P2.11

THE LAKE SHADOW EFFECT OF LAKE BREEZE CIRCULATIONS AND RECENT EXAMPLES FROM GOES VISIBLE SATELLITE IMAGERY

Frank S. Dempsey

1. ABSTRACT

The lake shadow effect is a component of the lake breeze circulation caused by the cool and stable marine boundary layer flowing onshore and causing a cloud-free region close to the lakeshore. The lake shadow appears as a narrow band of cloudless sky parallel to the lakeshore and extending inland following the lake breeze front. The lake shadow affects local convection and precipitation patterns, hydrology and agriculture, ground-level ozone production and air quality, and aviation. One impact on ground-level ozone production is the enhanced ozone photochemistry that can result where strong insolation combines with a residual layer of ozone precursor pollutants flowing onshore. Some recent examples have been selected of the shadow effect of the Great Lakes as they appear on GOES visible satellite imagery, along with some descriptions of the associated synoptic conditions, and with several examples of contrasting ground-level ozone observations near the Lake Michigan lake breeze front.

2. OVERVIEW OF POSTER

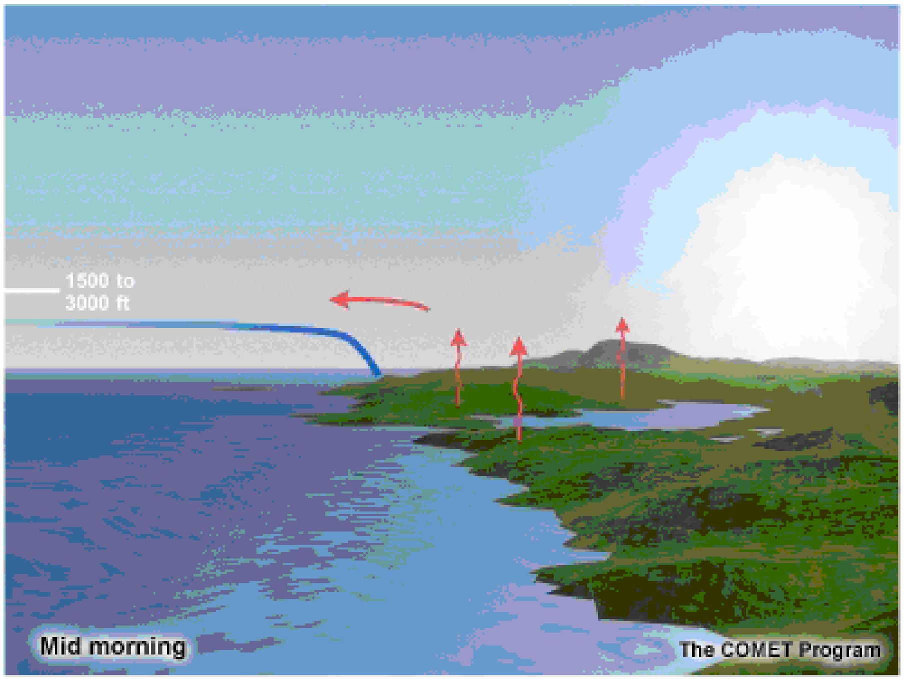
This poster examines an interesting effect of lake breeze circulations on ground-level ozone concentrations, and resulting air quality, in the Great Lakes region beginning with an introductory overview of lake breeze circulations, the lake shadow effect of the lake breeze, and relevant ozone chemistry, followed by several examples that highlight this interesting component of the lake breeze circulation.

3. OVERVIEW OF THE LAKE BREEZE CIRCULATION

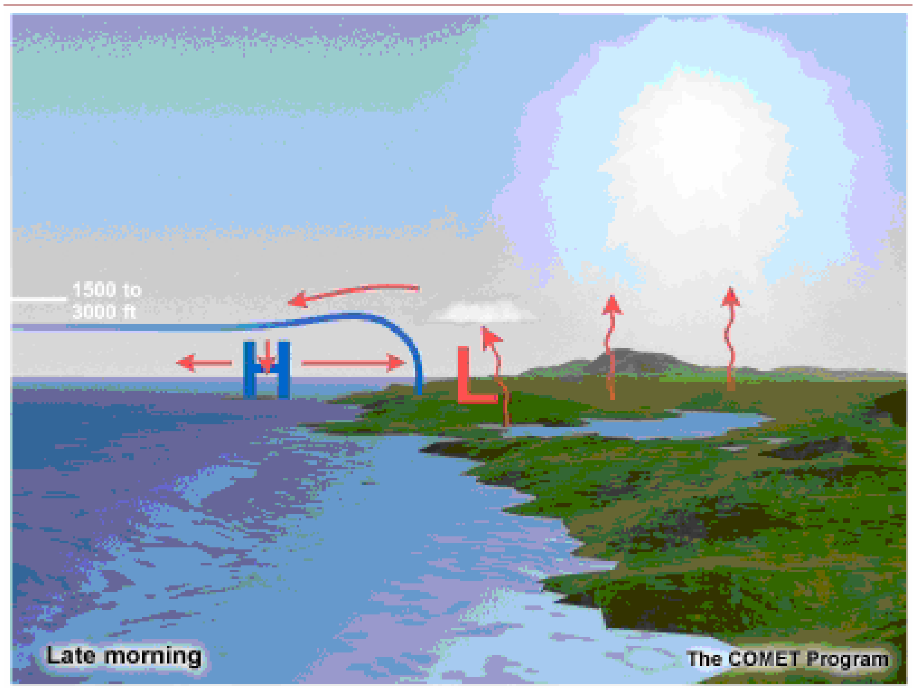
Main aspects:

- Spring-summer season phenomenon
- Land warmer than water (by mid-late morning)
- Weak mesolow over land surface, weak mesohigh over cooler water
- Lake breeze circulation develops a breeze from lake to land at surface level when synoptic flow is weak
- Onshore surface flow is cool marine air and delays cumulus development
- Inland, cumulus develops by late morning or mid-afternoon and may cause broken to overcast sky cover by mid-late afternoon
- The onshore flow may include air pollutants or ozone precursor chemicals, residing over the lake since the previous day, that contribute to ozone production

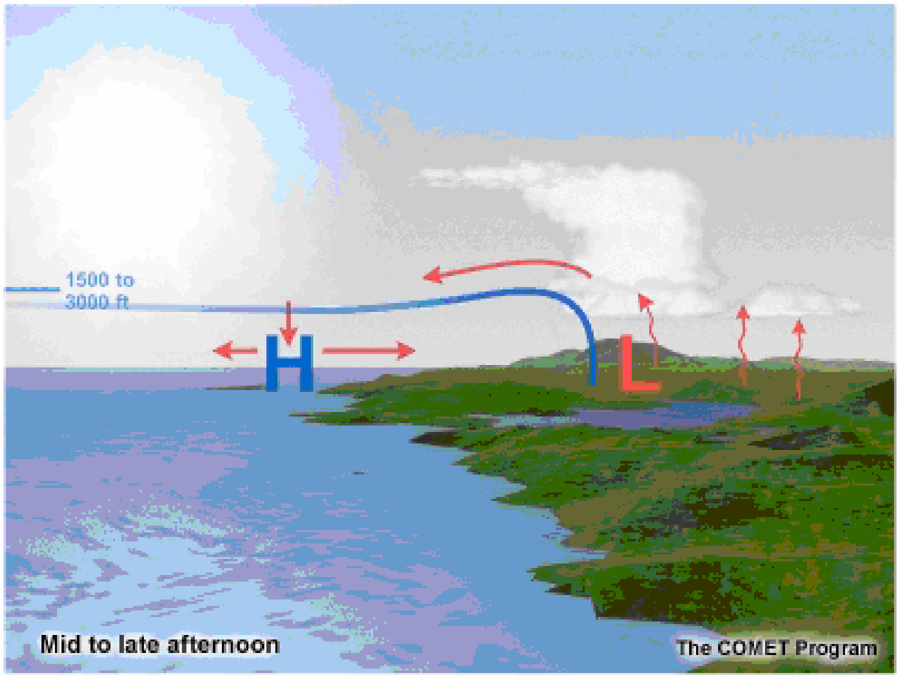
Corresponding author address: Frank S. Dempsey, 1152 Tanzer Court, Pickering, Ontario L1W 3S6; email: frank.dempsey@utoronto.ca



Mid-morning lake breeze development (above): solar heating, land becomes warmer than lake surface. (Image courtesy of The Comet Program.)



Late morning progression of the lake breeze circulation (above): convection over the land starts cumulus development while subsidence over the cooler water develops a mesohigh resulting in a weak pressure gradient and an onshore breeze at low levels. (Image courtesy of The Comet Program.)

