Implementation of a Semiphysical Model for Examining Solar Radiation in the Midwest

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ABSTRACT

A semiphysical solar radiation (SR) model is implemented to generate a new historical daily SR database for 53 locations in nine Midwestern and six adjacent states (available from the Midwestern Climate Center). This model estimates daily SR using standard hourly meteorological observations (surface atmospheric pressure and dewpoint temperature; cloud height and fractional sky cover by layer) as well as time of day, day of year, latitude/longitude, and the daily presence/absence of snow cover as input. Because of an extensive effort to interpolate for missing input (especially cloud) data, the daily SR dataset generated is 92% complete for all 53 stations for 1948–91, and 99% complete for the 43 stations with continuous hourly meteorological observations that commenced during 1945–50 and extended through 1991. Consistent with previous work, the model validates favorably against sets of daily SR measurements from (three) contrasting parts of the study region, and so its output is used here without adjustment.

Analyses of the dataset document the basic Midwestern spatial and temporal SR variability since the mid- to late 1940s. The spatial variation of calendar monthly mean SR is dominated by a near-meridional (northeastward) decrease in fall and winter. This fundamental pattern is substantially perturbed from midspring through summer by subregional-to-mesoscale variability around and across the Great Lakes. Time series of individual monthly station mean SR values exhibit a pronounced, regionwide 1945–91 downtrend for August–November. This decline is strongest (~12%) and most statistically significant (>99% level) for October in a belt extending east-southeastward from west-central Wisconsin across southern Lake Michigan and western Lake Erie to western Pennsylvania. The SR trends for December–July are largely positive but of lesser spatial coherence, temporal consistency, and statistical significance.

1. Introduction

Radiant heat energy originating from the sun is a crucial input for many environmental systems, both natural and humanly constructed. This energy is variously referred to as shortwave radiation, solar radiation (SR), global radiation, solar energy, or insolation, and will henceforth be designated by SR. The wide variety of systems for which SR is an important energy source results in there being a large number of actual or potential users of SR data, including those in agriculture, atmospheric science, building design, engineering, forestry, horticulture, hydrology, and land-use planning.[1] In many cases, such users require that the information be representative of long-term conditions. With these applications in mind, a new SR database has been developed for 53 locations in nine agriculturally important Midwestern states (Minnesota, Iowa, Missouri, Illinois, Wisconsin, Michigan, Indiana, Ohio, and Kentucky) (Fig. 1) and six adjacent states (North Dakota, South Dakota, Nebraska, Tennessee, West Virginia, and Pennsylvania) (Fig. 1) for their periods of available record during 1945–91. This paper describes the procedures used to construct the database and presents some analyses of it that document the basic spatial and temporal variability of SR throughout the Midwest.

The National Science Foundation's Research Applied to National Needs program of the early 1970s initiated research and technological studies concerning the economic applications of solar energy. Consequently, a number of papers (reviewed below) have been published in the last two decades on SR and its temporal and spatial variation in the United States. The research they report is rather varied with respect

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[1] Note that when this energy reaches the surface of the earth over a specific time period, it is defined as the radiant flux density, which is indeed the subject matter of this paper.

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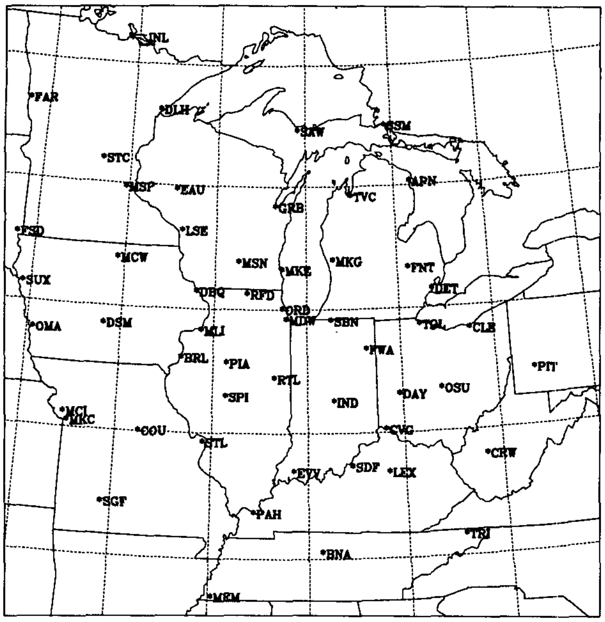

FIG. 1. Orientation map. Midwestern stations for which daily solar radiation (SR) is estimated for their periods of available records during 1945–91 are located by asterisks. Three-letter station identifiers are defined in Table 1.

to the period length studied, the number and density of the stations used, the datasets used, the methods of analysis employed, and the results obtained. Many of these investigations used "rehabilitated" data from the only long-term, nationwide SR network that has existed in the United States, while others constructed and analyzed relatively new, smaller-scale SR datasets using various techniques.

Publication of the raw SR data from the above-mentioned long-term network by the U.S. National Weather Service ceased in 1972, when it became clear that they contained errors of ±5% to ±30% (Thekarhara 1976). However, the historical hourly SR data for a subset (26) of the network stations were subsequently rehabilitated by the National Oceanic and Atmospheric Administration for approximately 1952–75 by applying a correction that largely accounted for a slow instrument deterioration. These stations are known as the SOLMET (solar meteorological) stations. The aforementioned studies that examined long-term SR generally used the spatially sparse SOLMET data, as well as denser data generated by models developed through regressions of SOLMET SR data with more frequently observed meteorological parameters such as cloud cover or percent possible sunshine (i.e., regression-extended SOLMET or ERSATZ). In both cases, uncertainties exist because of the adjustments (described above) inherent in SOLMET data. Some of the studies documented the climatological spatial variations of SR across the entire United States (Bennett 1965, 1975; Enmap Corporation 1980; Solar Energy Research Institute 1981; Balling and Vojtesak 1983) and the north-central region (Baker and Klink 1975), while others identified secular trends in the SR data (Balling 1983; Balling and Cerveny 1983). In addition, long-term actual sunshine hours were used in similar temporal and spatial analyses (U.S. Department of Interior 1970; Bryson and Hare 1974; Angell and Korshover 1975, 1978; Doehring and Karl 1981).

