6th Conference on Mesoscale Processes and
10th Conference on Numerical Weather Prediction
American Meteorological Society
Portland, OR 17-22 July 1994

DD13

OBSERVATIONS AND MODELING OF SHALLOW LAKE BREEZE CIRCULATIONS ON LAKE MICHIGAN

Walter A. Lyons, Craig J. Tremback, Roger A. Pielke and Ian Baker

Mission Research Corporation / ASTER Division
Ft. Collins, CO

1. INTRODUCTION

The role of Lake Michigan in exacerbating regional ozone problems has been investigated for almost 20 years (Lyons and Cole 1976; Lyons et al. 1994). As of 1993, the Lake Michigan region contains two severe ozone non-attainment areas, Chicago and Milwaukee. During the very hot summers of 1987 and 1988, exceedances of the 120 ppb ozone NAAQS were 4.5 times more likely at monitors located within 20 km of the lake shore than those further inland (Fig. 1). Numerous instances have been documented in which high levels of ozone were associated with lake breeze circulations. During the 1991 Lake Michigan Ozone Study (LMOS) field program, measurements from a shoreline Doppler sodar, profilers and anchored vessels reveal that the depth of the inflow layer over the southern basin of the lake was often confined to less than 200-250 meters. With southerly and southwesterly gradient flow, the inland penetration of such lake breezes at the Wisconsin-Illinois border was often no more than 5 km. For those days on which a lake breeze was detected by a Doppler sodar located on the lake shore at Zion, IL, peak ozone readings along the west shore were significantly higher (Fig. 2). In 30 days without a lake breeze, the highest reading was 102 ppb, with an average of 72 ppb. On 24 days with a lake breeze at Zion, fully half of the days recorded one or more site reading above 120 ppb. The average peak ozone level was 121 ppb and the highest reached 189 ppb. Interestingly, the strength of the lake breeze, as indicated by the depth of the inflow layer at Zion, did not seem to influence the severity of the measured peak ozone level (Fig. 3). This supports prior work suggesting that even weak or shallow lake breezes can result in significantly elevated ozone levels in the region (Lyons et al. 1991).

2. A SHALLOW LAKE BREEZE DAY

This day, 16 July 1991, was typical of many high ozone days along the western shore of Lake Michigan. A broad southwesterly flow of maritime tropical air about a anticyclone centered in Pennsylvania dominated the LMOS region. Daytime surface wind speeds were generally 8 m s^{-1} or less over land. Temperatures over Wisconsin and Illinois warmed to highs between 30-34°C while over the lake maximum temperatures reached 20-25°C. Cloud cover was minimal throughout the LMOS domain. These conditions are known to be favorable both for the development of a lake breeze (Lyons 1973) and elevated regional ozone levels (Haney et al. 1989) The lake breeze on the western shore began by late morning but did not penetrate very far inland. In fact the winds remain offshore all day on the south side of Chicago. Buoys and LMOS research ships showed the influence of the lake is very subtle, appearing as a south to southeast flow only 200-300 m deep above the western half of the lake and the shoreline. At Zion, IL just south of the Wisconsin-Illinois border and about 1 km inland, initially winds were persistent from the southwest and gradually increased in speed. At 1700 UTC the direction suddenly shifted to onshore at both the 11 m and 76 m levels and remained southeast for the next seven hours. The passage of the front was marked by about a 2°C temperature fall and a 3°C dewpoint rise. A Doppler sodar operated by the Illinois Department of Nuclear Safety at Zion, approximately 200 m inland from the beach, monitored both the duration and depth of the lake breeze inflow (Fig. 4). Given the essentially north-south western shoreline of Lake Michigan, a lake breeze can be easily classified by a wind shift from offshore to one having an easterly component ($u \leq 0$). The sodar shows the lake breeze present from a few minutes after 1100 LST (1700 UTC), breaking down with a sharp shift from onshore to offshore at 1730 LST (2330 UTC). The depth of the lake-breeze inflow was very shallow, limited to a maximum of about 230 m (agl). An east-west chain of 10 m anemometers at the shoreline and 3, 8 and 24 km inland along the Wisconsin-Illinois border provided information on the inland penetration. At the 3 km site, the wind shifted onshore only between 13-16 LST (19-23 UTC), and winds remained southwesterly all day at the 8 km site. Thus the furthest inland the lake breeze penetration could have extended was 7 km.

