Ozone and Visibility Reduction in the Midwest: Evidence for Large-Scale Transport

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ABSTRACT

For June and July 1975, ozone concentrations throughout the Midwest showed a consistent dependence on wind direction with the highest concentrations associated with winds from the southeast. This systematic pattern suggests that large-scale transport rather than local sources control the general trends of the ozone level in the study area.

Ozone and meteorological data covering an episode period 29 July–2 August have been analyzed using weather maps, visibility reports, upper air soundings, trajectories and aircraft measurements to ascertain the scale of the ozone problem. Results indicate that the highest ozone concentrations occurred within regions of reported haze, and that these regions had definite bounds which could be followed over the country. Moreover, distinct areas of reported obscured sky formed in the vicinity of St. Louis and Pittsburgh which could be followed over thousands of kilometers reducing visibilities substantially even in upper Ontario. Trajectories indicate that adverse conditions occurred when stagnant air over the Ohio River valley was transported northward on the western half of a high pressure system. The haze region was preceded to the north and east by extremely high temperatures (>35°C). Vertical ozone profiles obtained by aircraft measurements show that ozone concentrations above the surface inversion in the haze remain quite high overnight, but above the subsidence inversion the ozone was low. It is suggested that the episode was due primarily to large-scale transport of ozone produced from precursors accumulated during the stagnant period over the eastern Midwest.

1. Introduction

In recent years ambient air ground-level ozone concentrations in excess of the federal standard of 0.08 ppm have been reported at numerous urban and rural sites in the United States during certain summer days. The spatial extent of the high O_3 episodes has come as somewhat of a surprise, especially in the Midwest, because of the volume of air involved relative to the size of the urbanized areas. In the last several years State and Federal air pollution control agencies have deployed a number of continuous, chemiluminescent ozone monitoring instruments with accuracy to a few parts per billion. Thus a considerable amount of accurate data is now available. While it is generally agreed that the high O_3 levels are due to photochemical reactions of nitrogen oxides, hydrocarbons and other precursors of both anthropogenic and natural origin, it has neither been clear what control strategies would be most effective nor how large a region must be controlled to alleviate the problem.

This paper is a case study of the O_3 concentrations in the Midwest during the 5-day period 29 July–2 August 1975. This period was selected primarily because the O_3 levels were high and the meteorological conditions were characteristic of other O_3 episodes during the summer. We have reviewed the available ozone monitoring data from the States of Illinois, Indiana, Michigan and Wisconsin during this period and have also analyzed available meteorological data. The variations of ozone concentrations with time and location in the Midwest are presented, and the meteorological conditions associated with the extensive regions of high ozone concentrations are analyzed.

During the study period, O_3 concentrations in excess of 0.20 ppm were measured in northern Illinois, southeastern Wisconsin and Detroit, Michigan. Concentrations in excess of 0.10 ppm were reported at virtually every reporting station in the study area. The location and names of the stations used in this paper are presented in Fig. 1. The locations of the three Weather Service radiosonde stations used for upper air soundings are also shown. Not shown are the many Weather Service stations from which visibility data were obtained. In addition to these data, information has been compiled from special instrumented flights conducted over southern Wisconsin by the Wisconsin Department of Natural Resources.

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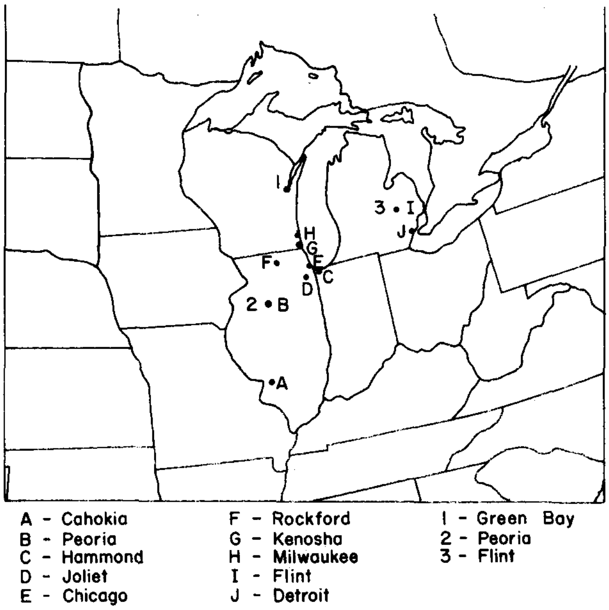

