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Conceptual Models of Ozone Formation in the Great Lakes Region

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Report to LADCO Members
May 18, 2023

LADCO Ozone Conceptual Model Report

- Technical report
- Released February 2023
- Available on LADCO's website: https://www.ladco.org/wp-content/uploads/Projects/Ozone/Ozone-conceptual-model-report-FINAL-Feb-2023.pdf
- 135 pages + an appendix (13 pages)

LADCO Ozone Conceptual Model Report

Goal: Pull together and synthesize current understanding about the drivers of ozone formation in the region into a document that states can use in their SIPs

- Organize and integrate findings from many different sources, including:
  - Classic studies
  - New insights from recent studies
  - Some new analyses
- Include conceptual models for each nonattainment and maintenance area that can be excerpted and included as an attachment to a SIP submittal
  - Posted as a pdf but can provide a Word document if that would be helpful

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Report Outline

Executive Summary

1. Introduction
2. Drivers of ozone formation:
    1. Meteorology
    2. Transport
    3. Ozone precursors (emissions and concentrations)
    4. Ozone formation chemistry
3. Ozone concentrations and trends
    1. Distribution
    2. Trends
    3. Meteorological adjustment
    4. Conclusions: roles of drivers in creating ozone patterns and trends

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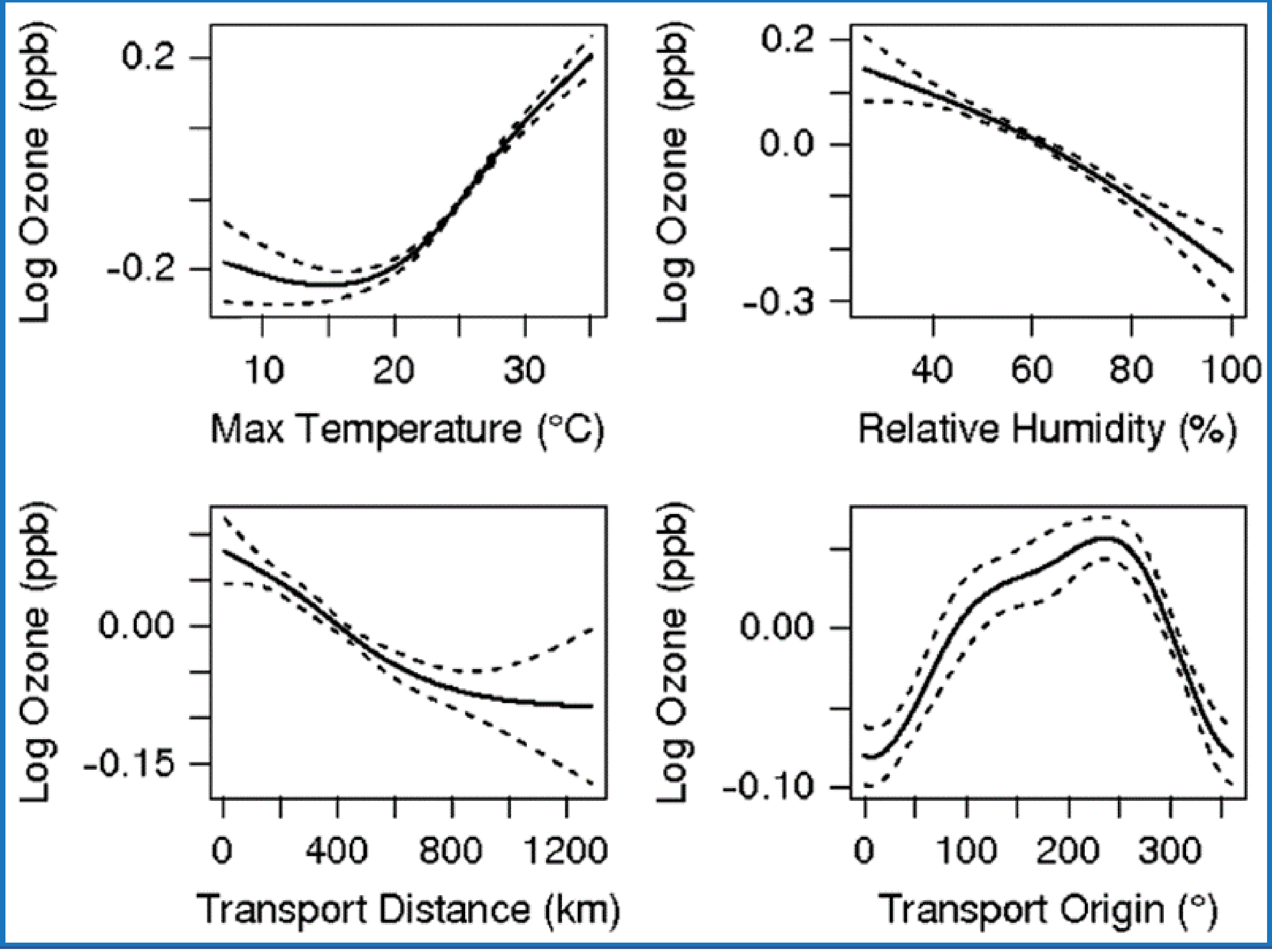
Report Outline

4. Synthesis: Conceptual models of O_3 formation in each nonattainment or maintenance area
    1. Each model:
        1. Meteorology and transport
        2. Ozone precursor emissions and concentration trends
        3. Ozone formation chemistry
        4. Trends in ozone concentrations
        5. Origins of ozone trends
    2. Models for:
        1. Chicago, Detroit, Cleveland, St. Louis, Louisville, Cincinnati
        2. Wisconsin lakeshore and Western Michigan

Drivers of Ozone: Meteorological factors



- Response of O_3 to met parameters in Cleveland from a GLM (EPA analysis)
- Most O_3:
  - High temperatures
  - Low relative humidity
  - Little transport
  - Transport from the west

Universal (high temperatures, low relative humidity)

Site-specific (little transport, transport from the west)

Figure from Camalier et al. (2007)

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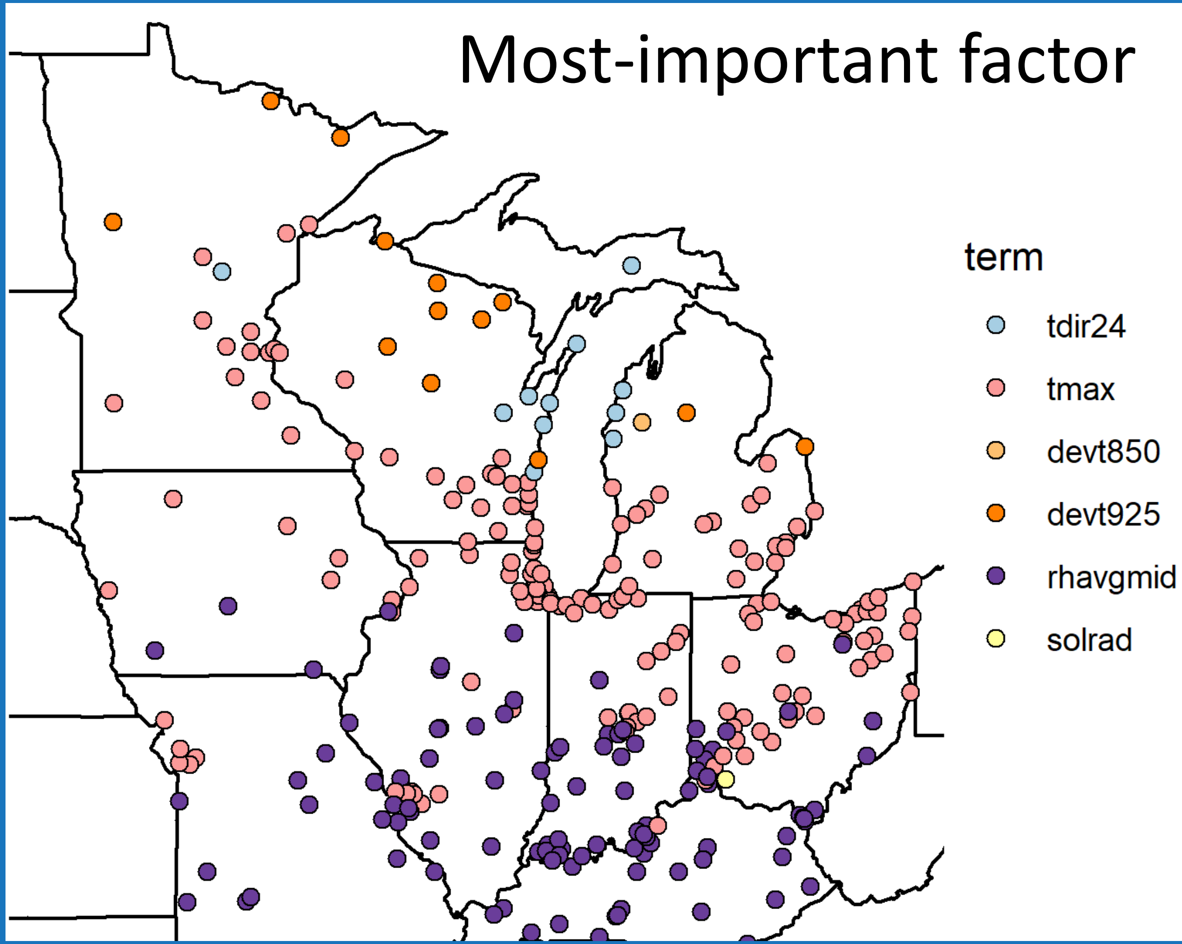
Drivers of Ozone: Meteorological factors



- Maps of the most important factors driving high O_3
- Based on EPA's GLM analysis (Wells et al., 2021)
- Factors vary around the region:
  - Relative humidity in the south
  - Max temperature or temperature deviation in most of the region
  - Transport direction in northern Lake MI
- Also have maps based on LADCO's CART analysis

Meteorology: Synoptic weather

- Two main types of synoptic weather patterns on high-ozone days:
  - Stagnant conditions
    - Emissions stay near their source and build up to high levels
    - Peak concentrations in urban areas
    - Often last for many days with building ozone concentrations
    - May have high ozone over a wide area
  - Lake-driven transport (especially in Lake Michigan)
    - Transport-driven events
    - Confined to a narrower area around the lake than stagnation events
    - AM winds carry emissions from Chicago/Milwaukee and regional sources over Lake MI
    - Precursors react in stable marine boundary layer
    - O_3-rich air is transported north (WI) or northeast-ward (MI) and pulled onshore, usually by a lake breeze
      - Lake breeze is more important in WI than in MI