The maximum hourly ozone readings in the LMOS domain suggest substantial lake impact. Values above 100 ppb, peaking at 130 ppb near Zion, IL, were found over water, along the immediate western shoreline impacted by the lake breeze inflow, and in a broad region over western lower Michigan. This suggests that a "pool" of ozone was present over the lake by afternoon, portions of which were advected onto the western shore by the lake breeze. A rawinsonde observation taken at 2100 UTC by a research vessel anchored about 15 km offshore from Zion, IL. showed the shallow inflow layer was restricted to the lower 300 m . A regional subsidence inversion was present at 1700 m (msl). Above 1700 m (msl) ozone levels were typically 50 ppb or less to above 6000 m (msl). LMOS aircraft measurements confirmed the presence of high ozone levels (>100 ppb) beneath the synoptic inversion over most of the lake.

3. APPLICATION OF THE RAMS MODEL

The Regional Atmospheric Modeling System (RAMS) (Pielke et al. 1992) is providing the meteorological fields for the LMOS photochemical modeling studies. Periods of up to ten days were simulated in order to provide input to both the USEPA's Regional Oxidant Model and the SAI advanced Urban Airshed Model (UAM-V). All computations were conducted on an IBM RS/6000-550 workstation. The nested grid configuration included an 80 km mesh covering the entire U.S. with two inner

Corresponding author address: Walter A. Lyons, MRC/ASTER, P.O. Box 466, Ft. Collins, CO 80522 (303-221-1355).

nests (16 km and 4 km Δx) over the LMOS domain. The NGM analysis fields provided the outer boundary conditions. Variable soil moisture and land uses were employed. NWS surface and upper air reports at 0000 and 1200 UTC were utilized in four dimensional data assimilation to control error growth during the multi-day simulations. Figure 5 shows the predicted low level (12 m) wind streamlines at 1400 and 2100 UTC. A lake breeze front formed at 1700 UTC and moved only slightly onshore from the Wisconsin-Illinois border northward. The west shore lake breeze moved onshore only as far south as the northern part of Chicago, leaving offshore flow for the entire day over much of the Chicago urban area. Qualitatively, the RAMS-generated surface layer wind field shows a strong resemblance to the observed.

Vertical (XZ) profiles in an east-west plane at the latitude (42.5°) of the Wisconsin-Illinois border are shown in Figs. 6 a-d. The UW streamline field outlines the general flow field including the sea breeze circulation, the lofting of the "inland" air over the frontal surface into the return flow layer over the lake and the general subsidence over the lake. The u wind component emphasizes the shallowness of the lake breeze inflow ($u \leq 0$) as well as the acceleration in the return flow layer over the western lake between 500 and 1800 m (msl). The western shore updraft/subsidence couplet is shown, though it should be noted that the mesh size used (4 km) most likely resulted in an updraft zone that was both wider and weaker than would be observed. Weak subsidence (several cm s^{-1}) was present over almost the entire lake below 1800 m (msl). The potential temperature field shows a deep mixed layer over the western shore extending to 1700 m (msl), whereas a combination of no convectively driven vertical heat transport and subsidence resulted in stable conditions throughout the entire column of the boundary layer over the lake surface. A very shallow conduction inversion was present just above the now-colder lake surface.

Figures 7 and 8 show the model-predicted inflow depth and inland penetration along the Wisconsin-Illinois border in comparison to Doppler sodar and surface wind measurements. The inland penetration was resolved to within one model grid cell (4 km). Overall there was excellent agreement between the model and the observations at the Zion site, with the exception that the simulated lake breeze broke down and pushed offshore somewhat later than in the observations.