FIG. 1. Location of ozone monitors (letters) and weather service radiosonde stations (numbers) used in this paper.

2. Summer ozone versus wind direction

The air-mass dependence of ozone concentrations can be demonstrated in a crude sense by determining the average concentrations as a function of wind direction. This was done using the hourly ozone and wind direction data collected for June and July 1975 for six of the sites in the study where both ozone and wind information was available. The concentration distribution for 30° sectors is shown in Table 1. In general the highest concentrations of O_3 occurred with winds from the two sectors centered at 120° and 150° regardless of location with respect to local urban or industrial areas. Similar analyses for segregated daytime (0900–2000 LT) and nighttime (2100–0800) concentrations showed this pattern to hold over both periods as well as the total. This systematic pattern indicates that air mass rather than local sources control the basic trends of O_3 levels in the Midwest. The variations in magnitude of average O_3 concentrations from station to station are the result of a complex function of variables including nearness and strength of ozone-scavenging emissions, distance and direction from areas of precursor accumulation, and local meteorological processes such as lake breezes.

The directional dependence for the Midwest is also interesting because of other reports of wind direction relationships in adjoining regions. Chung (1977) has reported high O_3 from the south and southwest in southern Ontario. Coffey and Stasiuk (1975) have indicated that winds from the southwest bring the highest concentrations to New York State. Meanwhile, Spicer *et al.* (1976) have shown that high O_3 is associated with no particular wind direction in southwest Ohio. These results would suggest that the area around and including the eastern Midwest may be very critical to the concentrations of ozone measured through the Midwest, southern Ontario and parts of the northeast United States. This is a probable source region because of the high emission of ozone precursors (see Wolff and Lioy, 1977) and the relatively frequent periods of stagnation in that area.

The case study which follows typifies the episodes of high ozone concentrations measured in the Midwest during the summer of 1975.

3. Synoptic conditions for the case study

The weather pattern during this period was dominated by a large high pressure system centered over the Mid-Atlantic States. The air flow was initially stagnant during the study period, but became east to southeasterly by the second day. Fig. 2 shows the surface pressure pattern at 2000 GMT (1500 CDT) for each day of the period. Surface pressure remained high in the four-state region through 1 August. On the fifth day, an upper level wave moving from the west destroyed the support for the high, and the surface system weakened and moved eastward. A cold front accompanying the upper level wave produced precipitation and clouds from west to east in advance of the front during the fourth and fifth day.

Also shown in Fig. 2 are the areas which reported temperatures greater than 35°C (95°F). The significance of the movement of these "hot" areas will be discussed later. Not visible, but present through the period, is a stationary low pressure system over the

TABLE 1. Average ozone concentration (ppb) as a function of wind direction during June and July 1975. (The maximum concentration is italicized).

	Wind direction (deg)											
Site	030	060	090	120	150	180	210	240	270	300	330	360
Milwaukee	37	35	44	*60*	50	43	47	38	36	32	28	22
Rockford	32	20	31	*58*	38	32	38	33	33	32	28	25
Joliet	14	14	33	*41*	30	25	22	20	28	30	20	11
Chicago	26	28	37	*41*	37	28	23	31	26	25	26	25
Detroit	37	35	36	*62*	*62*	52	49	43	41	43	32	35
Flint	19	24	16	28	*39*	29	25	17	13	22	18	28

Gulf States which produced precipitation and cloudiness to the south of the area in study. The southeasterly flow remained through the area until the frontal system passage caused a wind shift to the northwest.