The second group of papers mentioned above used sets of highly reliable short-term SR measurements from special observing networks to investigate the SR climate of particular states or small regions within the United States—for example, California (11 stations) (Granger 1980); the Washington, D.C. area (3 stations) (Pinker and Militana 1981); the New England, mid-Atlantic, and Georgia–South Carolina regions (7 to 8 stations each) (Atwater and Ball 1978); San Diego County, California (8 stations) (Aguado 1986); Arizona (6 stations) (Suckling 1983); the Tennessee Valley Authority region (12 stations) (Suckling 1983); Wisconsin (17 stations) (Kerr and Rosendal 1968; Kerr et al. 1968); and the intermountain region (37 stations) (Bennett 1964). The analyses for these areas were based on datasets ranging in length from only 7 months up to 5 years, and often focused on the mesoscale variability of SR from which interpolation schemes could be developed for estimating insolation at locations where no measuring stations exist. Few investigators have proposed schemes to classify and regionalize SR data (Terjung 1970; O'Brien 1978; Willmott and Vernon 1980; Balling and Vojtesak 1983), and their results often differed due to the contrasting timescales (e.g., daily versus monthly) of the SR data used and differences in the statistical techniques employed.

The SR climate of the Midwest region, which includes the most important crop-producing area in the United States and perhaps the world, has thus not yet been reliably documented in detail. We here initiate the redressing of this deficiency, which first required the creation of a long-term SR dataset because the available SR measurements, be they SOLMET data or from localized networks, are either spatially sparse or lacking in longevity. A semiphysical SR model was used to generate daily totals for 53 stations in the aforementioned 15-state region for their periods of available records during 1945–91. The next section describes the model and outlines its implementation and validation. It is followed by the presentation of analyses that were designed to elucidate the basic spatial and temporal SR variability that has occurred in the Midwest in recent decades. The overall goal is to acquaint the reader with an important new database that is available for further investigation and application, not just concerning SR itself, but also in contexts where SR plays an important role or driving force (e.g., evapotranspiration, plant and tree growth, solar heating research, etc.).

2. Methodology

a. Semiphysical model

Numerous statistical models have been proposed and used for the estimation of SR from a wide range of parameters. For example, the models of Reddy (1974) and Schmetz and Raschke (1978) used cloud amount and type; Rangarajan et al.'s (1984) approach used cloud height and coverage; many models have employed sunshine duration (e.g., Glover and McCulloch 1958; Baker and Haines 1969; Schulze 1976; Rietfeld 1978; Biga and Rosa 1980; Martínez-Lozano et al. 1984); Bristow and Campbell's (1984) method used daily maximum and minimum temperatures, and Reddy (1987) attempted to use precipitation and latitude. In contrast, the present investigation used a more sophisticated semiphysical model that has been under development since the mid-1970s (Atwater and Brown 1974; Atwater and Ball 1978, 1981; Meyers and Dale 1983). This model estimates the radiant flux density received at the earth's surface from

$$I = I_0(\cos Z) T_R T_g T_w T_a T_c, \qquad (1)$$

where I_0 is the extraterrestrial flux density on a surface normal to the incident radiation, Z is the solar zenith angle, and T_i denotes the transmission coefficients after Rayleigh scattering (R), absorption by permanent gases (g) and water vapor (w), absorption and scattering by aerosols (a), and cloud attenuation (c). Although Eq. (1) is strictly valid for monochromatic radiation, it has been used in broadband models to approximate the real atmosphere (Atwater and Ball 1981). The I_0 and $\cos Z$ terms in Eq. (1) were evaluated using standard equations, with the attenuation coefficients being given by

$$T_R T_g = 1.021 - 0.084[m(949p \times 10^{-5} + 0.051)]^{1/2} \qquad (2)$$

$$T_w = 1 - 0.077(um)^{0.3} \qquad (3)$$

$$T_a = x^m \qquad (4)$$

and

$$T_c = \prod_{i=1}^{n_c} R_i[1 - c_i(1 - t_i)], \qquad (5)$$

where

$$m = 35(1224 \cos^2 Z + 1)^{-1/2} \qquad (6)$$

$$u = \exp[0.1133 - \ln(\lambda + 1) + 0.0393 T_d] \qquad (7)$$

and

$$R_i = (1 - r_e r_{ci})^{-1}. \qquad (8)$$

In Eqs. (2)–(8), m is the dimensionless optical air mass at a surface atmospheric pressure of 101.3 kPa, p (kPa) is the actual surface atmospheric pressure, u (cm) is the precipitable water, T_d (°F) is the surface dewpoint temperature, λ is an empirical constant that varies with latitude and season (taken from Smith 1966), x is a clear-sky constant assumed to be 0.935 (taken from Meyers and Dale 1983), n_c is the number of cloud layers, R_i is the cloud-to-ground reflectance from the ith cloud layer, c_i is the fractional sky coverage of the ith cloud layer, t_i is the transmission coefficient for the most abundant cloud type in the layer (taken from Meyers and Dale 1983), r_e is the earth's surface albedo, and r_{ci} is the albedo of the ith cloud layer. Following Meyers and Dale (1983), r_e was assumed to be 0.20 (0.65) in the absence (presence) of snow cover, and r_{ci} was taken as 0.5 (zero) for all clouds with bases lower (higher) than 5486 m (18 000 ft). Further information on the above model is available in Meyers and Dale (1983) and Petersen (1990). Additionally, validation of this model is discussed in section 2c.

