MEASUREMENTS OF ATMOSPHERIC TURBIDITY IN AN ARC DOWNWIND OF ST. LOUIS

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Introduction

Changes in the amount of particulate material suspended in the atmosphere, especially those particles in the size range from 0.1 to 1.0 μm in diameter, can alter significantly the amount and nature of solar irradiation at the surface of the earth. In a previous study,[1] it has been shown that during the summer near Chicago under cloudless skies over mixed rural and suburban surroundings, the direct-beam component, I, of solar irradiance can be reduced significantly by haze, but the diffuse irradiance, D, increases to compensate for 60 to 70% of the loss. Evidently, changes in the value of I, D, or a ratio of the two can be used as a measure of atmospheric turbidity. Thus, in addition to providing information on the possible alteration of mean levels of solar radiation, which can be important in studies of energy balances on a large scale, measurements of D and I provide an indirect indication of particulate concentration averaged vertically through the lower atmosphere, which can be useful in studies of air quality.

Of concern in the present study is the role of local sources of particulate material, or of material that has been transformed to particles, as compared to sources that are as far away as 1000 km (identified as a regional-scale distance). Obviously, there can be considerable confusion about the spatial distribution of increased atmospheric turbidity when radiation measurements at only a single location are studied. As experienced in the previous study,[1] wind directions associated with greater atmospheric turbidities can be partially correlated, perhaps by coincidence, with the directions from local sources. Radiation sensors should be located at several sites in order to remove the resulting ambiguities. Nevertheless, since the emphasis in the earlier and in the present study is on the large changes in atmospheric turbidity caused by haze, it seems unlikely that local sources could produce material sufficient in quantity to result in such changes, at most locations in the midwestern United States.

Measurements

The measurements of diffuse and direct solar irradiance were obtained with several silicon-cell pyranometers operating from July 15 to August 15, 1975, at several locations on an arc about 110 km northeast of St. Louis. The pyranometers are a small commercially-available* version of the one described by Kerr et al.[2] Since the silicon cell has a time response less than 0.001 s, the device can be shaded and unshaded quickly in order to separate the direct-beam component from the diffuse component. To accomplish this shading automatically, a thin blackened occulting strip was attached to a shaft driven by a small synchronous motor and aligned in the horizontal plane. In the field, the device was leveled and pointed roughly south. A photograph of the pyranometer and shading apparatus is shown in Figure 1; despite its simple construction, the shading mechanism has not failed during several months of continuous usage. Since the unit is a D-and-I-CHOpped pryanometer, the prefix "dicho-" is suggested, which is appropriate since "dicho" is also a Greek root meaning "in two" or "asunder." The pyranometer assembly in this paper will therefore be called the "dichopyranometer."

Samples of the output from the dichopyranometer are shown in Figures 2 and 3. The length of the spikes correspond to the direct irradiance, and the distance from the minima of the spikes to the zero level corresponds to the diffuse component. On a cloudless day, the position on the strip chart corresponding to solar noon is usually found easily by identification of the peak of the curve for total irradiance (D + I), which should occur at a point equidistant from the points at which the total is only slightly above the zero line. One of the main limitations of this scheme for measuring D and I is that rather tedious manual data reduction is required.

During the 1975 experiment, the occulting strips rotated at a speed of 0.2 rpm, counter to the movement of the sun across the sky. Thus, the spikes occurred at time intervals slightly less than 5 min. The width of the strips was about 1 mm wider than the diameter of the sensing element, so that only a small

