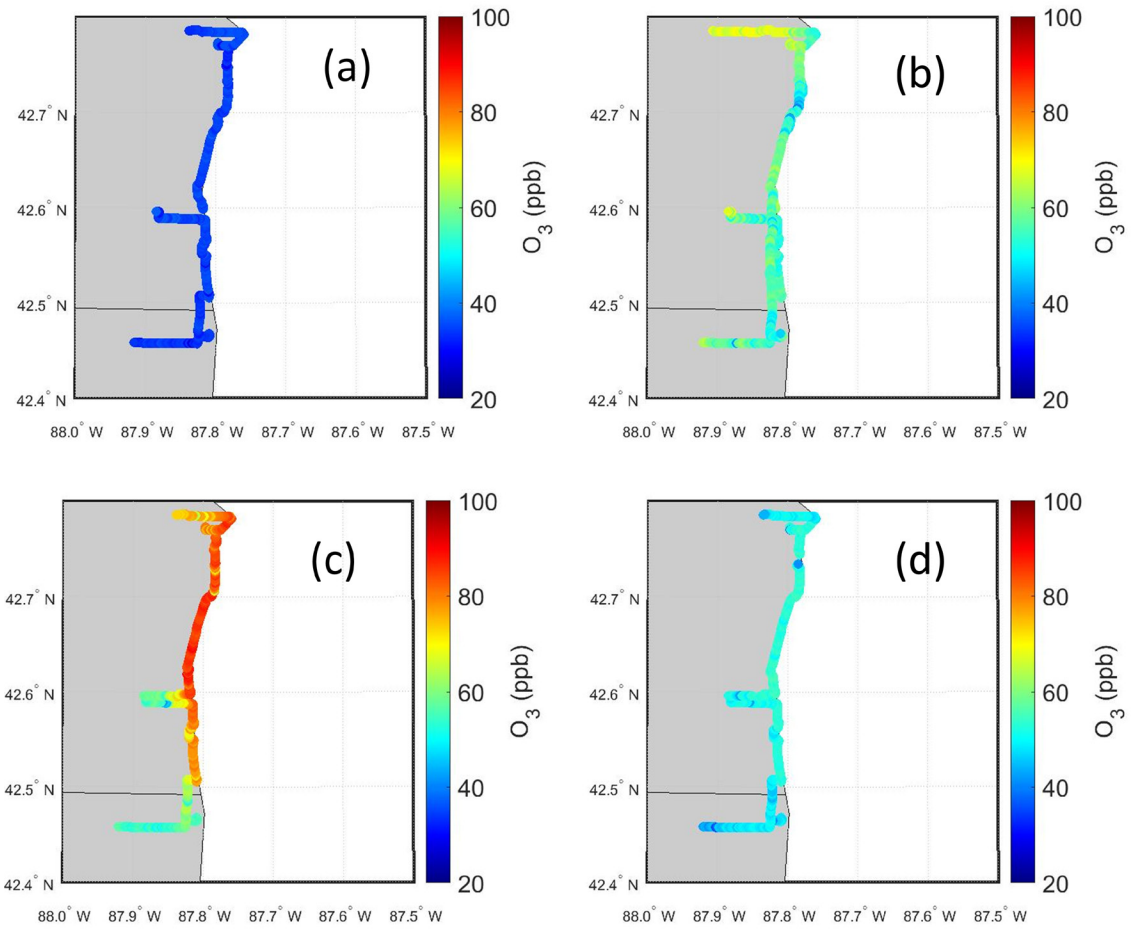

Fig. ES1. Ozone vs position for the GMAP vehicle on the four research drive days. (a) 6 Jun with low ozone and no lake breeze; (b) 8 Jun with moderate ozone and lake breeze with deep inland penetration; (c) 12 Jun with high ozone and lake breeze with shallow inland penetration; and (d) 13 Jun with no lake breeze. Panel (c) for 12 Jun is also part of Fig. 8 in the main paper.

