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Long-Range Transport of Air Pollution: A Case Study, August 1970

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ABSTRACT—An air pollution episode during August 1970 over the central United States is examined. By use of surface visibilities and an 850-mb wind trajectory analysis, we observed the pollution to advance as much as 700 mi from the central midwest (source region) into the upper midwest and Great Plains (impact area). A large, nearly stationary high-pressure system over the source region allowed the pollution to accumulate beneath a mid-level subsidence inversion located generally near 700 mb. Southeasterly flow around the backside of the High and the northeasterly flow around a weak Low to the south advected the pollution into the impact area. At times, surface visibilities in parts of the impact area were restricted by haze to as little as 4 mi. Although particulate count data were meager, several stations recorded their highest particulate count of the year during the episode.

1. INTRODUCTION

During the past decade, the causes, distribution, and effects of air pollution have been investigated by many scientists in various fields. Most investigators of pollution problems have dealt with local pollution sources and local dispersion of these pollutants.

It is a known fact that under certain atmospheric conditions natural pollutants such as volcanic dust and forest fire smoke can be carried long distances from their source. Recent observations by Schaefer (1970) are proving this to be true of manmade pollution. He notes that pollution from the metropolitan area of New York City and northeastern New Jersey may be found in the upper Hudson Valley, in southeastern New England, or over the Atlantic Ocean. Commercial airline pilots have sighted pollution plumes hundreds of miles at sea. Bryson and Wendland (1970) have data supporting their belief that the distribution of particulate matter may be important on a global scale. In addition, a numerical simulation by Langlois and Kwok (1971) shows that carbon monoxide from North American and European sources may produce abnormally high concentrations over much of the Northern Hemisphere.

This paper reports a case of the transport of a large, hazy, smoky mass of air from the industralized midwest (source region) into the Great Plains States (impact area) that occurred during August of 1970. Meteorological visibilities from airways reporting stations were the primary tool used in identifying the general area over which this mass of air passed. Air quality measurements of suspended particulate mass from the areas so identified were then evaluated for some locations in an attempt to determine whether a significant increase occurred at locations within this hazy mass of air. Air parcel trajectories were used to verify that advection of air from the industralized areas of the midwest to the areas affected was in agreement with the motion derived from the visibility changes.

Since there is no analysis of the chemical constituents of the collected particulate mass, the individual pollutants that caused the observed restricted visibilities cannot be determined. Robinson and Robbins (1970*a*, 1970*b*), Kellogg et al. (1972) and others discuss the conversion of SO_2 and/or NO_x to aerosols in the atmosphere and give residence times of these particles as "several days." Thus, we recognize that, in addition to fly ash, soot, and dust, the pollution may have contained aerosols converted from gaseous material. This conversion process would also account for the reduction in concentration of gaseous material in the impact area with respect to the source region.

The results of this paper demonstrate, to the authors' satisfaction, that long-distance transport of manmade pollution is a reality, and that, under certain meteorological conditions, this pollution can retain significant concentrations. They further indicate that this pollution traveled a distance far exceeding the size of any established air pollution monitoring and control agency except that of the U.S. Environmental Protection Agency.

2. METHODS OF ANALYSIS

Impact Area and Source Region

The impact area is designated as the section of the Great Plains and upper midwest that reported unusually persistent periods of haze and reduced visibilities during the time period under study. A source region was located by tracking air parcels back in time from the impact area until they passed through a region where widespread industrial haze had occurred earlier. The source region and impact area are depicted in figure 1. The boundaries shown are not definitive but indicate the general confines of each zone.

The impact area is noted for small amounts of industrial pollution since the economy of the area depends mainly on

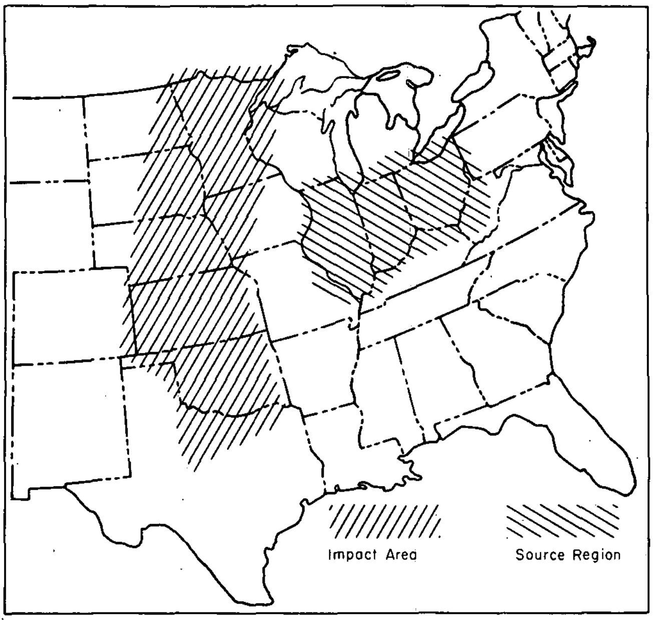

FIGURE 1.—Impact area and source region.

agriculture. In contrast, the source region is known to be densely populated and heavily industrialized so that during extended periods of light winds much of the source region lies under a heavy blanket of haze. That this haze has been increasing is shown by Miller et al. (1972).