Detailed statistical model evaluation exercises, including comparisons to tracer studies, have been conducted are the subject of an extensive article that will appear in the peer reviewed literature.

4. CONCLUSIONS

While high ozone levels along the western shore of Lake Michigan have been previously associated with lake breezes, we find that even very shallow lake breezes can have substantial impact upon regional air quality. This implies that any numerical simulation of the regional photochemical air quality must be configured to resolve such low-level phenomena. In the case of RAMS, vertical grid nesting was implemented which allowed for the lowest model levels to be separated by only 10 m over the lake versus 50 m over land.

It would appear that at least in a qualitative way the basic meteorological features over the Lake Michigan region are well represented by RAMS for 16 July 1991. Though the lake-induced perturbation in the low-level wind field was subtle, and would be difficult to detect using the conventional observing network, nevertheless it had substantial influence on regional pollution transport, convective cloud dissipation and the thermal structure of the boundary layer over the lake.

8. ACKNOWLEDGMENTS

This research was supported by the Lake Michigan Air Directors Consortium (LADCO). In particular, we acknowledge the assistance of Michael Koerber. The Zion, IL Doppler sodar data were provided by the Illinois Department of Nuclear Safety with special credit to Thomas Bellinger for his enthusiastic assistance. MRC/ASTER staff playing a key role in this effort included Scot Randell, Greg Thompson, Cecil S. Keen and Liv Nordem.

9. REFERENCES

Haney, J.L., S.G. Douglas, L.R. Chinkin, D.R. Souten and C.S. Burton, 1989: Ozone air quality scoping study for the Lower Lake Michigan Air Quality Region. Final Report, Systems Application Inc., San Rafael, CA, SAISAPP-89/101, 197 pp.

Koerber, M., Kaleel, R., Pocalujka, L. and Bruss, L., 1991: An overview of the Lake Michigan Ozone Study. *Preprints, 7th Joint Conf. on Applications of Air Pollution Meteorology*, AMS/AWMA, New Orleans, pp. 260-263.

Lyons, W.A., 1973: The climatology and prediction of the Chicago lake breeze. *J. Appl. Meteor.*, **11**, 1259-1270.

Lyons, W.A. and Cole, H.S., 1976: Photochemical oxidant transport: mesoscale lake-breeze and synoptic-scale aspects, *J. Applied Meteorology*, **24**, 733-743.

Lyons, W.A., J.L. Eastman, R.A. Pielke, C.J. Tremback, D.A. Moon D.A. and N.R., Lincoln, 1991: The mesometeorology of ozone episodes in the lower Lake Michigan air quality region. *Proceedings, Paper 91-67.8, 84th Annual Meeting*, AWMA, Vancouver, 16 pp.

Lyons, W.A., R.A. Pielke, W.R. Cotton, M. Uliasz, C.J. Tremback, R.L. Walko and J.L. Eastman, 1993: The applications of new technologies to modeling mesoscale dispersion in coastal zones and complex terrain. in, Air Pollution, P. Zannetti et al., Eds., Elsevier Applied Science, London, pp. 35-85.

Lyons, W.A., R.A. Pielke, C.J. Tremback, R.L. Walko, D.A. Moon and C.S. Keen, 1994: Modeling the impacts of mesoscale vertical motions upon coastal zone air pollution dispersion. *Atmos. Environ.* (in press).

Pielke, R.A., Cotton, W.R., Walko, R.L., Tremback, C.J., Lyons, W.A., Grasso, L., Nicholls, M.E., Moran, M.D., Wesley, D.A., Lee, T.J. and Copeland, J.H., 1992: A comprehensive meteorological modeling system - RAMS. *Meteorol. and Atmospheric Physics*, **49**, 69-91.

Fig. 1. Number of exceedances of the 120 ppb federal ozone standard during the summers of 1987 and 1988.