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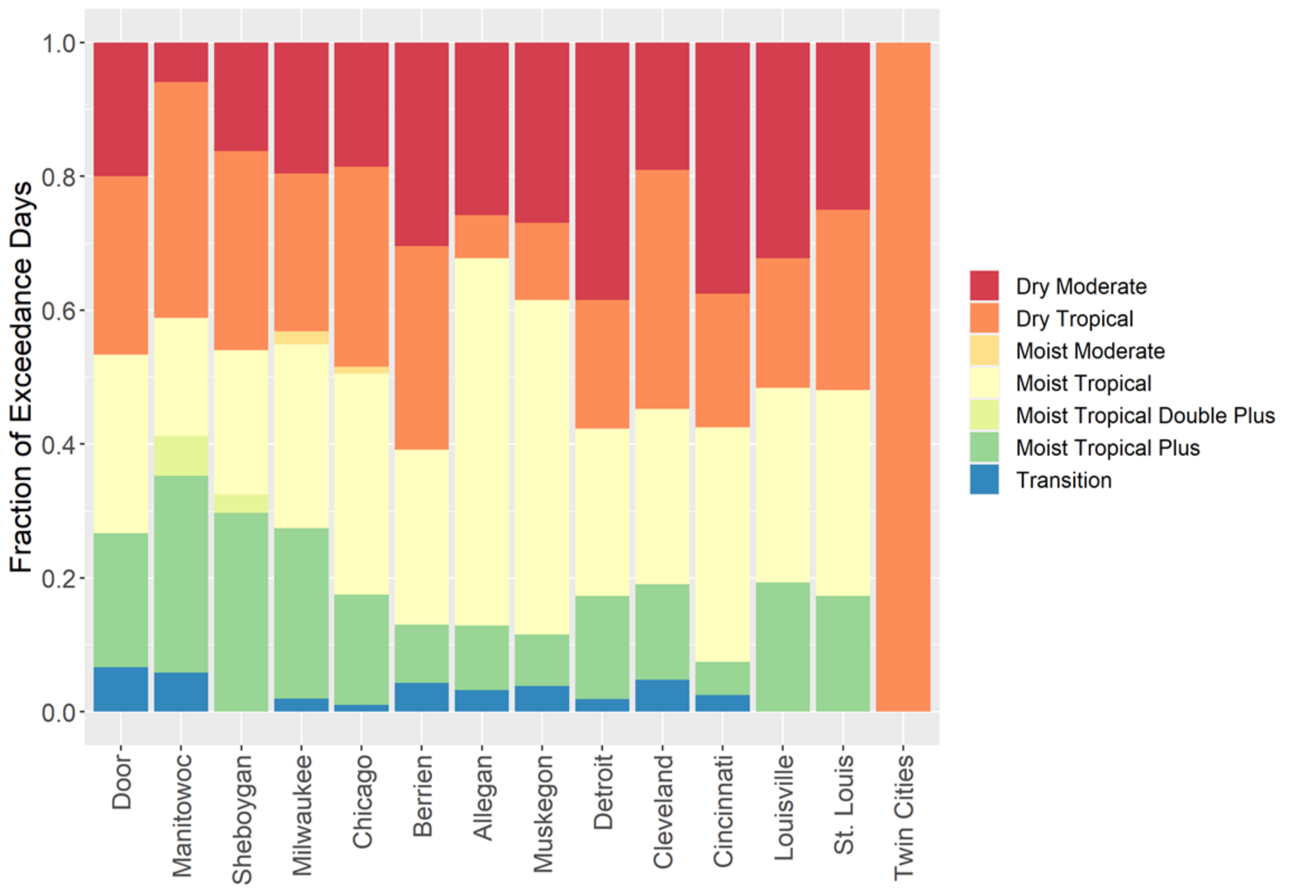
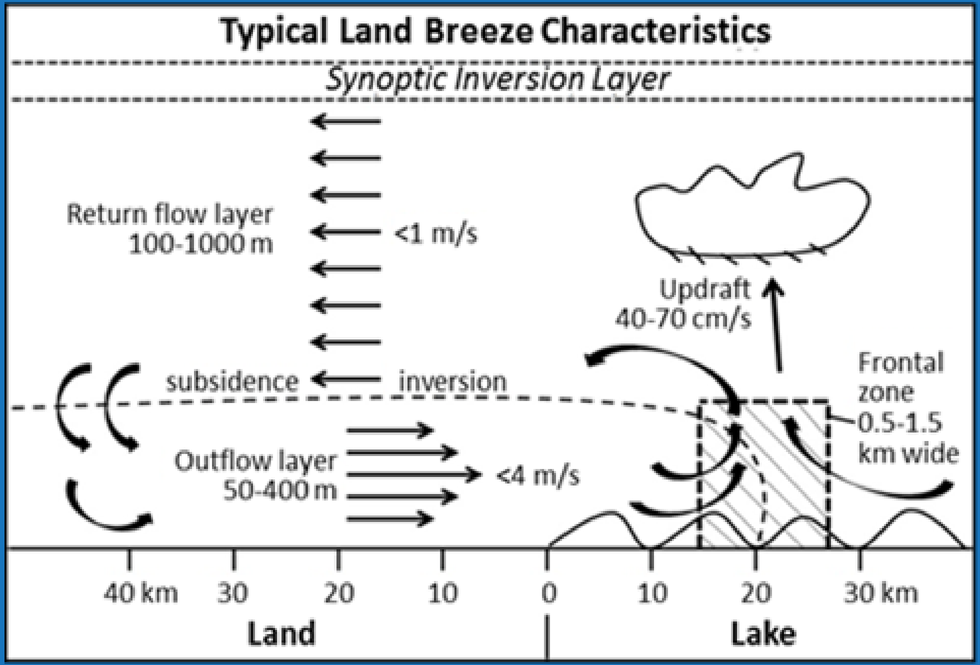
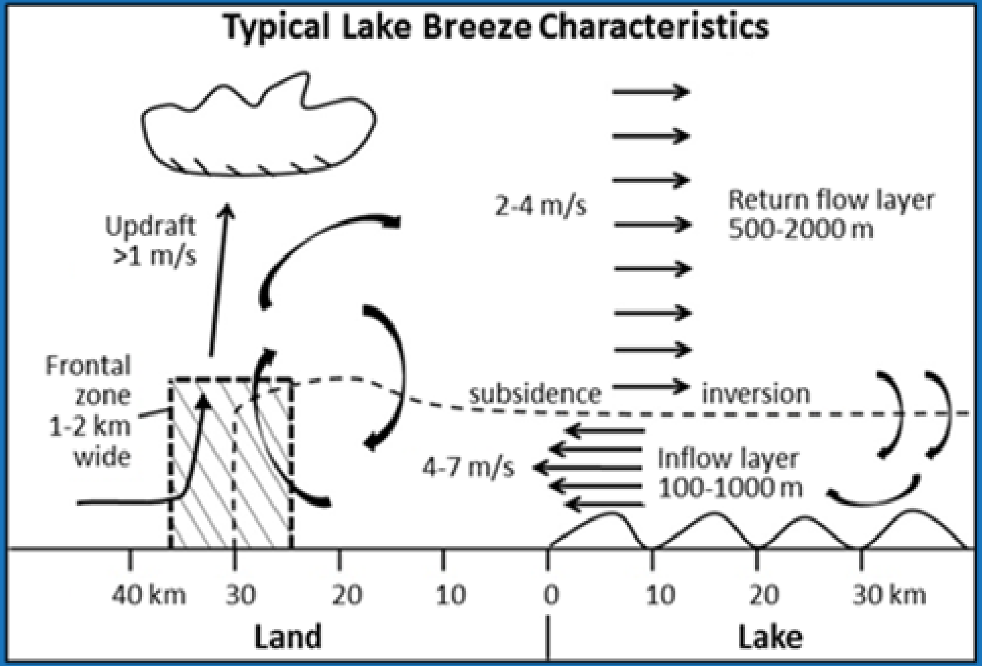
Meteorology: Synoptic weather



- Synoptic weather on O_3 exceedance days
- Tropical (hot) weather accounts for most exceedance days
  - Dry moderate (warm) days were also important in southern areas & MI
    - Where GLM says RH is more important than temperature (except for MI)
- Humid (moist) weather accounted for 40-70% of exceedance days
  - Less important in the south and east
    - Where GLM says low RH is most important

Meteorology: Lake Breezes





- Offshore (overnight/am) to onshore (midday) wind shift
- Divergence over lake and convergence onshore
- Ozone formation in shallow marine boundary layer

Figure modified from Foley et al. (2011); from Pierce et al. (2016)

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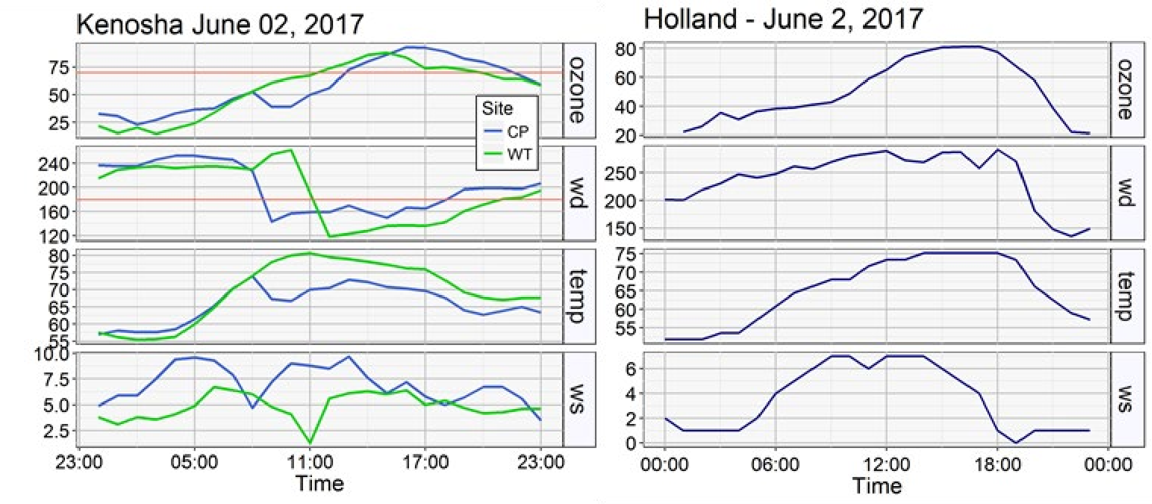
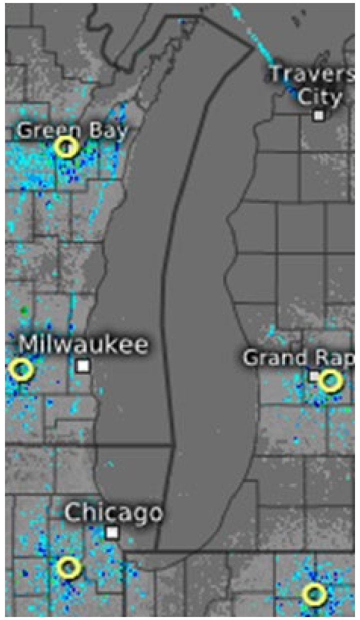
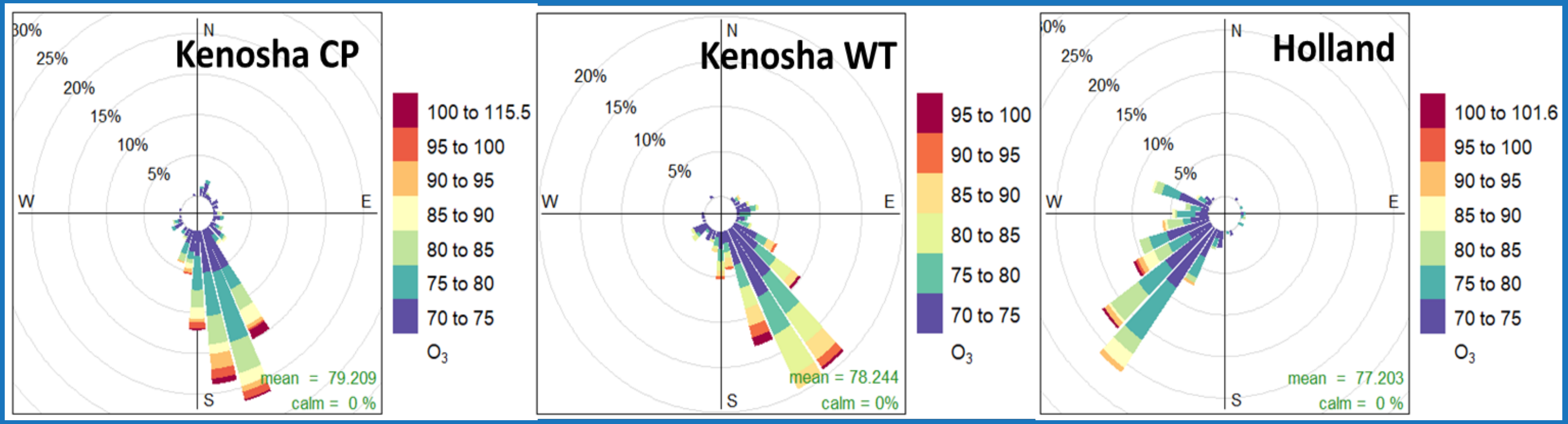
Meteorology: Lake Breezes – Lake Michigan