Detecting Pollution by Reduced Visibilities

Specific criteria are required to determine whether or not significant air pollution is affecting an area. The most reliable method would be to consult the records of municipal air pollution control agencies in the hope of obtaining air quality measurements. Generally, however, only larger cities collect such data and the data examined during the course of this investigation show a low sampling frequency. For this reason, we decided to use a method of delineating the pollution area by observing areas of restricted visibility.

One of the most obvious indicators of air pollution is reduced surface visibilities. Several published articles have shown a strong correlation between reduced visibilities and suspended industrial pollutants. One of the best known and most widely referenced articles demonstrates a definite relationship between aerosol mass concentration and visibility (Charlson 1969). For this reason, visibility was the criterion used in this study for location of the boundaries of the air mass being studied. Air quality measurements from the impact area were later used to subjectively verify that the restriction to visibility in the air mass was due to pollution.

Some phases of the analysis were hampered by an inability to readily determine whether or not an area was in the air pollution cloud. One problem deals with the fact that visibility restrictions (other than precipitation) are only reported when the visibility is 6 mi or less. In air with low relative humidity ($<$70 percent), high concentrations of pollution may exist without restricting visibilities to 6 mi or less (Griggs 1972). Thus, it was necessary to devise some method for determining whether visibility was restricted below that which is normal for a given station on days with low pollution concentrations. Standard practice at weather stations is to report a maximum visibility equal to the distance from the weather observation site to some recognizable landmark. Therefore, some stations never report visibilities greater than 7 mi, while others report visibilities up to 30, 50, or even 100 mi. For August 1970, the maximum visibility reported at Huron, S. Dak., was 30 mi (and 30 mi was reported frequently); at International Falls, Minn., it was 7 mi.

The method used was to look for sudden reductions in visibility (not necessarily below 6 mi) within a group of neighboring stations. If a spatial pattern of reduced visibilities emerged that was consistent with the prior location of the air pollution cloud, then a new cloud position was drawn. Stations with a low maximum visibility, like International Falls, Minn., and within the group, could also be included in the cloud, despite their reporting maximum visibility.

Another problem was the presence of fog at various stations. When such difficulties were encountered, the station was considered to be in the cloud if it reported reduced visibilities with haze or smoke before the fog formed or after it dissipated or reported fog with relative humidity less than 80 percent. Also, stations reporting fog inside a well-defined pollution boundary were considered to be in the pollution cloud. A station not reporting reduced visibilities and haze or smoke before or after a period of fog was analyzed as being outside of the polluted air.

Trajectory Analysis

The trajectories were plotted using a method described by Saucier (1955, pp. 312–316). Their construction is based on a backward extrapolation in time using wind reports from 0000 and 1200 GMT. If a shift in the flow pattern was noticeable between the two standard observation times, an adjustment was made in the orientation of the streamline field and velocity field through which the air parcel was moving at 0600 and 1800 GMT. This allowed the trajectories to be constructed using time steps of 6 hr even though winds were available only every 12 hr.

Rawinsonde reports along the advection path indicate that winds from the surface layer up to approximately 800 mb were nearly constant with respect to both speed and direction. The lapse rates during the afternoon were nearly dry adiabatic with pronounced inversions between 850 and 700 mb at nearly every station. Since an air parcel would be under the influence of similar winds slightly above and below 850 mb, the 850-mb winds were used to compute the trajectories.

The validity of the trajectories used in this study depends on two factors. Of paramount importance is the assumption that the mean vertical motion along the trajectory through the 850-mb surface is negligible. The second assumption is that the trajectory is a reasonable approximation of the actual path traveled by the air