4. Haze regions and ozone

A region of reduced visibility was associated with the high pressure system. The reported haze (visibility $\leqslant 6$ mi) region (RHR), as established from the hourly reports of the U. S. Weather Service, had definite spatial dimensions and could be traced through the period. In Fig. 3, the RHR is shown for each day at 2000 GMT. The hatched areas are areas of reported obscured sky (typically, visibility $\leqslant 3$ mi).

Selected wind trajectories originating at St. Louis, Chicago, Cincinnati and Pittsburgh are also shown on Fig. 3 for the period. The trajectories are computed from observed wind data for the lowest 1000 m of the atmosphere using a scheme developed by Heffter *et al.* (1975). Trajectories start at 0000 GMT on the day in question (1900 CDT the previous day) and each vector represents a time increment of 24 h. On the second day, in addition to that day's trajectories, the 24–48 h trajectory for the first day is shown to indicate the approximate location of the previous day's air mass. The third day shows the trajectories for 0–24 h for that day, 24–48 h for 30 July and 48–72 h for 29 July. The fourth and fifth days show trajectories responsible for movement of the RHR.

On 29 July, the RHR was confined along the Ohio River valley, and there was very little movement of the air mass in the region as indicated by the short, looping trajectories. By 30 July, the southeasterly flow was established in the Midwest, while flow in the Pittsburgh area remained rather stagnant. The proximity of the two trajectories for St. Louis, Chicago and Cincinnati demonstrate the previous day's stagnation. These trajectories infer a long period of pollutant loading into a relatively small volume of air on the first day of the study period. On 31 July, the trajectories for the previous two days for Cincinnati, as well as the Chicago 24 h trajectory, were located over northern Illinois and southern Wisconsin. It will be seen later that this was a day of very high ozone concentrations in this area. The previous day's trajectories for Chicago were located in the upper Great Lakes areas and the St. Louis trajectories showed rapid advection through Minnesota into Canada.

It is interesting to note the relationship between areas of obscured sky and the major urban and industrial centers. Obscured sky areas formed early in the period downwind of St. Louis on the 30th and then Pittsburgh on the 31st. The obscured sky reported in the St. Louis area on 30 July appears to have traveled into Iowa on 31 July, where it covers about half the state. By 1 August an area of obscured sky is centered over northern Lake Superior and, from trajectory analysis, would appear to be the same area advected from Iowa. The obscured sky over Pittsburgh grew northward on 1 August and another area formed northwest of Buffalo, N. Y. On 2 August the area grew dramatically and covered the region from western New York to eastern