- Lake Michigan lake breezes:
  - Offshore/onshore wind shifts clear in WI
    - Earlier at monitor closer to the lakeshore (CP)
    - Temperature (and O_3) drop with onset
    - Less clear/important in MI because synoptic winds are already onshore
  - Ozone peaks hours after lake breeze onset
  - Convergence front visible in satellite and radar (sometimes)
  - Divergence and convergence apparent in model winds

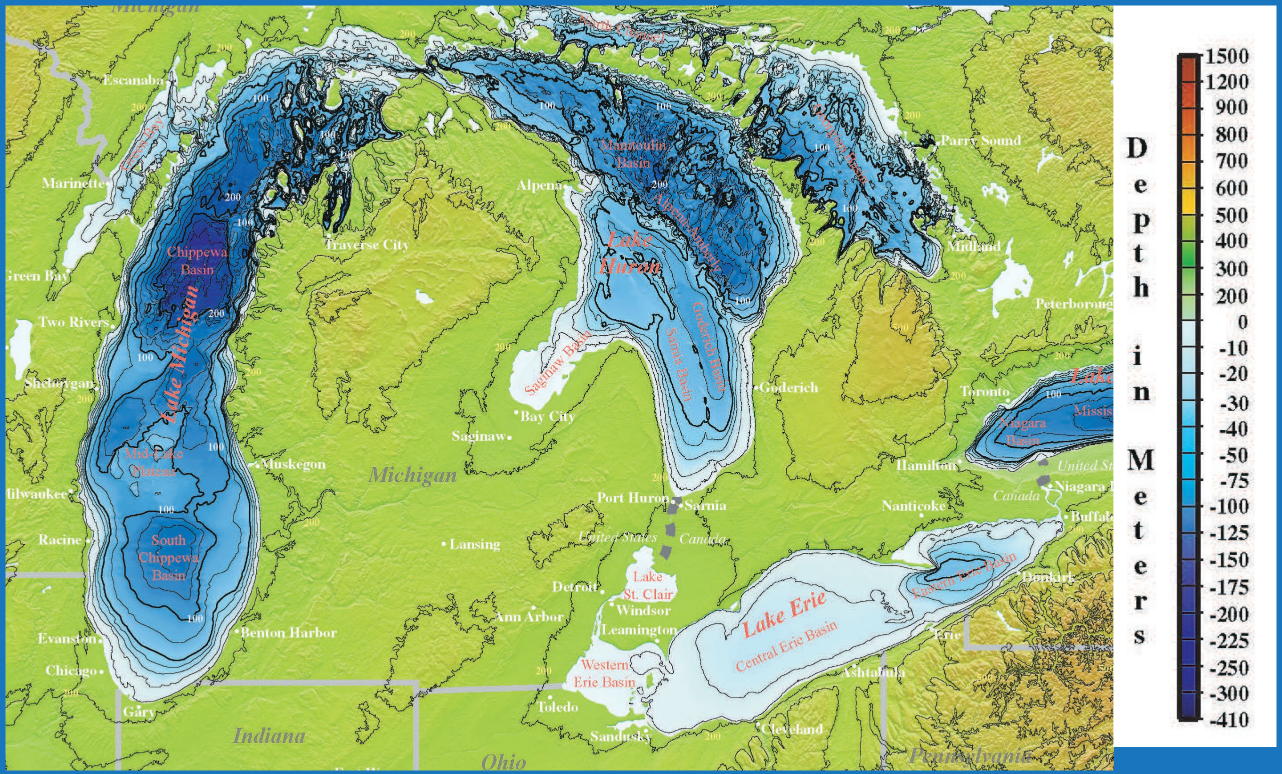
Meteorology: Lake Breezes – Lake Michigan



- Wind directions during high-O_3 hours:
  - Typical lake breeze wind directions
  - Kenosha Chiwaukee Prairie (CP), WI on the lakeshore: South-southeast
  - Kenosha Water Tower (WT), WI inland: Southeast
  - Holland, MI: Southwest

Transport from Chicago over the lake

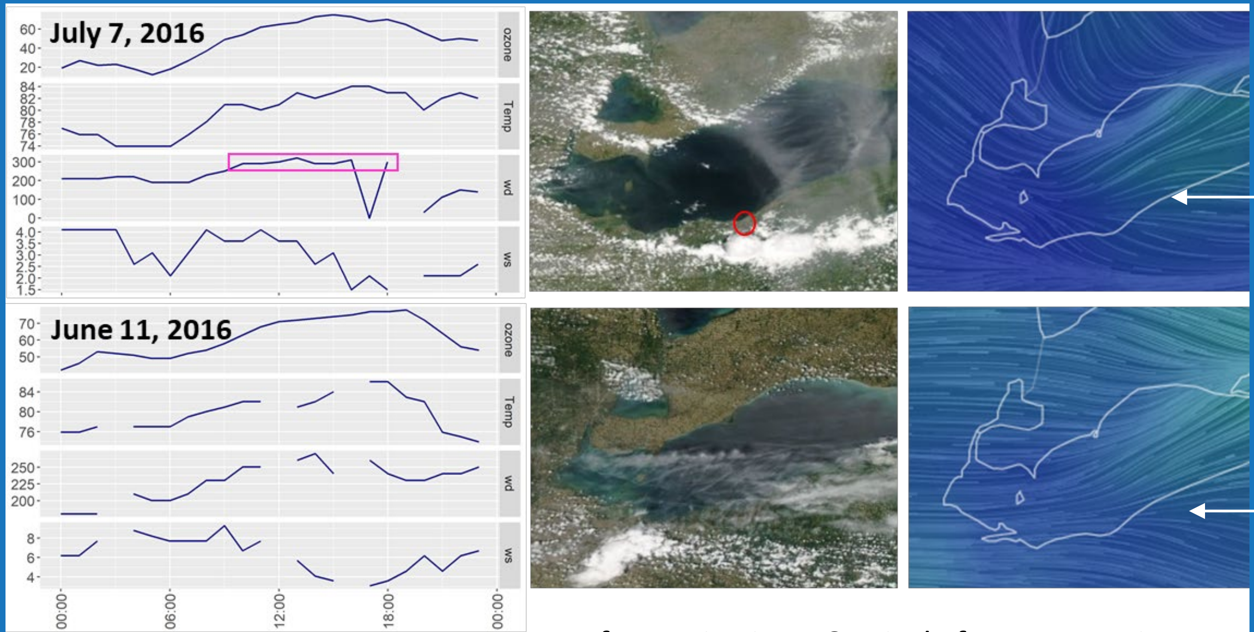
Meteorology: Lake Breezes – Cleveland



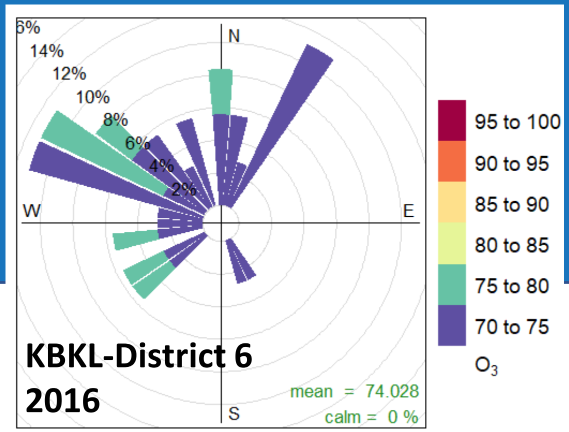
https://www.ncei.noaa.gov/sites/default/files/2021-09/greatlakesbasin.jpg

- Compared with Lake Michigan, Lake Erie:
  - Is much shallower and smaller, so that it heats up faster in the spring
    - Should lead to weaker lake breezes
  - Has its long axis running SSW to NNE
    - Different interactions with synoptic winds (primarily from W or SW)
  - Has its major emissions source (Cleveland) in the middle/south side of the lake
    - Cleveland emissions may not be transported over the lake on synoptic winds
    - Much of the lake will not be impacted by these emissions
    - Smaller city so fewer emissions

Meteorology: Lake Breezes - Cleveland

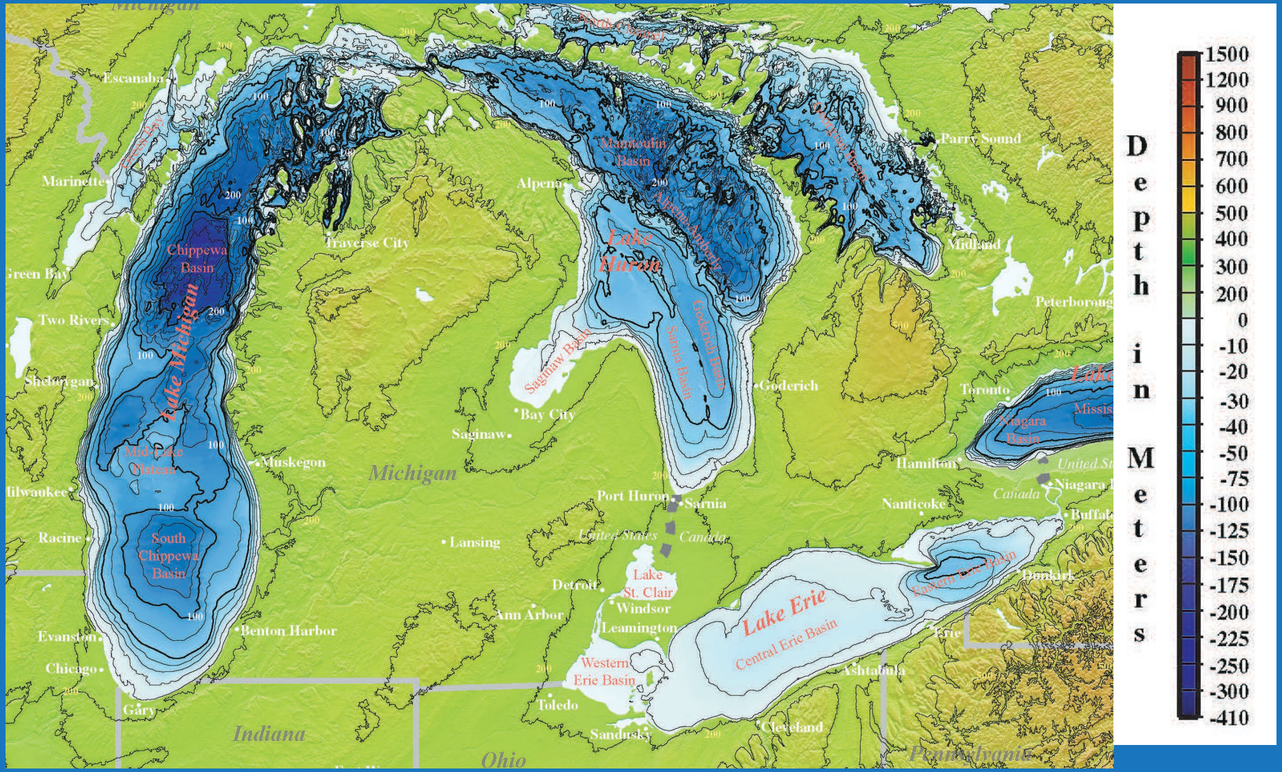


O_3 from District 6 & winds from KBKL airport



- Cleveland high-ozone days are a mix of:
  - Lake breeze days:
    - Winds from the West-northwest OR
    - Winds from the North-northeast
    - Divergence over the lake and convergence onshore
  - Days with only synoptic winds
    - Winds from the southwest, west, or north-northwest
- Toledo high-O_3 days mostly impacted by synoptic winds