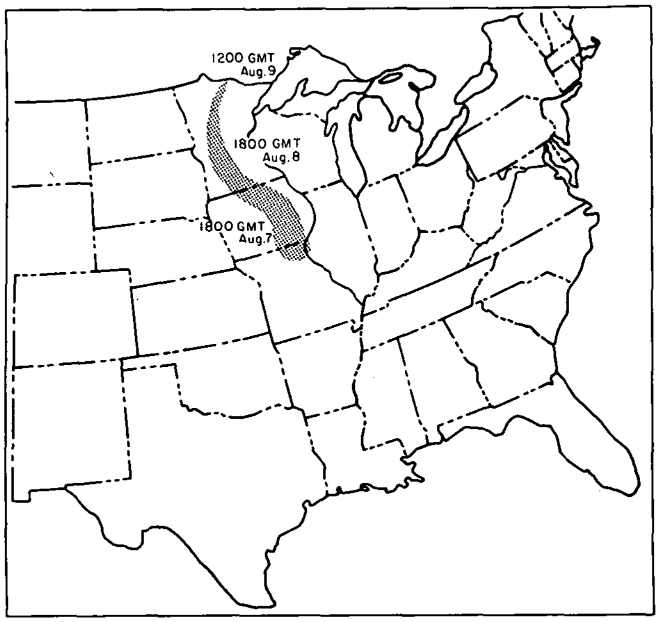

FIGURE 2.—Envelope of trajectories terminating at International Falls, Minn., at 1200 GMT, Aug. 9, 1970.

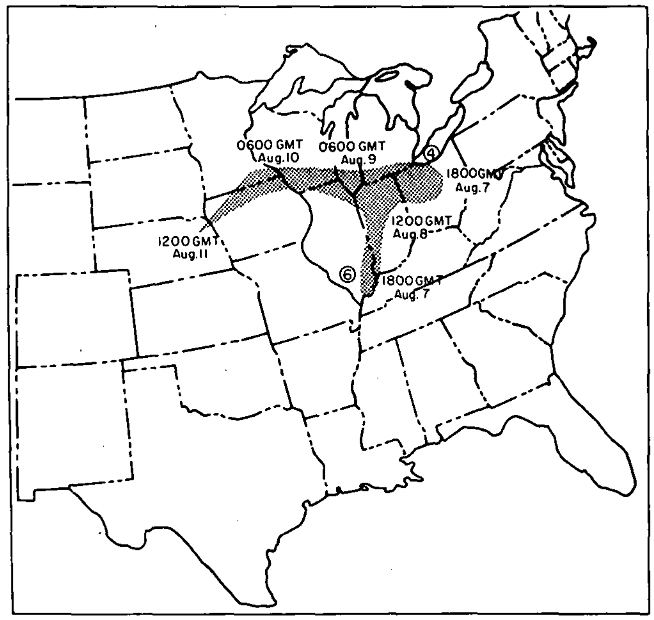

FIGURE 4.—Envelope of trajectories terminating at Norfolk, Nebr., at 1200 GMT, Aug. 11, 1970. The circled numbers represent the number of trajectories out of 10 in each branch.

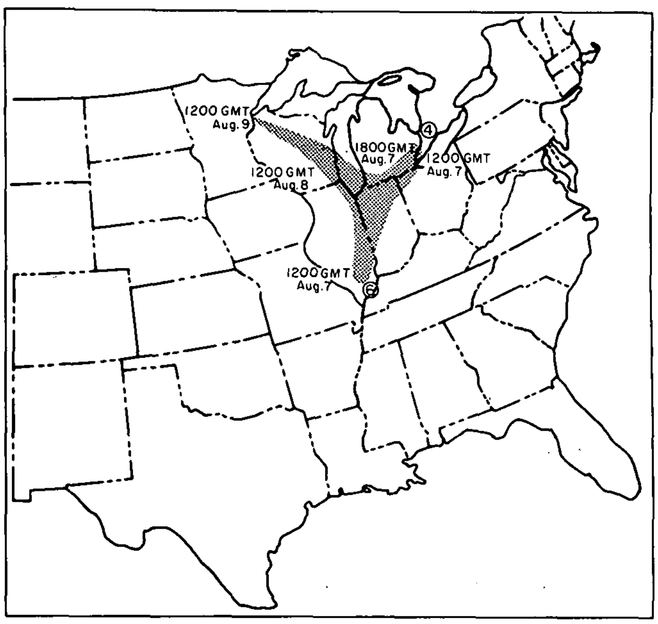

FIGURE 3.—Envelope of trajectories terminating at Duluth, Minn., at 1200 GMT, Aug. 9, 1970. The circled numbers represent the number of trajectories out of 10 contained in each branch.