Table ES1. Site and instrument information. Instruments are in situ except where noted as "remotely sensed" in variables measured. Some routine monitoring locations did not have instrumentation added, but 1-min time resolution data were uploaded to the NASA repository from several sites during LMOS 2017, supplementing routine 1-h resolution data. See Note for Table ES1 for a listing. For a list of meteorological measurements near the Sheboygan and Zion enhanced monitoring sites, see Doak et al. (2021) supplement. See the List of Acronyms for the definitions of acronyms in the table.

Instrument	Time interval	Variables measured	Principal investigator	Comments
Site: Zion, IL (42.4676°N, 87.8100°W). AQS ID: 17-097-1007				
Ozone analyzer (Teledyne T400)	1 min	Ozone	IEPA	Routine monitor station/instrument
10-m meteorological tower (Met One)	1 min	Temperature, WS, WD, RH, pressure, rainfall	IEPA	Data available starting 30 May 2017. Met One AIO Weather Sensor.
NO_x analyzer (Thermo 42i)	1 min	NO, NO_2, NO_x	Bertram	
CO analyzer (Thermo 48i)	N/A	CO	Bertram	Data not reported in final R1 ICARRT file—Bertram group determined instrument failed calibration checks
CIMS (Tofwerk AG, Switzerland, and Aerodyne Research Inc., USA)	1 min	HNO_3, H_2O_2, and others	Bertram	See Vermeuel et al. (2019)
Pyranometer (PSP, Eppley Laboratory)	1 min	Solar radiation	Bertram	Spectral range 295–2,800 nm
Aerosol particle sizer (TSI 3321)	2 min	Particle size distribution (0.5–10 μm)	Stanier	See Doak et al. (2021)
Condensation particle counter (TSI 3025A)	2 min	Aerosol number concentration	Stanier	Data available starting 1 Jun
Scanning mobility particle sizer (TSI 3936L85)	2 min	Particle size distribution (12–562 nm)	Stanier	See Doak et al. (2021)
1-nm Scanning mobility particle sizer (TSI 3938E57)	2 min	Particle size distribution (1–30 nm)	Stanier	
Carbon dioxide analyzer (Vaisala flow-through GMP343)	10 s	CO_2	Stanier	Data available starting 15 Jun
SO_2 analyzer (Teledyne 100E)	10 min	SO_2	Stanier	Data available starting 28 May, UV fluorescence
Airbeam optical particle sensor	1 s	$PM_{2.5}$	Stanier	$PM_{2.5}$ derived from optical particle counts by red light scattering, sensor is Shinyei PPD60PV-T2
Audio volume from Android Verizon Ellipsis Tablet	1 s	Audio volume near train tracks as locomotive detection	Stanier	See Doak et al. (2021)
Proton Transfer Reaction Quadrupole Interface Time-of-Flight mass spectrometer (PTR-Qi-TOF, Ionicon Analytik)	1 min	Acetaldehyde, acetone, acetonitrile, benzene, aromatics (C8, C9, C10), carbonyls (C4, C5, C6), isoprene, methanol, methylfuran, monoterpenes, toluene, MVK/MACR	Millet	See Millet et al. (2018) and Doak et al. (2021)
Medium-volume integrated filter samplers	12 h	$PM_{2.5}$ mass, EC, OC, ions (sodium, potassium, magnesium, calcium, ammonium, chloride, nitrite, nitrate, sulfate), select metals, molecular organic tracers	Stone	See Hughes et al. (2021)
NMVOC by GCMS (TRACE 1310, ISQ LT, Thermo Scientific)	60 min	45 NMVOC compounds, online trapping and analysis by GCMS	Stone	Data available starting 8 Jun
Acoustic profiler (miniSODAR, Atmospheric Systems Corporation)	2 min	Remotely sensed horizontal WS and WD, vertical velocity, gust WS and WD, *U* and *V* component WS	Czarnetzki	Vertical resolution 10 m from 30 to 200 m in altitude; see Abdi-Oskouei et al. (2020)
Microwave radiometer (MP-3000A, Radiometrics)	3 min (avg)	Remotely sensed temperature, RH, pressure. Rain sensor (binary) at surface.	Czarnetzki	At varying angles and altitudes from 0 to 3 km (except rain)
Pandora spectrometer	90 s (avg)	Remotely sensed column O_3 and NO_2	Valin/Szykman	

Table ES1. Continued.