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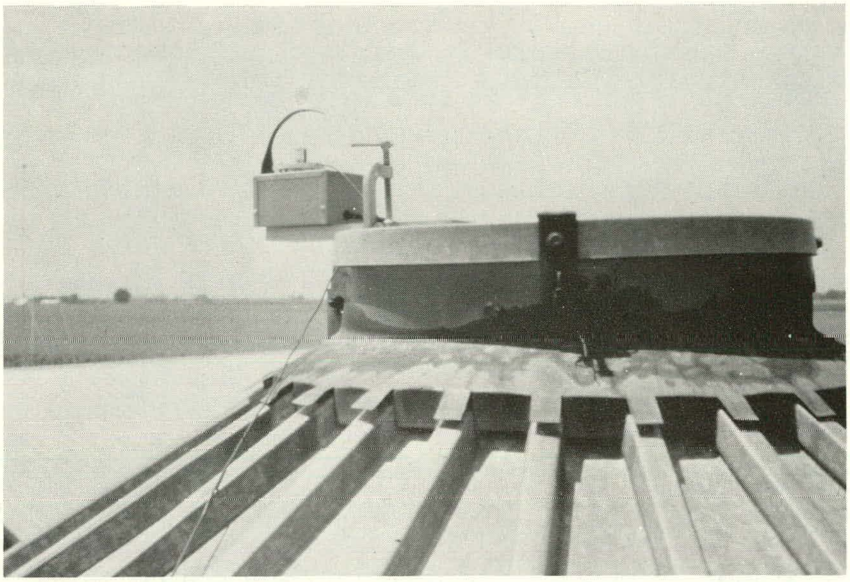

FIG. 1.--The dichopyranometer attached to the top of a farm structure at the main site (Sangamon, azimuth 24 deg) during 1975. The sensing element is the small cylinder, about 2.5 cm tall, under the curved occulting strip.

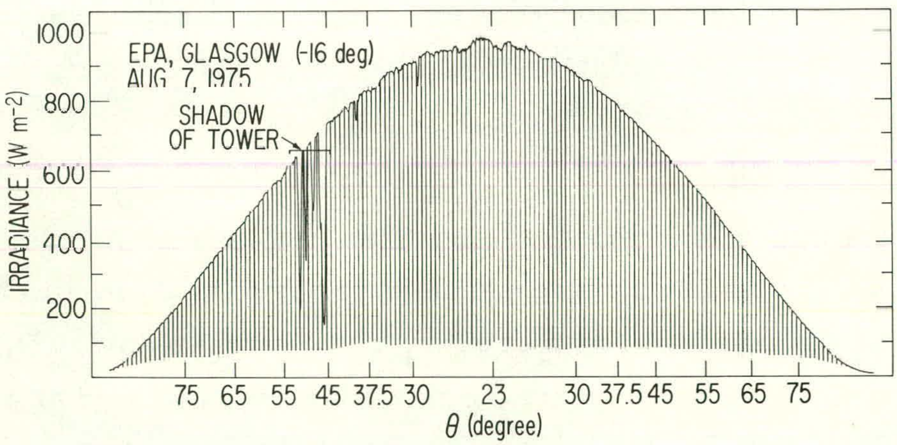

FIG. 2.--Strip-chart output of the dichopyranometer for most of one day when very little haze was present. Although labeled in terms of solar zenith angle, the horizontal axis actually corresponds to a constant value of time per unit length. Solar noon occurred when the zenith angle was about 23 deg.

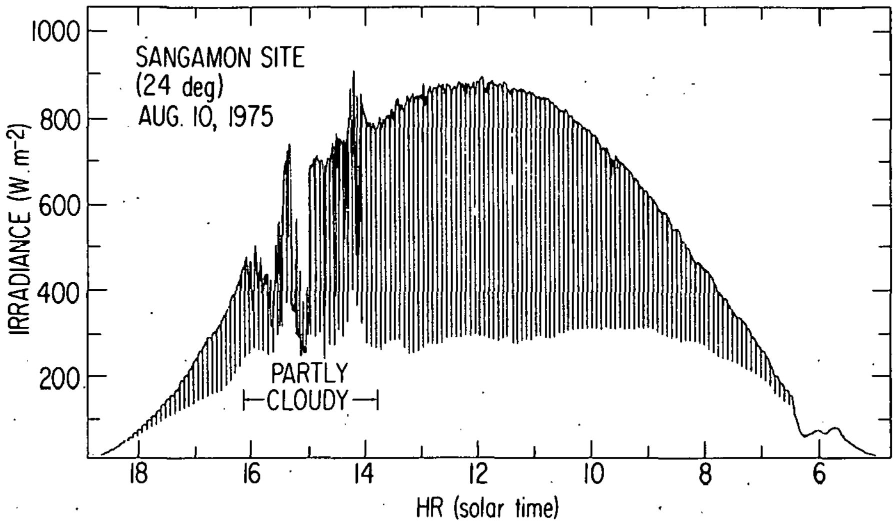

FIG. 3.--Strip-chart output of the dichopyranometer for a hazy day, with a few clouds present for part of the afternoon. The horizontal axis is labeled in terms of solar time.