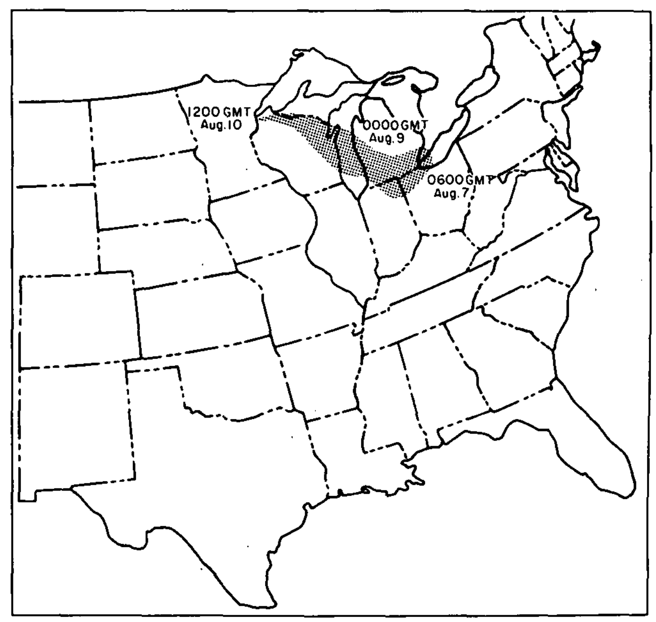

FIGURE 5.—Envelope of trajectories terminating at Duluth, Minn., at 1200 GMT, Aug. 10, 1970.

parcel under question. Having made the first assumption, it is important to realize that subjectivity plays a major role in the computation of the trajectories, especially in areas of low wind speeds. To obtain a qualitative idea of the variability attributed to the subjective analysis, we independently constructed 10 trajectories at four different times. Figures 2–5 show the areas of influence or "envelope" surrounding each group of 10 trajectories. The envelope is the smallest area containing all of the trajectories. The figures show that the trajectory envelopes generally broaden as they move away from the impact point. Thus, as would be expected, the uncertainty is cumulative with time.

The splitting of the trajectory envelopes seen in figures 3 and 4 are excellent examples of the ambiguity involved in the computation during periods of light winds. In these two instances, the air parcel being tracked was in or near an area of light and variable winds over the midwest. Such a wind field makes a distinct flow pattern difficult to detect. Lack of definition in the flow pattern is reflected

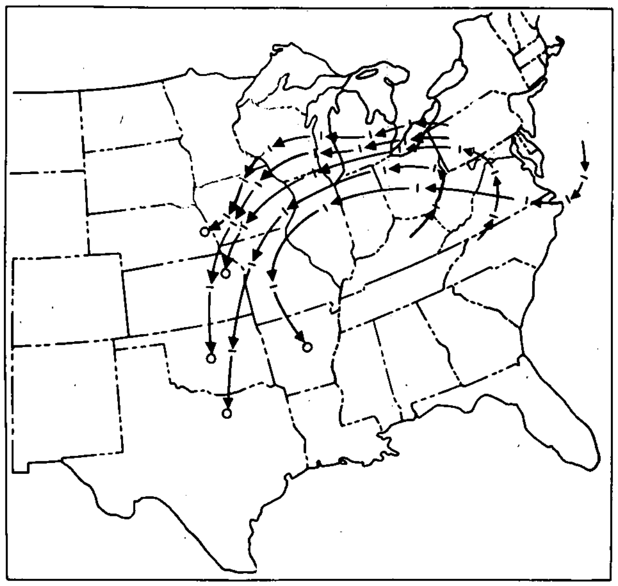

FIGURE 6.—Individual 850-mb trajectories for the period 0000 GMT, Aug. 8 –1200 GMT Aug. 11, 1970. Tick marks occur every 12 hr.

in the two branches of the trajectory envelope over the source region. In both figures, four of the trajectories ended in the northern branch and six in the southern branch. Figure 6 shows individual trajectories in the southern part of the impact region.

3. ADVECTION OF POLLUTED AIR

The major weather features usually associated with high air pollution concentrations have been summarized by Gross (1970). These meteorological conditions are:

1. A slow-moving anticyclone with a weak horizontal pressure gradient.
2. Light surface winds not exceeding 7 kt, and winds aloft not exceeding 25 kt.
3. Subsidence in the lower layers of the atmosphere. The resulting warming and drying effect produces stabilization and the formation of inversions that limit vertical mixing.

The source region and portions of the impact area were under the influence of such a system at various times of the August 1970 episode. From the analysis of available data, it appears that air pollution concentrations increased in the source region while a large anticyclone remained centered over the Great Lakes. The slow movement of air through the source region during this period permitted the buildup of large concentrations of pollution. This pollution-filled air was then advected into the impact area and remained largely undispersed. This occurred despite the fact that, in some portions of the impact area, surface wind speeds exceeded the criteria above by at least a factor of two. In addition, in the Oklahoma, Kansas, and north Texas region, the flow of air was characterized by circulation around a small cyclone rather than a circulation typical of the anticyclone in the source region and the northern portion of the impact area.