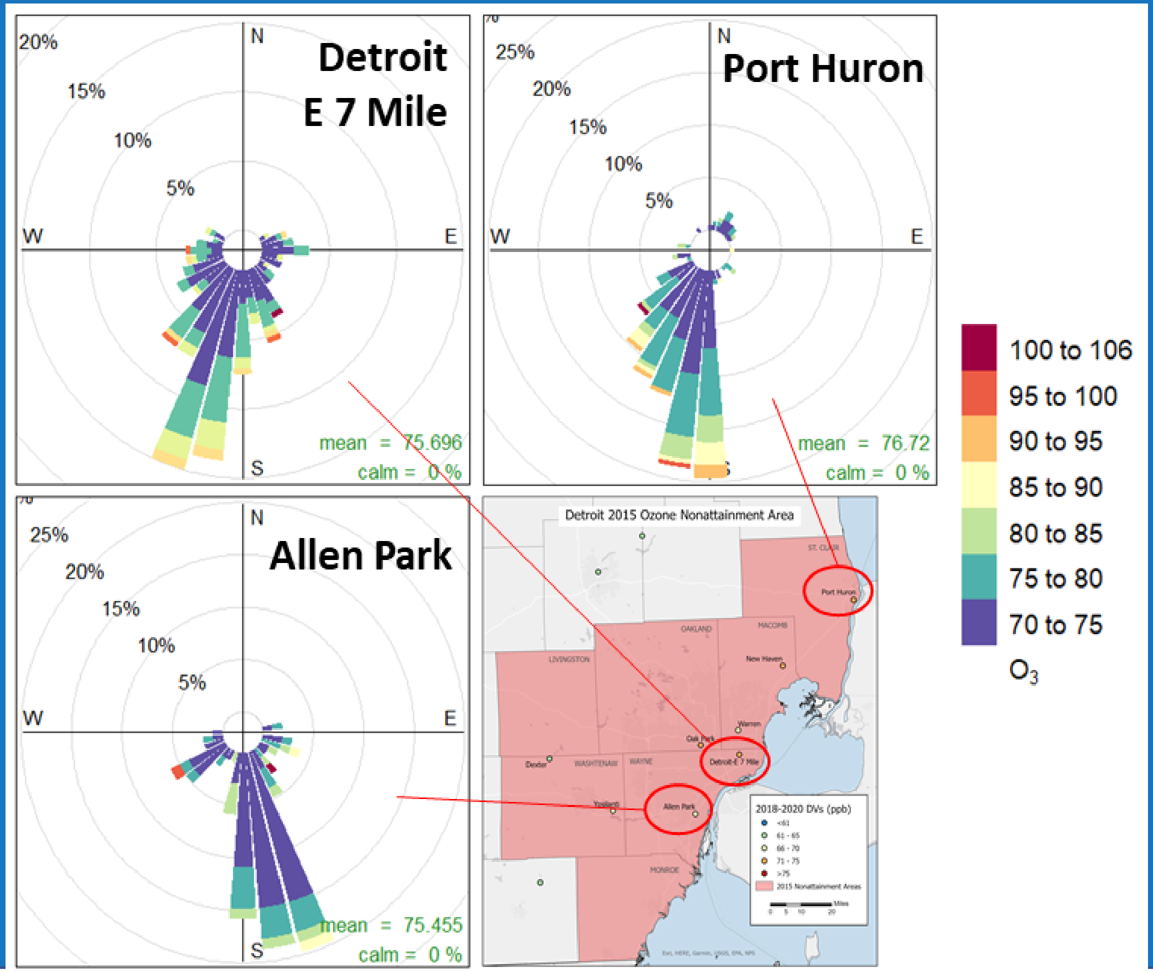
Meteorology: Lake Breezes – Detroit



- Detroit may be influenced by Lake St. Clair, as well as Lakes Erie & Huron:
  - Very complex geography leads to complexity in lake breeze fronts and ozone formation & transport

https://www.ncei.noaa.gov/sites/default/files/2021-09/greatlakesbasin.jpg

Meteorology: Lake Breezes - Detroit



- High-O_3 winds from different directions at different sites
  - Port Huron: transport from Lake St. Clair/Detroit
  - Detroit E 7 Mile: transport from downtown Detroit
  - Allen Park: transport from Lake Erie

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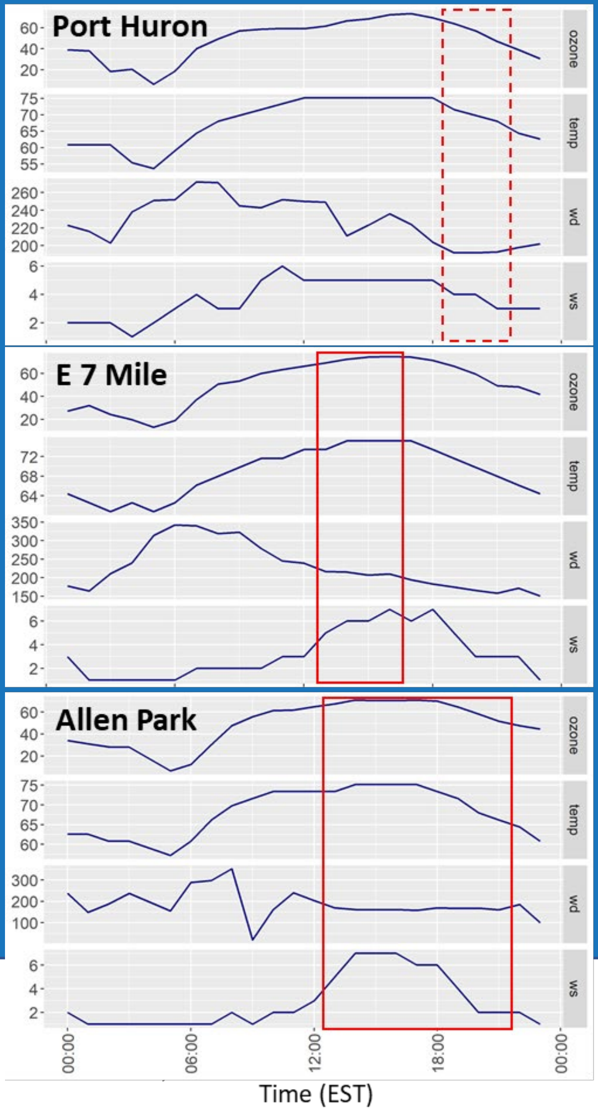
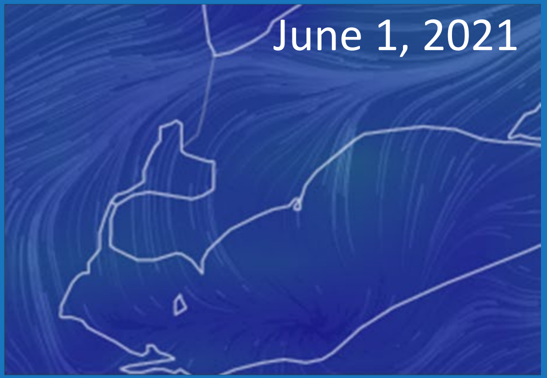
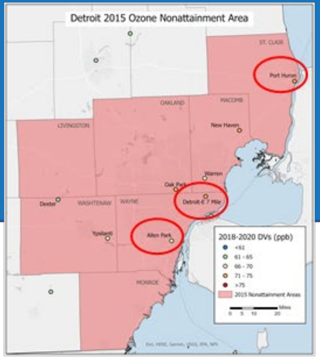
Meteorology: Lake Breezes - Detroit

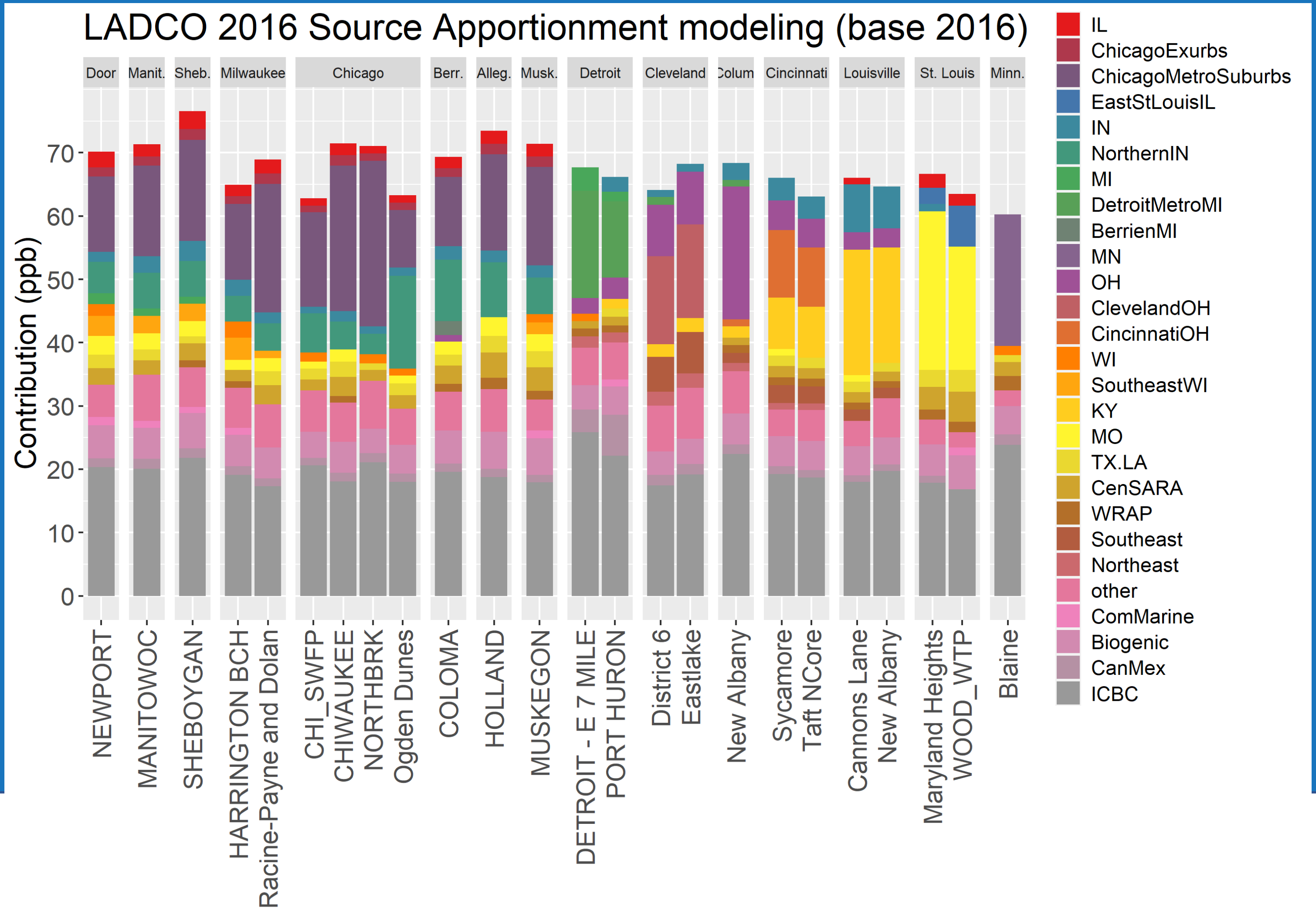






- Generally, Allen Park more impacted by lake breezes than the other sites
  - Lake breezes from Lake Erie
  - Model suggests more contributions from Ohio
- Detroit E 7 Mile less frequently impacted by lake breezes
  - From Lakes Erie or St. Clair
- Port Huron least impacted by lake breezes
  - Mostly synoptic transport
- The lakes often influence/shift the winds without developing a true lake breeze

