Analysis of Urban-Rural Solar Radiation Data from St. Louis, Missouri

JAMES T. PETERSON

Air Resources Laboratories, NOAA, Boulder, CO 80303

THOMAS L. STOFFEL[1]

Solar Energy Research Institute, Golden, CO 80401

(Manuscript received 5 September 1979, in final form 5 December 1979)

ABSTRACT

The results of an analysis of simultaneous measurements of incident solar radiation from six locations in metropolitan St. Louis, Missouri are described. The measurements were taken continuously from September 1975 through March 1977 with pyranometers with all-wave and 395 and 695 nm cutoff filters. This report documents typical urban-rural variations of incident solar radiation.

Atmospheric pollutants over the center of metropolitan St. Louis reduced incident all-wave solar irradiation by ~3%. Under cloudless conditions, differences between urban and rural irradiation were ~4.5% during winter and 2% in summer. At two suburban sites, the irradiation depletion averaged 1 and 2% for summer and winter seasons, respectively. Under all conditions, the ratios between stations for the complete experiment were similar to those for cloud-free conditions.

Although the comparisons were stratified by wind direction and speed, visibility, time of day and day of the week, only wind direction had a significant effect on the interstation ratios. For cloudless days two suburban sites and a rural site north of the city received ~3.5% less radiation (compared to a control site) with south than north winds. Wind direction had an effect because pollutants were advected from major sources near the city center. The two urban sites exhibited only ~1% change due to north-south wind differences. The interstation comparisons for all days were also partitioned by wind direction. With north winds, the suburban and northern rural sites showed ~2–3% more irradiation (compared to a control site south of the city) on all days than on cloudless days for both the summer period and the complete experiment.

1. Introduction

Incident solar radiation was measured simultaneously at six locations in metropolitan St. Louis, Missouri as part of the Regional Air Pollution Study (RAPS) sponsored by the U.S. Environmental Protection Agency (EPA) (Schiermeier, 1978). The data presented herein were collected continuously from September 1975–March 1977 with pyranometers with all-wave and 395 and 695 nm cutoff filters. This report documents typical variations between urban and rural incident solar radiation from the RAPS measurements. The variations have such applications as identification and quantification of urban pollution effects, input to urban-scale diffusion models that rely on local energy budget formulations, design of solar energy systems, and design of space heating and cooling for buildings.

In reviews such as those by Landsberg (1956), Peterson[2] and Oke,[3] the older literature indicated that typical differences between urban and rural global irradiance[4] are 15–20%. However, particulate pollution levels over many U.S. cities have decreased as a result of pollution emission controls. Recent measurements during the Los Angeles smog season showed an average urban depletion of global irradiance of only 6–8%, although the average aerosol optical depth there is probably as great as that of any major U.S. city, except during air stagnation episodes (Peterson *et al.*, 1978). In an experiment

---

[1] Work performed while at Cooperative Institute for Research on Environmental Science, University of Colorado, Boulder.

[2] Peterson, J. T., 1969: The climate of cities: a survey of recent literature. Rep. No. AP-59, Nat. Air Poll. Control Assoc., Raleigh, NC, 48 pp. [NTIS PB 190260].

[3] Oke, T. R., 1974: Review of urban climatology 1968–1973. WMO Tech. Note No. 134, 132 pp.

[4] In this report we use the nomenclature recommended by Beckman *et al.* (1978). Radiant flux per unit area (e.g., instantaneous measurement by a pyranometer) is termed *irradiance* and has the units watts area^{-2}. The time integral of irradiance (radiant energy per unit area or quantity of radiation per unit area) is termed *irradiation* and has the units joules area^{-2}.

0021-8952/80/030275-09$06.25

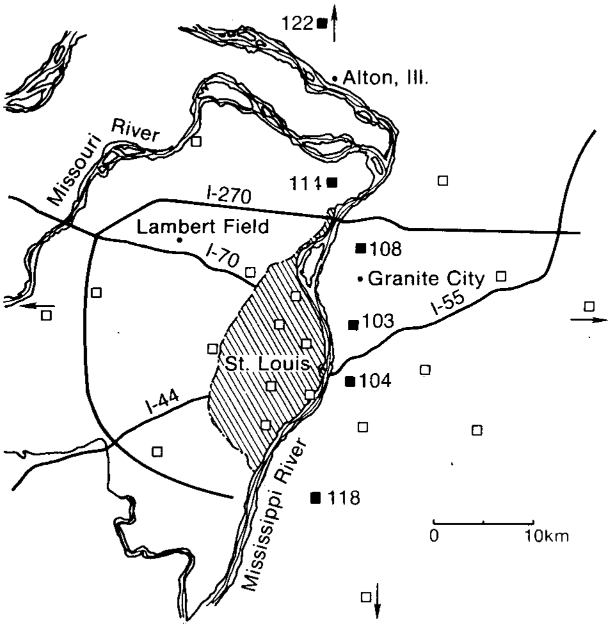

FIG. 1. Map of the St. Louis area. St. Louis city limits are hashed. Squares denote RAPS stations. Solid squares indicate stations with radiation measurements. The actual location of site 122 was ~18 km north of Alton.

preliminary to this, measurements on 11 summer days at St. Louis showed only a 2% urban irradiation decrease (Peterson and Flowers, 1977). White *et al.* (1978) did not find "any appreciable" urban-rural differences at St. Louis from two days of aircraft measurements at 150 m altitude.