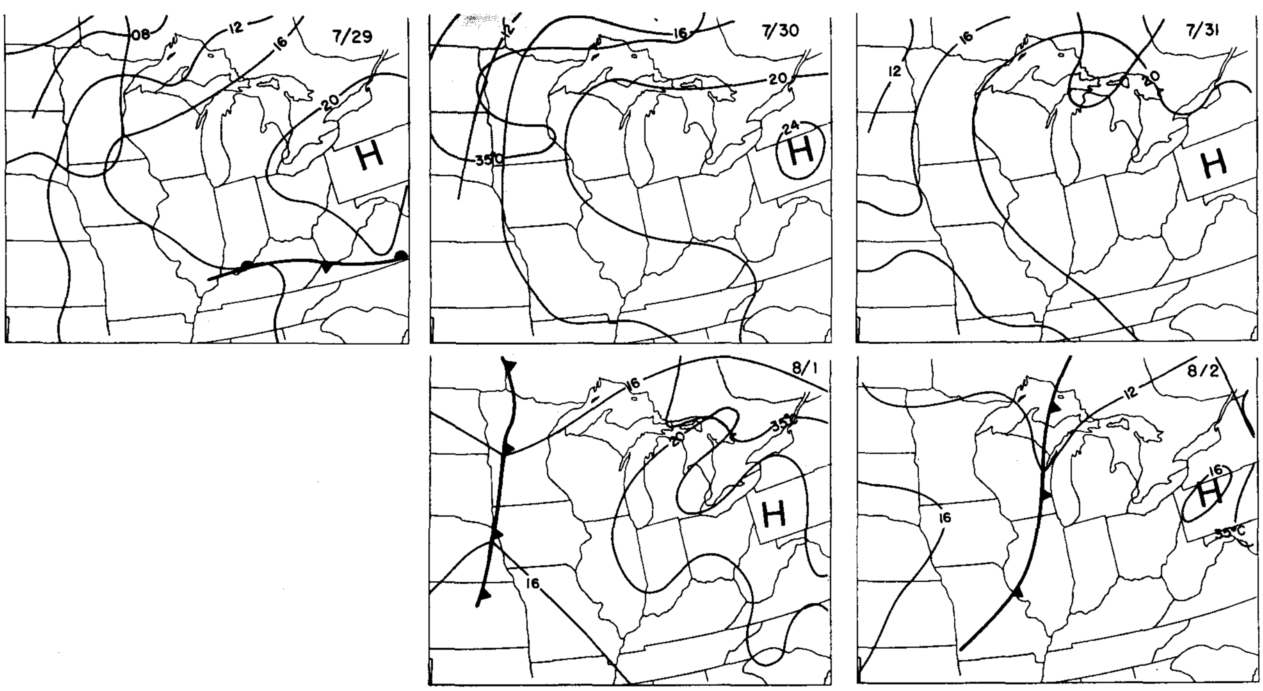

Fig. 2. Synoptic weather patterns at 2000 GMT from 29 July–2 August 1975. Hatched areas are regions of surface temperature $\geqslant 35°C$.