Role of Transport



- Transport is most important for downwind sites around Lake Michigan (WI & MI)
  - Southerly transport from Chicago over the lake
- All other urban areas mostly impacted by local emissions
- Confirmed by pollution roses and back-trajectories
- All areas have some impact from upwind areas

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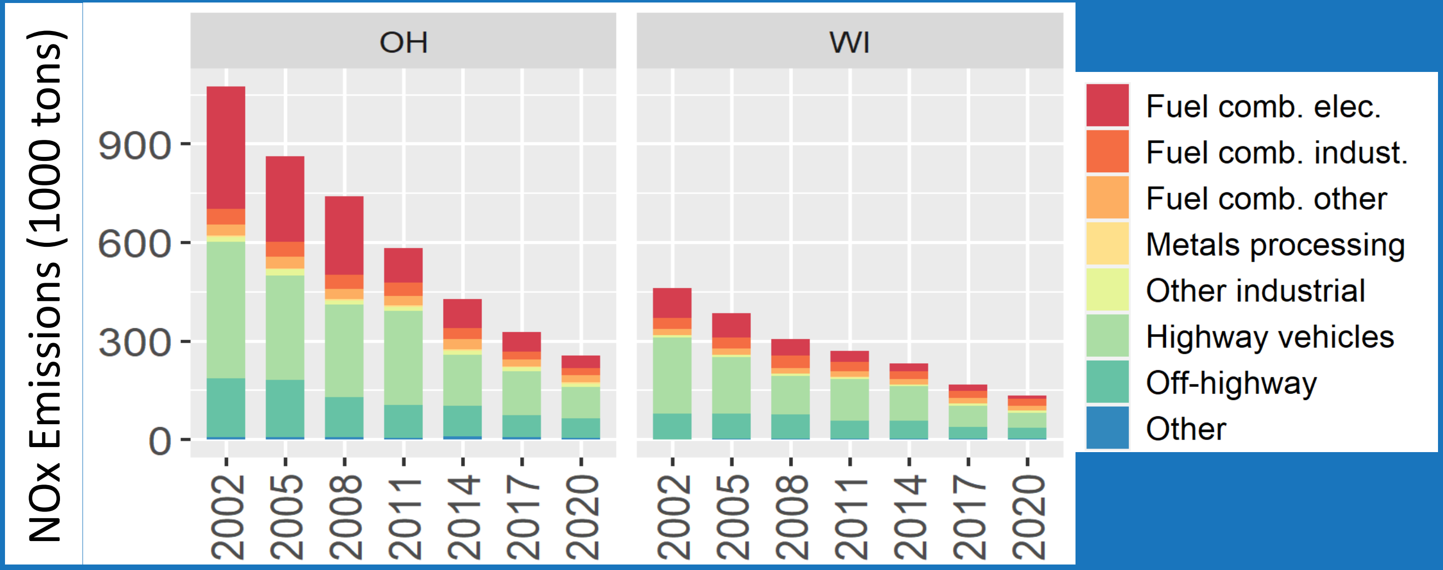
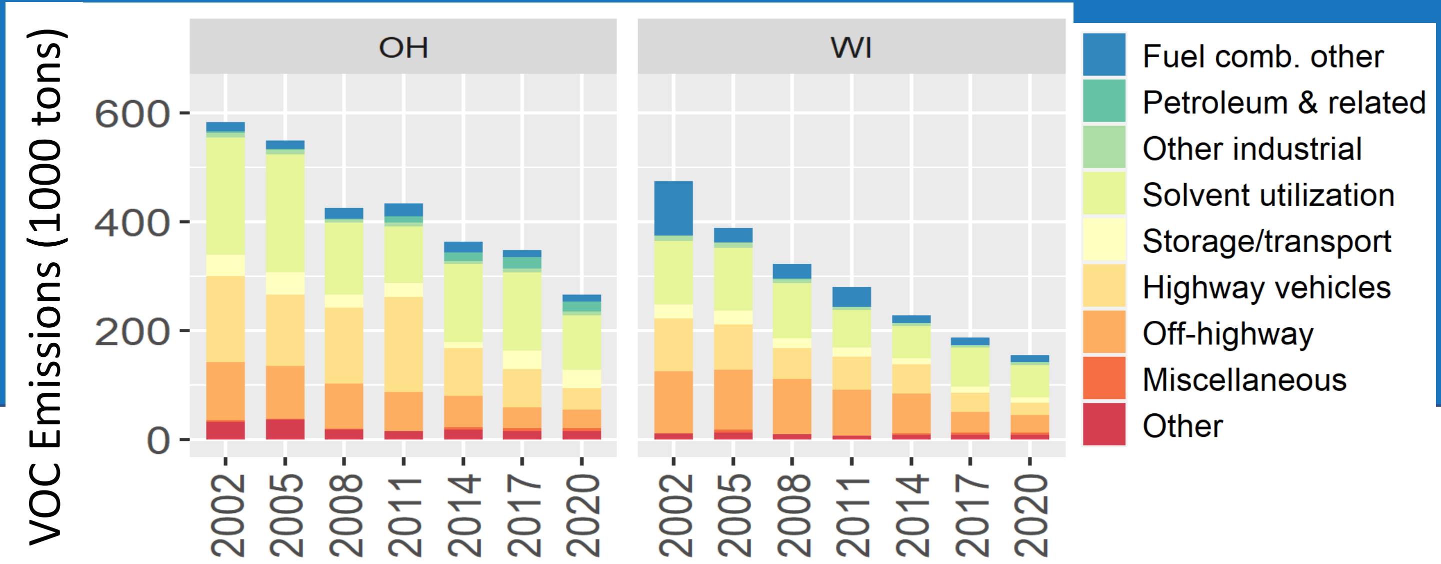
Ozone Precursor Emissions





- Large reductions in both NOx and VOC emissions from all states:
  - 68 to 76% reductions in NOx
    - Largest from EGUs, highway vehicles, & off-highway
  - 41 to 67% reductions in VOCs
    - Most states: 53 to 55% reductions
    - Large reductions from solvent utilization, off-highway, and highway vehicles

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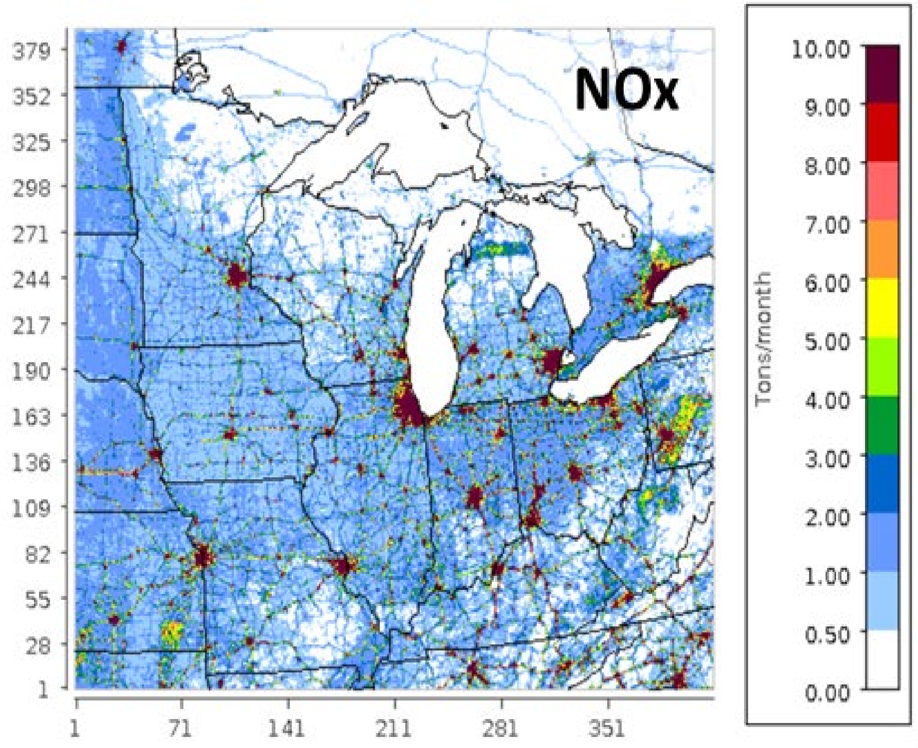
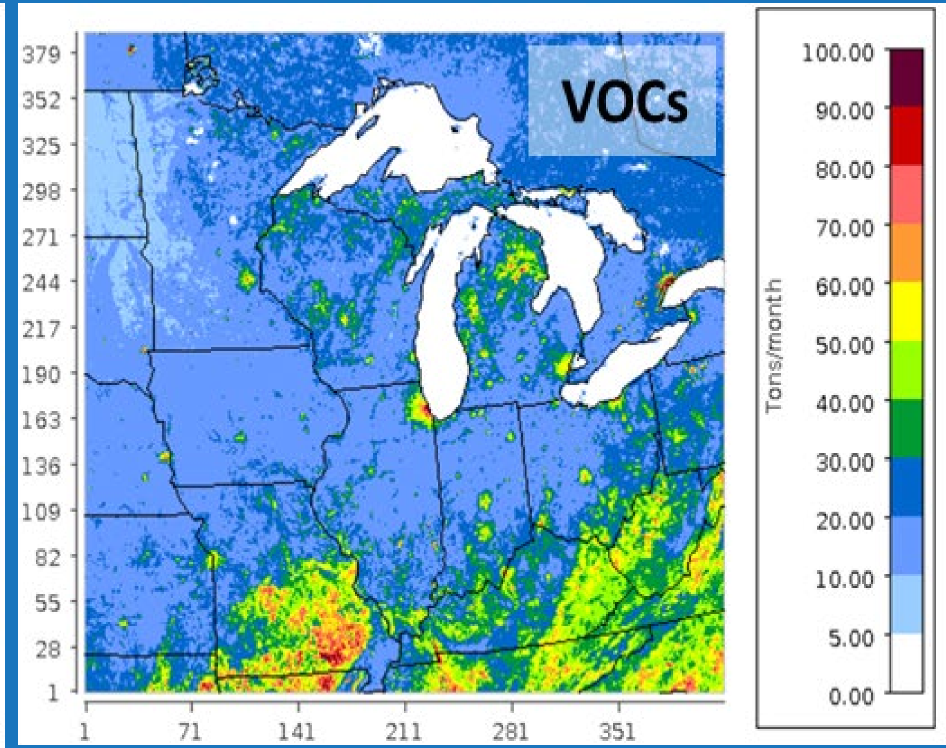
Ozone Precursor Emissions