Differences in radiation from the six metropolitan St. Louis locations are analyzed during cloudless periods to yield information on differences of the locations' pollutant concentrations. Radiation differences during all periods depend also on differences in cloudiness. We compare our results with those of the METROMEX program (Changnon *et al.*, 1971), which studied the distribution of precipitation, cloudiness, severe storms, etc., throughout metropolitan St. Louis. The interstation radiation differences are then stratified by wind speed and direction, visibility, time of day and day of the week. A detailed description of this project is available in an agency report by Peterson and Stoffel.[5]

2. Description of experiment

One component of RAPS was a 25-station monitoring network covering metropolitan St. Louis (Fig. 1). Radiometers were installed at six of the 25 sites and operated from autumn 1974 until 31 March 1977. The six sites were oriented approximately north-south so that cross sections over the metropolitan area could be obtained. The sites selected for radiation measurements had to have an unobstructed horizon; thus, no sites were established within the city center where tall buildings made this impossible.

Site 104, directly east of downtown St. Louis in East St. Louis, Illinois was the most urban setting and had the most nearby significant pollution sources. Site 103 was only a few kilometers northeast of downtown St. Louis and south of the heavy industry of Granite City, Illinois. Site 118 was located at the southern edge of the metropolitan area. Site 122 had the most rural location, some 15 km north of Alton, Illinois, in agricultural land. Sites 108 and 114 were classed as (low density) suburban.

Five radiometers were installed at each of sites 103, 114, 118 and 122. These included three Eppley[6] precision spectral pyranometers, a normal incidence pyrheliometer and a pyrgeometer. Pyranometers measured incident global (direct plus diffuse) irradiance on a horizontal surface. They had outer filter hemispheres to give the all-wave, >395 nm and >695 nm irradiance. At the other two sites pyranometers with clear and 395 nm cutoff wavelength filters were installed. Only data from the pyranometers are analyzed herein.

Each RAPS station consisted of a small, 3 m tall steel building. Pyranometers were located on a 2 m stand on the building roof. The outside of each pyranometer outer dome was continuously bathed with a flow of air to reduce the occurrence of dew and frost (Peterson *et al.*, 1973). A triangular meteorological tower was located on the northern side of each building, otherwise the horizons were generally unobstructed except for three utility poles at station 108. Station elevations above sea level were 103–127 m, 104–124 m, 108–130 m, 114–162 m, 118–155 m and 122–180 m. No corrections were made for these elevation differences. Routine maintenance of the sensors was provided by a contractor. Each site was usually visited twice a week.

Output voltages from each sensor were increased by about 200:1 with operational amplifiers. On-site data acquisition systems sampled the amplified signals twice per second, from which 1 min average values were obtained. This set of basic, 1 min values (cal cm^{-2} min^{-1}) was supplied to the authors by EPA from the RAPS archive along with hourly average wind speed and direction and ambient surface temperature and dew point at the six radiation sites.[7]

---

[5] Peterson, J. T., and T. L. Stoffel, 1979: Urban-rural solar radiation measurements in St. Louis, Missouri. NOAA Tech. Memo. ERL-ARL-76, Boulder, CO., 51 pp.

[6] Mention of company or product names should not be considered as endorsement by the U.S. Department of Commerce.

[7] Requests for RAPS data should be addressed to Director, Meteorology and Assessment Division, ESRL, Environmental Protection Agency, Research Triangle Park, NC 27711.

The EPA data are based on factory-supplied instrument calibration factors. Immediately after the experiment, pyranometers were recalibrated at the NOAA Solar Radiation Calibration Facility in Boulder using the absolute scale for all data presented here. All but three of the original and Boulder quartz pyranometer calibrations were within 1.3% of each other, showing good instrument stability with time. Transmission characteristics of the 695 nm cutoff filters were not satisfactory. Boulder-derived 695 nm calibration values showed significant within-day variability of more than 10% in some cases. Apparently, the opacity of the glass filter hemispheres became nonuniform and progressively worsened while the filters were exposed to the St. Louis environment. This added variability of the 695 nm cutoff data considerably reduced the accuracy of those measurements.

3. Data reduction and processing

The 1 min average irradiances supplied by EPA were processed in five steps. First, they were adjusted for instrument calibrations according to the Boulder intercomparisons. Second, to account for amplifier zero drift for each instrument, each day, average signals for the 2 h before morning daylight and after evening darkness were used to adjust the corresponding daily irradiances. Third, obviously erroneous data were deleted by visually inspecting plots of the 1 min values for each day. Fourth, the plots were used to determine when the instruments at site 108 were shaded from direct sun by three nearby utility poles, and data were reconstructed by linear interpolation between unaffected points. Finally, the 1 min data were combined to form hourly averages when no more than 5 values per hour were missing.