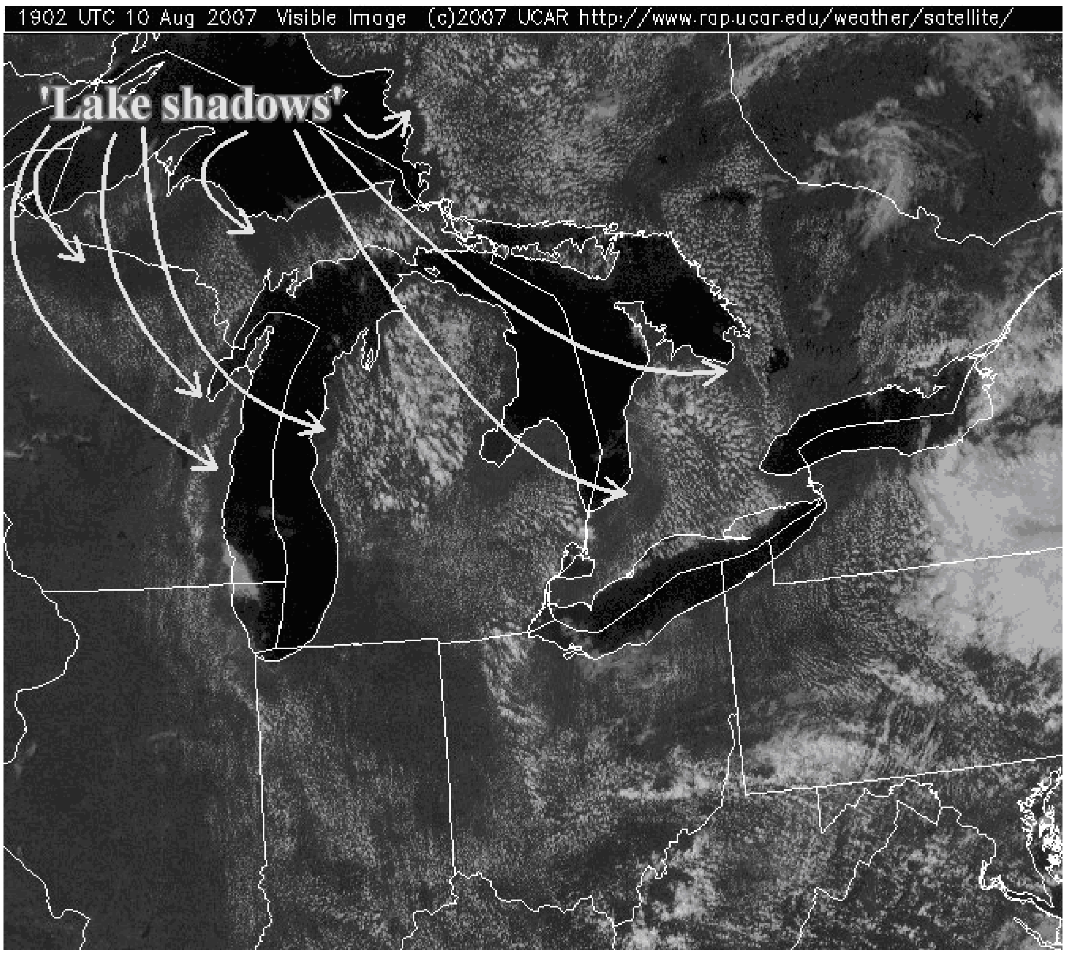


Afternoon fully developed lake breeze circulation (above): Inland, cumulus clouds have developed with a warm, well mixed boundary layer. Near the lakeshore (and some distance inland following the lake breeze 'front'), the cooler marine layer flowing onshore suppresses cumulus development, resulting in sunny conditions with a stable and shallow mixed layer (possibly loaded with pollutants). (Image courtesy of The Comet Program.)

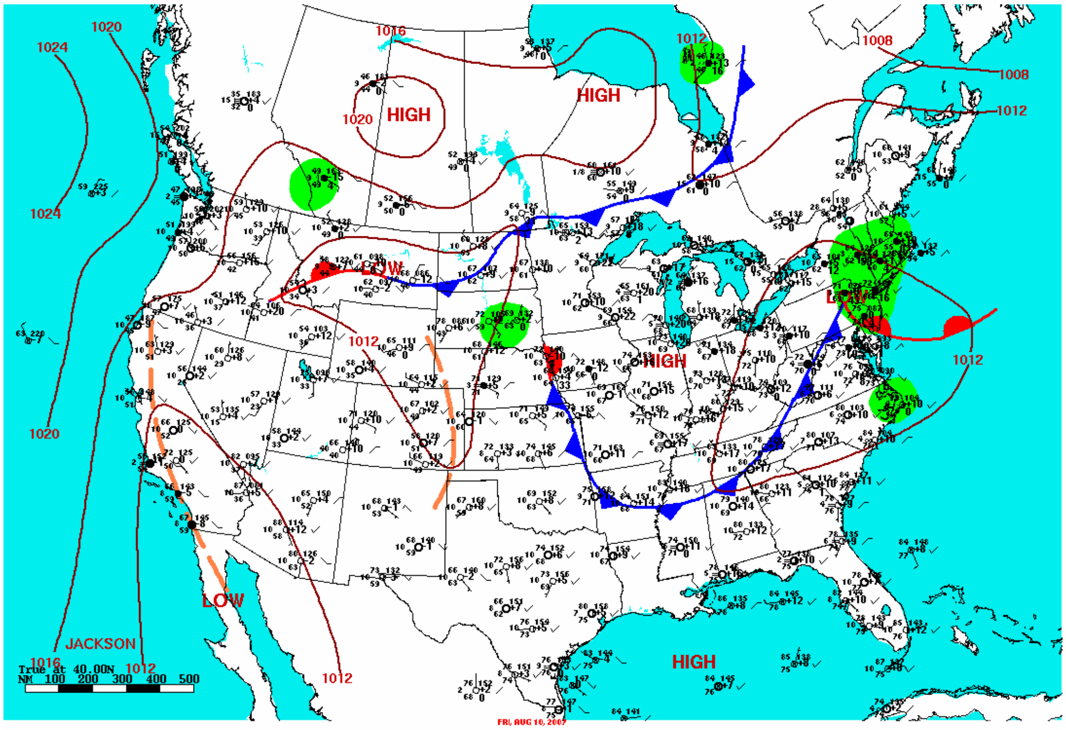
4. OVERVIEW OF THE LAKE SHADOW EFFECT

- Inland penetration of the lake breeze causes clear sky along a narrow strip parallel to lakeshore.
- Inland from the lake breeze front, cumulus cloud development causes afternoon cloudiness.

- Examples below are GOES-12 visible channel images around mid-afternoon during generally clear days when synoptic conditions (post-cold front, partly unstable air) favor cumulus development.

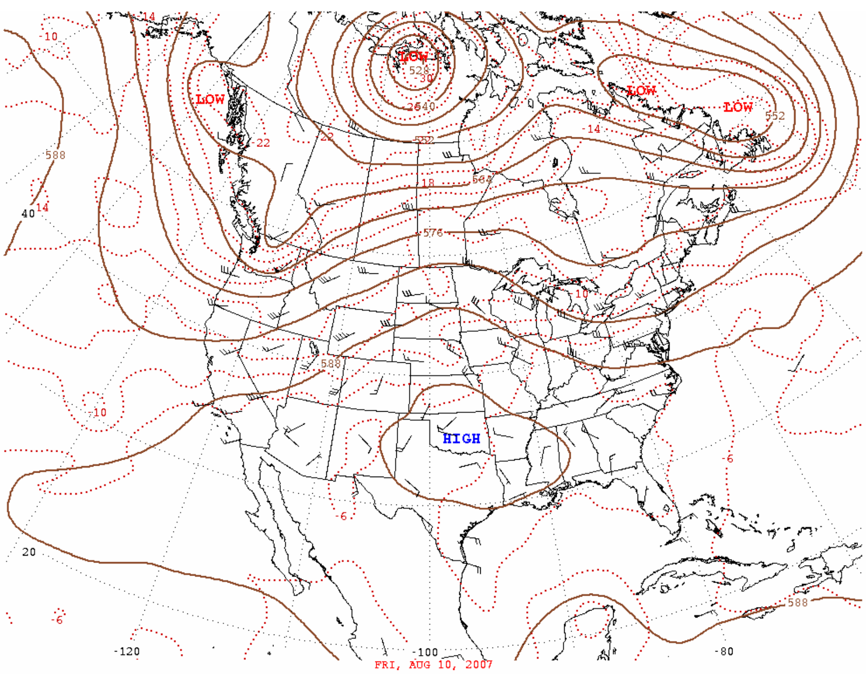


Visible image for 2007 August 10, illustrating some lake shadows. (Image courtesy of University Center for Atmospheric Research.)