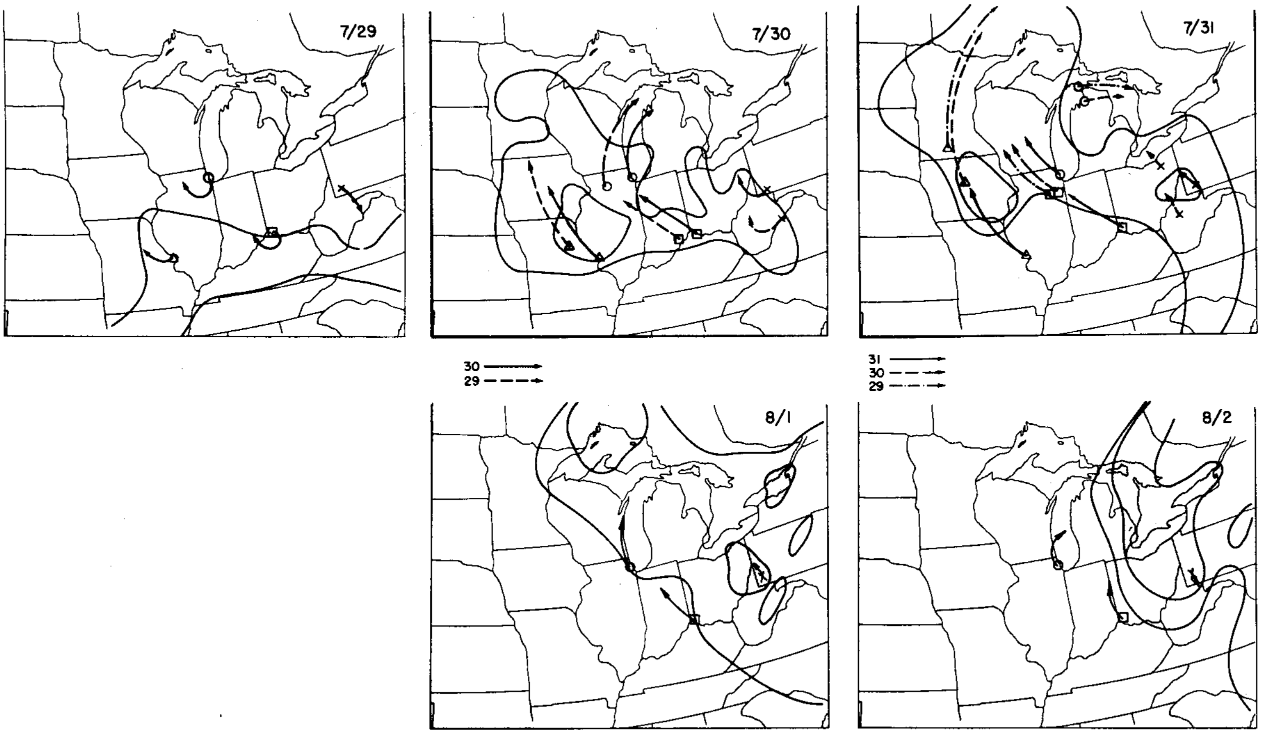

FIG. 3. Bounds of regions of reported haze at 2000 GMT for 29 July–2 August. Hatched areas are areas of reported obscured sky. Vectors represent 24 h trajectories terminating at 1800 CDT on the day shown as diagnosed from observed wind data. Trajectories originating in Chicago are designated by circles, in St. Louis by triangles, in Cincinnati by squares, and in Pittsburgh by crosses.

Michigan. This increase may be due to the accumulation of emissions from the industrial and urban sources in the area into an area of already low visibility. Haze was also reported behind the cold front, but this was scattered and appeared to be associated with the rain and fog accompanying the front. Only nonprecipitation haze is outlined in Fig. 3.

The relationship of the RHR to the areas of very high surface temperatures, shown in Fig. 2, is also of interest. Inspection of Figs. 2 and 3 indicates that the "hot" regions and RHR did not overlap, but rather bordered on each other with the highest temperatures preceding the movement of the RHR. These "hot" regions appear to be due to strong solar heating and subsidence. Temperatures within the haze at 2000 GMT were slightly less than those in the hot areas which ranged between 30–35°C. This difference can probably be attributed to the attenuation of solar radiation by the haze.

Fig. 4 shows the time variation of ground level O_3 concentrations during the study period at 10 selected monitoring stations. A strong diurnal cycle is evident with concentrations lowest at night, peaking in the afternoon. The Cahokia site shows the smallest day-to-night change indicating lower emissions of O_3 scavenging pollutants in the vicinity of that receptor. Nighttime fluctuations in concentration at rural stations during ozone episodes are thought to be a function of the concentrations of ozone scavengers in the stable surface layer, the concentration of ozone in the remnant daytime layer above the surface layer, and the intensity of vertical mixing (see Samson, 1977).

Maximum O_3 concentrations throughout the Midwest showed a marked relationship with the RHR through the period. Inspection of trends at each station indicates that the highest concentrations occur when the station was within the RHR. While this pattern holds at all stations, urban and nonurban, the magnitude of the increase varies from location to location. Highest concentrations occurred in northern Illinois, southeastern Wisconsin, and Detroit, Michigan. In southeastern Wisconsin, these high concentrations occurred with winds off Lake Michigan and may, in part, be due to mesoscale lake breeze transport as suggested by Lyons and Cole (1976). However, judging from the trajectories and the spatial extent of the episode, it would appear that large-scale transport carrying O_3 and precursors over the lake from more distant sources was the dominant mechanism in this case. Interestingly the maximum concentration at Rockford exceeded that at Kenosha and Milwaukee on 31 July and this difference can probably be attributed to upwind precursor emissions in the Chicago area. Assuming that the maximum concentration of about 0.15 ppm O_3 at Kenosha represents the regional "background" coming across the lake from distant sources, the contribution from the Chicago area would be a net gain of about 0.05 ppm at 150 km downwind.