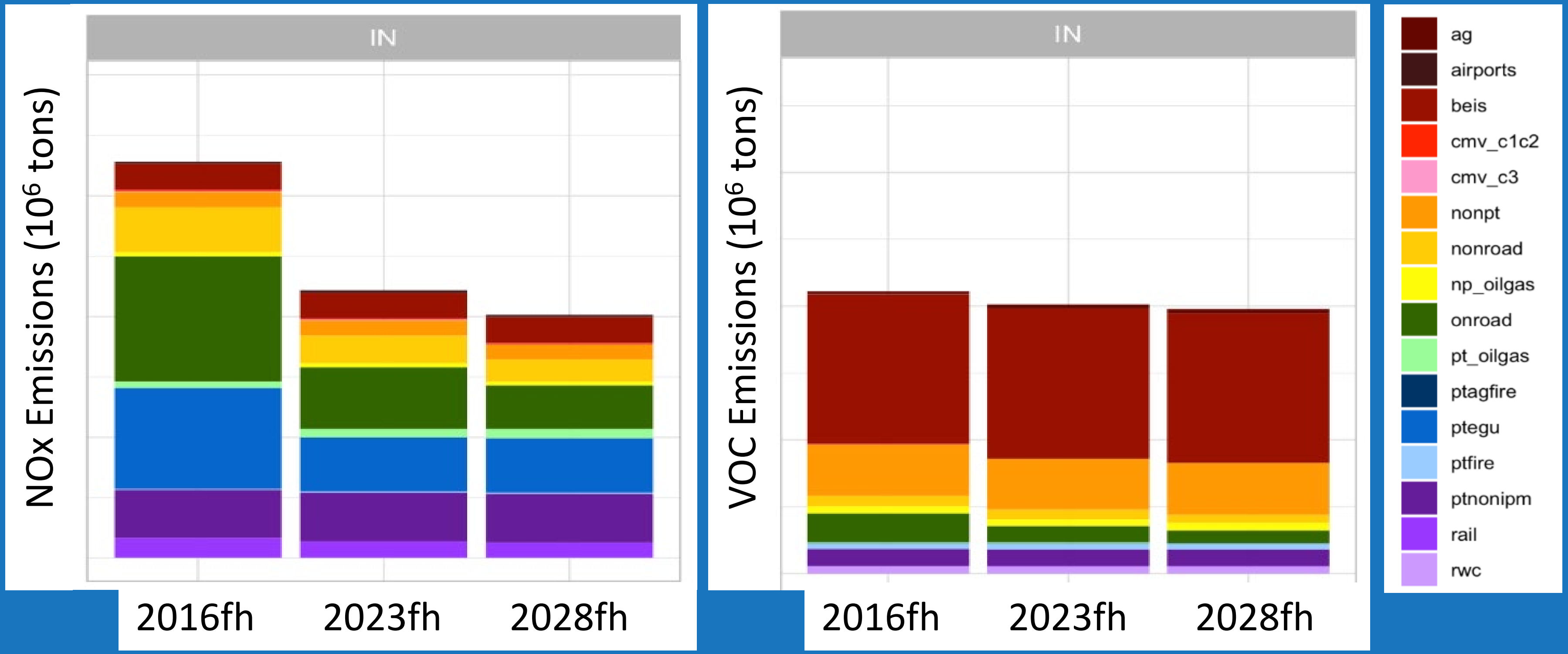




- NOx emissions concentrated in urban areas & along major highways

- VOC emissions split:
  - Urban VOC emissions
  - Biogenic VOCs in forests

Ozone Precursor Emissions



- Projected to continue to decrease through 2028
  - 28 to 38% NOx reductions 2016-2028
    - Mostly onroad & EGU emissions
  - Only 5% VOC reductions

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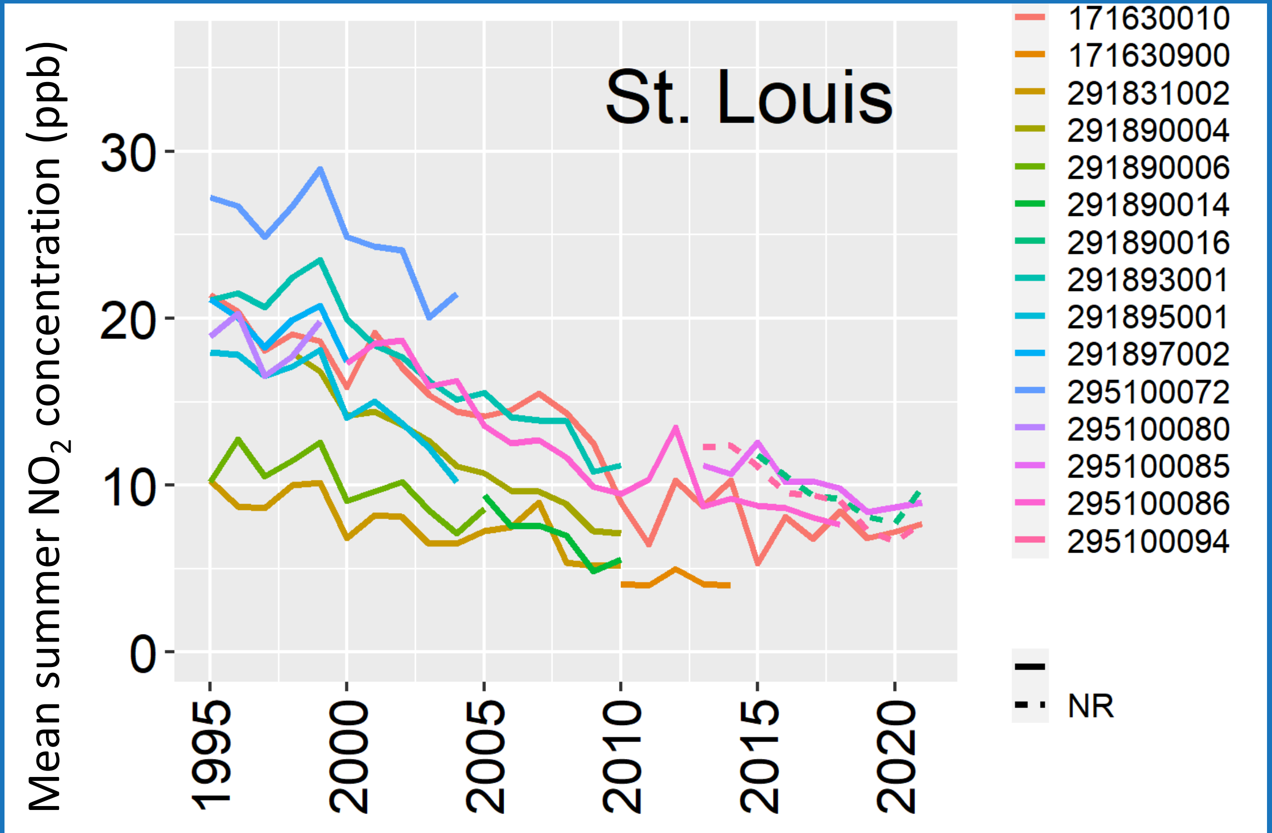
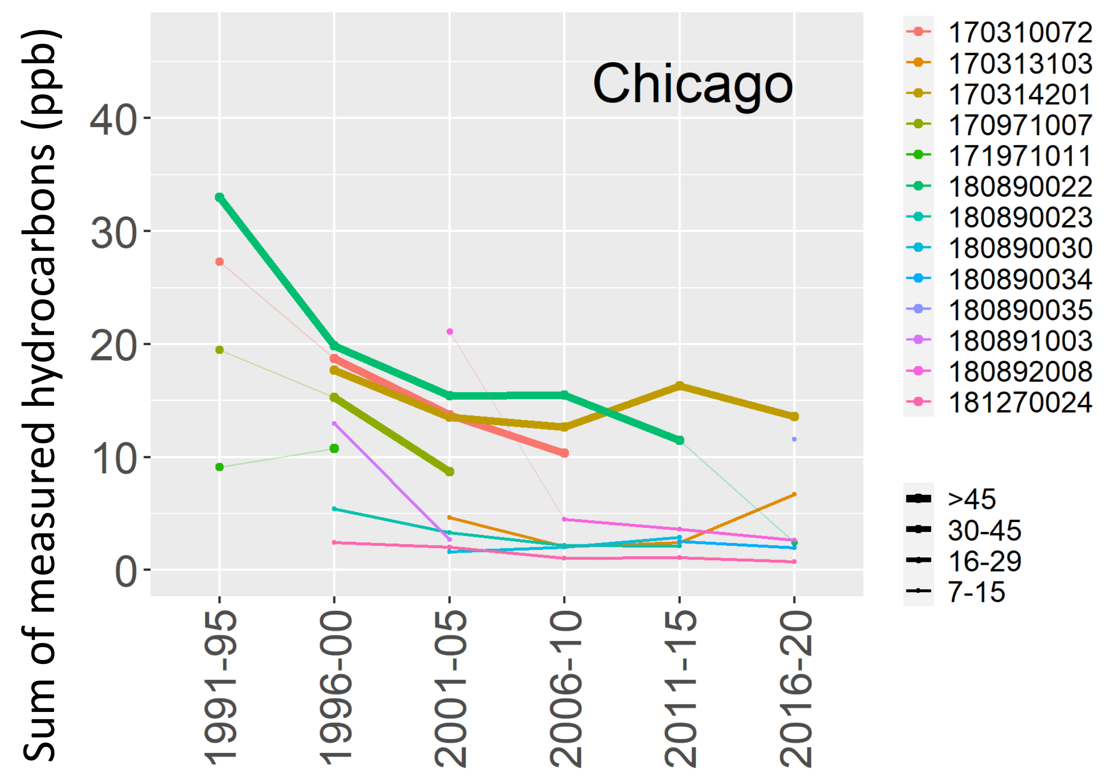
Ozone Precursor Concentrations



- Monitored NO_2:
  - 58 to 71% reductions 1995 to 2021
    - Similar reductions to those in emissions
  - Especially large reductions in mid-late-2000s due to control programs
  - Concentrations seem to still be decreasing but more slowly than before
  - Concentrations at near-road monitors are higher than at other monitors

Ozone Precursor Concentrations



- Monitored hydrocarbon VOCs:
  - Much more sparse than NO_2 over space & time
  - Generally decrease through the late 2000s
  - Since the late 2000s, many concentrations have leveled off
    - Doesn't agree with inventories, which are still decreasing
      - Unmeasured compounds may have decreased more than those measured
      - Inventories may be missing important sources