Surface Synoptic Conditions

A cold front that traveled across the midwest on Aug. 3 and 4, 1970, replaced a hazy, smoky air mass with a new continental polar high-pressure system accompanied by clean air and excellent visibilities. Industrial and manufacturing centers such as Cincinnati, Ohio, Cleveland, Ohio, and Detroit, Mich., reported no smog or haze for the 3d and 4th. However, on August 5, the high-pressure center ceased to move to the east and centered itself over the state of Michigan. The properties of this new air mass began to change with the addition of pollution from sources located in the source region. There was a significant decrease in visibility over the source region by August 5. The 1200-GMT surface map sequence from August 5 through August 12 is shown in figure 7. Figure 8 shows the position of the western edge of the area of low visibilities at 24-hr intervals beginning at 1800 GMT on August 5. The positions shown identify the western edge of the area that was experiencing reduced visibilities due to smoke and haze. The western edge of the area of reduced visibilities is referred to hereafter as the "pollution front." West of this pollution front, visibilities were reported as unrestricted during afternoon and evening hours with some stations reporting fog in the early morning hours.

From August 4 through August 7, a small stationary low-pressure center over eastern Colorado, western Kansas, and a frontal system from this low-pressure center through the southeastern part of the United States was a major feature of the synoptic pattern. On August 7, this Low started moving to the east and southeast along the front, gradually filling to become a general trough of low pressure along the front by August 11. The large high-pressure cell maintained itself through mid-August over the source region. Commencing on August 6, the pollution front drifted first to the west and to the north and then south to the position shown for August 10 (fig. 8). It is apparent that significant variations occurred in the speed of motion, and these can be readily related to the strength of flow, first around the anticyclone to the north and to the west and then around the cyclone which moved south and east. A lack of available data prevented identifying the southern edge of this pollution front on August 11 and later. However, one of the authors (Hagan) was in the Big Bend country of Texas during the period of August 12 and for several days following. He stated that visibilities in the Big Bend Park area, which are normally near 100 mi, were restricted to 15–20 mi by an abnormal haze condition not usually present in this area. From this, it is evident that this cloud of pollution did extend at least to the Rio Grande River in west Texas. Between August 14 and 17, a new cold front moved across both the source region and the impact area, so that by 1800 GMT on August 17 the entire midwest was under the influence of a fresh high-pressure system and the pollution cloud ceased to exist as an identifiable mass of air.