These hourly average irradiances form the basic data set for this report. Data begin at day of the year (DOY) 244 (1 September) 1975 (after installation of improved amplifiers) and continue through DOY 90 (31 March) 1977, when the RAPS network ended operation. Data are continuous except for the last 22 days of 1975. The data were processed and analyzed in blocks: DOY 244–343, 1975; DOY 1–100, 1976; DOY 101–200, 1976; DOY 201–300, 1976; DOY 301–366, 1976, DOY 1–90, 1977. During only a few of these day-of-year intervals did an instrument not achieve at least 80% valid hourly data. All instruments at site 114 had many missing data from DOY 256–297, 1975 because of a data acquisition malfunction. The quartz-pyranometer at site 114 from DOY 329, 1976 to DOY 65, 1977, and the 395 nm pyranometer at site 104 from DOY 301–348, 1976 were frequently inoperative due to amplifier problems.

This analysis emphasizes site-to-site differences during all periods and when all six sites had cloudless skies. The 1 min daily plots, along with official hourly meteorological observations were used to determine cloudless periods. For the 556 total days of data, 162 had at least 1 h between sunrise and sunset with clear skies at all sites; 1339 cloudless hours occurred on those days, an average of 8.3 h day^{-1}. The distribution of clear days and the average number of clear hours per day were consistent during the two years. During summer two to three times more clear hours occurred before noon than after because of convective clouds.

The primary technique used here for intersite comparisons involves the quantity of radiation per unit area (irradiation) at pairs of sites calculated day-by-day by summing over all hours when both sites had valid data. Comparing only two sites at a time minimized the effects of missing data. By summing the incident irradiance over a day, or over a group of days, those hours with greatest radiation have most influence on the site-to-site comparisons. Ratios of such irradiation at one site to another are referred to as "ratios of irradiation sums." An alternate technique uses intersite differences determined on an hourly basis. For each hour when at least five of six sites had valid data, the ratio of average irradiance at each location to that at site 118 was calculated. If a value for 118 is missing, site 122 is used. Site 118 is used as primary reference site because its data had the best quality of the two most rural sites. Data from 1 h after sunrise and before sunset were not analyzed. This technique of computing hourly, site-to-site ratios equally emphasized each hour of the day. Ratios computed by this method are referred to as "ratios of hourly irradiance."

4. Interstation differences—Cloudless periods

A summary of the interstation ratios is presented in Table 1 for all cloudless periods. The average ratio to the reference site (118) is given for each station and instrument by day-of-year intervals. These ratios of irradiation sums (i.e., sums of irradiance over the number of hours specified) were computed when each site together with 118 had valid data. The numbers in parentheses are the number of hours that comprise the ratio. For the quartz pyranometers, the grand average ratios are based on about 140 kJ cm^{-2} of measured irradiation.

A set of computations (not presented) identical to those in Table 1 was compiled using ratios of hourly irradiance (the two computation methods were described in the previous section). These results were similar to the Table 1 values. The quartz pyranometer complete experiment ratios for the two methods differ by no more than 0.004 for any site. For individual day-of-year intervals, like ratios between methods are somewhat greater but still small. This agreement is surprising since the hourly irradi-

TABLE 1. For cloudless periods only, summary of ratios of irradiation sums referenced to site 118. Numbers in parentheses give the hours of comparable measurements used to compute the ratios in each category. Interstation differences are summarized by station, instrument type and day-of-year intervals.

	Quartz pyranometers					395 nm pyranometers					695 nm pyranometers		
Day of year	103	104	108	114	122	103	104	108	114	122	103	114	122
244–343 (1975)	0.974	0.965	0.976	0.979	0.984	0.953	0.967	0.945	0.984	0.980	0.905	0.966	0.975
	(125)	(140)	(126)	(69)	(136)	(121)	(136)	(128)	(68)	(133)	(143)	(76)	(156)
1–100 (1976)	0.980	0.970	0.989	0.987	0.987	0.959	0.974	0.959	0.987	0.983	0.962	1.018	0.989
	(123)	(123)	(124)	(127)	(115)	(127)	(130)	(129)	(130)	(117)	(136)	(136)	(121)
101–200 (1976)	0.991	0.969	0.990	0.996	1.007	0.973	0.958	0.975	1.000	1.009	0.963	1.019	0.998
	(157)	(154)	(155)	(144)	(153)	(153)	(152)	(154)	(145)	(151)	(164)	(153)	(161)
201–300 (1976)	0.995	0.955	0.985	0.987	0.999	0.948	0.953	0.972	0.991	1.002	0.966	1.021	0.997
	(181)	(186)	(176)	(168)	(176)	(182)	(186)	(175)	(168)	(177)	(185)	(171)	(182)
301–366 (1976)	0.975	0.914	0.982	0.984	0.975	0.926	0.882	0.957	0.986	0.973	0.962	1.004	0.982
	(81)	(83)	(79)	(47)	(84)	(78)	(48)	(77)	(73)	(78)	(109)	(103)	(109)
1–90 (1977)	0.965	0.945	0.984	0.994	0.994	0.926	0.900	0.972	0.993	0.995	0.960	1.018	0.998
	(101)	(93)	(103)	(65)	(96)	(128)	(108)	(117)	(117)	(99)	(115)	(131)	(119)
Complete experiment	0.982	0.956	0.985	0.989	0.993	0.950	0.948	0.965	0.991	0.993	0.953	1.012	0.990
	(768)	(779)	(763)	(620)	(760)	(769)	(760)	(780)	(701)	(755)	(852)	(770)	(842)

ance analyses equally weight each hour of comparison data regardless of time of day, whereas the irradiation sums are weighted toward those (midday) hours with greatest energy.