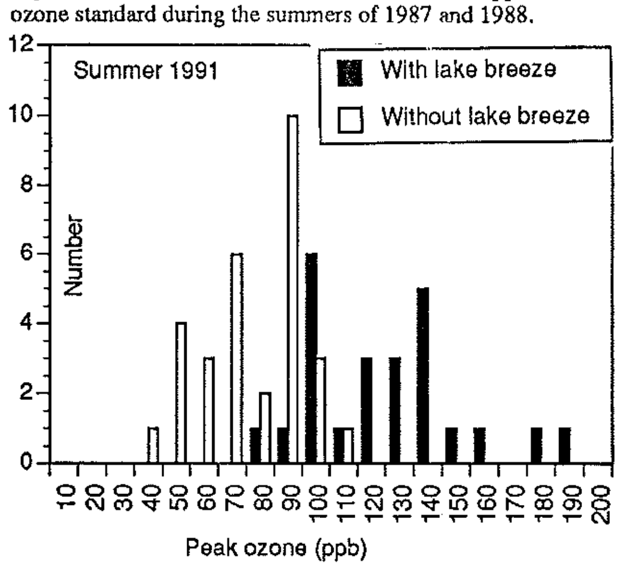

Fig. 2. Highest daily value of ozone recorded by monitors along the western shore of Lake Michigan as a function of whether there was or was not a lake breeze at Zion, IL.

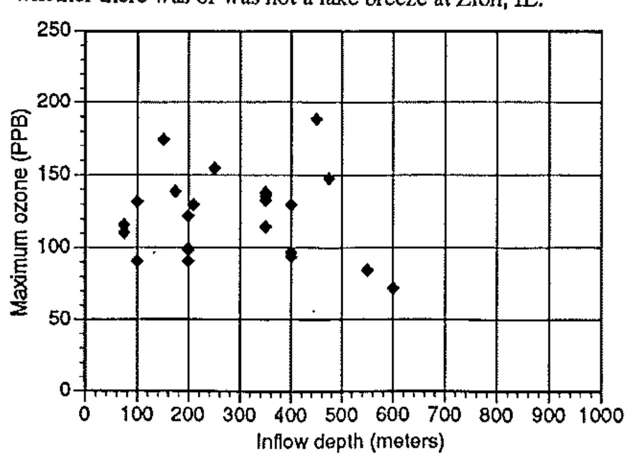

Fig. 3. Peak daily ozone readings along the west shore as a function of the maximum lake breeze inflow depth at Zion.

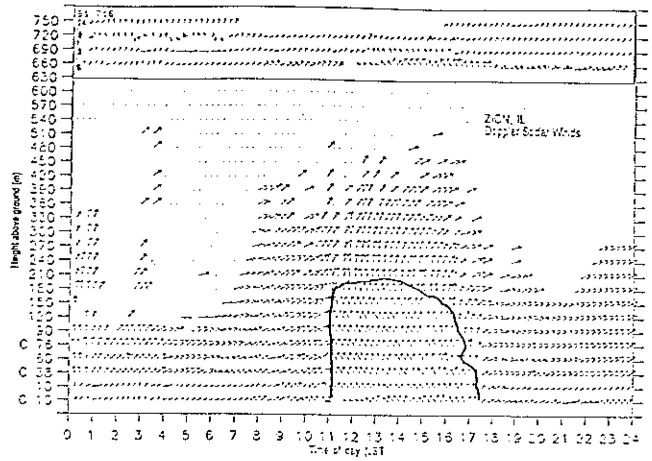

Fig. 4. Doppler sodar wind measurements at Zion, IL on 16 July 1991. The lake breeze inflow is indicated by the heavy line. Inset shows the 10 m wind vectors at anemometers in an east-west line inland from Zion and located at the shoreline, 3, 8 and 24 km.