To evaluate the terms in Eqs. (1)–(8), the following information is required: time of day, day of year, latitude and longitude, surface atmospheric pressure and dewpoint temperature (hourly), height and fractional sky coverage for various cloud layers (hourly), and the presence or absence of snow cover (daily). The necessary data were acquired on magnetic tape from the TD-3280 surface airways hourly tape deck of the National Climatic Data Center (NCDC 1986) for 53 Midwestern and nearby stations for their entire periods of available record. The locations of these stations are shown in Fig. 1, while the station names and time periods are given in Table 1. Equation (1) is an estimate of the instantaneous flux density (J s^{-1} m^{-2}) occurring at the time of the meteorological observation. The instantaneous value is then converted from joules per second to joules per hour through multiplication with the assumption that the data input are constant over the hour.

b. Model implementation

The computation of the most accurate possible SR values from the TD-3280 data using Eqs. (1)–(8) required a significant effort because of the variability and inconsistency of that database, particularly concerning the crucial cloud cover information. Pertinent cloud information was available in up to four elements: ceiling height, sky cover classification or sky condition (e.g., clear, scattered, broken, overcast) and fractional coverage for each cloud layer, cloud type and height for each layer, and, for prior to June 1951, a general sky condition category (higher layer fraction, lower layer fraction, height of lowest scattered layer).

Considerable examination of the entire hourly dataset suggested that a mixture of cloud reporting (or perhaps archiving) procedures was used for the bulk of the study period (from June 1951 onward). Three categories of hourly observations were identified for entire days—(i) both sky condition and cloud heights were

TABLE 1. Alphabetical listing of the stations for which daily solar radiation (SR) was estimated using Eqs. (1)–(8) and input data from the TD-3280 surface airways hourly tape deck of the National Climatic Data Center.

Station name	Identifier	Period of record
Illinois		
Chicago (Midway)	MDW	Jan 1948–Dec 1979
Chicago (O'Hare)	ORD	Nov 1958–Dec 1991
Moline	MLI	Feb 1948–Dec 1991
Peoria	PIA	Jan 1948–Dec 1991
Rantoul	RTL	Jan 1949–Dec 1970
Rockford	RFD	Dec 1948–Dec 1954, Nov 1958–Dec 1991
Springfield	SPI	Jan 1948–Dec 1991
Indiana		
Evansville	EVV	Jan 1948–Dec 1991
Fort Wayne	FWA	Jan 1948–Dec 1991
Indianapolis	IND	Jan 1948–Dec 1991
South Bend	SBN	Jan 1948–Dec 1991
Iowa		
Burlington	BRL	Jan 1948–Jan 1980
Des Moines	DSM	Jan 1945–Dec 1991
Dubuque	DBQ	Feb 1951–Sep 1981, Nov 1982–Dec 1991
Mason City	MCW	Jan 1948–Dec 1991
Sioux City	SUX	Jan 1948–Dec 1991
Kentucky		
Covington (Cincinnati)	CVG	Jan 1948–Dec 1991
Lexington	LEX	Jan 1948–Dec 1991
Louisville	SDF	Jan 1948–Dec 1991
Paducah	PAH	Sep 1949–Dec 1964, Oct 1984–Dec 1991
Michigan		
Alpena	APN	Sep 1959–Dec 1991
Detroit	DET	Jan 1948–Dec 1991
Flint	FNT	Dec 1948–Dec 1991
Gwinn	SAW	Oct 1956–Dec 1957, Apr 1958–Dec 1958, Sep 1959–Dec 1970
Muskegon	MKG	Jan 1948–Dec 1991
Sault Ste Marie	SSM	Jan 1948–Dec 1991
Traverse City	TVC	Dec 1948–Dec 1991
Minnesota		
Duluth	DLH	Jan 1948–Dec 1991
International Falls	INL	Jan 1948–Dec 1991
Minneapolis–St. Paul	MSP	Jan 1945–Dec 1991
St. Cloud	STC	Jan 1948–Dec 1991
Missouri		
Columbia	COU	Jan 1945–Dec 1991
Kansas City (Downtown)	MKC	Jan 1948–Sep 1972, Jan 1975–Oct 1988
Kansas City (International)	MCI	Jan 1972–Dec 1991
Springfield	SGF	Jan 1948–Dec 1991
St. Louis	STL	Jan 1945–Dec 1991
Nebraska		
Omaha	OMA	Jan 1948–Dec 1991
North Dakota		
Fargo	FAR	Jan 1948–Dec 1991
Ohio		
Cleveland	CLE	Jan 1948–Dec 1991
Columbus	OSU	Jan 1948–Dec 1991
Dayton	DAY	Jan 1948–Dec 1991
Toledo	TOL	Jan 1946–Dec 1991
Pennsylvania		
Pittsburgh	PIT	Jan 1945–Dec 1991
South Dakota		
Sioux Falls	FSD	Jan 1948–Dec 1991
Tennessee		
Bristol	TRI	Jan 1948–Dec 1991
Memphis	MEM	Jan 1948–Dec 1991
Nashville	BNA	Jan 1948–Dec 1991
West Virginia		
Charleston	CRW	Feb 1949–Dec 1991
Wisconsin		
Eau Claire	EAU	Oct 1949–Dec 1991
Green Bay	GRB	Sep 1949–Dec 1991
La Crosse	LSE	Jan 1948–Dec 1991
Madison	MSN	Jan 1948–Dec 1991
Milwaukee	MKE	Jan 1948–Dec 1991