The 395 nm cutoff and quartz filter pyranometers measured much the same energy. Their signals typically differed by ~5–7%, depending on cloudiness and solar zenith angle. Throughout the experiment, the quartz and 395 site-to-site ratios agreed well at some sites (114, 122) but differed significantly at others (103, 108). These discrepancies could have resulted from instrument or amplifier errors or from atmospheric phenomena. The 695 nm pyranometer site-to-site ratios for the complete experiment were not dissimilar from those of the other instruments. However, the large within-day variations of the 695 nm calibration factors (discussed in Section 3) were smoothed for these many-hour averages. The calibration variations precluded analyses over shorter time scales.

To estimate the average irradiation at each site relative to that at 118 for the complete experiment, the ratios for the quartz and 395 nm instruments were combined for each analysis method. Results are given in Table 2. Corresponding values of the two analysis methods are very close to one another. The ratios increase progressively from the most urban to most rural (most southern to the most northern nonreference) locations. If all values for sites 103 and 104 are combined, an average urban-rural irradiation depletion of 4% is obtained relative to reference site 118. Combining the two suburban sites yields a depletion of ~2%. The rural location to the north (122) had less than 1% less incident irradiation than 118. Much of the 122-118 difference can be explained by the natural winter north-south gradient of midlatitudes. Moreover, instrumental and other errors decrease the significance of these differences where the percentage depletions are small.

TABLE 2. For cloudless periods only, average ratios of irradiation at each site to irradiation at site 118, as obtained by two analysis methods separately for the complete experiment, summer, and winter for quartz and 395 nm pyranometers combined. Station order is from most urban (104) to most rural (122).

Analysis method Period	Station 104	Station 103	Station 108	Station 114	Station 122
Irradiation sums					
Complete experiment	0.952	0.966	0.975	0.990	0.993
Summer	0.959	0.977	0.981	0.994	1.004
Winter	0.931	0.955	0.974	0.989	0.985
Hourly irradiance					
Complete experiment	0.958	0.965	0.974	0.988	0.990
Summer	0.965	0.977	0.982	0.992	0.999
Winter	0.936	0.951	0.969	0.984	0.979

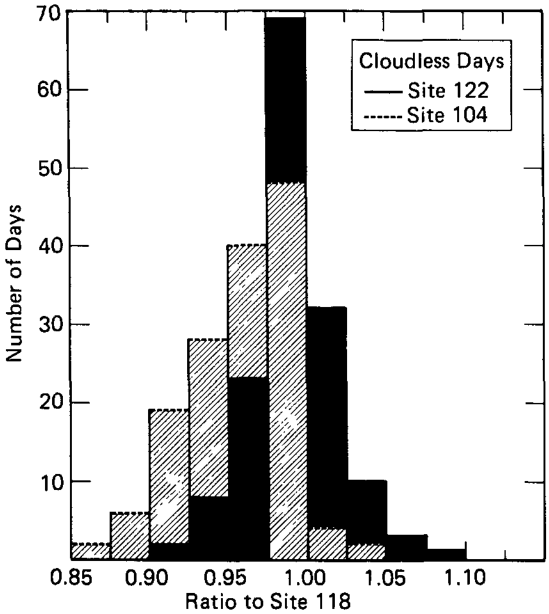

Fig. 2. Histograms showing distribution of ratios of daily irradiation at site 104 and 122 to that at site 118 for cloudless days during the complete experiment.

The Table 2 results show a progressive irradiance increase from urban to rural sites. This partly reflects the lack of strong pollution sources near any of the three northernmost sites. Had there been a site near the industrial complex east of Alton, an area of extensive aerosol emissions (Gatz, 1978), it might have shown as much depletion as the East St. Louis site.

The distributions of interstation ratios of daily irradiation at sites 104 and 122 to that at site 118 are shown in Fig. 2 for cloudless days during the complete experiment. Sites 104 and 118 highlight the urban-rural variability of incident irradiation. On only six days did the irradiation at site 104 exceed that at 118. The number of occurrences of 104-118 daily ratios steadily decreases for values < 1.0. In contrast, the 122-118 ratios have a sharp maximum in the 0.975–1.0 interval with similar distributions above and below that interval. The day-to-day variation of the interstation ratios is also indicated by the standard deviation about the complete experiment mean; at site 104 it was ~0.03, at site 103 ~0.02, and at the other three sites ~0.025.

A seasonal urban-rural effect is evident from Table 2 information. The summer data are from DOY 101–300, 1976; the winter statistics from DOY 1–100 and 301–366, 1976 and DOY 1–90, 1977. All sites had more radiative depletion, relative to 118, during winter than summer. This can be partly ascribed to the greater solar path length during winter which causes an effective increase in the optical depth of a given aerosol ensemble. Averaging the data from the two urban locations yields an overall urban-rural, cloudless-sky difference of ~3% during summer and 5.5% during winter. The two rural sites had nearly identical incident summer irradiation.

A natural north-south gradient of daily solar irradiation across the mid-western United States is evident in winter and annual climatological statistics (Baldwin, 1973). During summer this gradient is practically nil near St. Louis while the winter gradient is about 1% from sites 118 to 122 (0.6° latitude). Thus, more than half of the measured

Table 3. For all time periods, summary of ratios of irradiation sums referenced to site 118. Numbers in parentheses give the hours of comparable measurements used to compute the ratios in each category. Interstation differences are summarized by station, instrument type and day-of-year intervals.