Instrument	Time interval	Variables measured	Principal investigator	Comments
Vaisala CL51 Ceilometer	16 s (avg)	Remotely sensed attenuated backscatter profiles (910 nm), aerosol layer heights, mixing layer heights	Szykman	
Canisters analyzed for gases	Varying	74 compounds analyzed, C2-10 NMVOC, halocarbons, select alkyl nitrates, OCS, DMS, CS2, and dimethyl disulfide	Blake	Canisters collected (30-min fill time) based on forecasted air quality to focus on high ozone periods. Data not in repository, collected a total of 35 canisters. Analysis and precleaned canisters from Don Blake's group, UC Irvine. See Blake et al. (1999)
Cimel Sunphotometer	Varying	Spectral AOD (1,640–340 nm), Angstrom exponent	Pierce	Cloud cleared, quality assured with pre-field and post-field calibration applied data available at NASA Aeronet archive under "LMOS_Zion_Site" for June 2017; instrument relocated to Zion from Milwaukee SER on 4 Jun 2017.
Spaceport Sheboygan at Sheboygan Harbor (43.7456°N, 87.7087°W)				
Aerodyne QCL-TILDAS (TDL Wintel v14.91)	1 min	HCHO, HCOOH, H_2O	Whitehill/USEPA	At 1,765 cm^{-1}
High Spectral Resolution lidar (HSRL)	30 s (avg)	Remotely sensed aerosol backscatter, extinction, and linear polarization	Eloranta	0.1–3 km
Pandora spectrometer	90 s (avg)	Remotely sensed column O_3 and NO_2	Valin/Szykman	
NO_x analyzer (Teledyne-API T200U)	1 min	NO, NO_2, NO_x	Long	
NO_2 analyzer (Teledyne-API T500U CAPS)	1 min	NO_2	Long	
NO_y analyzer (Teledyne-API T200U NO_y)	1 min	NO_y, NO	Long	10-m inlet height
In situ meteorology (Vaisala WXT530)	1 min	Temperature, RH, pressure, WD, WS, rain	Long	Met measurements at 10 m
Ozone analyzer (2B Model 211)	1 min	Ozone	Long	
Atmospheric Emitted Radiance Interferometer (AERI)	2 min	Remotely sensed temp, water vapor, CH_4, N_2O, CO_2, liquid water path, ice cloud optical depth, cloud base height	Wagner	Located in the SPARC Trailer, located NE side of the Spaceport Museum; profiles up to 3 km or cloud base (except rain), whichever is lower
Doppler lidar (WINDPRO)	2 min (avg)	Remotely sensed WS, WD	Wagner	Located in the SPARC Trailer, located NE side of the Spaceport Museum; reported at 44 vertical layers ranging from 140 m to 2.4 km.
NASA UC-12 Aircraft, based in Madison, WI (Aircraft sampled at approximately 8-km flight altitude)				
Geostationary Trace gas and Aerosol Sensor Optimization (GeoTASO)	Varying	Remotely sensed CH_2O, NO_2 (columns below aircraft)	Judd/Al-Saadi/ Janz	See Judd et al. (2019)
Airborne Hyper Angular Rainbow Polarimeter (AirHARP)	Varying	I, Q, and U Stokes parameters at 440, 550, 670, and 870 nm	J. Vanderlei Martins	Dataset is Level 1B-R0 version that can be used for cloud and aerosol retrievals. See McBride et al. (2020) and Puthukkudy et al. (2020)
Scientific Aviation (SA Mooney), Airport Base: Sheboygan County Municipal Airport (Aircraft sampled from the surface up to an altitude of about 3.1 km)				
Ozone analyzer (2B Model 202)	1 s	Ozone	Conley	
NO_2 analyzer (Aerodyne CAPS)	1 s	NO_2	Conley	
Cavity ring down spectrometer (Picarro 2301F)	1 s	CO_2, CH_4, H_2O	Conley	

Table ES1. Continued.