reported, (ii) sky condition only was reported, and (iii) neither were reported. When neither cloud element was reported for all hours of a day, it was assumed from examination of National Weather Service observing forms that no clouds were present. When the hourly sky condition was given but not accompanied by cloud-height information for an entire day, the latter was obtained from the ceiling observation. For example, if a ceiling height was given and the sky condition indicated that only one cloud layer existed, the height of that layer was assumed equal to the ceiling height. When two cloud layers were present, the sky condition indicated which layer was the ceiling because a ceiling is defined as the height of the lowest layer of clouds reported as broken or overcast (not "thin"). Specifically, if the lower layer constituted the ceiling, its height was set equal to the ceiling height. If that lower cloud height was 3049 m (10 000 ft) or less, the height of the upper cloud layer was assumed to be 1524 m (5000 ft) higher than the lower cloud layer; or if the lower cloud height was greater than 3049 m (10 000 ft), the upper cloud layer was assumed to be 3049 m (10 000 ft) higher than the lower layer. Alternatively, if the upper cloud layer provided the ceiling (i.e., the lower layer must have contained scattered clouds), its height was assumed equal to the ceiling height. If that upper cloud height was (i) less than 1524 m (5000 ft), the height of the lower cloud layer was taken to be the same as the upper layer; (ii) between 1524 and 3049 m (5000–10 000 ft), the lower cloud height was assumed to be 1524 m (5000 ft) less than the upper cloud layer; or (iii) greater than 3049 m (10 000 ft), the lower cloud was considered to be 3049 m (10 000 ft) below the upper cloud. Hourly estimates of cloud height for combinations of 3, 4, or 5 layers were similarly determined for entire days, as described in Petersen (1990).

A similar use of ceiling height to estimate hourly cloud layer heights for complete days was performed (where needed) for the small portion of the study period prior to June 1951. This was necessary because the "general sky condition" element additionally available for that period either had many missing values or yielded unrealistically low SR estimates.

When all the necessary input data were available, including data resulting from the application of the procedures just described, Eqs. (1)–(8) were used to estimate the SR for each hour of a given day. Those hourly values were then summed to yield the SR total for that day. If any input parameter was missing for a particular hour, the SR value for that hour was initially also set to be missing. However, some of those gaps were able to be filled in the following ways. First, for occasional hours when only the sky condition was not reported, the sky was assumed clear provided all other parameters were available. Close examination of observation forms supported this assumption. Second, when hourly cloud heights were not available, which occurred frequently because of a tendency to report them only every 3 h, the T_c values for up to two consecutive missing hours were linearly interpolated from their adjacent hour counterparts during that day. Third, when the sky condition was reported to be partially obscured and the corresponding cloud height was given as unknown or was missing, that obscuring cloud height was assumed to be low and set at 274 m (900 ft). In addition, occasional inconsistencies between the reported sky condition and reported fractional cloud cover for the same layer and hour (i.e., departures from the definitions: clear—0 tenths, scattered—1–5 tenths, broken—6–9 tenths, overcast—10 tenths) were removed by using adjacent cloud-layer information to adjust the sky condition to fit the cloud cover. Fourth, sensitivity analyses were conducted that showed that the model output changed by 0.07 MJ m^{-2} h^{-1} or less when mean monthly values of pressure and dewpoint temperature were used as input in place of the hourly observed values. Thus, missing hourly values of dewpoint temperature and surface pressure were replaced by average values for other hours of the same day when available, or else by averages for the month concerned. Fifth, a missing daily snow cover (presence/absence) observation for a given station was either assumed to be the same as that for the next closest station or, in the absence of such supplementary information, snow cover was assumed to exist (not exist) if the 1948–87 historical probability was at least (less than) 50%. Sixth, if application of the above procedures still left hours of missing transmission coefficients T_i [Eqs. (1)–(5)], the combined depletion factor for all T_i [$T_R T_g T_w T_a T_c$ in Eq. (1)] was interpolated using the method already described for T_c.

This model implementation yielded a daily SR dataset that is 92% complete for the years 1948–91 for all stations shown in Fig. 1. Furthermore, if we exclude the 10 stations whose records either began after 1950 (ORD, DBQ, APN, MCI) (Fig. 1), ceased before 1989 (MDW, RTL, BRL, SAW, MKC), or contained a 20-yr gap (PAH), the remaining SR data are 99% complete.

c. Model validation

As documented in Table 2, the model described above was validated by comparing its daily estimates with four sets of daily SR measurements from different parts of the study region. The measurements used were from recently established state SR networks, and adequately spanned the annual cycle for the region as a whole. They were the only SR measurement sets available, at the time of the investigation, for locations close to model stations. Full details of the validation procedures employed appear in Petersen (1990).