	Quartz pyranometers					395 nm pyranometers					695 nm pyranometers		
Day of year	103	104	108	114	122	103	104	108	114	122	103	114	122
244–343 (1975)	0.968 (706)	0.969 (738)	0.972 (658)	0.952 (394)	0.975 (711)	0.945 (704)	0.966 (742)	0.940 (658)	0.948 (394)	0.969 (710)	0.923 (726)	0.953 (405)	0.981 (726)
1–100 (1976)	0.982 (729)	0.967 (766)	0.987 (728)	0.991 (731)	0.994 (623)	0.965 (684)	0.971 (769)	0.959 (722)	0.988 (740)	0.986 (655)	0.963 (703)	1.012 (708)	0.996 (632)
101–200 (1976)	0.971 (876)	0.964 (886)	0.996 (893)	0.996 (754)	1.025 (873)	0.954 (857)	0.964 (882)	0.977 (881)	0.993 (794)	1.025 (873)	0.968 (874)	1.014 (759)	1.026 (859)
201–300 (1976)	0.977 (945)	0.951 (976)	0.980 (844)	0.982 (853)	0.995 (936)	0.937 (943)	0.950 (956)	0.961 (864)	0.985 (848)	0.996 (939)	0.949 (956)	1.015 (820)	0.998 (927)
301–366 (1976)	0.956 (395)	0.920 (381)	0.965 (382)	0.968 (118)	0.965 (400)	0.920 (365)	0.885 (206)	0.936 (375)	0.977 (386)	0.965 (397)	0.956 (386)	1.000 (399)	0.973 (412)
1–90 (1977)	0.949 (694)	0.936 (744)	0.987 (714)	0.976 (483)	0.983 (700)	0.921 (657)	0.911 (672)	0.973 (705)	0.985 (802)	0.981 (704)	0.966 (698)	1.014 (807)	0.989 (709)
Complete experiment	0.970 (4345)	0.955 (4491)	0.984 (4219)	0.983 (3403)	0.995 (4243)	0.943 (4210)	0.951 (4227)	0.962 (4205)	0.984 (3964)	0.993 (4278)	0.954 (4343)	1.008 (3898)	0.998 (4265)

TABLE 4. For all time periods, average ratios of irradiation sums for the complete experiment, summer and winter at each site to those at site 118 for quartz and 395 nm pyranometers combined. Station order is from most urban (104) to most rural (122).

Period	Station 104	Station 103	Station 108	Station 114	Station 122
Complete experiment	0.953	0.957	0.973	0.984	0.994
Summer	0.957	0.960	0.979	0.989	1.010
Winter	0.941	0.951	0.971	0.985	0.981

118–122 wintertime radiative difference resulted from the natural latitudinal decrease.

5. Interstation differences—All periods

A summary of the interstation ratios of irradiation sums for all time periods is presented in Table 3. The values were computed identically with those in Table 1 (cloudless periods only), except for different time periods. The entries are average ratios of incident radiation for a site and instrument to the corresponding measurement at site 118 for the six day-of-year intervals.

Ratios of hourly irradiance were also computed for all time periods. However, these results cannot be directly compared to those in Table 3. For cloudy periods average hourly irradiance often differed widely between sites and the site-to-site ratio differed greatly from 1.0. This ratio is a statistic bounded on one side, i.e., it cannot be less than zero, but can be much greater than one. Thus, as the distance between sites increases with an increase in the variability of the hourly ratios, the average ratio of hourly irradiance increases.

For specific day-of-year intervals, about two-thirds of the corresponding entries in Tables 1 and 3 are within 1% of each other; for the complete experiment all but one pair have less than 1% separation. The Table 3 irradiation sums for the quartz and 395 nm pyranometers are combined in Table 4 and stratified for summer and winter periods. The irradiation sums for the three groupings are quite similar to the corresponding Table 2 (cloudless) results.

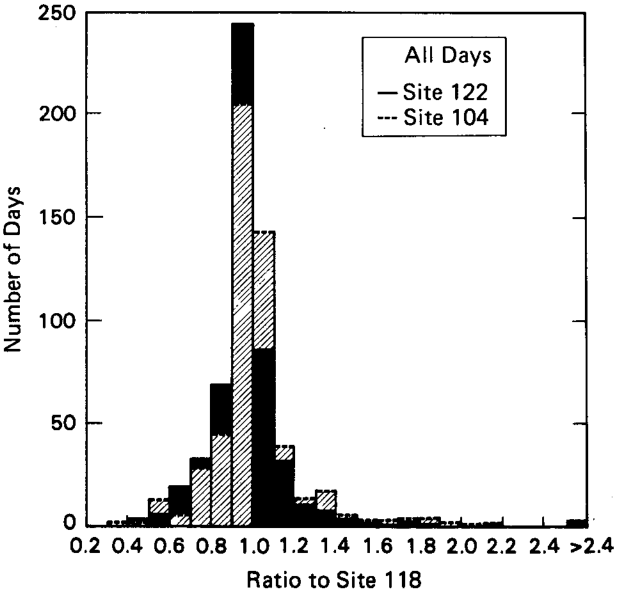

FIG. 3. As in Fig. 2 except for all days.