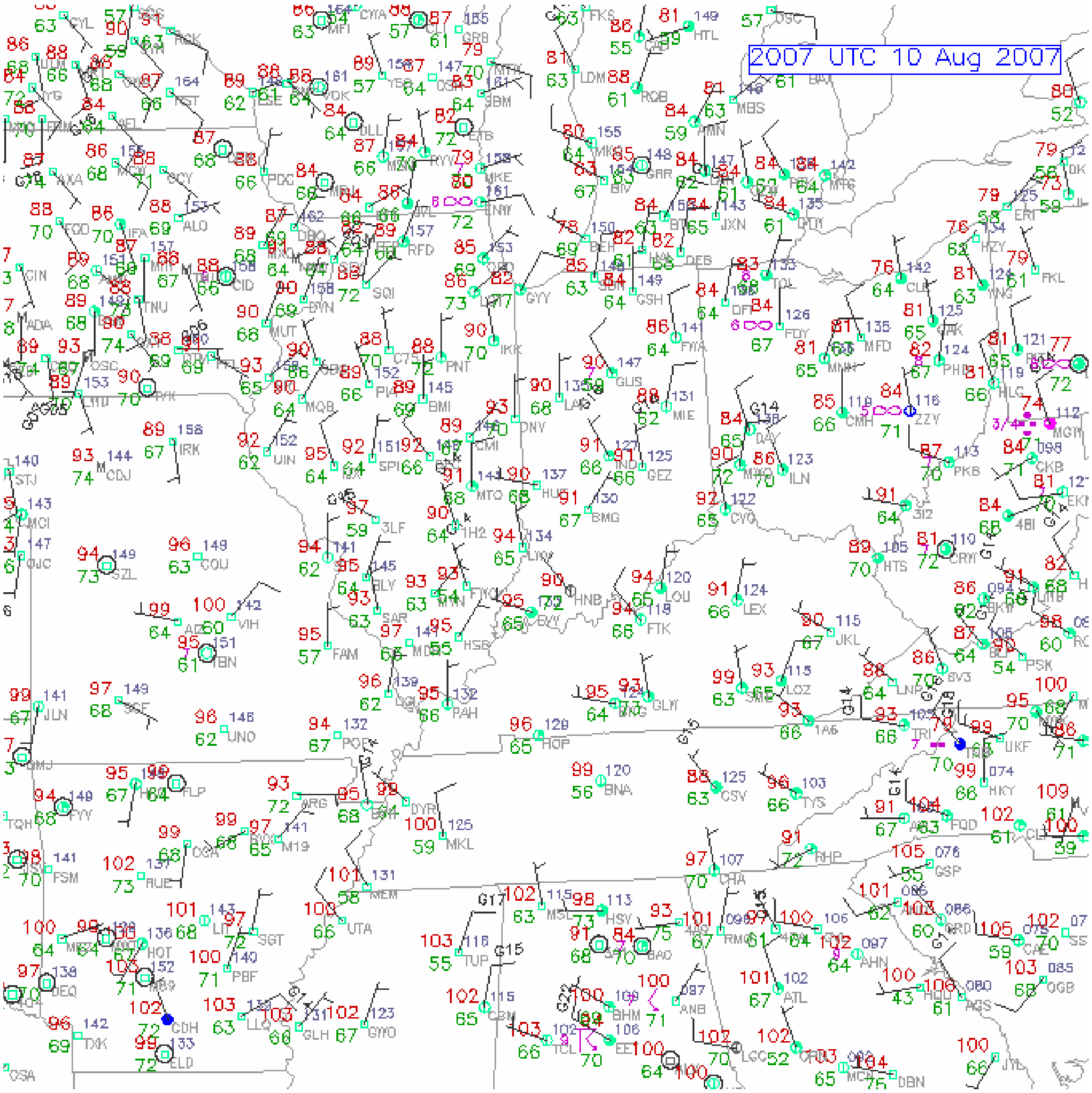


Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Example of synoptic conditions associated with lake breeze and lake shadow development, for the 2007 August 10 example (above): surface high pressure region in the vicinity, weak synoptic flow, and upper ridge to the west (shown in 500 mb chart below). (Charts courtesy of Hydrometeorological Prediction Center).



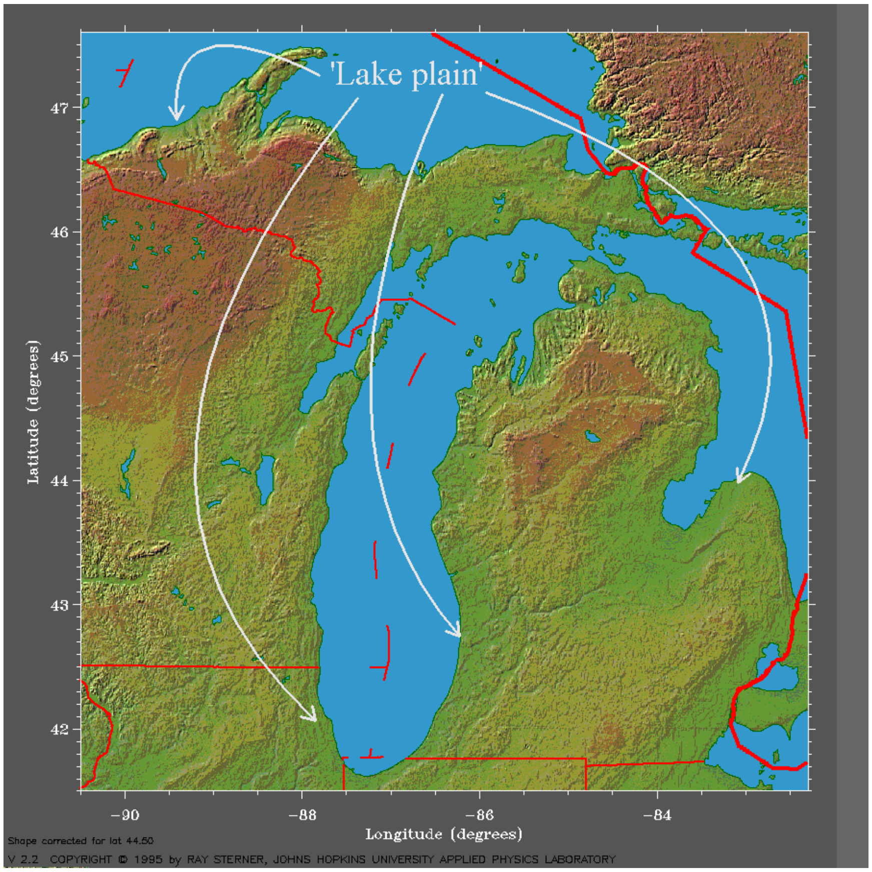
500-Millibar Height Contours at 7:00 A.M. E.S.T.



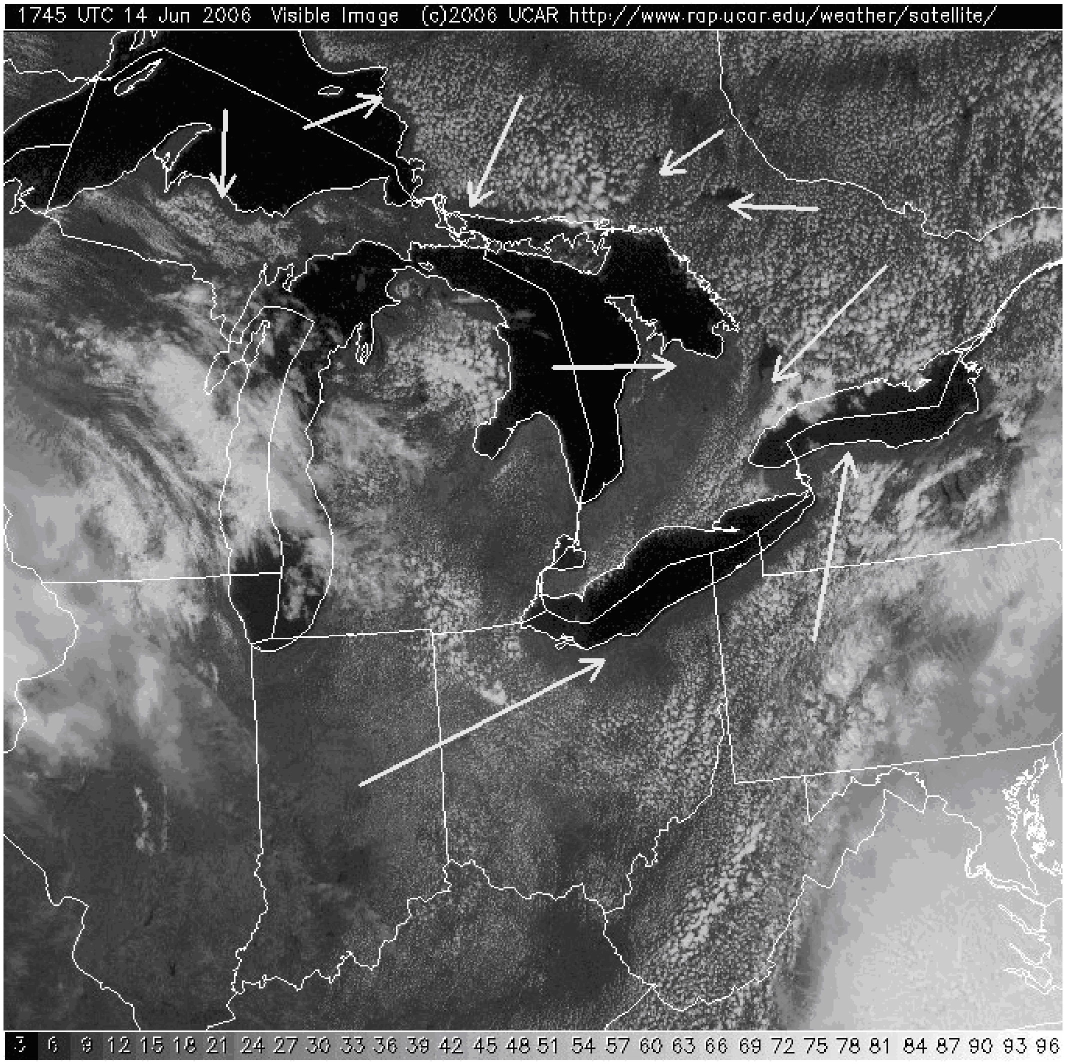
Surface plot for the 2007 August 10 example (above): some details relevant to the lake breezes include distinct onshore flow each side of Lake Michigan in contrast to the generally northerly flow across the southern Great Lakes region, and cooler and more moist conditions near the lakeshores. (Image courtesy of University Center for Atmospheric Research.)

