SOLAR RADIATION DATA SOURCE FOR OPERATIONAL ESTIMATION OF POTENTIAL EVAPORATION

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ABSTRACT

Daily estimation of solar radiation is an important intermediate step used to compute Potential Evaporation (PE) in hydrologic models. The National Weather Service (NWS) requires it in support of operational river forecasts for flood and water supply prediction. Solar radiation is presently estimated by NWS using sky cover observations in a method developed by Thompson (1976). Sky cover has been widely available in the past, however, the number of NWS sites with recorded sky cover is expected to decrease significantly in the near future. Current manual weather observations will be taken by the new NWS Automated Surface Observing System (ASOS). It appears that manual sky cover observations cannot be duplicated by the ASOS sensors. Therefore, the requirement for sky cover observations as an input for daily river forecasts will not be filled. Another reasonable method for estimating solar radiation to compute PE must be identified for computing real-time operational estimates of PE. Several options have been identified and investigated. Satellite estimates of solar radiation (SATRAD) provide the greatest data availability with the least error for operational estimation of PE. SATRAD can be obtained on a nationwide basis for use with the Penman equation. The use of SATRAD should produce PE estimates that are comparable to those based on direct measurements of solar radiation. We recommend that satellite estimates of solar radiation should replace other methods of estimating radiation for use in PE computations.

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INTRODUCTION

Forecasts of river flows to support the issuing of flood watches and warnings and/or for projections of water supply are made daily by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS). These forecasts are produced for over 3000 points throughout the United States. For many areas of the country, daily estimates of evapotranspiration (ET) are needed as input to the rainfall/runoff models. Daily estimates of solar radiation, along with other weather observations, are used to compute potential evaporation (PE) required for estimating ET. The PE estimates are obtained by using the Penman equation (Penman, 1948), which require as input air temperature, dewpoint temperature, wind speed, and solar radiation. Solar radiation is presently estimated based on sky cover observations using a method developed by Thompson (1976).

Sky cover is observed manually at over 250 synoptic stations around the country. However, sites where sky cover is recorded are expected to decrease significantly in the very near future. In general, weather observations that are now taken manually will be taken by the new NWS Automated Surface Observing System (ASOS). An automated measurement of total sky cover was initially planned for ASOS, but it now appears that the manual observation cannot be duplicated by the ASOS sensors. Therefore, the requirement for sky cover observation as a daily input for estimating PE will not be filled. Therefore, it is apparent that another reasonable method for estimating solar radiation to compute PE must be identified for computing real-time operational estimates of PE. In order to select a substitute method, the following questions must be answered. First, what options are available? Second, how will new observing systems and their resulting values impact the accuracy and/or the timeliness of the reported solar radiation and ultimately the ET estimates? What limitations will result from the change? Third, how will changes influence operational forecasts derived from models with calibrated parameters which were fixed using observed sky cover as an input to obtain estimates of PE?

POSSIBLE OPTIONS

Several options have been examined to address the need for an alternative means of estimating solar radiation in the future. One option would be to continue manual sky cover measurements. There have been some requests by climatologists to retain personnel to make some manual observations at ASOS sites. A second option would be to find an alternative source of sky cover estimates. Estimation of solar radiation using percent sunshine would be a third option. A fourth option would be to find a source of daily solar radiation which could be used directly in the Penman equation. NWS staffing plans do not support the first option of continuing manual sky cover observations at ASOS sites. The other three options, however, will be addressed in more detail.

An alternative source of sky cover estimates (option 2) has been developed by the NOAA National Satellite, Data, and Information Service (NESDIS). A method has been developed which determines sky cover from satellite imagery obtained through the Geostationary Operational Environmental Satellite (GOES) satellite using a procedure developed by Dr. Paul Menzel at the University of Wisconsin (Menzel and Strabala, 1989). This procedure estimates sky cover by combining satellite estimates of cloud cover over 12,000 ft above sea level (ASL) with ceiliometer estimates of cloud cover from the surface up to 12,000 ft ASL.

Each observation used for estimating PE has its own inherent errors. The NESDIS procedure involves adding yet another observation to a procedure for modeling sky cover to estimate solar radiation which would in turn be used to estimate net radiation as an input for estimating PE. This raises questions that are difficult to address. The uncertainty in the ultimate estimation of ET is compounded by unique sets of observational and theoretical errors for each intermediate value used with little verification possible for any of them. Therefore, this option has not been selected.

The third option, the estimation of solar radiation using percent sunshine, is a procedure which has been successfully used in the past, but is currently limited by the lack of readily accessible data. The technique that has been used by NWS is one developed by Hamon, Weiss and Wilson (1954).

The fourth option examined is a technique developed by NESDIS over 10 years ago. This method estimates solar radiation from GOES satellite imagery. This option offers several advantages. There is at least a 10 year overlap in the data. Also, these estimates are for an area rather than a point. The areal estimates consist of grid squares 1 degree latitude by 1 degree longitude which cover the contiguous 48 United States and could be used to estimate PE wherever the ancillary data needed as input to the Penman equation (air temperature, dewpoint temperature, and wind speed) were available. The areal extent for this estimate is emphasized because its application in hydrologic forecast models is for river basins rather than discrete points.