The validation results establish that the model estimates SR comparable to or better than previous modeling efforts for the Midwest (Baker and Haines 1969; Tarpley 1979; Meyers and Dale 1983). Table 2 shows that the model accounted for 88%–96% of the measurement variance in the four intercomparisons undertaken, with the regression lines involved being very close to 1:1 lines. The principal possible bias evident from the regression analyses is that the model may slightly underestimate SR, especially when it is low. Table 2 also indicates that the present error estimates are only slightly larger than counterparts Meyers and Dale (1983) obtained in a nationwide validation of the same model. Root-mean-square errors as a percentage of mean values range from 12.2% to 23%, depending on the station, and the error is 15.7% for all stations combined, compared to 11.5% found by Meyers and Dale (1983). The present validation for each intercomparison period was also performed on a seasonal basis and for its complete subset of clear days (Petersen 1990). While the model estimates tended to be higher relative to the measurements for the cooler October–March semester than the warmer April–September one, the errors involved depart only slightly from the individual intercomparison period values in Table 2. Furthermore, for the clear-sky days, the daily modeled SR values were generally within 4% ± 3% of the corresponding measurements.

Given the present favorable model validation plus the similarly supportive earlier validation of Meyers and Dale (1983), it was decided to here use the daily SR estimates of the model without adjustment.

3. Results and discussion

a. Monthly mean spatial patterns

Calendar monthly mean SR values were calculated for each of the 53 stations for their entire periods of

TABLE 2. Details and results of validation of daily SR model estimates against nearby daily SR measurements. Regression parameters are for a daily measurement (ordinate) versus model (abscissa) linear formulation; all r^2 values are significant at greater than the 99.9% confidence level. Error estimates are computed from daily measurement-minus-model differences. Meyers and Dale's (1983) validation was for 5 days in each month of 1980 (60 days total) for 12 stations approximately evenly distributed across the United States. NA indicates not available.

SR model station (Fig. 1)	SR measurement site and instrument used for validation	Intercomparison period	Regression r^2	Regression slope	Regression ordinate-intercept (MJ m^{-2} day^{-1})	Mean error (MJ m^{-2} day^{-1}/% of mean daily SR measurement)	Mean absolute error (MJ m^{-2} day^{-1}/% of mean daily SR measurement)	Root-mean-square error (MJ m^{-2} day^{-1}/% of mean daily SR measurement)
EAU	Chetek, Wisconsin (96 km north of EAU) LI-COR LI200S Silicon pyranometer	1 Jan–13 May 1986 (130 days of observations)	0.88	1.05	−1.59	+1.02/9.2	1.89/17.0	2.55/23.0
OSU	Delaware, Ohio (38 km north of OSU) LI-COR LI200S Silicon pyranometer	1 Jan–31 Dec 1987 (361 days of observations)	0.93	0.96	−0.92	+1.49/11.4	1.97/15.0	2.55/19.5
PIA	Peoria, Illinois (15 km east of PIA) Eppley 8-48 black and white pyranometer	30 May–1 Nov 1987 (136 days of observation)	0.92	1.10	−1.12	−0.59/−3.2	1.79/9.7	2.28/12.3
		6 Jan–31 Dec 1988 (361 days of observation)	0.96	1.06	−0.69	−0.62/−3.7	1.67/10.0	2.04/12.2
All four above intercomparison period combined			0.96	1.04	−1.04	+0.37/2.5	1.82/12.3	2.34/15.7
Counterpart combined validation results from Meyers and Dale (1983)			NA	NA	NA	−0.12/−0.8	1.28/8.7	1.69/11.5

available record between 1945 and 1991, and then spatially isoplethed. The resulting patterns for the four midseason months are presented in Fig. 2; they are also strongly representative of the remainder of their seasons, which are documented in Petersen (1990) using a slightly shorter (1945–87) database.

The most basic feature of Fig. 2 is the expected northward decrease of SR. However, the annual variation of this gradient is quite pronounced, being strongest in fall (especially October) (Fig. 2d) and weakest in spring (e.g., April) (Fig. 2b). The tight fall gradient reflects that season's lack of cloudiness, particularly on the subregional to mesoscale, and hence stronger astronomical control on SR, relative to the rest of the year. It weakens noticeably (but without distortion) between October and December. For most months, the general poleward SR gradient actually has a northeastward orientation rather than being purely meridional. This principally results from the westward decrease in cloudiness and humidity.

The calendar monthly mean SR patterns exhibit the greatest subregional-to-mesoscale variability from midspring through summer (i.e., April–August). Particularly prominent in this regard is a SR minimum extending from northern Wisconsin across southern Upper Michigan and northern Lake Michigan to northern and eastern Lower Michigan (e.g., Figs. 2b,c). The credence of this feature was confirmed through detailed analyses of the cloud data for the stations concerned (EAU, GRB, SAW, TVC) (Fig. 1). At one extreme, the quality of the cloud data for GRB was found to be excellent. At the other extreme, although all EAU cloud-layer heights had to be inferred from ceiling heights (section 2b) and are therefore somewhat uncertain: the total sky cover statistics for that station include 2%–5% less clear-sky hours and 5% more overcast hours than those for either MSP to the west or GRB to the east. In addition, this Wisconsin–Michigan spring–summer SR minimum is broadly apparent in early analyses of the spatially sparser SOLMET data discussed in the introduction (Bennett 1965; Baker and Klink 1975). During April–May, the area of this SR minimum is also one of mean confluence between airstreams of tropical and arctic origins (Bryson 1966). Although that mean confluence migrates farther north in the summer, the rainfall analyses of Lamb and