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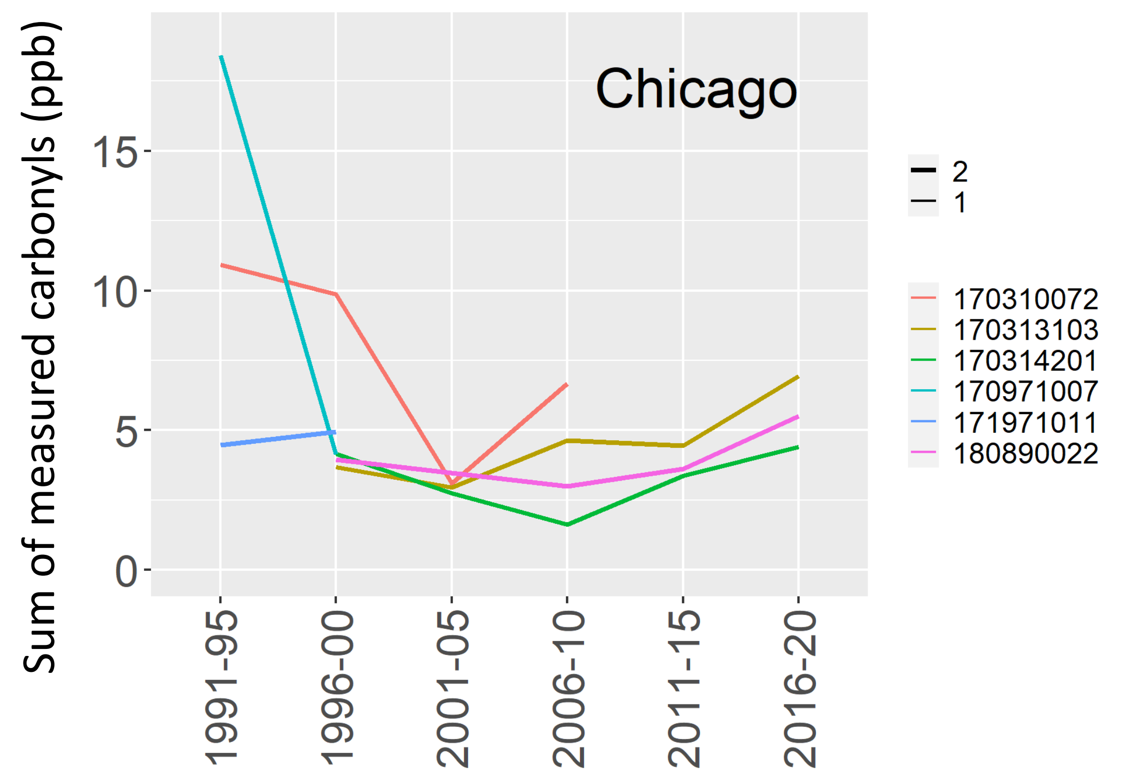
Ozone Precursor Concentrations



- Monitored carbonyl VOCs:
  - Two sources: oxidation of other VOCs or primary emissions
  - Including formaldehyde & acetaldehyde
  - Concentrations decreased through the 2000s
  - Increased in Chicago & Detroit since the 2000s
    - Flattened in Milwaukee & St. Louis
    - Possibly due to increased oxidation of other VOCs
      - Could be due to increased biogenic VOC emissions due to increasing temperatures
    - Unknown changes in chemistry or meteorology

Ozone Formation Chemistry

Area	Recent ozone-NOx-VOC chemistry (best estimate)
St. Louis	NOx-sensitive with transitional chemistry downtown
Louisville	NOx-sensitive with possible transitional chemistry downtown
Cincinnati	NOx-sensitive with transitional chemistry downtown
Detroit	NOx-sensitive with transitional chemistry downtown and to northeast
Cleveland	NOx-sensitive with transitional chemistry downtown and along lakeshore
Chicago	VOC-sensitive/transitional in the central 60 km or so; transitional/NOx-sensitive beyond.
WI Lakeshore	NOx-sensitive with transitional chemistry in downtown Milwaukee & along the southern lakeshore
Western MI	NOx-sensitive

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Ozone Concentrations & Trends

Ozone formation drivers

- Meteorology
- Transport
- Ozone precursors
- Ozone formation chemistry

→ Ozone distribution

→ Ozone concentrations

→ Ozone trends

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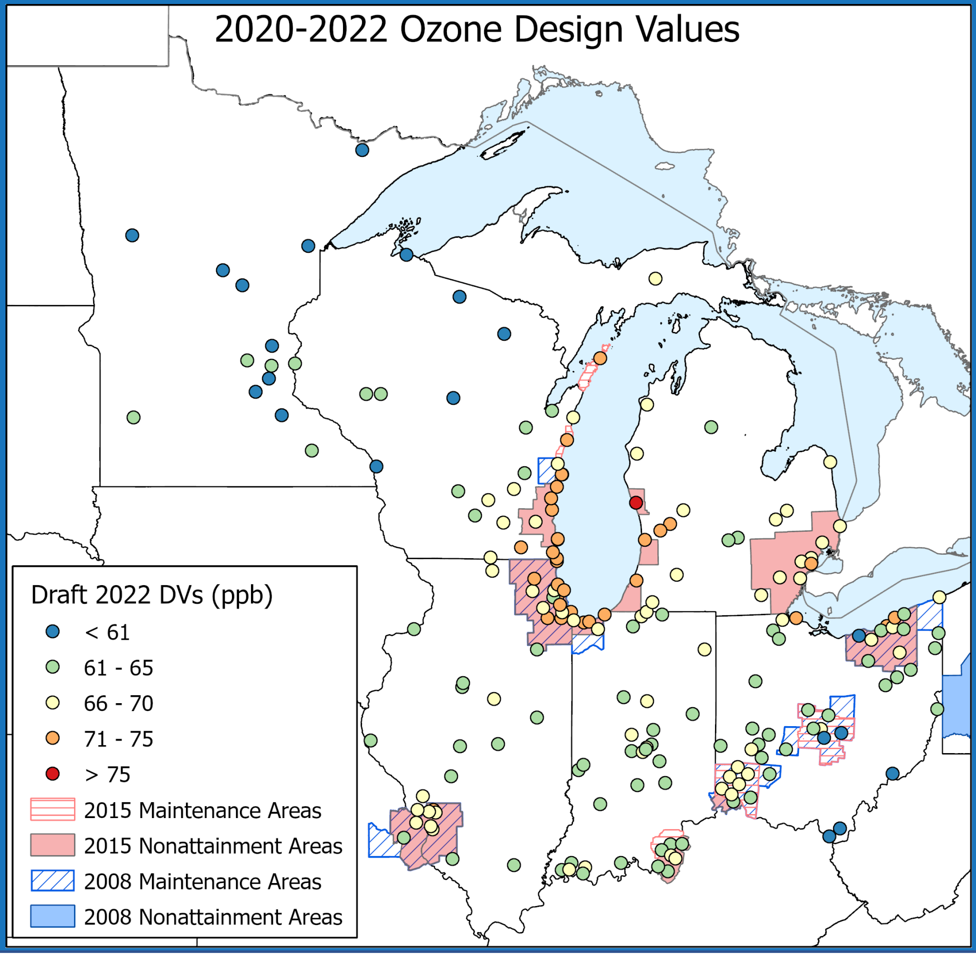
Ozone Concentrations & Trends



- Urban areas:
  - Concentration of emission sources
  - Biggest episodes with stagnant meteorology
  - Can have lowest O_3 in city center due to NOx-suppressed chemistry (VOC sensitivity)
    - Currently only in Chicago
- Around Lake Michigan
  - Transport of O_3 and O_3 precursors
  - Days with southerly or southwesterly winds
  - Onshore lake breezes especially important along the Wisconsin lakeshore

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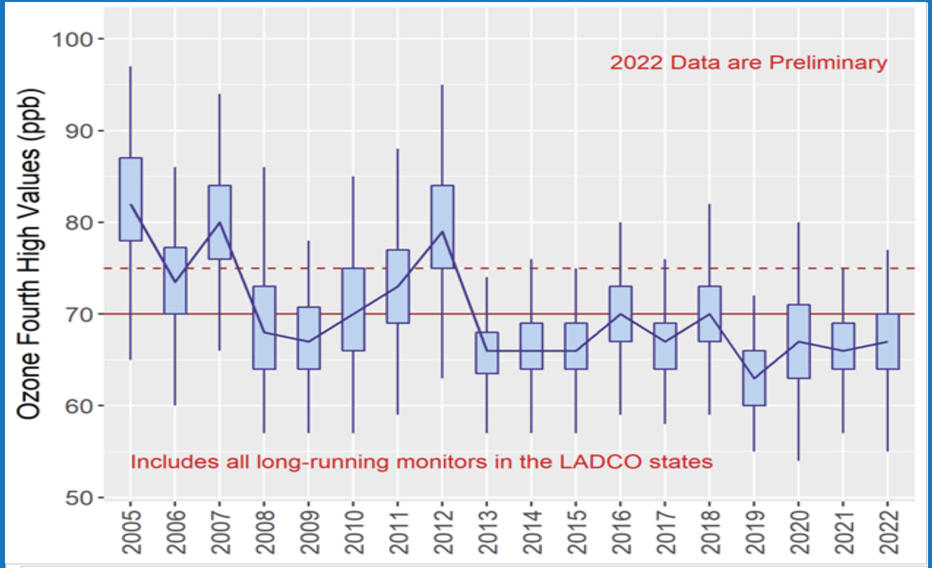
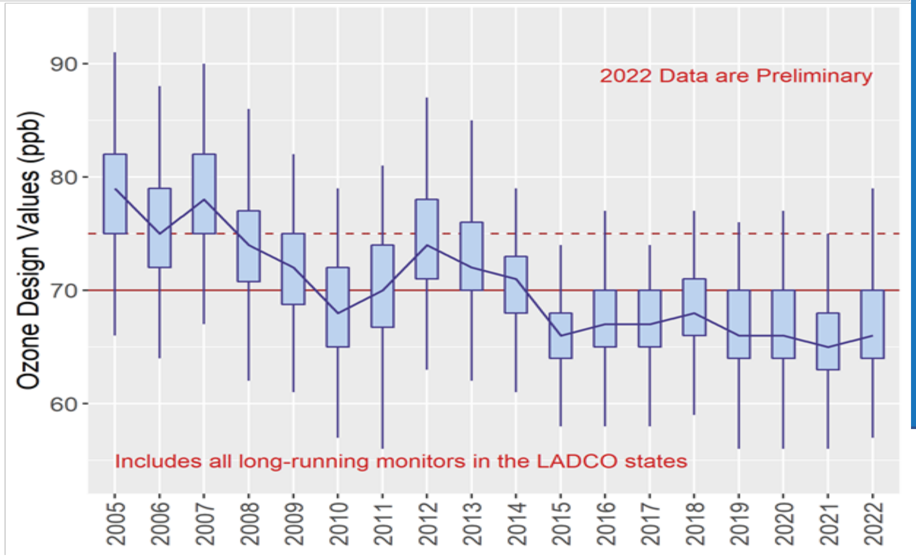
Ozone Concentrations & Trends





- Median O_3 decreased by 16% from 2005
  - Most of the decrease was in the first half of the time period
  - Median O_3 design values are close to their all-time lowest values
  - 25% of monitors had 2020-2022 DVs above the 2015 O_3 NAAQS
- Meteorology → Interannual variability
- Emissions reductions → Long-term reductions