To summarize, the alternatives appear to be as follows:

1) To continue the present use of sky cover measurements which would be manually observed at a very limited number of ASOS sites and extrapolated to areas of interest.

2) To use an alternative method of estimating sky cover such as one developed by NESDIS which estimates sky cover from a combination of satellite and ground observing systems.

3) To arrange to access the percent sunshine data to estimate solar radiation using the Hamon, Weiss, and Wilson method as has been done in the past.

4) To access and use gridded NESDIS estimates of solar radiation developed directly from GOES satellite images.

Because of the reasons previously cited, the first two alternatives have been rejected. Solar radiation estimates from alternatives 3 and 4 will be further analyzed.

USE OF PERCENT SUNSHINE FOR ESTIMATION OF SOLAR RADIATION

Minutes of sunshine have been and are currently recorded at various sites. At stations where pyranometer measurements of solar radiation have not been available, solar radiation estimates based on percent sunshine have often been used in the Penman equation to obtain approximations of daily potential evaporation. In the sections that follow, the term percent sunshine is frequently used and its use implies percent sunshine based on minutes of sunshine.

In the past, percent sunshine was used where available to estimate solar radiation, but has almost ceased to be used in recent years because these data have not been available on the same operational or historical data sets with the other synoptic data needed to estimate PE. The NWSRFS currently uses sky cover observations with few exceptions for real-time operations. This switch has introduced problems in operations because model parameters for some basins were derived in calibrations using solar radiation estimated from percent sunshine and yet operationally use sky cover estimates of solar radiation.

If percent sunshine were to be used in the future in NWS operations, several questions would have to be answered.

1) How will the implementation of ASOS affect the measurement of percent sunshine (location, consistency, data accessibility, and continuity)?

2) How does the accuracy of current techniques for estimation of solar radiation from percent sunshine compare with other sources of solar radiation estimates?

Plans for ASOS include the development of an automated sunshine sensor. The timeline for implementation of this sensor is uncertain at this time. An automatic sunshine sensor would create the additional problem of needing an overlapping period of data to determine whether observations from the new sensor were consistent with the old observations. Currently, daily total sunshine measurements are made at 138 observing sites in the U. S. which will receive ASOS. With the commissioning of ASOS sites over the next several years, it is unclear how many of those sites will continue to collect observed minutes of sunshine. As long as NWS personnel are available to record sunshine data on site, those measurements will be obtainable, but there is a possibility that a gap in data collection could exist for individual stations. When automated sensors are implemented, data accessibility should improve.

The accuracy of the Hamon, Weiss, and Wilson technique has been investigated by using 15 stations scattered throughout the contiguous 48 states which, for the period 1965 to 1974, observed both percent sunshine and pyranometer data (Table 1). These data were compared with concurrent data from sky cover observations (Lindsey and Farnsworth, 1993). Both the bias and the daily RMS of the solar radiation estimates from percent sunshine (SUNP) are better than those estimated from sky cover (SKYRAD). The long-term means of solar radiation from percent sunshine were on the average unbiased relative to the pyranometer data while estimates of solar radiation from sky cover for the same stations and period of record were 10 percent low. Similarly, the daily RMS error averaged 19.4 percent for the SUNP estimates while the error of the SKYRAD estimates averaged 28.0 percent. The RMS error of the SUNP estimates ranged from 14 to 35 percent, which is better than those from the SKYRAD estimates (19 to 41 percent), but can lead to considerable variability in the calculation of daily PE.

When solar radiation estimates using percent sunshine are used to calculate PE in the NWSRFS, care must be taken to ensure consistency between the estimation procedures used in calibrating basins and those used for operational activities.

SATELLITE ESTIMATION OF SOLAR RADIATION

Description of the NESDIS Model for Estimating Solar Radiation

An operational system for estimating solar radiation was developed under the Agricultural and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) program which estimates daily total radiation for a horizontal surface. Up to 7 images each day are sampled for agriculturally important regions of North, Central, and South America. Daily estimates are made on a 1° x 1° latitude-longitude grid. The NESDIS solar radiation estimation model was developed by regressing observed solar radiation measured with pyranometers against visible radiance from the Visible and Infrared Spin Scan Radiometer (VISSR) on the GOES satellite (Tarpley, 1979). The daily estimates are based on 6 different observations taken during the day and cover the contiguous 48 states (Justus and Tarpley, 1983).

Errors Associated with the GOES Solar Radiation Estimates

There are two recognized limitations to these estimates. First, since the satellite estimate of solar radiation is based upon radiation reflected from highly reflective cloud surfaces, it suffers a significant loss of accuracy when used over grid square areas that are largely covered with water or snow (Justus, Paris and Tarpley; 1986). In fact, NESDIS does not compute estimates for grid squares that are primarily covered by water. Second, the NESDIS procedure tends to underestimate radiation on clear days.