The distribution of interstation ratios of daily irradiation at sites 104 and 122 are shown in Fig. 3 for the all-days analysis during the complete experiment. The all-days ratios cover a much wider range than do the Fig. 2 distributions, from more than 2.0 to less than 0.5. Site 104 is much closer to the reference site than is 122 and has a more peaked distribution.

The Table 1-Table 3 and Table 2-Table 4 intercomparisons show good agreement. Sums of irradiance over approximately 100-day periods, seasons or the complete experiment show little difference between the results for cloudless periods and all periods. No variation of cloudiness over the network was large enough to alter cloudless period results. In addition, the overall cloudless urban-rural difference of some 4% was still evident in the all periods results, with slightly more urban attenuation during winter than summer.

These St. Louis solar radiation measurements indicate that metropolitan-scale variations of cloudiness were not sufficiently large to alter the spatial distribution of irradiation averaged over the complete experiment. During METROMEX, such cloud-related parameters as rainfall, hail, severe local storms, radar first-echoes and convective cloud heights were measured (Huff and Vogel, 1978; Changnon, 1978; Braham and Wilson, 1978; Braham and Dungey, 1978). Although all these studies identified urban-oriented anomalies, these anomalies did not translate into long-term radiative anomalies at our network. Some possible reasons for this follow. The METROMEX anomalies (e.g., point hailfall frequencies) were usually centered east of the urban center and radiation monitoring sites; thus, the radiation sites may not have been strategically located in terms of the major urban-induced precipitation anomalies. Some anomalies (e.g., summer rainfall amount) had a diurnal maximum after 1800 hours, when radiation is small.

Some precipitation-related parameters, such as number of days per year with thunder, may not be indicators of variable areal coverage or vertical density of cloudiness. The cloud and radiation measurement periods did not overlap much since METROMEX operated from 1971 to 1975. Finally, the METROMEX anomalies may not occur with sufficient frequency to affect irradiation sums over 100 days.

To amplify this last point, recall that the ratios of irradiance sums were computed by summing over each data block the irradiances at site pairs when both sites reported valid data. Consequently, those periods with high irradiance (i.e., times with no clouds or only thin, scattered clouds) are given the most weight. In contrast, for a day with small radiation, a large difference in irradiation percentage between sites would have a small impact on 100-day irradiation sums. Thus, the important climatological effect of a well-developed raincell, giving 1.0 cm of rain in the city but only 0.8 cm out of the city during late afternoon, may not significantly affect irradiation sums.

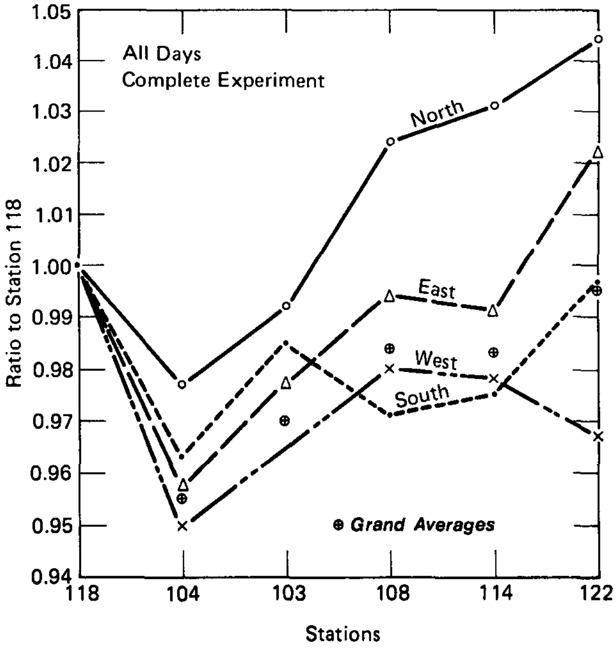

FIG. 4. Average of ratios of daily irradiation at five stations to that at station 118 for cloudless days during the complete experiment. For each station results are stratified by wind direction (curves are so labeled).

6. Wind direction effects

If pollutants emitted from the metropolitan area influence incident irradiance, the location of that impact ought to depend on wind direction. The station-to-station comparisons were stratified by wind direction for cloudless-days and all-days analyses. Only the irradiation sums approach was used. Prevailing wind direction over the network during the cloudless period of each day was determined from hourly official observations at Lambert Field (22 km NW of site 103) and EPA measurements at the six sites. Of approximately 150 useable cloudless days only six had excessively varying wind direction. Four direction sectors were used centered on north (330–029°), east (030–149°), south (150–209°) and west (210–329°). For the all-days' analysis, the Lambert surface observations from 0600–1800 LT were used. Wind directions were required to be within a 60° sector centered on each of the four cardinal points; otherwise, that day was excluded for directional studies. About half of all days were used.

Results of the wind direction stratification for cloudless periods during the experiment are shown in Fig. 4. For each station pair (103–118, 104–118, etc.), daily ratios of irradiation sums were computed and then averaged for all similar wind types. An average of 136 days were used for these comparisons; 70 of the days had west winds, 13 north, 24 east and 29 south.