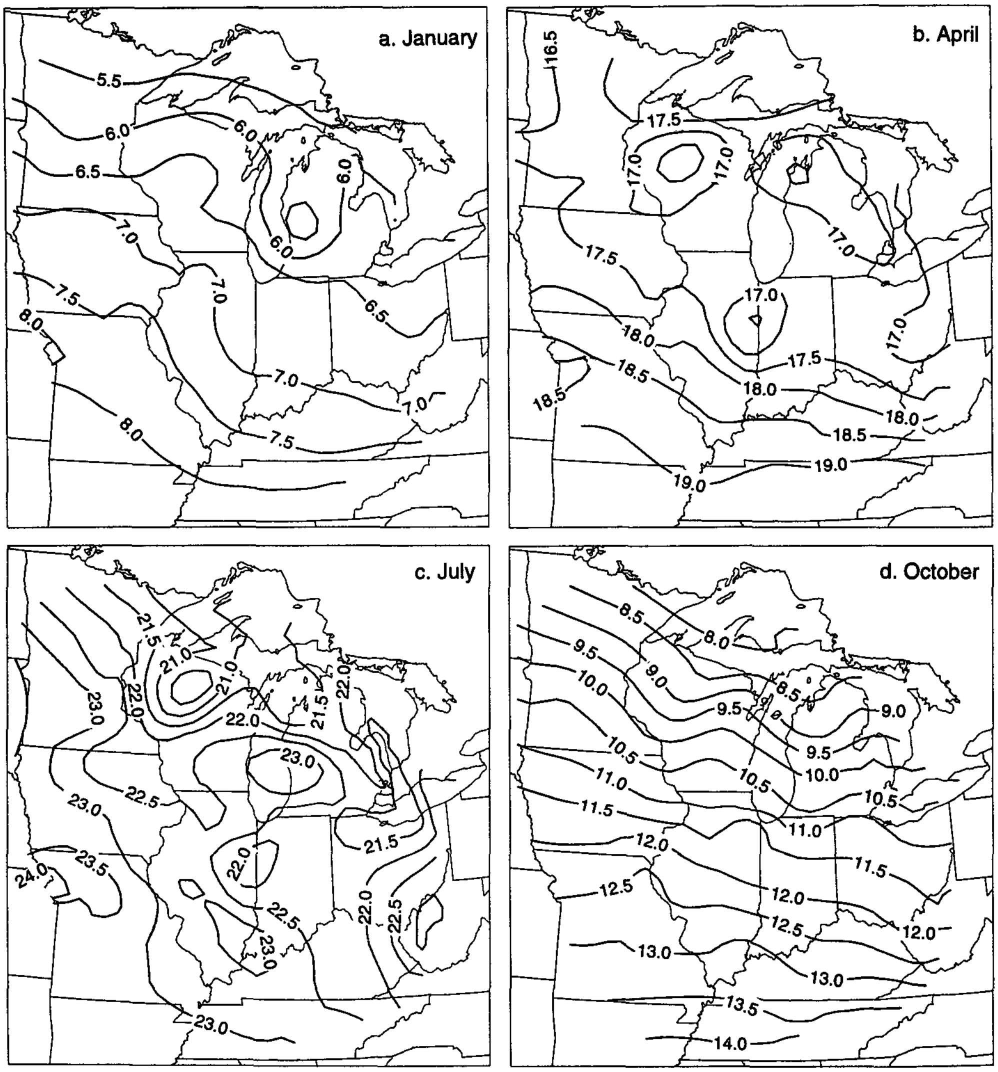

FIG. 2. Mean spatial SR (MJ m^{-2} day^{-1}) patterns for midseason months for approximately 1945–91.

Richman (1990) indicate that during this season the Wisconsin–Michigan SR minimum tends to lie within one or two areas of spatially coherent 3–7-day rainfall. The general west–east elongations of those rainfall regions were considered suggestive of the slow southward sagging and northward retreat of weak frontal systems.

The thermal effects of the Great Lakes are clearly evident in the mean SR patterns for all calendar months (Fig. 2). Particularly prominent is the SR maximum centered over the eastern shore of southern Lake Michigan during May–August. This feature, for which the July pattern (Fig. 2c) is typical, results from the relatively cool southern Like Michigan surface waters (Eichenlaub et al. 1990) suppressing convection and cloudiness in the overlying, predominantly southwesterly, airstream (Bryson 1966). This "lake effect" clearly propagates downstream over west-central Lower Michigan (e.g., Fig. 2c). During much of the remainder of the year, a strongly contrasting "lake effect" emanates from Lakes Superior and Michigan being warmer than the surrounding land or surface air (Eichenlaub et al. 1990). During the fall and winter, this temperature difference supports strong evaporation into the cold and dry prevailing northwesterly and westerly airstreams that cross those lakes (Bryson 1966), which, in turn, enhances the cloudiness over Lake Michigan and all but extreme eastern Lower Michigan. These processes are manifest in the pronounced and progressive amplification of a SR minimum over Lake Michigan/Lower Michigan from September through January (e.g., Figs. 2a,d). This SR minimum is more diffuse in February and has disappeared by March.

A final interesting mesoscale feature of the monthly mean SR patterns is the elevation of the June–September (e.g., Fig. 2c) values for the rurally located Kansas City International Airport (MCI) (Fig. 1) over those obtained for the downtown airport (MKC). This difference reflects (presumably urban) enhanced warm season cloudiness at MKC. No comparable difference emerged for the other pair of closely collocated airport stations studied (MDW, ORD) (Fig. 1), both of which lie *within* the Chicago metropolitan area.

b. *Temporal trends*

Time series of individual monthly mean SR values were produced for all 53 stations for their entire periods-of-available-record between 1945 and 1991, and then fitted with linear regression lines. The statistical significance of the slope of each regression line was subsequently determined using Student's t-test. Figure 3 documents the spatial patterns of the overall SR station trends identified by this procedure for each midseason month, which are also strongly representative of the remainder of their seasons [not shown, but available in Petersen et al. (1991)]. Petersen (1990) presents the raw SR time series, plus their associated regression lines and accompanying statistical significance, for each station for the midseason months of the slightly shorter 1945–87 period. A selection of those results, extended through 1991, appears in Fig. 4.