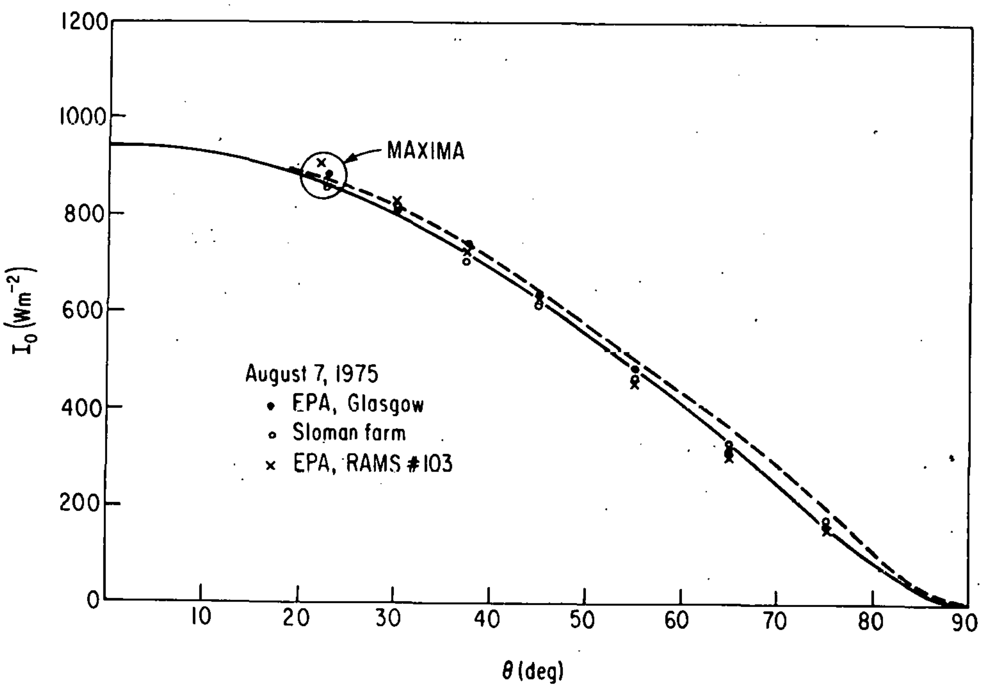

FIG. 4.--Values of I obtained when very little haze was present. The solid line is the empirical fit given by Eq. 2, and the dashed line is the empirical fit found earlier[1] for measurements made during fine days with an Eppley pyranometer of wide spectral response.

portion of the diffuse radiation was not allowed to reach the element, while ensuring that the disk of the sun was hidden for about 0.5 s, a time sufficient for the strip-chart recorder to respond fully to the sudden change in sensor output.

Method of Analysis

The radiation data were analyzed to find values of the extinction coefficient τ given by

$$\tau = m^{-1} \ln(I/I_0) \ , \qquad (1)$$

where m is the optical air mass, I is the incident direct-beam irradiance, and I_0 is the "reference" irradiance. It should be noted that since all these variables are strongly dependent on values of the angle θ of the sun from the zenith position, times corresponding to certain values of θ had to be determined accurately.

The values chosen for I_0 were those values of I obtained on August 7, a day on which the number of light-scattering particles in the atmosphere appeared to be exceptionally small. Figure 4 shows the values of I_0 obtained at three of the most widely separated locations (the raw data for one of the sites is shown in Figure 2). Surprisingly, the site only a few kilometers from downtown St. Louis (EPA, RAMS #103) yielded values of I_0 very near those obtained at the rural site, so that the measurement near the urban area seems to have escaped the effects of local plumes.