A distinct difference between the effects of north and south winds is evident for sites 108, 114 and 122. These sites received ~3.5% more irradiation, relative to site 118, with north than with south winds. The suggested cause is advection of pollutants from urban sources. With north winds site 118 is downwind of the city and its pollutant sources. The quartz-pyranometer, cloudless periods, irradiation sums, complete-experiment results (labeled as Grand Averages) are also shown in Fig. 4. Irradiation variability across the metropolitan area is greater when the data are stratified by wind direction. For north winds, the three northern sites had more average irradiation than site 118, whereas when south winds carry pollutants over these sites they average 2–3% less irradiation than 118. The north wind maximum urban-rural difference (122–104) averages ~4.5%, which is similar to that for southerly flow (118–104). Sites 103 and 104, near the city center, show the same relative effect, but have an absolute north-south change of only ~1%. At these sites, the greatest average departure from 118 irradiation occurs with west winds, a wind flow associated with a long suburban-urban fetch. The south wind minimum at 108 relative to 103 could be a local urban feature stemming from pollutant emissions from steel manufacturing at Granite City, Illinois, within 4 km south of 108.

Results of the wind direction stratification for all days during the complete experiment are shown in Fig. 5. Sums over all hourly valid data yielded average daily irradiation for most station pairs of ~800–1000 J cm^{-2}. An average of 5% of all days had no

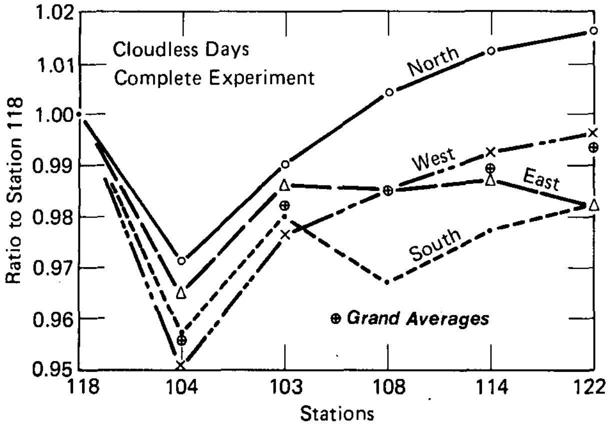

FIG. 5. As in Fig. 4 except for all days.

available data. Of the remaining days, ~40% could not be typed by wind direction, 20% had west winds, 18% south, 10% east and 12% north.

At sites 103 and 104 the ratios for all four wind direction components for all days are within 1% of those for cloudless days, except for the west component of 103. The greatest change between the cloudless and all-days analyses occurred at sites 108, 114 and 122 for north winds. Here the all-days analysis showed ~2–3% more irradiation relative to site 118 than that for the cloudless analysis. This may have resulted because 118 had more cloudiness than the other three sites during north wind conditions, which would agree with the METROMEX findings of increased cloud and precipitation anomalies downwind (usually to the east) of the city. For north winds the all-days results indicated that these three sites also received more absolute irradiation than 118 and their northwind-southwind difference averaged ~5% relative to 118. The Fig. 5 data also show a large urban-rural difference of nearly 7% for north winds, with a consistent irradiation decrease from site 122 toward the city center.

7. Wind speed, visibility, time-of-day and weekday-weekend effects

The site-to-site ratios were studied further to test their dependence on wind speed, visibility, time-of-day and day-of-the-week parameters. Only wind speed had a significant effect on the urban-rural irradiation differences. For each of the other three parameters, interstation irradiation ratios were partitioned according to values of the parameters: for visibility < 9.6, 9.7–16 and > 16 km; for time-of-day before 0900, 0900–1100, 1100–1300, 1300–1500 and after 1500 CST; and for Saturday–Sunday and weekdays. There wasn't a consistent pattern of irradiation depletion over the network sites for any of these parameters.

As low-level wind speeds increase, urban pollutant concentrations due to local sources ought to decrease, along with urban-rural differences of incident irradiation. To test this concept, the station-to-station irradiation intercomparisons were stratified by wind speed using the cloudless-days interstation ratios of daily sums of irradiation. As for wind direction (Section 6), average wind speed over the network was estimated during the cloudless hours of each day from the Lambert Field and EPA six-station hourly measurements. Wind speed was classed in three groups: 0–2.5, 2.6–5.0 and >5.0 m s^{-1}.

Results of the wind speed partitioning showed some positive dependence on wind speed. At the two most urban sites (104 and 103) the greatest average depletion of irradiation occurred in association with slowest surface winds over the network. From low to moderate speeds, irradiation increased relative to that at site 118 by about 2%. However, from moderate to the highest speeds, average irradiation ratios decreased slightly. In contrast to the urban locations, at sites 114 and 122 (the most rural locations) irradiation relative to site 118 decreased somewhat as wind speeds increased.

8. Summary and discussion

As part of the EPA-sponsored Regional Air Pollution Study, incident solar radiation on a horizontal surface was measured at six sites in metropolitan St. Louis, Missouri. Data were taken continuously from September 1975 through March 1977 with pyranometers with all-wave and 395 and 695 nm cutoff filters. Measurements were analyzed to determine typical urban-rural variations of incident solar radiation and its dependence on wind direction and speed, visibility, time-of-day, day-of-the-week and season.

The main finding of this analysis is that incident irradiation near the center of St. Louis during cloudless conditions averaged ~4% less than that at a nearby nonurban location. However, this 4% figure is probably an upper limit to the true average effect of the St. Louis urban atmosphere since network operation and data reduction caused some uncertainty about measurement accuracy. For example, pyranometer domes were cleaned only twice a week which was not sufficient; this was most important at site 104.