Other details that affect the lake breeze and shadow:

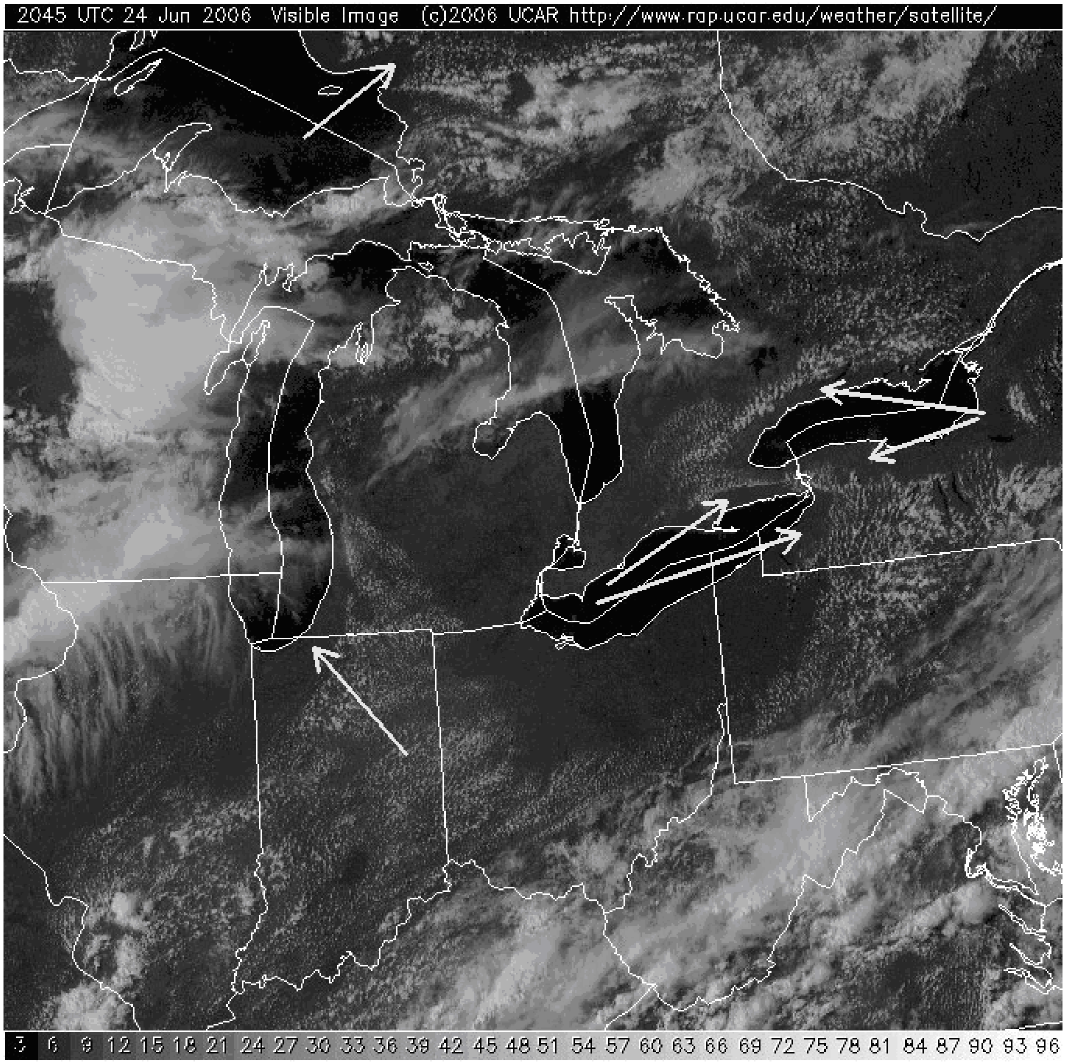
- Sufficient temperature contrast between water and land: a significant air temperature gradient along the length of a lake may reduce or enhance lake breeze development; water temperatures also may vary significantly across the lake surface
- Upper clouds may reduce insolation and hinder development of the lake breeze circulation
- Topography: a flat ‘lake plain’ close to the lakeshores allows the lake breeze to penetrate inland before encountering higher terrain that provides orograghic lift, as illustrated on the relief chart below



Relief chart showing several flat coastal ‘lake plains’ where lake breezes can penetrate onshore without encountering significant orographic lift. (Image courtesy of Johns Hopkins University Applied Physics Laboratory.)



Visible image for 2006 June 14, illustrating some lake shadows. (Image courtesy of University Center for Atmospheric Research.)



Visible image for 2006 June 24, illustrating some lake shadows. (Image courtesy of University Center for Atmospheric Research.)

5. OVERVIEW OF BACKGROUND CHEMISTRY FOR AIR QUALITY (DUE TO GROUND-LEVEL OZONE)

Main atmospheric gases relevant to ground-level ozone chemistry:

- nitric oxide NO
- nitrogen dioxide NO_2
- ozone O_3

Synopsis of the primary chemical process:

Photolysis of NO_2 by sunlight (hv with wavelength λ) causes NO_2 to dissociate and produce monatomic oxygen:

$$NO_2 + h\nu\ (\lambda < 400\ \text{nm}) \rightarrow NO + O \qquad \text{(Eqn 1)}$$

followed by combination with molecular oxygen to form ozone:

$$O + O_2 \rightarrow O_3 \qquad \text{(Eqn 2)}$$

Then, the oxidation of NO by ozone:

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad \text{(Eqn 3)}$$

would provide a cycle with the ozone oxidizing the NO to regenerate NO_2 and no net gain or loss of ozone. Then, if considering only these reactions, the resulting concentrations of NO, NO_2 and O_3 would be determined only by the amount of available sunlight.

Further reactions occur in polluted atmospheres that contribute to further ozone formation, but the photolytic splitting of NO_2 followed by combination with O_2 to generate O_3 as described by Equations 1 and 2 above, are the relevant ozone-production reactions that proceed more strongly under sunny skies, and less strongly under cloudy skies.

Summary

Sunny skies (and shallow boundary layer) → more ground-level ozone

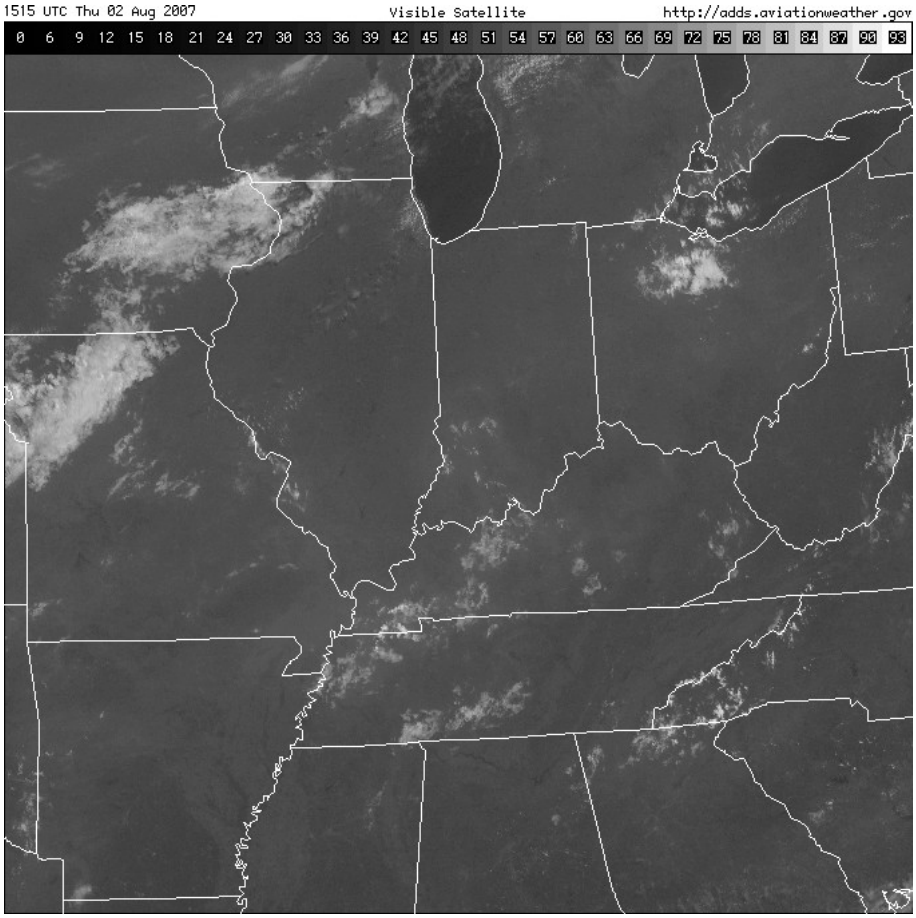
Cloudy skies (and convective boundary layer) → less ground-level ozone