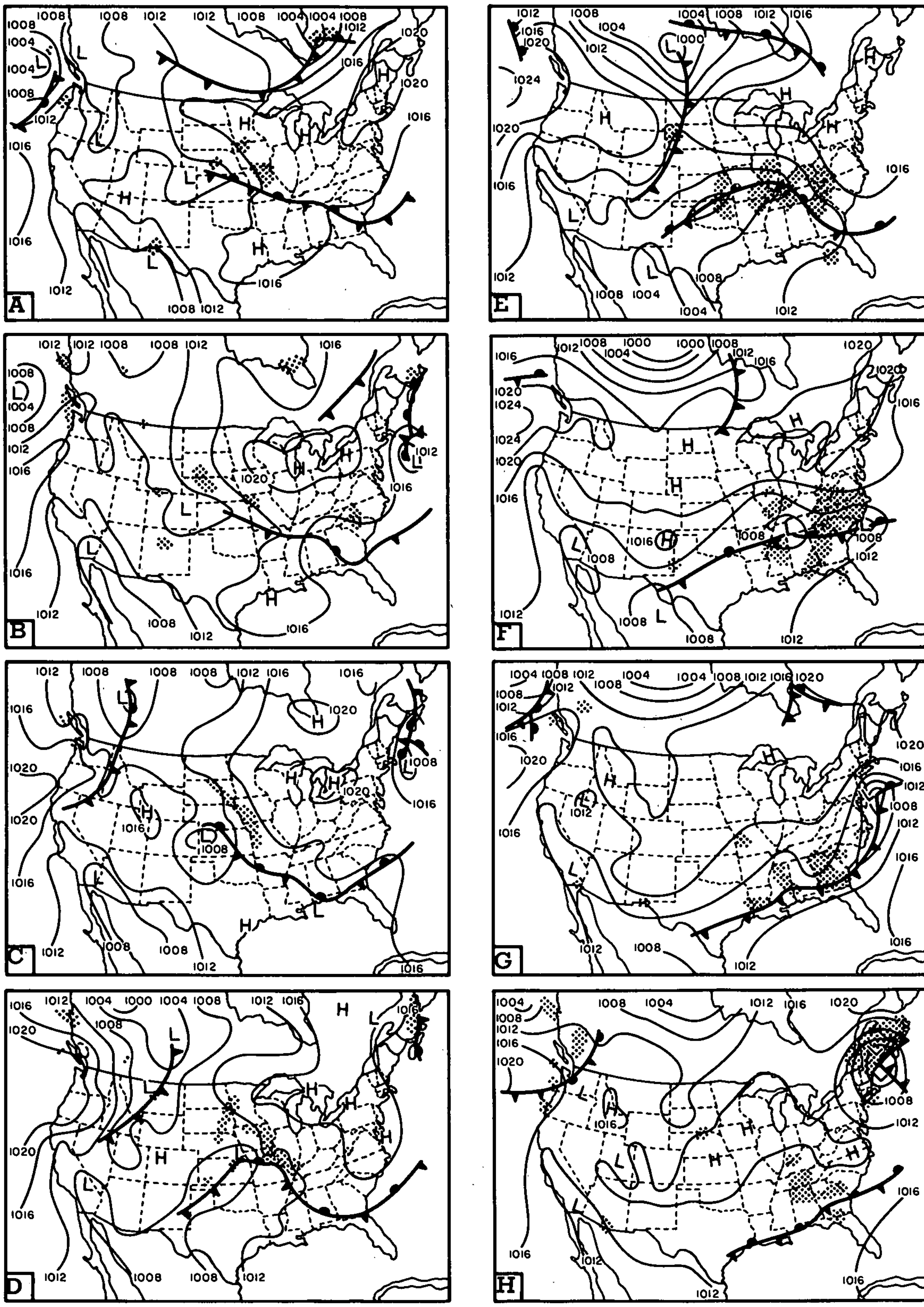

FIGURE 7.—Sea-level analyses for (A) Aug. 5, (B) Aug. 6, (C) Aug. 7, (D) Aug. 8, (E) Aug. 9, (F) Aug. 10, (G) Aug. 11, and (H) Aug. 12, 1970.

Vertical Temperature Profiles

Radiosonde data were plotted on skew-T, log P thermodynamic diagrams for representative stations in both the source region and the impact areas as shown in figures 9 and 10. Some startling similarities among these soundings are obvious. One of the more prominent features is the existence of one or more stable layers or inversions between

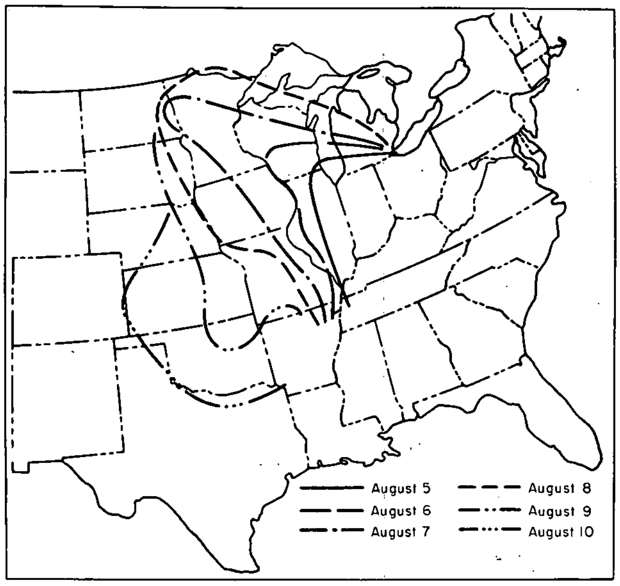

FIGURE 8.—Pollution front position at 24-hr intervals from 1800 GMT, Aug. 5–1800 GMT, Aug. 10, 1970.

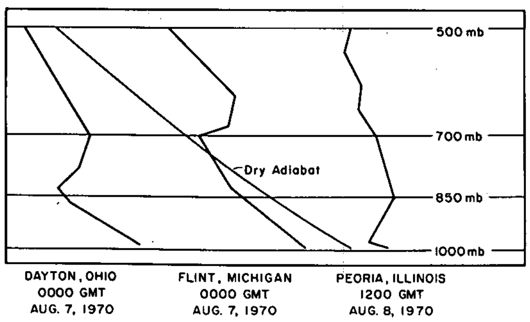

FIGURE 9.—Vertical temperature profiles typical of the source region.

850 and 500 or 600 mb on all soundings. In all cases, 0000 GMT soundings show the presence of a nearly dry adiabatic lapse rate up to the vicinity of 850 mb, indicating that mixing was active to 5,000 ft and above. Thus, conditions were conducive to the dispersion of surface pollution to at least the 850-mb level in the source region. Although some of the morning soundings reveal the existence of a low-level radiation inversion, this inversion disappeared in all cases during the afternoon and permitted any pollution which had concentrated below this inversion during the night to be mixed to considerably higher levels in the atmosphere. However, the pollution mixed upward to and through the 850-mb level was prevented from being dispersed to much higher altitudes by the presence of the stable air or inversion surfaces existing through the source region and the entire impact area. Very few pilot reports were available to the authors during the period of this study; nevertheless, those that were available indicated that the top of a haze layer was between 6,500 and 11,000 ft. This level corresponds quite well to the stable layer shown on the soundings.