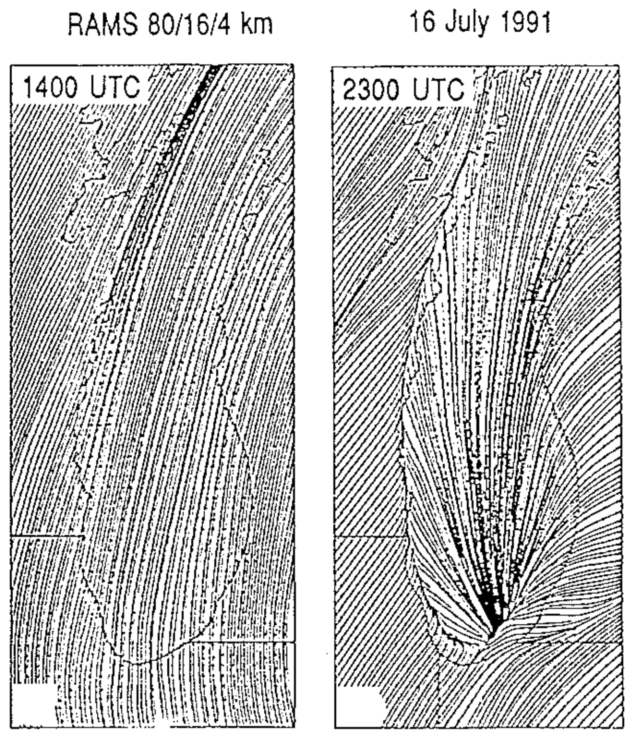

Fig. 5. RAMS-generated surface wind streamlines at 1400 UTC (left) and 2300 (UTC) on 16 July 1991. Note the minimal inland penetration of the lake breeze along the western shoreline north of Chicago.