Further details

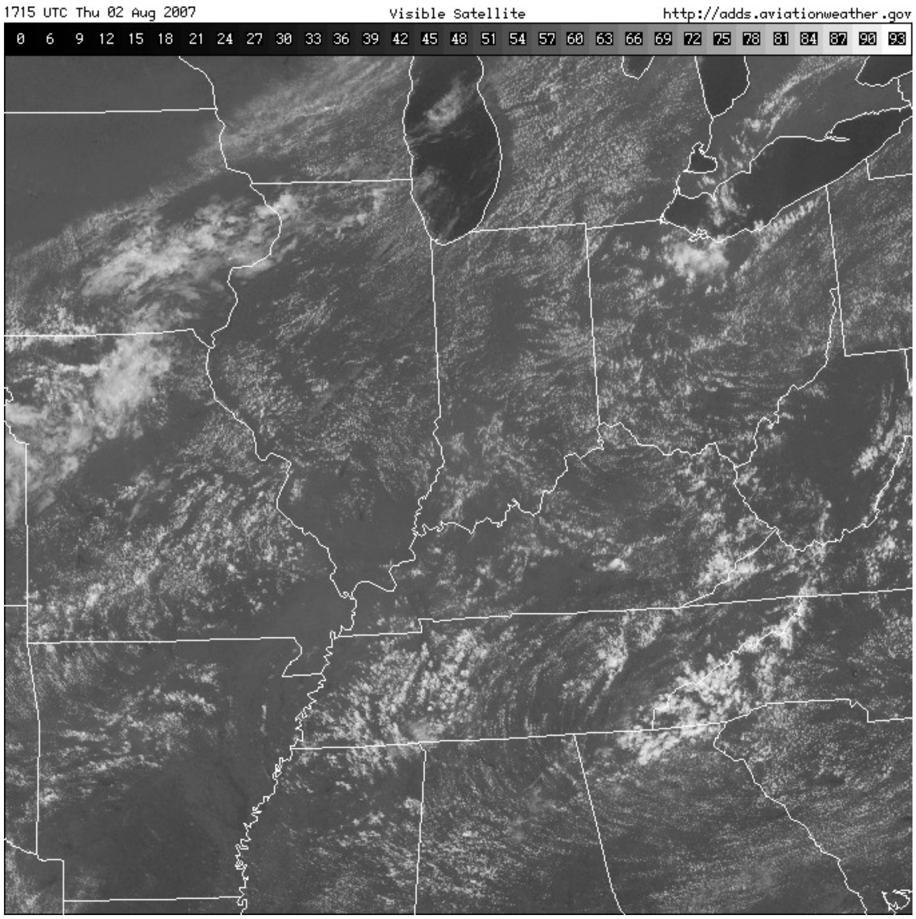
- In polluted air: ozone generation is catalyzed by reactive hydrocarbons and volatile organic compounds, or 'VOC's (from emissions)
- High concentrations of ground-level ozone can be accounted for by including catalytic oxidation cycles and the generation of radical molecules and ions, particularly the hydroxyl radical OH and peroxy radicals from various hydrocarbon precursors
- The significance of the OH radical is that OH is the critical oxidant of hydrocarbon molecules or of VOCs driving ozone formation, and the oxidation of the VOCs propagates increased ozone formation
- The importance of the oxidation by reactive radicals (derived from oxidation of reactive hydrocarbons by OH) is the catalytic generation of NO_2 and resulting photolytic ozone generation, as well as the regeneration of more radicals (and their potential for further oxidation)
- The sunny conditions under the lake breeze shadow often coincide with a stable, shallow mixing layer which contributes to higher concentrations of pollutants. The cloudy conditions inland from the lake breeze front coincide with a deeper and convective mixed layer which contributes to lower concentrations of pollutants
- After sunset: ozone reacts with NO_2 and diminishes (or disappears completely) in the boundary layer. Overnight, 'chemical reservoirs' and ozone-rich air remaining above the nocturnal boundary layer provide the potential for ozone to increase again the next day (by mixing down to the surface after daytime convection begins, as well as by circulation from over the lake to land with the lake breeze)
- Highly populated areas: more vehicles and other combustion sources (sources of NO), more industrial emissions (sources of reactive hydrocarbons and VOCs)
- Trees and foliage: sources of reactive hydrocarbons and VOCs

(More detailed and extensive treatments of further reaction mechanisms are available, e.g., Wayne, 2000 and Finlayson-Pitts, 1999.)