Instrument	Time interval	Variables measured	Principal investigator	Comments
Meteorology (Vaisala HMP60)	1 s	Temperature, RH	Conley	
Aspen Avionics PFD1000	1 s	Pressure, true airspeed, *U*, *V*	Conley	*U* and *V* wind components measured by difference between true airspeed and ground speed (Conley et al. 2014)
Hemisphere VS101 differential GPS	1 s	Position, ground speed, *U*, *V*	Conley	*U* and *V* wind components measured by difference between true airspeed and ground speed (Conley et al. 2014)
NOAA R5503 research vessel, based at Spaceport Sheboygan, WI				
Ozone analyzer (FEM 2B-205)	1 min	Ozone	Williams	Ship position is also reported in the file with ozone, to ±0.1° accuracy based on linear interpolation in time between waypoints recorded in the ship transit log
GMAP Truck Mobile, based at R5 office in Chicago, IL				
Ozone analyzer (TEI49CPS, CR850 datalogger)	1 s	Ozone	Fuoco	
GPS and meteorology sensor	1 s	WS, WD, vehicle speed, position	Fuoco	
UWEC Mobile				
Ozone analyzer (2B POM)	1 min	Ozone	Cleary	5 min at each stop
Grafton (43.3430°N, 87.9200°W). AQS ID: 55-089-0008—Routine monitoring supplemented with Pandora and Ceilometer				
Ozone analyzer	1 min	Ozone	WDNR	Routine monitor
Meteorology	1 min	Temperature, WS, WD	WDNR	Routine observation
Pandora Spectrometer	90 s (avg)	Remotely sensed column O_3 and NO_2	Valin/Szykman	
Vaisala CL51 Ceilometer	16 s (avg)	Remotely sensed attenuated backscatter profiles (910 nm), aerosol layer heights, mixing layer height	Szykman	
Schiller Park (41.965°N, 87.876°W). AQS ID: 17-031-3103—Routine monitoring supplemented with Pandora				
Ozone analyzer	1 h	Ozone	IEPA	
$PM_{2.5}$	24 h	$PM_{2.5}$ (gravimetric)	IEPA	Every third day
NO_x (Teledyne T500U)	1-min	NO_x	IEPA	LMOS Repository (hourly NO and NO_2 in USEPA AQS)
Pandora Spectrometer	90 s (avg)	Remotely sensed column O_3 and NO_2	Valin/Szykman	
Milwaukee WDNR SERS (43.0609°N, 87.9135°W). AQS ID: 55-079-0026—Routine monitoring supplemented with Pandora and Ceilometer				
NO_2 (Teledyne T500U)	1 min	NO_2	WDNR	Routine monitor
Ozone analyzer	1 min	Ozone	WDNR	Routine monitor
SO_2 analyzer	1 min	SO_2	WDNR	Routine monitor
PM (Teledyne T640)	1 min	$PM_{2.5}$, PM10	WDNR	Routine monitor; at 16.7 LPM
Meteorology	1 min	Temperature, WS, WD	WDNR	Routine observation
NO_x analyzer	1 min	NO_x (NO, NO_2)	WDNR	Routine monitor
Pandora spectrometer	90 s (avg)	Remotely sensed column O_3 and NO_2	Valin/Szykman	
Vaisala CL51 Ceilometer	16 s (avg)	Remotely sensed attenuated backscatter profiles (910 nm), aerosol layer heights, mixing layer height	Szykman	
Sheboygan ozone network sites: Chamber of Commerce (43.74794°N, 87.71256°W), Fire Station (43.75935°N, 87.74003°W), Kolher Public Works Dept. (43.73721°N, 87.78052°W)				
Ozone analyzer (2B POM)	5 min (avg)	Ozone	Long	Internal instrument data logging issues resulted in data completeness issues for all three sites.