An empirical formula chosen to provide values of I_0 is

$$I_0 = (1100/m) \exp(-0.15\ m) \ , \qquad (2)$$

where the units are W/m^2. For comparison, an earlier determination[1] of I_0, found by use of Eppley "black-and-white" pyranometers, is also shown in Figure 4. While the values of I_0 obtained with the two instruments are in close agreement for small zenith angles, the outputs of the silicon-cell pyranometers seem to drop off more quickly with increasing θ than do those of the more standard Eppley pyranometers. Because of the nature of the spectral

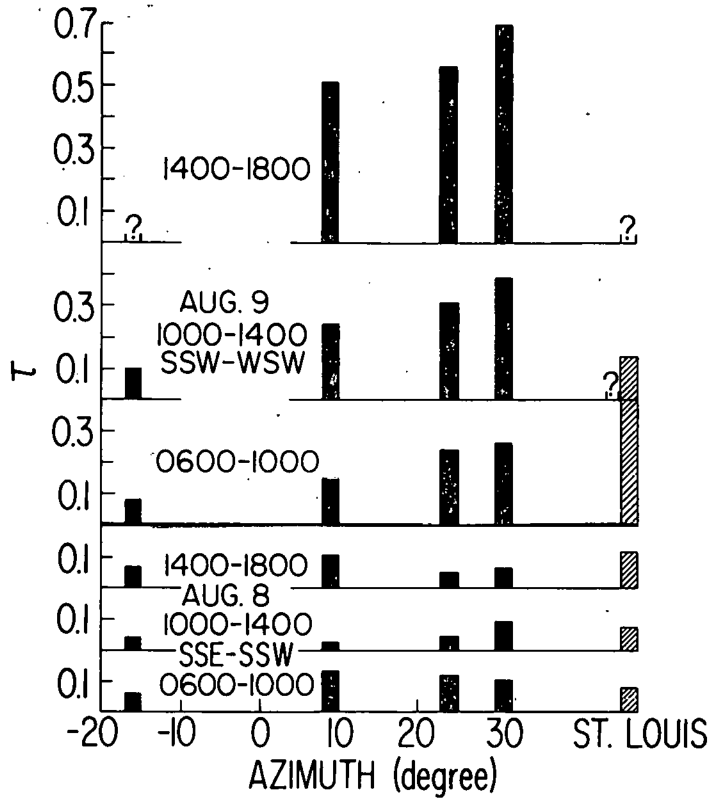

FIG. 5.--Measurements of turbidity on an arc 110 km from St. Louis, August 8 and 9. An azimuth of 0 deg corresponds to a direction directly north of the Gateway Arch. The directions listed are the surface wind directions measured at the Sangamon site located on an azimuth of 24 deg.

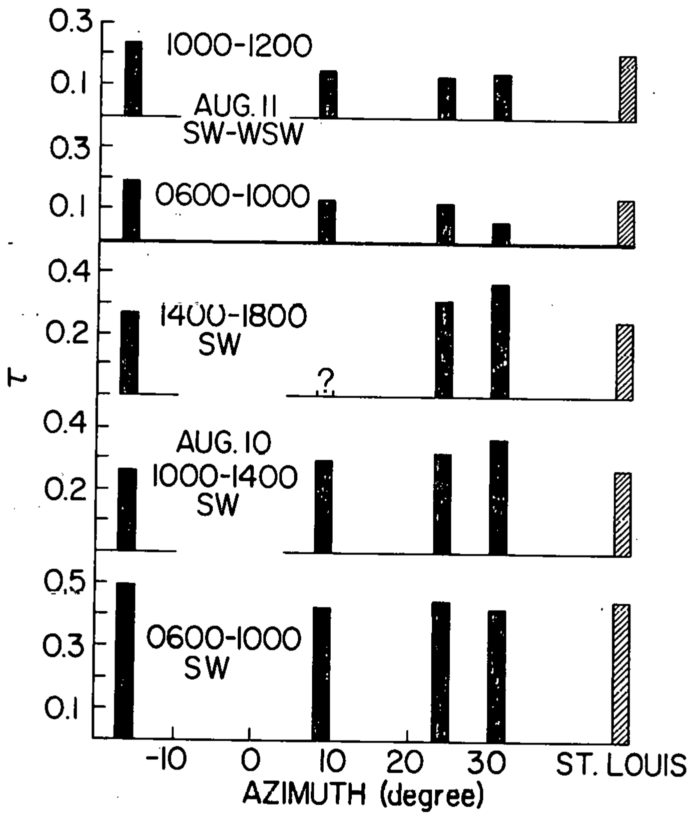

FIG. 6.--Measurements of turbidity August 10 and 11, similar to those shown in Fig. 5.

responses of the two instruments, this differing response to increasing optical air mass is not necessarily expected, and side-by-side comparisons of the two pyranometers are at present being performed at Argonne National Laboratory. Whatever the outcome of further tests, it is felt that the August 7 values of I_0 are a valid reference for use in Eq. 1. Although the very small response of the silicon cell to radiation of wavelengths greater than 1.1 μm can lead to minor errors in the measurement of solar radiation, for the present purpose of measuring atmospheric turbidity this is an advantage. This is because corrections for the variations of water vapor in the atmosphere, which change the amount of radiation received mostly in the near infrared, were not considered necessary.