The sites are listed roughly in the order that the RHR occurred, with Cahokia having its maximum concentration for the period on the first day and Detroit on the fourth. The maximum concentration at Rockford occurred on 31 July when direct transport from the Chicago area was the likely cause of the peak judging the trajectories shown in Fig. 3. The Rockford concentration dropped significantly the next day and visibility improved as clouds moved into the area and the wind shifted more to the south.

5. Boundary-layer temperature structure

The vertical temperature structure obtained over the study period from the radiosonde stations at Green Bay, Peoria, and Flint, indicated the RHR was a well-mixed air mass during the day capped by an inversion between 1 and 2 km. The 1200 GMT soundings (0700 CDT) in the RHR indicated strong radiational inversions at the surface ~400 m in depth. Correspondingly, many of the wind profiles at this time showed a moderate wind maximum just above the surface inversion. At Peoria the maximum on the morning of 31 July was ~9 m s^{-1} from 150° at a height of about 600 m. The thermal decoupling and increased wind speed at night would be expected to produce a very efficient ozone transport mechanism. On the other hand, however, the main mechanism for destruction of remnant ozone above the surface inversion at night is probably mixing into the inversion from above. The mixing would be enhanced by the increase in wind sheer at the top of the inversion. Thus, O_3 concentrations in the remnant layer would be expected to decrease during the night as a function of the O_3 scavenging concentrations in the surface inversion and the degree of vertical mixing.

The strong degree of daytime mixing in the boundary layer of the high ozone region can be demonstrated by observing the vertical profiles of both temperature and ozone. Fig. 5 shows these profiles as collected from a light aircraft on three different days at a rural location 20 mi north of Madison. The afternoon profile on 30 July shows very high concentration of 0.12–0.15 ppm throughout the boundary layer (dropping off rapidly above the inversion). The morning sounding on 31 July shows an overnight drop in total O_3 in the layer which has not been compensated by morning production. From Fig. 2 it is evident that this sounding represents the time when the trajectory from Chicago and two days' trajectories from the Ohio River valley are located in southern Wisconsin. By 1 August, the profile represents conditions on the edge of the RHR. Cloud cover had begun to form in the area and concentrations have been reduced through the layer.

6. Discussion

High ozone concentrations covering large extents during this case study can be explained phenomenologically by large-scale transport of ozone and ozone pre-

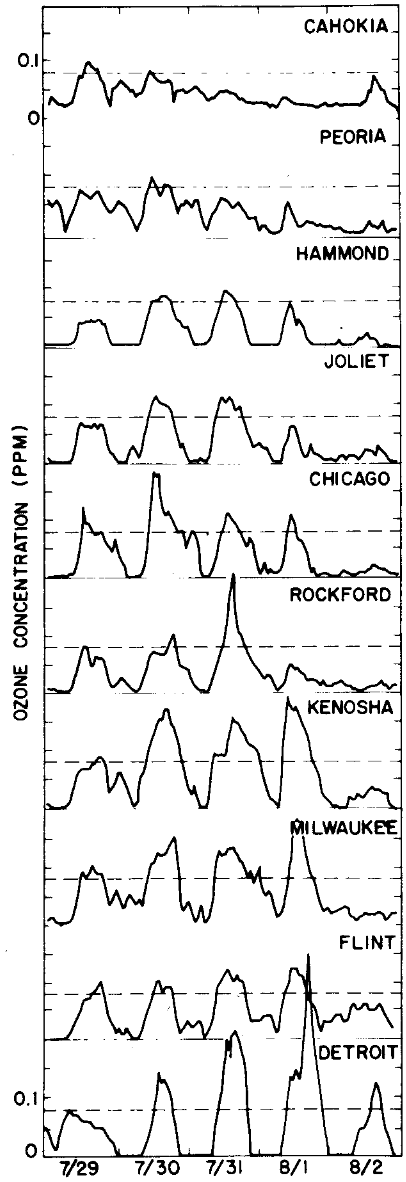

FIG. 4. Times series of ozone concentrations. Increments of concentration scale are 0.05 ppm with the dashed lines representing the Federal oxidant standard of 0.08 ppm.

cursors in the boundary layer of the atmosphere. The air mass which produced the high concentrations originated as a stagnant system in the Ohio River Valley. The ozone and ozone precursors were advected northward as the high pressure moved eastward.