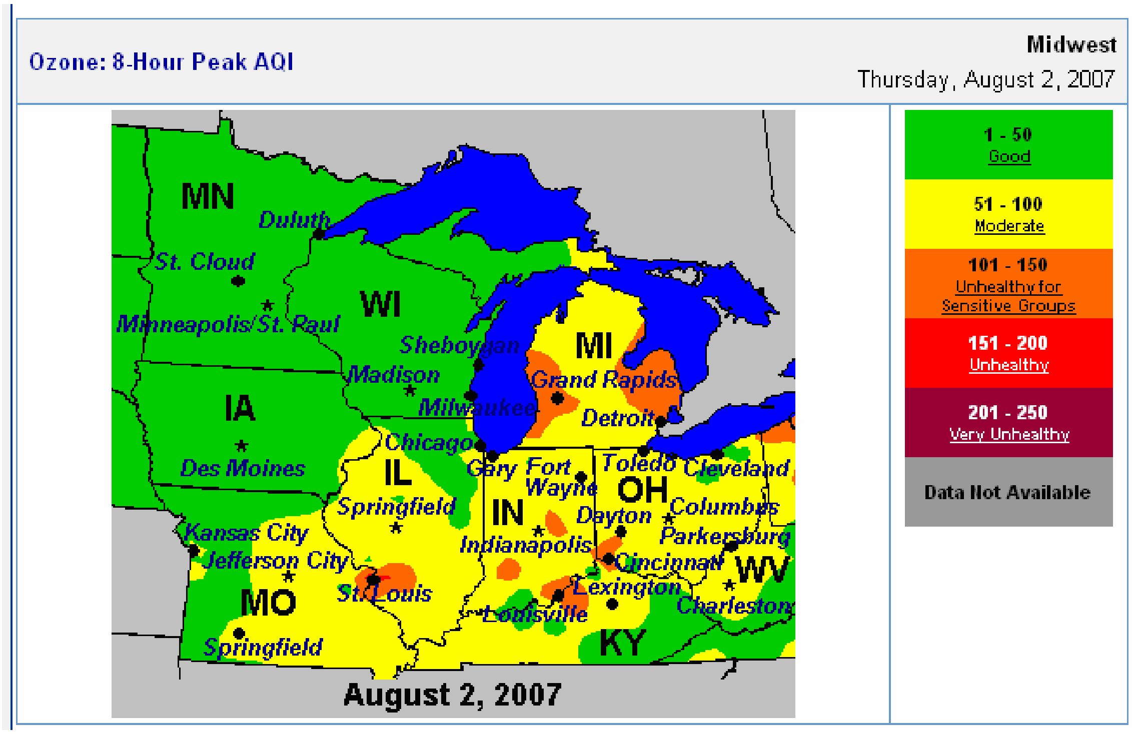
6. EXAMPLE #1: 2007 August 02



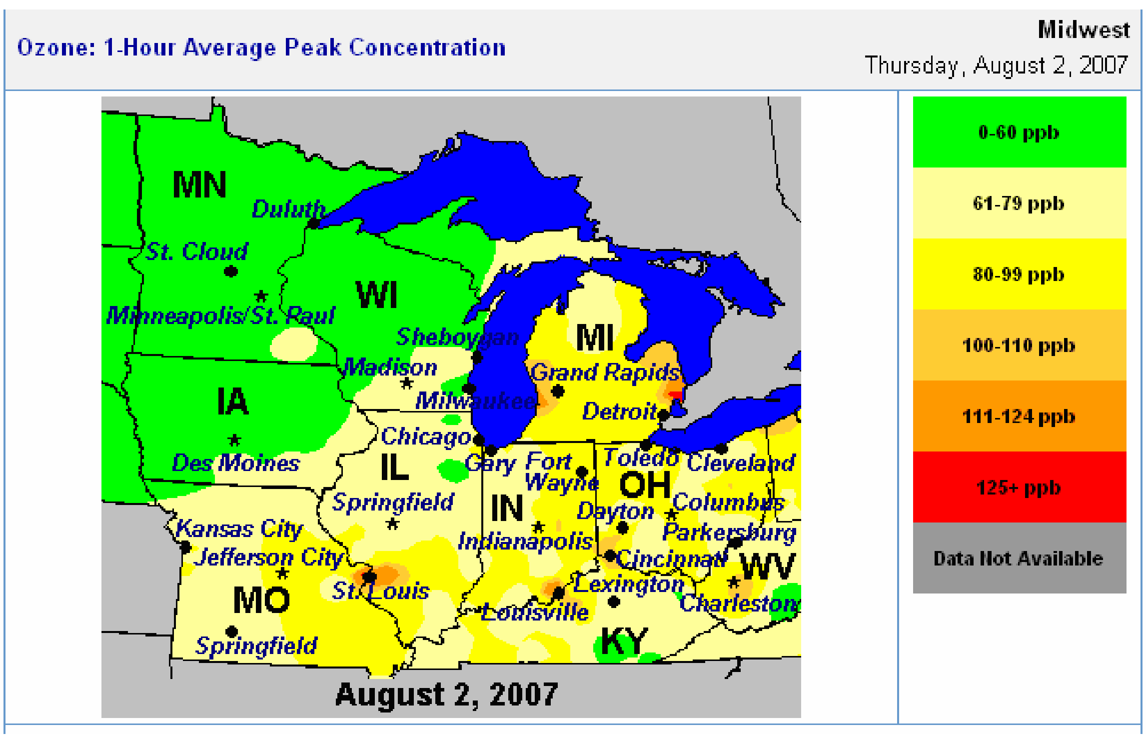
Visible image during mid-morning (above) showing cumulus development and lake shadow over western Michigan. (Image courtesy of Aviation Weather Center.)



Visible image near noon (above), showing distinct lake shadow east of Lake Michigan shoreline and cloudiness along western shoreline. (Image courtesy of Aviation Weather Center.)

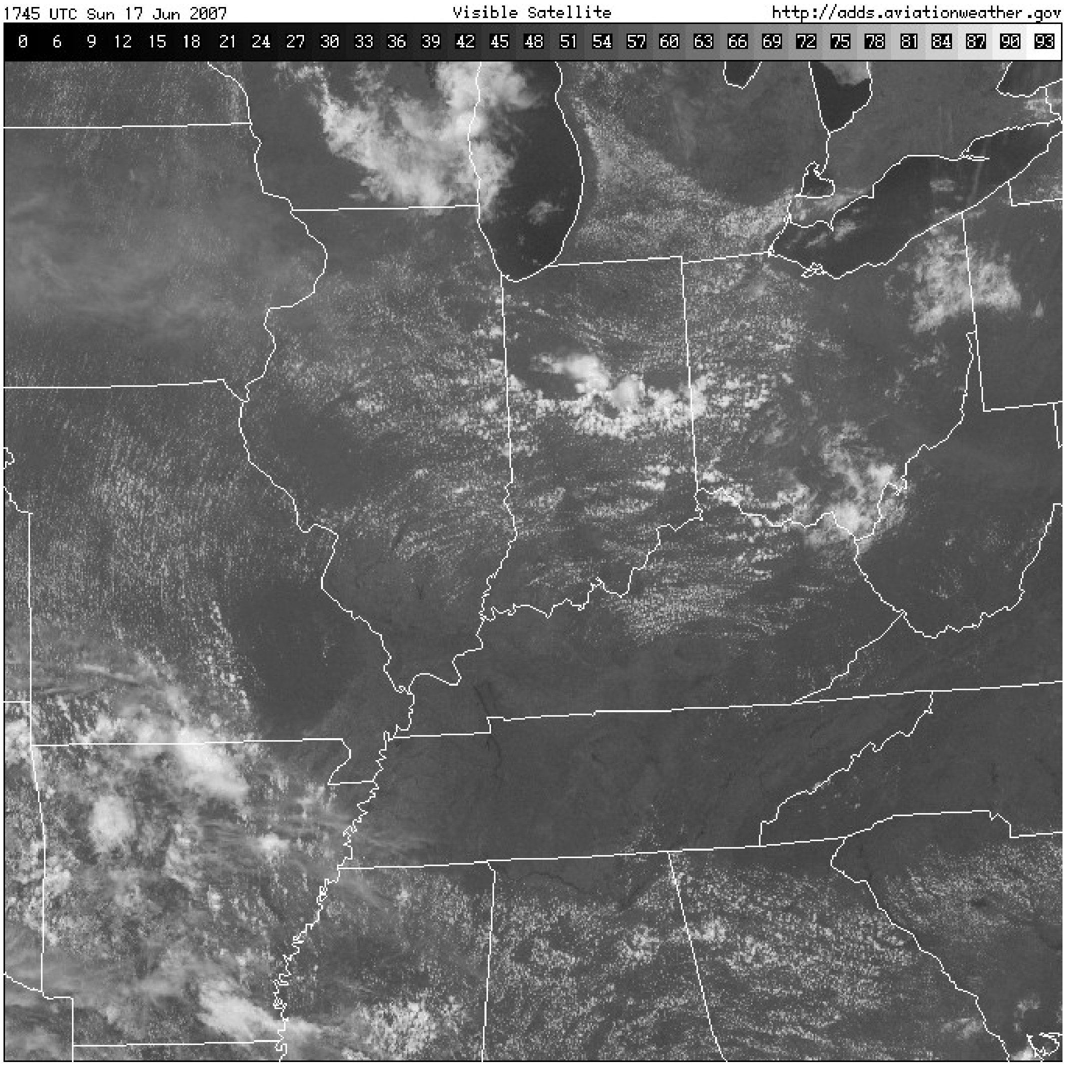


AIRNOW 8-hr peak ozone AQI (above) showing highest AQI approximately coinciding with lake shadow locations. (Courtesy of AIRNOW.)