The most striking and spatially coherent SR trend results were obtained for fall, especially October (Fig. 3d), the season that the previous section found to be least characterized by long-term subregional-to-mesoscale SR variability. Most stations exhibited negative SR trends for all three fall months, with many being statistically significant at greater than the 95% and 99% levels, particularly for October (Fig. 3d). The strongest and most statistically significant October SR downtrends occur in a belt extending east-southeastward from west-central Wisconsin across southern Lake Michigan and western Lake Erie to western Pennsylvania. When the analysis period terminated in 1987 (Petersen 1990), this feature extended farther west-northwestward into southeastern Minnesota and northeastern Iowa. Further (time series) documentation of it appears in Fig. 4, which shows the decline to have been highly uniform, both temporally and spatially, and to have typically involved an approximate 12% SR reduction over the 1945–91 period (i.e., a yearly average of $\sim$0.03 MJ m^{-2} day^{-1}). Note, in particular, that relatively little interannual variability occurred about the downtrend lines for this belt during 1965–87. These overall fall SR results are broadly consistent with recent analyses of the temporal trends in Midwestern cloudiness and sunshine during 1901–77 (Changnon 1981) and 1950–82 (Angell et al. 1984).

In contrast, the SR station trends for the three winter months were mostly positive (e.g., Fig. 3a). For the central portion of the study region, many of those upward trends were significant at better than the 95% or 99% levels, especially for January (Fig. 3a) and February, and resulted in about 10% SR increases over the 1945–91 period. However, a coherent area of negative SR trends dominated the east-central area for December (not shown).

The SR trends for the spring months were of lesser spatial coherence, temporal consistency, and statistical significance than those previously discussed for fall and winter. While the northern part of the study region was dominated by negative trends for March, they were statistically significant for only a few stations (not shown). In contrast, SR underwent a small overall April increase at most stations during 1945–91, but the statistical significance of these trends was generally less than 95% (Fig. 3b). The SR trends for May (not shown) were the least spatially coherent of the spring season, with a mixture of weak and statistically insignificant positive and negative values occurring throughout the region.

The 1945–91 summer SR trends fall into two distinct intraseasonal categories. For June and July, they were positive for most stations not located along Great Lakes shorelines, with some of the trends being statistically significant at greater than the 95% and 99% levels (e.g., Fig. 3c). The June–July trends for the Great Lakes stations tended to be weakly negative overall, and not statistically significant. In striking contrast, the 1945–91 SR trends for August were negative at most stations, with their statistical significance levels often exceeding 95% and 99% (not shown). This was particularly characteristic of the eastern stations, for which the 1945–91 SR decreases were approximately 8%. The August SR trend results are thus very similar to those described above for the immediately following fall season.

4. Concluding remarks

This study implemented the Meyers and Dale (1983) semiphysical solar radiation (SR) model to generate a new historical ($\sim$1945–91) daily SR database for 53 locations in nine Midwestern and six adjacent states. It arose from the need for a hitherto unavailable, reliable, and detailed documentation of the SR climate of the Midwest for application in such diverse areas as agriculture, atmospheric science, building design, engineering, forestry, horticulture, hydrology, and land-use planning. The authors and their colleagues have already used this new SR dataset in the operational estimation of potential evapotranspiration and soil moisture (Kunkel 1990), when projecting the agricultural impact of possible climate change (Dixon et al. 1994), and as background for a counterpart effort for the southern Great Plains that is part of the Atmospheric Radiation Measurement Program (U.S. Department of Energy 1990). The dataset is available from the Midwestern Climate Center (217-244-8226 or requests@mcc.sws.uiuc.edu) in the hope that it may be useful in other contexts where SR plays an important role or driving force.

Previous long-term and large-scale SR investigations for the United States were generally limited and ren-