Day-by-day examination of the irradiation ratios for sites 103 and 104 showed that the values from about DOY 300, 1976 to DOY 50, 1977, were noticeably lower than those for the remainder of the experiment. This could be the result of poor instrument maintenance. If the data after DOY 300, 1976, are excluded from the cloudless analysis, the average urban effect (combining sites 103 and 104, the quartz and 395 nm instruments, and both analysis methods) is ~3%. An overall urban effect of ~3% would also result if the average effect of dustfall on the pyranometer domes is taken as 1% at the urban sites. In summary, we estimate that the effect of atmospheric pollutants over the center of metropolitan St. Louis was to reduce incident all-wave solar irradiation by ~3%.

The urban-rural differences were about 4.5% in winter and 2% in summer. At two suburban sites, the irradiation depletion averaged 1 and 2% for summer and winter seasons, respectively. During all conditions (cloudy and cloudless), the interstation ratios for the complete experiment were similar to those for cloud-free conditions. Thus, variations in cloudiness were not consistently distributed or were not sufficiently large enough to affect the grand average irradiation distribution over the network.

Urban-rural interstation irradiation comparisons were stratified by wind direction and speed, visibility, time-of-day and day-of-the-week; wind direction had the most significant impact. For cloudless periods, the two suburban sites and one northern rural site received ~3.5% less irradiation (compared to a control site) with south than north winds. This depletion apparently was caused by pollutants advected from the city. The two urban sites exhibited only ~1% north-south change. For all periods with north winds, the suburban and northern rural sites showed ~2-3% more irradiation (compared to the control site south of the city) than for cloudless days for both the summer period and the complete experiment, implying that more cloudiness occurred downwind of the city. However, these site-to-site cloudiness variations during certain periods evidently were not persistent enough to affect the grand average irradiation distribution over the network.

The major findings of this project can be summarized as follows:

Average annual cloudless-sky urban irradiation depletion	3%
Summer period	2%
Winter period	4½%
Range of irradiation depletion for north vs south winds	1%
Average annual cloudless-sky suburban irradiation depletion	1½%
Summer period	1%
Winter period	2%
Range of irradiation depletion for north vs south winds	3½%.

Acknowledgments. The assistance of Edwin Flowers and John Rudisill during the planning and execution of this experiment and of Michael Riches during the analysis phase is gratefully acknowledged. Gail Phillips typed the several drafts of the manuscript. RAPS measurements were supported by the Meteorology and Assessment Division, Environmental Protection Agency, Research Triangle Park, N.C. Data analysis and interpretation were partially funded by the Division of Solar Technology, Department of Energy, under interagency Agreement E (49-26)-1041 with the Department of Commerce.

REFERENCES

Baldwin, J. L., 1973: *Climates of the United States.* Environmental Data Service, NOAA, U.S. Department of Commerce, Washington, DC, 113 pp.

Beckman, W. A., J. W. Bugler, P. I. Cooper, J. A. Duffie, R. V. Dunkle, P. E. Glaser, T. Horigome, E. D. Howe, T. A. Lawand, P. L. vander Mersch, J. K. Page, N. R. Sheridan, S. V. Szokolay and G. T. Ward, 1978: Units and symbols in solar energy. *Solar Energy,* **21,** 65–68.

Braham, R. R., and M. J. Dungey, 1978: A study of urban effects on radar first echoes. *J. Appl. Meteor.,* **17,** 644–654.

——, and D. Wilson, 1978: Effects of St. Louis on convective cloud heights. *J. Appl. Meteor.,* **17,** 587–592.

Changnon, S. A., 1978: Urban effects on severe local storms at St. Louis. *J. Appl. Meteor.,* **17,** 578–586.

——, F. A. Huff and R. G. Semonin, 1971: METROMEX: An investigation of inadvertent weather modification. *Bull. Amer. Meteor. Soc.,* **52,** 958–967.

Gatz, D. F., 1978: Identification of aerosol sources in the St. Louis area using factor analysis. *J. Appl. Meteor.,* **17,** 600–608.

Huff, F. A., and J. L. Vogel, 1978: Urban, topographic and diurnal effects on rainfall in the St. Louis region. *J. Appl. Meteor.,* **17,** 565–577.

Landsberg, H. E., 1956: The climate of towns. *Man's Role in Changing the Face of the Earth,* University of Chicago Press, 584–606.

Peterson, J. T., and E. C. Flowers, 1977: Interactions between air pollution and solar radiation. *Solar Energy,* **19,** 23–32.

——, —— and J. H. Rudisill, 1973: Dew and frost deposition on pyranometers. *J. Appl. Meteor.,* **12,** 1231–1233.

——, —— and ——, 1978: Urban-rural solar radiation and atmospheric turbidity measurements in the Los Angeles Basin. *J. Appl. Meteor.,* **17,** 1595–1609.

Schiermeier, F., 1978: The St. Louis Regional Air Pollution Study (RAPS): An operational summary and projection. *Environ. Sci. Tech.,* **12,** 644–651.

White, J. M., F. D. Eaton and A. H. Auer, 1978: The net radiation budget of the St. Louis metropolitan area. *J. Appl. Meteor.,* **17,** 593–599.