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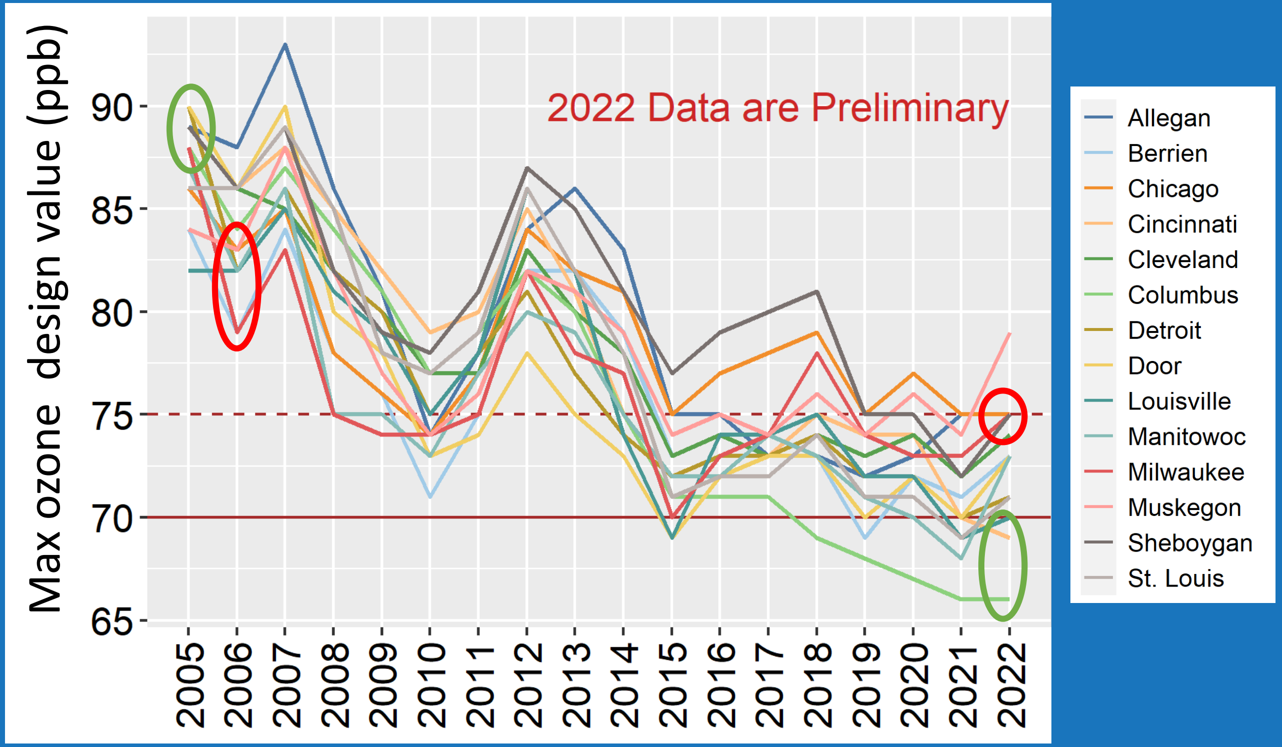
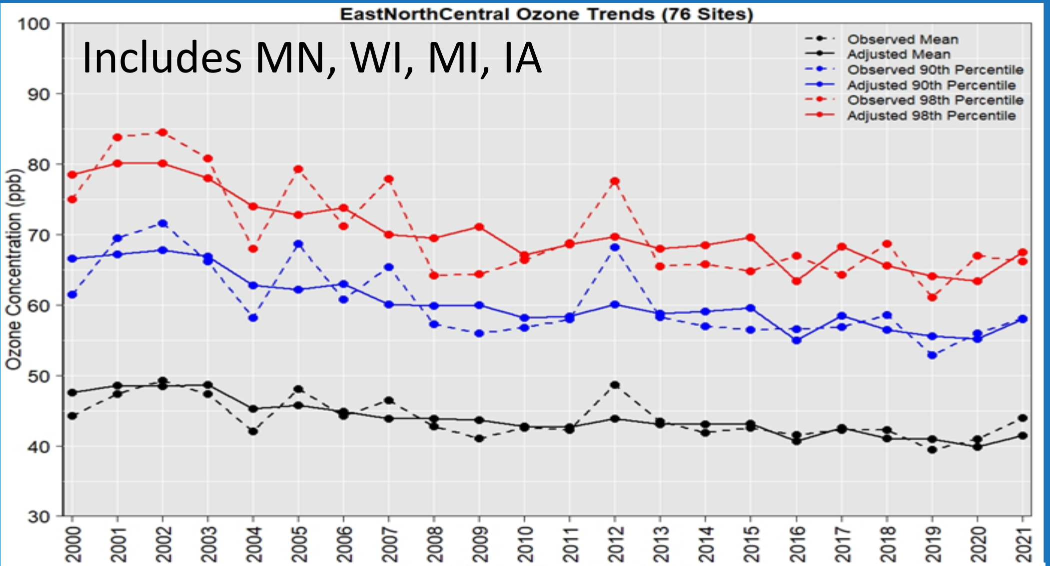
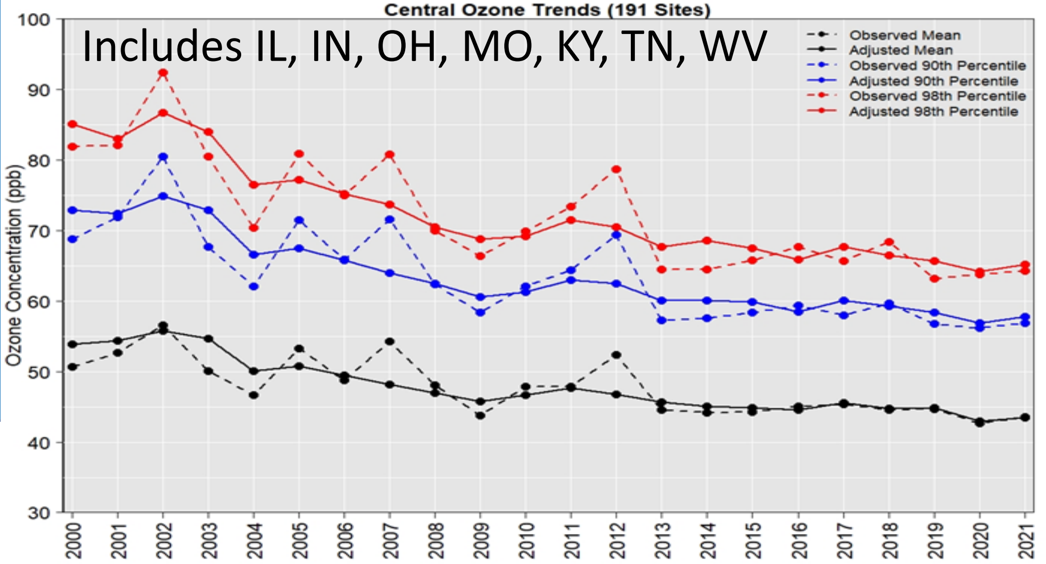
Ozone Concentrations & Trends



- DVs often move in tandem between years: shared meteorological factors
- Relative severity of problems in areas has changed:
  - Milwaukee and Chicago:
    - Started with some of the lowest values, ended with some of the highest
    - Chicago O_3 is increasing due to VOC-sensitivity (less NOx-suppression)
    - Changes in the magnitude of ozone in the over-lake plume reaching WI lakeshore
  - Cincinnati and Columbus:
    - Started among highest, ended among the lowest
    - Switched to fully NOx-sensitive, with large O_3 reductions

Meteorological Adjustment of O_3 Trends





- EPA's Generalized Linear Model (GLM) adjustment (Wells et al., 2021)
- Large reductions in 98th percentile value in both areas
  - Larger in Central (20 ppb) than East North Central (12 ppb)
  - Consistent with observed larger reductions in Cincinnati & Columbus compared with Milwaukee & Lake Michigan areas
- Slowing of reductions during the 2010s
  - Possibly due to slower decreases in NO_2 concentrations
  - Possibly due to changing O_3 formation chemistry

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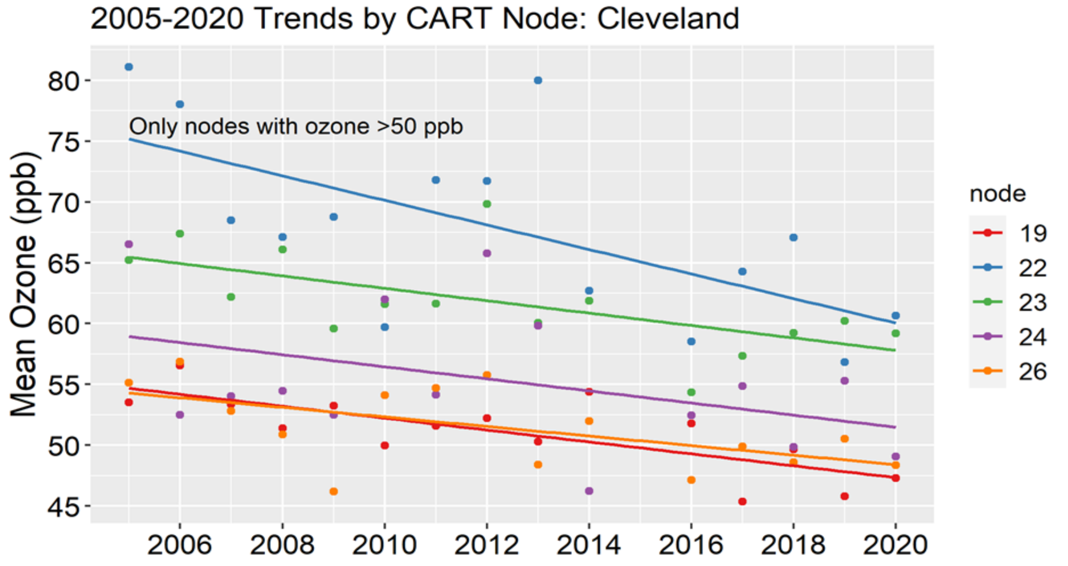
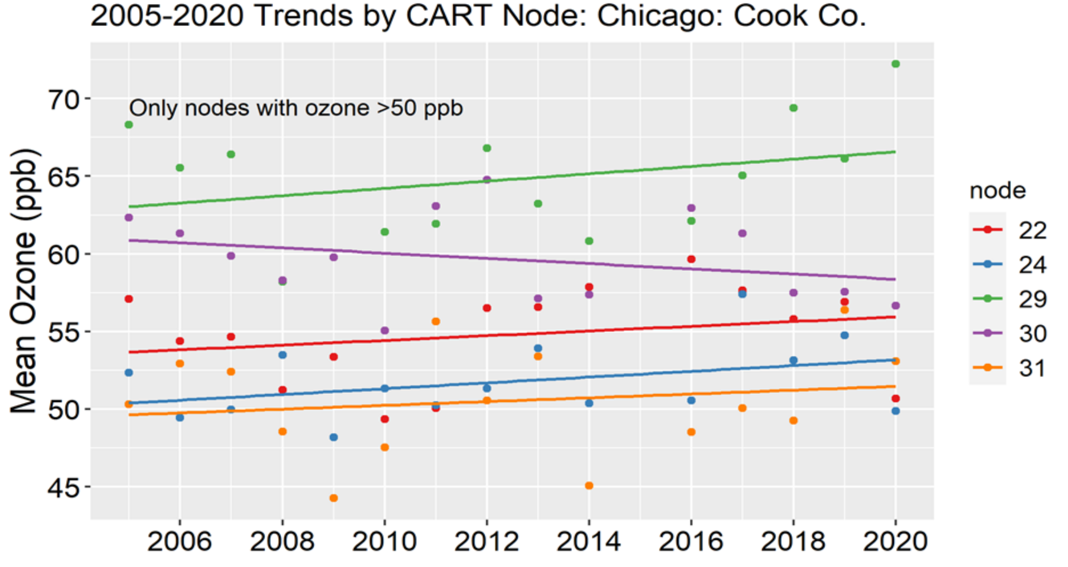
Meteorological Adjustment of O_3 Trends





- LADCO's Classification and Regression Tree (CART) analysis
  - O_3 on meteorologically similar days decreased from 2005 to 2020
    - As shown for Cleveland
  - Exception: Cook County (Chicago)
    - O_3 on most types of days has been increasing
    - Area is VOC-sensitive/NOx-suppressed, becoming less NOx-suppressed, leading to increasing O_3

Conclusions

- Ozone has decreased since the early 2000s
  - In response to decreasing precursor emissions
  - O_3 reductions are smaller than precursor emissions reductions
  - O_3 reductions have slowed in the last decade
- Meteorology → day-to-day variability
- Transport and location of emissions sources → geographic distribution
  - Lake breezes also affect geographic distribution
- Emissions and O_3 formation chemistry → Long-term O_3 trends

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Conceptual models for each area

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Thank you!
Questions?
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