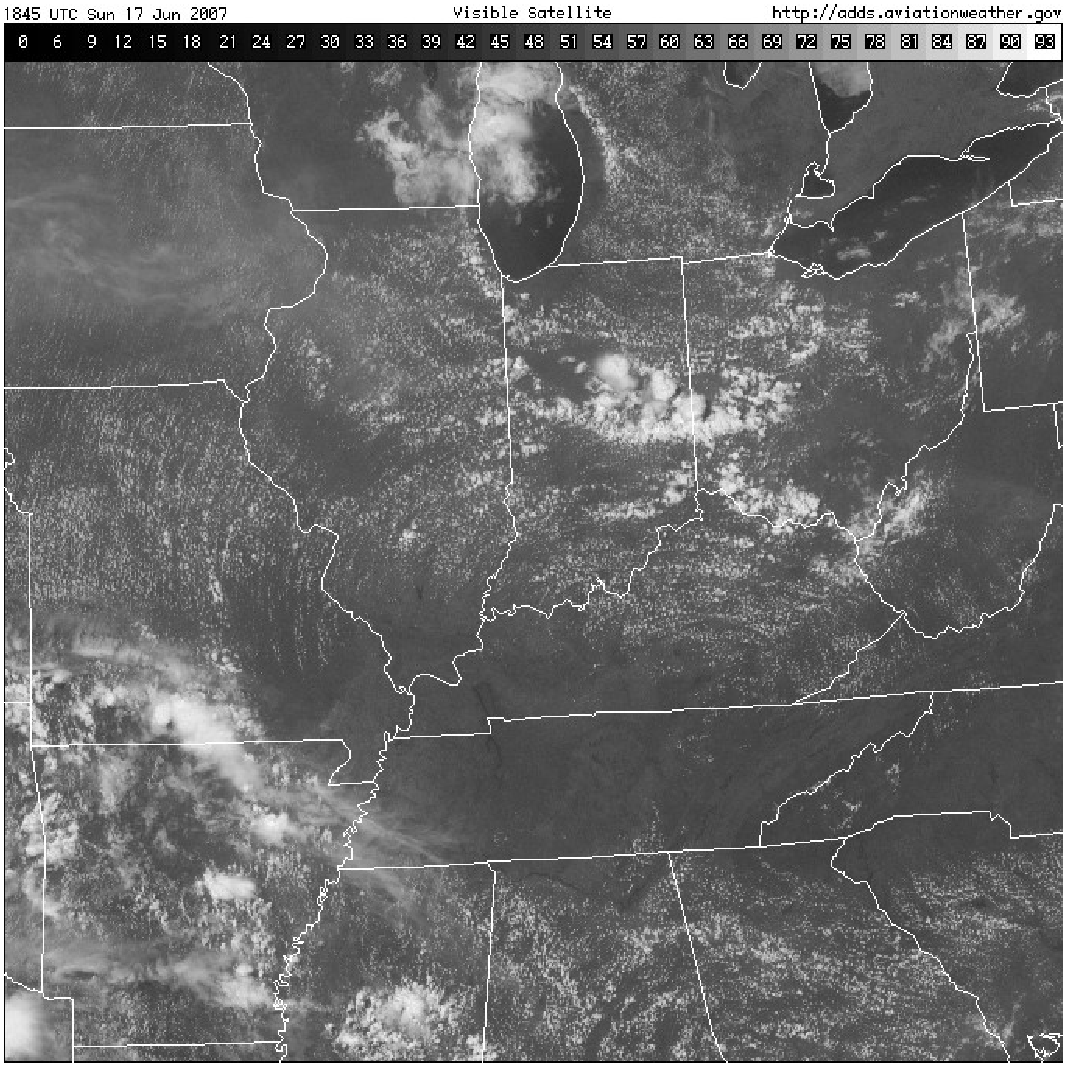


AIRNOW 1-hr average peak ozone concentrations (above) showing highest ozone concentrations approximately coinciding with lake shadow locations. (Courtesy of AIRNOW.)

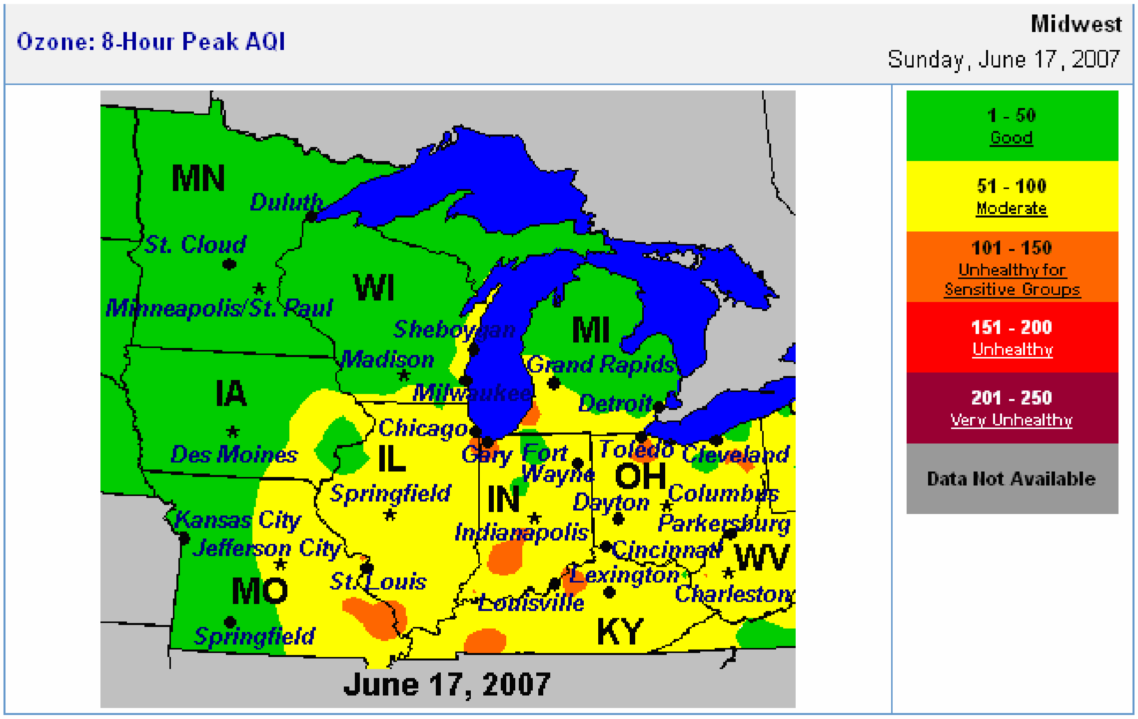
7. EXAMPLE #2: 2007 June 17



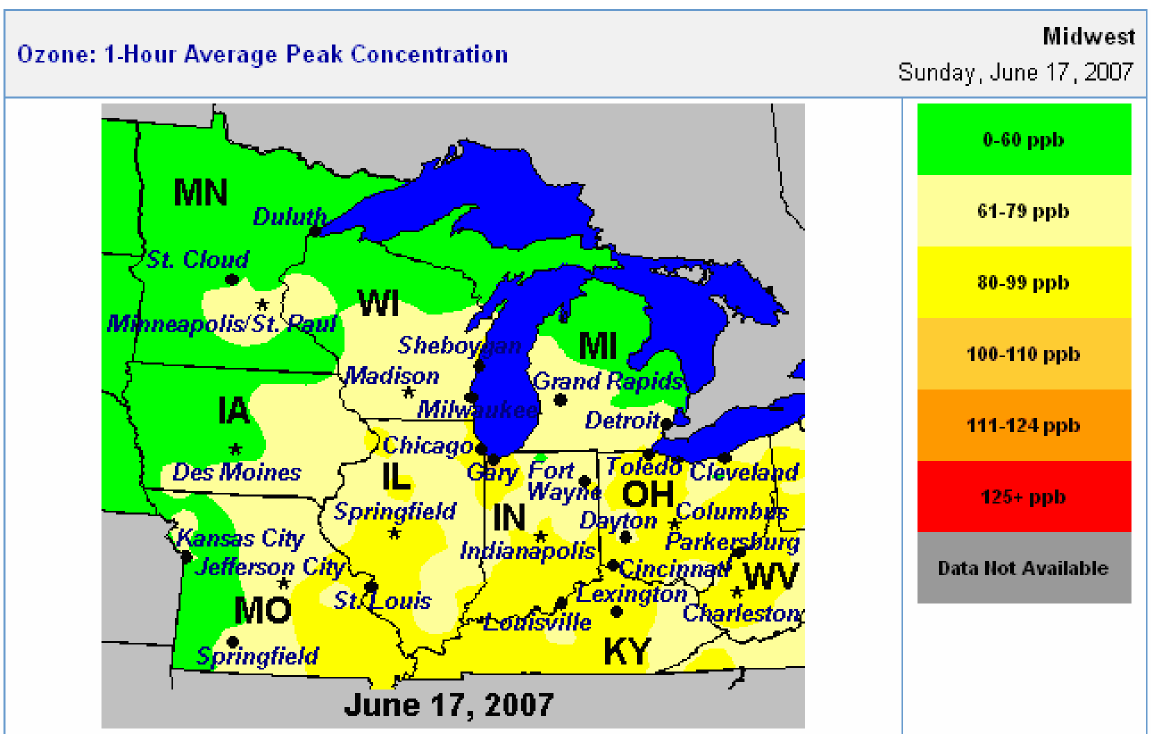
Visible image for UTC 1745, showing well-developed lake breeze and shadow over western Michigan. (Image courtesy of Aviation Weather Center.)



Visible image for 1 hour later, showing thicker cumulus development inland as well as the lake breeze and shadow west of southern Lake Michigan. (Image courtesy of Aviation Weather Center.)

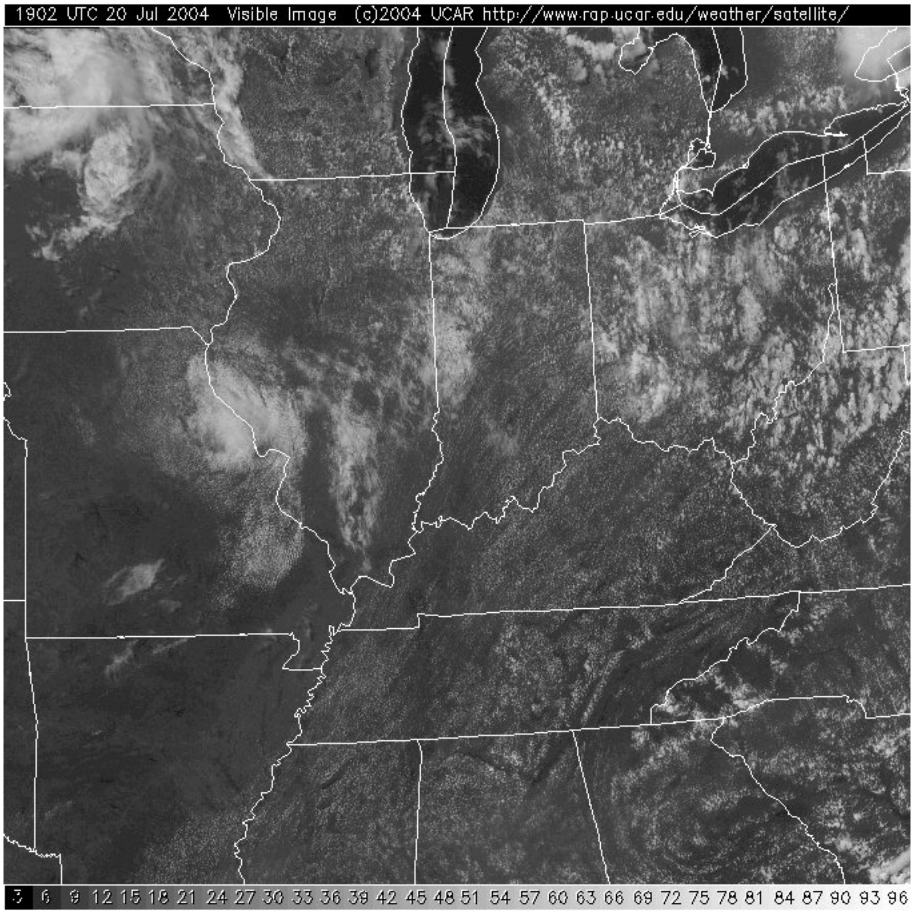


AIRNOW 8-hr peak ozone AQI (above) showing highest AQI approximately coinciding with lake shadow locations. (Chart courtesy of AIRNOW.)