Table ES2. WRF-Chem ozone performance statistics stratified by ozone MDA8. The *p* values are one-sided, and significant *p* values were set at 0.025 (two-sided significance level of 0.05).

	Zion		Sheboygan KA	
MDA ozone	Mean bias (ppb)	*n*	Mean bias (ppb)	*n*
Low (<50 ppb)	+7.8 ppb	15	+3.3 ppb	15
Moderate (50–65 ppb)	+1.5 ppb	8	–4.2 ppb	8
High (>65 ppb)	–4.6 ppb	6	–10.2 ppb	6

References

Abdi-Oskouei, M., and Coauthors, 2020: Sensitivity of meteorological skill to selection of WRF-Chem physical parameterizations and impact on ozone prediction during the Lake Michigan Ozone Study (LMOS). *J. Geophys. Res. Atmos.*, **125**, e2019JD031971, https://doi.org/10.1029/2019JD031971.

Blake, N. J., and Coauthors, 1999: Aircraft measurements of the latitudinal, vertical, and seasonal variations of NMHCs, methyl nitrate, methyl halides, and DMS during the First Aerosol Characterization Experiment (ACE 1). *J. Geophys. Res. Atmos.*, **104**, 21 803–21 817, https://doi.org/10.1029/1999JD900238.

Conley, S. A., I. C. Faloona, D. H. Lenschow, A. Karion, and C. Sweeney, 2014: A low-cost system for measuring horizontal winds from single-engine aircraft. *J. Atmos. Oceanic Technol.*, **31**, 1312–1320, https://doi.org/10.1175/JTECH-D-13-00143.1.

Doak, A. G., and Coauthors, 2021: Characterization of ground-based atmospheric pollution and meteorology sampling stations during the Lake Michigan Ozone Study 2017. *J. Air Waste Manage.*, **71**, 866–889, https://doi.org/10.1080/10962247.2021.1900000.

Hughes, D. D., and Coauthors, 2021: $PM_{2.5}$ chemistry, organosulfates, and secondary organic aerosol during the 2017 Lake Michigan Ozone Study. *Atmos. Environ.*, **244**, 117939, https://doi.org/10.1016/j.atmosenv.2020.117939.

Judd, L. M., and Coauthors, 2019: Evaluating the impact of spatial resolution on tropospheric NO_2 column comparisons within urban areas using high-resolution airborne data. *Atmos. Meas. Tech.*, **12**, 6091–6111, https://doi.org/10.5194/amt-12-6091-2019.

McBride, B. A., J. V. Martins, H. M. J. Barbosa, W. Birmingham, and L. A. Remer, 2020: Spatial distribution of cloud droplet size properties from Airborne Hyper-Angular Rainbow Polarimeter (AirHARP) measurements. *Atmos. Meas. Tech.*, **13**, 1777–1796, https://doi.org/10.5194/amt-13-1777-2020.

Millet, D. B., and Coauthors, 2018: Bidirectional ecosystem–atmosphere fluxes of volatile organic compounds across the mass spectrum: How many matter? *ACS Earth Space Chem.*, **2**, 764–777, https://doi.org/10.1021/acsearthspacechem.8b00061.

Puthukkudy, A., and Coauthors, 2020: Retrieval of aerosol properties from Airborne Hyper-Angular Rainbow Polarimeter (AirHARP) observations during ACEPOL 2017. *Atmos. Meas. Tech.*, **13**, 5207-5236, https://doi.org/10.5194/amt-13-5207-2020.

Vermeuel, M. P., and Coauthors, 2019: Sensitivity of ozone production to NO_x and VOC along the Lake Michigan coastline. *J. Geophys. Res. Atmos.*, **124**, 10 989–11 006, https://doi.org/10.1029/2019JD030842.