This scenario for O_3 production and transport may have been typical for the summer of 1975. Analysis of O_3 concentrations as a function of wind direction for June and July 1975 at six Midwestern sites showed that the highest concentrations occurred with winds from the southeast quadrant. Meteorologically, these large-scale episodes are produced on the western half of a slow moving high pressure system because 1) the preceding stagnant conditions in the area of small pres-

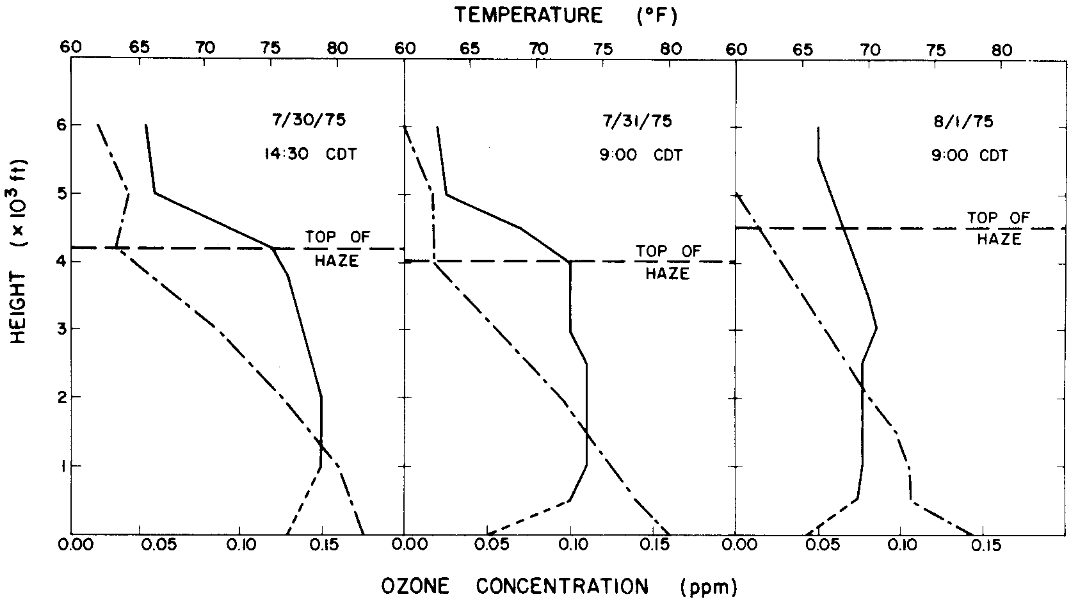

FIG. 5. Vertical ozone and temperature profiles measured from a light aircraft in the vicinity of Madison, Wisc. Solid lines show the ozone concentration profile and the dash-dot line the temperature profile.

sure gradients have made possible the accumulation of ozone precursors in a relatively small volume of air, 2) a well-mixed but capped boundary layer is present which serves to trap pollutants in a definite layer during the day, and 3) transport is aided by near geostrophic winds close to the surface inversion at night.

It is not possible to determine to what extent these results can be extended to other years. More work needs to be done to determine whether the location of stagnation affects the concentrations measured across the Midwest. It can be speculated that if high pressure tracked farther south during a summer, then the ozone in Wisconsin, for example, might be dominated by some other large source region and the directional dependence would change.

The correlation between ozone and haze in the Midwest has also recently been documented by Husar *et al.* (1976) and Wolff *et al.* (1976). This report suggests that urban and industrial areas may additionally be causing large areas of obscured sky with visibilities below 3 mi. These obscured sky regions appear to be able to move intact over thousands of kilometers causing degradation of visibility in areas far removed from urban or industrial sources.

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