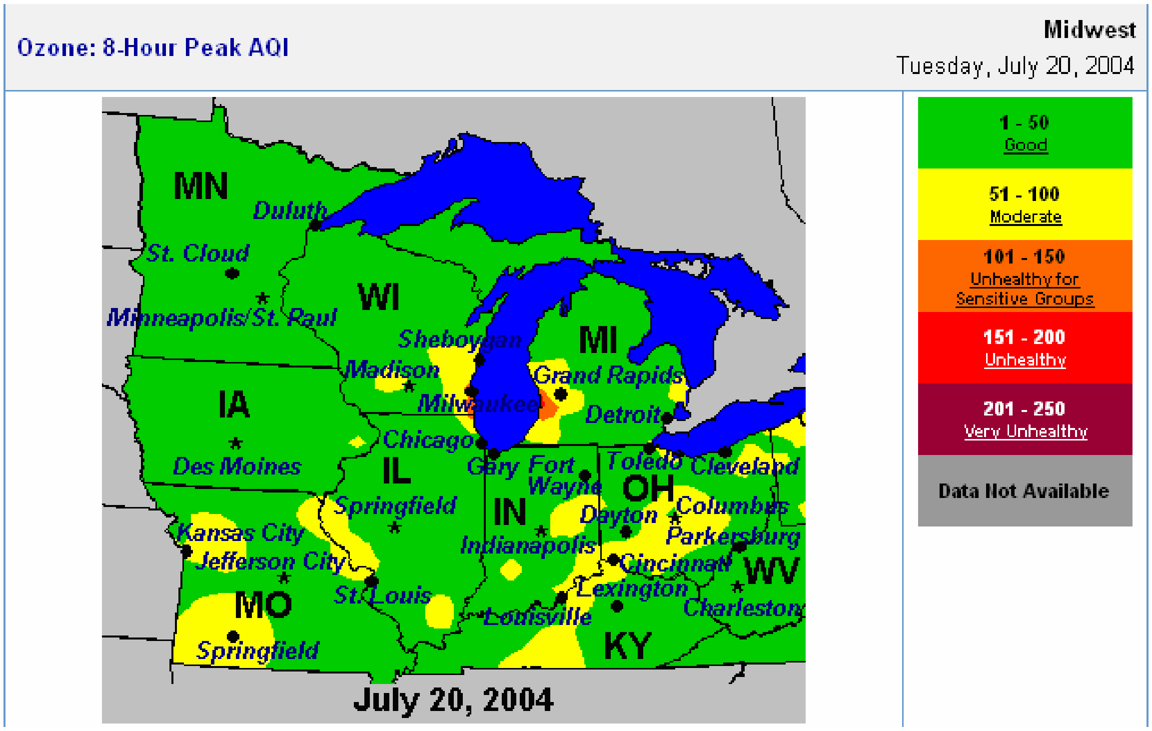


AIRNOW 1-hr average peak ozone concentrations (above) showing highest ozone concentrations approximately coinciding with lake shadow locations. (Chart courtesy of AIRNOW.)

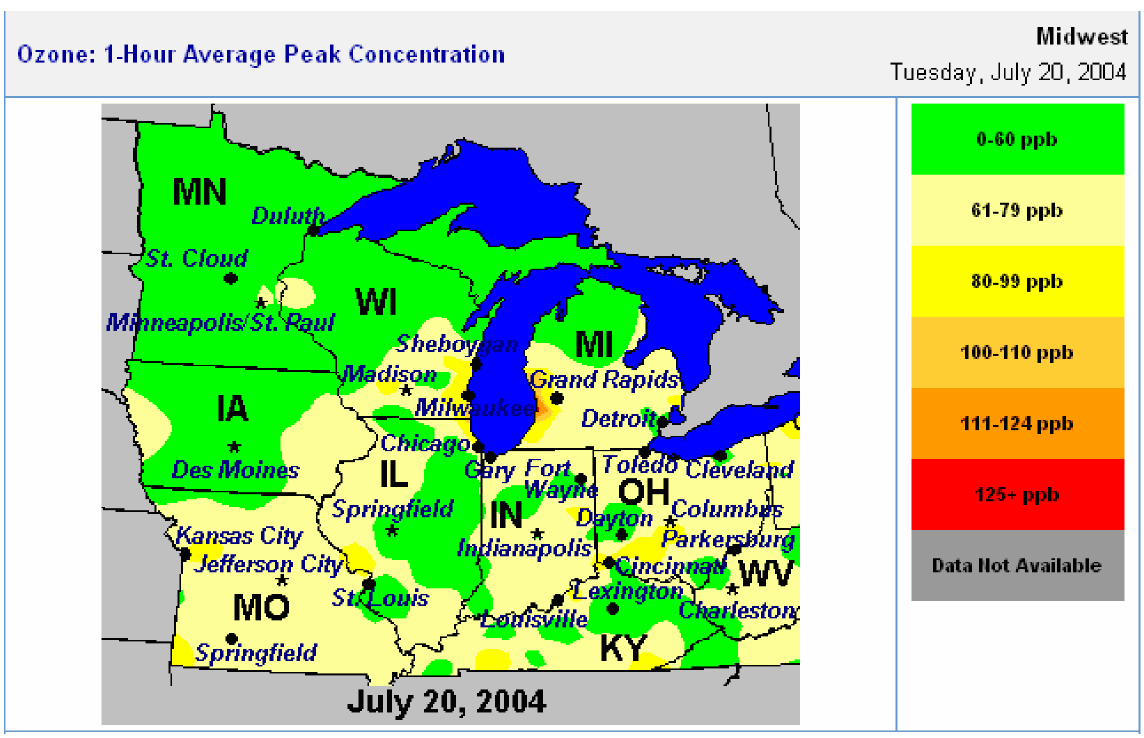
8. EXAMPLE #3: 2004 July 20



Visible satellite image during mid-afternoon showing lake breeze shadows east and west of Lake Michigan, and convergence band above central Lake Michigan. (Image courtesy of University Center for Atmospheric Research.)



AIRNOW 8-hr peak ozone AQI (above) showing highest AQI approximately coinciding with lake shadow locations. (Chart courtesy of AIRNOW.)



AIRNOW 1-hr average peak ozone concentrations (above) showing highest ozone concentrations approximately coinciding with lake shadow locations. (Chart courtesy of AIRNOW.)

9. SUMMARY

The lake breeze shadow effect has been illustrated with resulting effects on air quality in several examples for southern Lake Michigan, although the effect occurs for many lakes. While the effect is well known to Great Lakes area forecasters, the effect on air quality in some locations is dependent on many other factors including temperature and moisture content of the lower atmosphere, soil moisture and land use, lake temperatures, terrain and orographic influences, local emissions, and concentrations of pollutants in residual layers over the lake as well as in layers of air advected over the region. Other influences of the lake breeze shadow effect have not been described in this document but include sunshine, surface temperature and convective precipitation patterns and resulting effects on hydrology, aviation operations, and agricultural land use.

10. REFERENCES

AIRNOW, online at airnow.gov

Aviation Weather Center, online at http://adds.aviationweather.gov/satellite/

The Comet Program, online at http://www.meted.ucar.edu/

Finlayson-Pitts, B. J. and Pitts, J.N. Jr. (1999): Chemistry of the Upper and Lower Atmosphere: Theory, Experiments and Applications, Academic Press, New York

Hydrometeorological Prediction Center, online at http://www.hpc.ncep.noaa.gov/dwm/dwm.shtml

University Corporation for Atmospheric Research, online at http://www.rap.ucar.edu/weather/satellite/

Wayne, R. (2000): Chemistry of Atmospheres, Oxford University Press