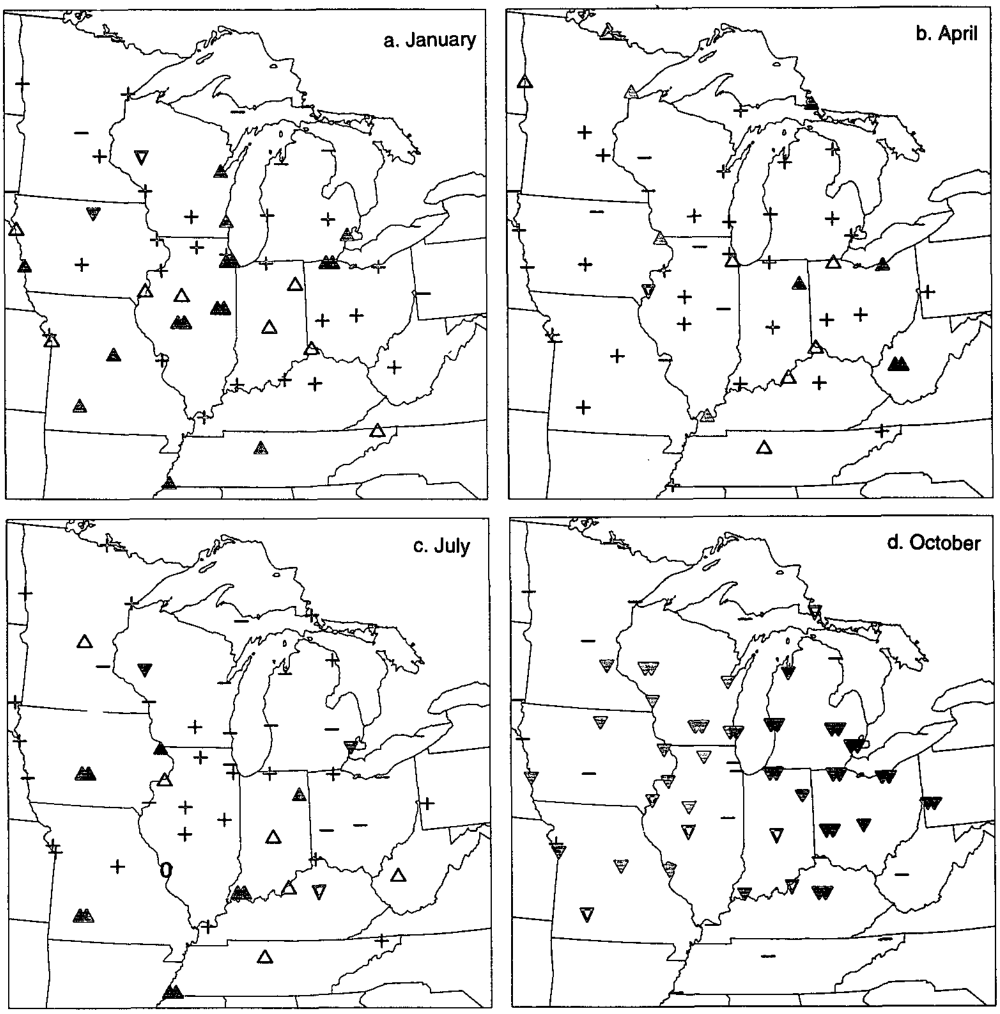

FIG. 3. Spatial patterns of SR trends for 1945–91 for midseason months. Symbols for each station indicate sign and statistical significance of slope of linear regression lines fitted to time series of individual monthly mean SR values. Positive trends whose statistical significance are <90%, 90%–95%, >95%–99%, and >99% are denoted by +, △, ▲, and ▲▲, respectively. Counterpart negative trends are denoted by −, ▽, ▼, and ▼▼, respectively. Zero indicates no trend.

dered somewhat uncertain by data availability and reliability. The model implemented here, to avoid these data problems, estimated daily SR using standard hourly meteorological observations (surface atmospheric pressure and dewpoint temperature; cloud height and fractional sky cover by layer) as well as time of day, day of year, latitude/longitude, and the daily presence/absence of snow cover as input. Because of an extensive effort to interpolate for missing input (especially cloud) data, the daily SR set generated was 92% complete for 1948–91 for all 53 stations, and 99% complete for the 43 stations with continuous hourly meteorological observations that commenced during 1945–50 and extended through 1991. Consistent with Meyers and Dale (1983), the model validated favorably against sets of daily SR measurements from (three) contrasting parts of the study region, and so its output was used here without adjustment.

Several atmospheric science–oriented analyses of the dataset documented the basic Midwestern spatial and temporal SR variability since the mid- to late 1940s. The spatial variation of calendar monthly mean SR was dominated by a near-meridional (northeastward) decrease in fall and winter. However, this fundamental pattern was found to be substantially perturbed from midspring through summer by subregional-to-mesoscale variability around and across the Great Lakes. Time series of individual monthly station mean SR values exhibited a pronounced, regionwide, 1945–91 downtrend for August–November. This decline was strongest (∼12%) and most statistically significant (>99% level) for October in a belt extending east-

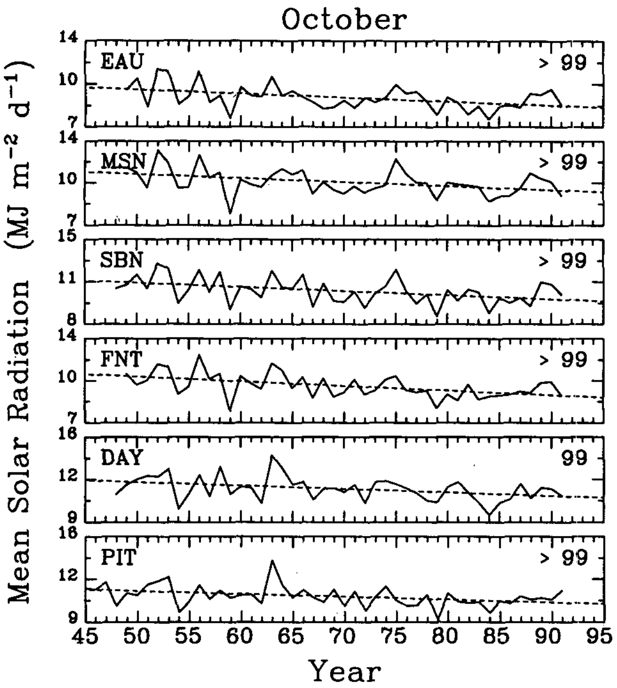

FIG. 4. Time series of individual October mean SR values (solid lines) for selected stations for 1945–91 and their associated linear regression fits (broken lines). Statistical significance of regression line is indicated in the upper right of each panel (%). Three-letter station identifier is in the upper left of each panel (see Table 1 and Fig. 1).

southeastward from west-central Wisconsin across southern Lake Michigan and western Lake Erie to western Pennsylvania. In contrast, the SR trends for December–July were largely positive but of lesser spatial coherence, temporal consistency, and statistical significance. The most distinctive of these SR results invite synoptic and larger-scale inquiry into their origin.

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