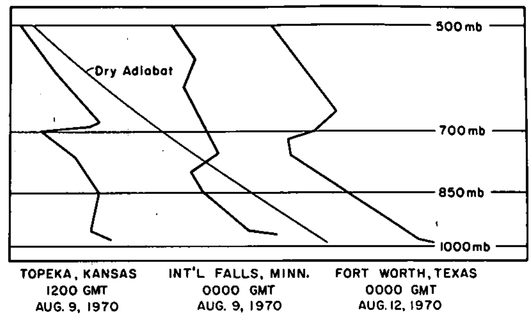

FIGURE 10.—Vertical temperature profiles typical of the impact area.

4. ANALYSIS OF AIR POLLUTION DATA

As a method of verifying that pollution was responsible for the reductions in visibility that were traced in this study, suspended particulate measurements were obtained where possible. One set of data employed consists of suspended particulate and gaseous pollutant measurements taken twice a month by stations of the National Air Surveillance Netwoık. Such a limited data coverage prevents any objective analysis from being accomplished. However, air pollution data were obtained from Tulsa, Okla., and Fort Worth and Dallas, Tex. The most desirable data are the type obtained from Fort Worth and Dallas. Fort Worth had an ensemble of 15 stations taking observations every third day and Dallas an ensemble of 19 stations taking data every other day. This provided a much shortened time period comparison of pollution concentrations than was possible in the northern portion of the impact area. All measurements used are 24-hr samples taken from high-volume samplers, and units are in micrograms per cubic meter.

Duluth, Minnesota

The suspended particulate measurement obtained during the episode was the highest value observed during 1970. Only three other observations taken during the year were greater than 100 $\mu g \cdot m^{-3}$. The maximum of 148 $\mu g \cdot m^{-3}$ was much above the average observed value of 73 $\mu g \cdot m^{-3}$.

Omaha, Nebraska

The only day during the episode that is contained in the data is August 10. The particulate measurement of 215 $\mu g \cdot m^{-3}$ observed on this day was one of the highest of the year and definitely higher than the average observed value of 132 $\mu g \cdot m^{-3}$.

Sioux Falls, South Dakota

Only 21 particulate observations were made during 1970. However, one reading was made during the episode; its value of 113 $\mu g \cdot m^{-3}$ was the second highest level measured. The average observed particulate count for the year was 70 $\mu g \cdot m^{-3}$.

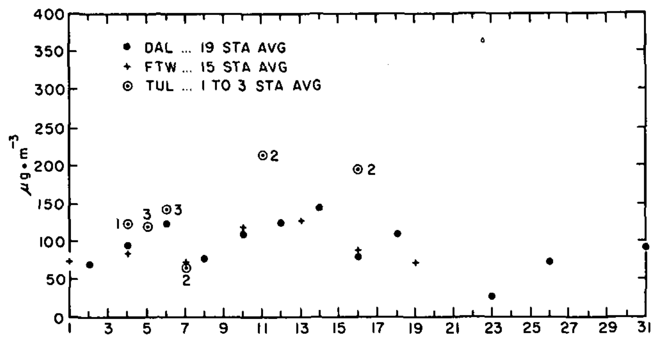

FIGURE 11.—Suspended particulate concentration as reported from Dallas and Fort Worth, Tex., and Tulsa, Okla., for August 1970. Numbers adjacent to Tulsa data are number of stations reporting for that day.

Superior, Wisconsin

The highest particulate measurement of the year was observed during the time of the episode. The average observed value for the year was 81 $\mu g \cdot m^{-3}$ as compared with the maximum observed value of 140 $\mu g \cdot m^{-3}$. Only three other values greater than 100 $\mu g \cdot m^{-3}$ were measured.

Tulsa, Oklahoma

Available Tulsa data varied from one to three stations on some days and no reports on other days (fig. 11). The numbers of reporting stations are plotted beside each Tulsa report. The values used are averages for the number of stations reporting. For example, on August 4, one station reported, and on August 11, two stations reported. On the 5th of August, three stations reported. Of particular interest from the Tulsa data is the fact that the pollution cloud entered Tulsa sometime August 9 after which time the prevailing winds were north to northeast. Since most of the local air pollution sources in Tulsa are located in the south and southwest portions of the city, it is significant that the maximum values reported for August occurred during this period.

Dallas and Fort Worth, Texas

As mentioned above, the Dallas and Fort Worth data in figure 11 are ensemble averages of 19 and 15 station measurements respectively. Such averages of high-volume filter measurements will significantly reduce the extremes of data that are so frequently associated with very localized effects on these samplers (e.g., an increase of an order of magnitude due to a spontaneous baseball game near the sampler location on a dry day). Fort Worth data for August 13 were described as "Anomalously high for Fort Worth" by Howell G. Grandburg, Director, Air Pollution Control, Fort Worth. Dallas data for August 14 yielded the highest ensemble average during a 30-day period.