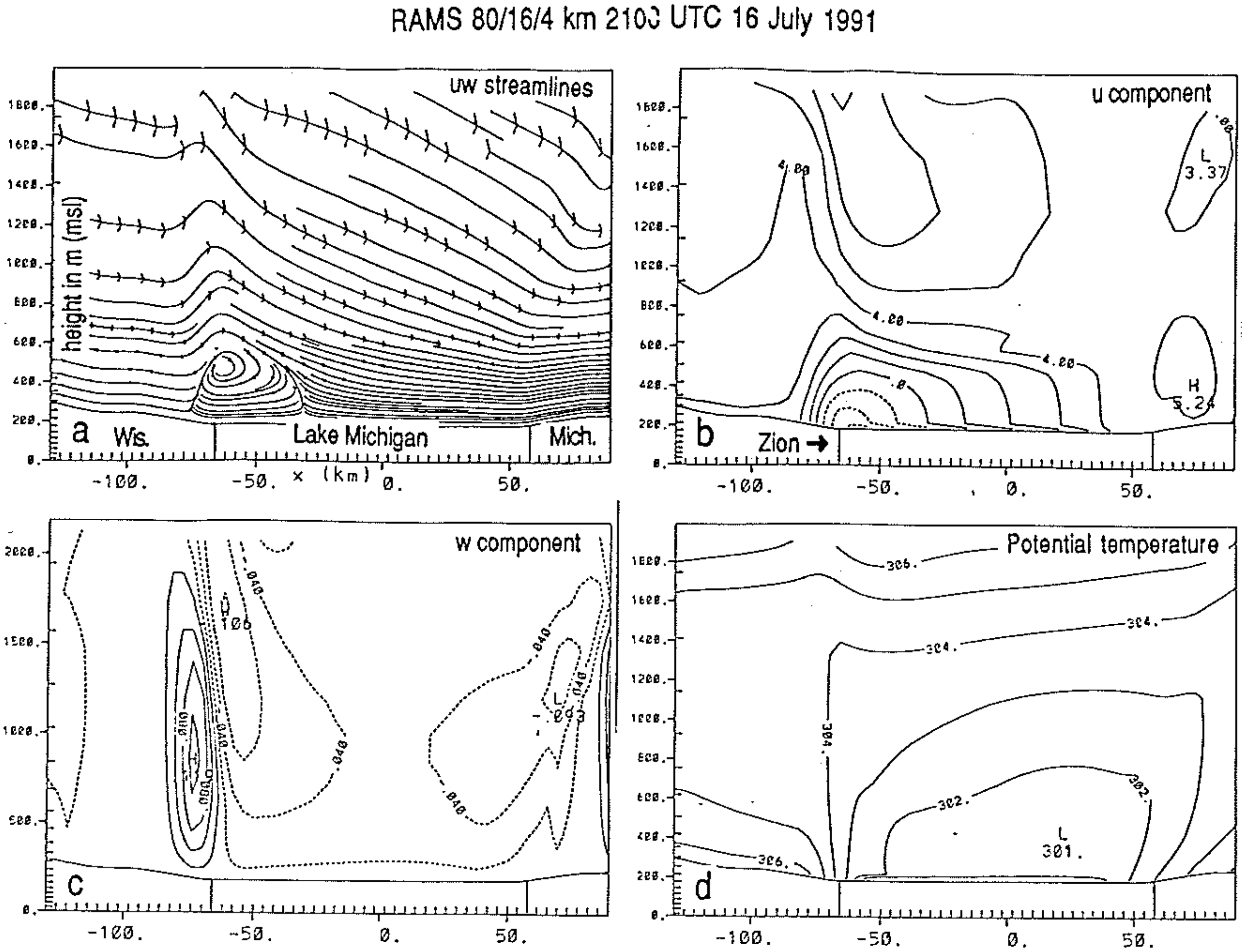

Fig. 6. RAMS-predicted fields at 2100 UTC 16 July 1991 in an east-west plane parallel to the Wisconsin-Illinois border showing (a) UW wind streamlines, (b) the U component of the wind (1 m s^{-1} isotachs with easterly flow shown as dashed lines), (c) vertical motions (4 cm s^{-1} isotachs with subsidence a dashed line), (d) potential temperature (1 K isotherms).

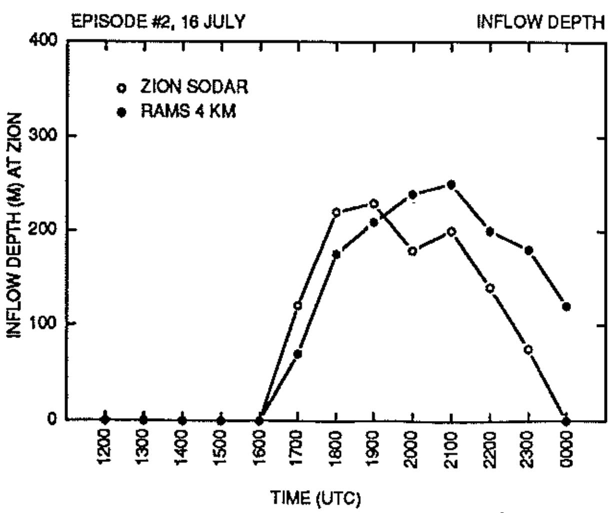

Fig. 7. RAMS-predicted lake breeze inflow depth at Zion, IL versus Doppler sodar observations.

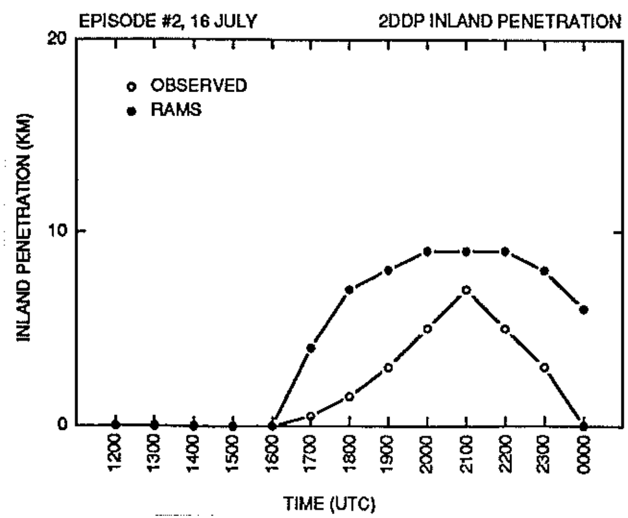

Fig. 8. RAMS-predicted lake breeze frontal inland penetration versus observations for 16 July 1991.