Results

A preliminary analysis of the data obtained with use of the dichopyranometer indicates that large decreases in the direct-beam irradiance occurred during August 9–11 at several of the monitoring sites, four of which were located on an arc about 110 km from the Gateway Arch, Jefferson Expansion National Memorial, a well-known landmark in St. Louis. The four sites have azimuthal bearings east of north from the Arch of −16 deg (EPA, Glasgow), 9 deg (Waverly), 24 deg (Sangamon Co.), and 31 deg (Sloman farm). Figures 5 and 6 show the variation of four-hour averages of τ at these sites. Also shown are the turbidity measurements at the St. Louis site, which was actually in Illinois at RAMS site #103, located about 7 km northeast of the Gateway Arch in a suburban area.

The urban plume from St. Louis was expected to be about 20 deg wide and perhaps 10 to 20 deg greater in azimuth than the surface wind direction would indicate.[3] Thus, on August 8, the effects of the plume should have been detected at the site on the azimuthal bearing of 24 deg, but this is not evident in Figure 5. On August 9, the plume should have been east of, or at a greater azimuthal bearing than, the easternmost site (at 31 deg), and this may be supported by the existence of the slightly greater values of turbidity at that easternmost site. However, on August 10 and 11, similar southwesterly wind directions were not always associated with a maximum in turbidity at the easternmost site. Hence, it appears that the St. Louis plume did not consistently have a dominant role in causing atmospheric turbidity.

Conclusions

Examination of the turbidity data reveals that the urban plume was not a major factor in the large increases in atmospheric turbidity during the episode from August 8–11. The synoptic situation was typical of that necessary for the creation of regional-scale "blob" (e.g., see Refs. 4 and 5), which is linked with significant decreases in visibility and increases in concentrations of gaseous oxidants. A large high-pressure system had previously been over the midwest and had slowly drifted east and southeast, so that, on August 8–11, the center of the high-pressure system was mostly east of the St. Louis region. Hence, it appears that a regional-scale air-pollution episode probably caused the large increases in atmospheric turbidity. This finding supports a similar earlier contention concerning the large attenuations of solar radiation during the summer under cloudless skies in the midwest.[1]

Further work on this project involves a more complete description of the wind direction (and speed) through the mixed layer, in order to predict the location of the urban plume from St. Louis more accurately. Also, it would be informative to perform a back-trajectory analysis in order to determine the origins of the particles in the air mass, and it would be useful to determine the size of the "blob" by means of inspection of contours of visibilities reported in the midwest.

References

1. M. L. Wesely and R. C. Lipschutz, An experimental study of the effects of aerosols on diffuse and direct solar radiation received during the summer near Chicago, Atmos. Environ., in press.
2. J. P. Kerr, G. W. Thurtell, and C. B. Tanner, An integrating pyranometer for climatological observer stations and mesoscale networks, J. Appl. Meteorol. 6, 688–694 (1967).
3. P. L. Haagenson and A. L. Morris, Forecasting the behavior of the St. Louis, Missouri pollutant plume, J. Appl. Meteorol. 13, 901–909 (1974).

4. F. P. Hall, Jr., C. E. Duchon, L. E. Lee, and R. R. Hagan, Long-range transport of air pollution; A case study, August 1970, Mon. Weather Rev. 101, 404–411 (1973).
5. R. B. Husar, N. V. Gillani, J. D. Husar, C. C. Paley, and P. N. Turco, Long-range transport of pollutants observed through visibility contour maps, weather maps, and trajectory analysis, Third Symposium on Atmospheric Turbulence, Diffusion, and Air Quality, Raleigh, North Carolina, Oct. 19–22, 1976, American Meteorological Society, pp. 344–347 (1976).