5. SUMMARY AND CONCLUSIONS

From Aug. 5–11, 1970, a large mass of air characterized by heavy smoke and haze overspread parts of seven States in the upper midwest and the Great Plains (impact area). Trajectory analysis utilizing 850-mb winds showed that the air mass containing smoke and haze originated over the central midwest (source region). The validity of the trajectories used in this study is supported by the fact that most of the time there was very little wind shear in either speed or direction, from above and below the 850-mb surface. Therefore, if the parcel moved a short distance above or below 850 mb, the 850-mb winds would still be representative of the advecting winds.

Some of the trajectories passed through a light wind field with the result that their paths became ambiguous. Thus, one of the conditions most favorable for the development of high concentrations of air pollution simultaneously introduces siginficant difficulty in determining the accurate location of sources by the trajectory method.

Even with the very limited amount of air quality data available, above-average particulate concentrations were observed at several stations in the impact area with a timing that agreed with the arrival and passage over this area of the mass of smoky, hazy air. Although not conclusive proof, this does support the assumption that the high values of particulate concentrations owe their presence to air pollution brought into the area from exterior sources. Furthermore, this pollution had crossed regions far larger than those under the supervision and monitoring of any current air pollution control organization except the U.S. Environmental Protection Agency.

It would be possible to speculate on the primary synoptic features responsible for the long-range transport of this pollution. However, a simple enumeration without speculation as to what were the most important features appears to be the extent of reasonable conclusions at present. Specifically, a large, relatively stationary high-pressure system was centered over or near a source region, afternoon mixing depths permitted the vertical dispersion of pollution to heights near 5,000 ft, and the presence of a stable layer or inversion surface over the surface region and impact area confined further dispersion of this pollution to a layer approximately 10,000 ft thick. The broad horizontal extent of the air pollution cloud prevented horizontal dispersion from reducing concentrations through the mixing of clean and polluted air; rather an exchange of particles due to dispersion probably resulted in a smoothing of the concentration but not a significant reduction.

One of the major conclusions obtained from this study is that the prudent use of meteorological visibility constitutes a significant tool in the study of the motion and dispersion of large air pollution clouds.

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REFERENCES

Bryson, Reid A., and Wendland, Wayne M., "Climatic Effects of Atmospheric Pollution," *Global Effects of Environmental Pollution*, S. Fred Singer (Editor), a symposium organized by the American Association for the Advancement of Science, Dallas, Texas, December 26–27, 1968, Springer-Verlag, New York, **1970**, pp. 130–138

Charlson, Robert J., "Atmospheric Visibility Related to Aerosol Mass Concentration," *Environmental Science and Technology*, Vol. 3, No. 10, American Chemical Society, Washington, D.C., Oct. **1969**, pp. 913–918.

Griggs, M., "Relationship of Optical Observations to Aerosol Mass Loading," *Journal of the Air Pollution Control Association*, Vol. 22, No. 5, May **1972**, pp. 356–358.

Gross, Edward, "The National Air Pollution Potential Forecast Program," *ESSA Technical Memorandum* WBTM NMC 47, U.S. Department of Commerce, Washington, D.C., May **1970**, 28 pp.

Kellogg, William W., Cadle, Richard D., Allen, Eric R., Lazrus, Allan L., and Martell, Edward A., "The Sulfur Cycle," *Science*, Vol. 175, No. 4022, Feb. 11, **1972**, pp. 587–596.

Langlois, W. E., and H. C. W. Kwok, "Digital Simulation of the Global Transport of Carbon Monoxide," *IBM Journal of Research and Development*, Vol. 15, No. 1, San José, Calif., Jan. **1971**, pp. 3–9.

Miller, Marvin E., Canfield, Norman L., Ritter, Terry A., and Weaver, C. Richard, "Visibility Changes in Ohio, Kentucky, and Tennessee From 1962 to 1969," *Monthly Weather Review*, Vol. 100, No. 1, Jan **1972**, pp. 67–71.

Robinson, Elmer, and Robbins, Robert C., "Gaseous Sulfur Pollutants From Urban and Natural Sources," *Journal of the Air Pollution Control Association*, Vol. 20, No. 4, Apr. **1970***a*, pp. 233–235.

Robinson, Elmer, and Robbins, Robert C., "Gaseous Nitrogen Compound Pollutants From Urban and Natural Sources," *Journal of the Air Pollution Control Association*, Vol. 20, No. 5, May **1970***b*, pp. 303–306.

Saucier, Walter J., *Principles of Meteorological Analysis*, University of Chicago Press, Ill., **1955**, 438 pp.

Schaefer, Vincent, J., "The Inadvertent Modification of the Atmosphere by Air Pollution," *Global Effects of Environmental Pollution*, S. Fred Singer (Editor), a symposium organized by the American Association for the Advancement of Science, Dallas, Texas, December 26–27, 1968, Springer-Verlag, New York, N.Y., **1970**, pp. 158–174.

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