The impact of errors introduced by snow cover on PE estimates will be minimal in most cases for the following reasons.

(1) Evaporation is very minimal in the winter and is further suppressed by snow cover.

(2) The presence of snow results in a high reflectivity which causes the solar radiation estimation model to respond as if the sky were cloudy. On clear days, this effect yields a low value of solar radiation. The low estimate of solar radiation results in a reduced estimate of potential evaporation. However, the assumption that solar radiation is correlated with net radiation assumes that the reflectivity of the ground surface remains rather constant. This assumption is significantly in error when the ground becomes snow covered. Net radiation, which is the required radiative constituent of the Penman equation, is significantly reduced by snow cover. The overall result is that the snow causes a significant reduction in the net radiation thereby reducing the estimated PE. Thus the error in the satellite estimate of solar radiation caused by snow moves the PE estimate in the direction that it would take if directly observed net radiation were used in the Penman equation.

One case where the errors introduced by the presence of snow may not be minimal is the effect of solar radiation estimates in mountainous areas late in the melt season (primarily May and June). Significant snowpacks can accumulate in mountainous areas and persist into the season when evapotranspiration becomes a significant component of the water balance. Underestimating solar radiation and therefore, PE, could introduce unacceptable errors into a rainfall/runoff model. However, at this time, this NESDIS solar radiation estimation procedure may be the only one available for basins in mountainous areas, and it appears that this will continue to be the case.

The limitation posed from receiving no estimates of solar radiation from the satellite for grid squares that are largely covered by water presents a challenge. This very problem prevented estimation of solar radiation for the exact latitude/longitude coordinates for New Orleans, Louisiana. This is illustrated in Table 2, which shows a comparison of estimated mean daily solar radiation values for the period from 1983 through 1988 for all of the stations for which NWS currently computes sky cover data. The SATRAD values at a lat/long of (30,90) were all zeros. As a test, SATRAD values at the grid square to the north of New Orleans (31,90), were compared with SKYRAD values at New Orleans. This appears to give a valid substitute for solar radiation at New Orleans. In general, sites falling in grid squares with large bodies of water would need to be examined on an individual basis to determine if adjacent grid squares could be substituted to obtain a valid estimate of solar radiation.

The effect of underestimation on clear days and overestimation on cloudy days is shown in Figure 1 where daily solar radiation is plotted for Jackson, Mississippi for the year 1983. SATRAD estimates are generally below the SKYRAD estimates for clear days and higher than values of SKYRAD on the very cloudy days. The differences observed in Figure 1 can also be explained by understanding that the SATRAD values are averaged over a 1x1 degree grid cell. This tends to lower the highest values and raise the lowest values.

COMPARISON OF SATELLITE ESTIMATES WITH OTHER SOURCES OF SOLAR RADIATION

Monthly estimates of solar radiation using the NESDIS model have been found to be accurate to within 5 percent (Justus, Paris, and Tarpley, 1986). Past studies have indicated that the model has a negative bias of 3 percent on clear days and a positive bias of 3.5 on cloudy days during the snow-free season (Klink and Dollhopf, 1986).

In Table 3 it should be noted that the mean solar radiation estimated using the satellite estimation (SATRAD) procedure is about 7 percent higher than that estimated from sky cover (SKYRAD). SKYRAD estimates of solar radiation have been shown to average approximately 9 percent lower than pyranometer measurements (Lindsey and Farnsworth, 1993). A comparison of both SKYRAD and SUNP to pyranometer data for 15 stations is shown in Figure 2 and illustrates the bias in SKYRAD. Table 3 shows a comparison of SATRAD to SKYRAD for each of the stations with sky cover available on a monthly basis from 1983 to 1988.

The daily ratios of SATRAD to SKYRAD show a fair amount of variation. Figure 3 shows a frequency plot of the daily ratios at Memphis, Tennessee for 1984. The spread in the daily ratios does not necessarily indicate that the SATRAD varies substantially from the true solar radiation. Comparing the satellite estimates of solar radiation to pyranometer measurements, Justus et al. (1986), found daily rms errors ranging from 5 percent to 12 percent for regions scattered around the United States and Canada. Klink and Dollhopf (1986) found a daily rms error of 5 percent to 15 percent for a study in the midwestern United States. Lindsey and Farnsworth (1993) showed the RMS error of the estimate based on sky cover data compared to the daily observed solar radiation ranged from 20 percent to 40 percent with an average of 28 percent for 15 stations. Thus SATRAD is likely to be closer than SKYRAD to the value measured with a pyranometer both on the average and on a daily basis.

Users wishing to develop time series longer than 10 years must currently go back beyond the available SATRAD observations. This means that a single time series would be derived from two different sources of observed data.

In order to see whether the estimates from SKYRAD and SATRAD are consistent with one another (have a constant relationship), a double mass plot of solar radiation estimates was constructed. This consistency plot was developed using daily accumulations. When data from independent observations are inconsistent, significant changes in the slope of the lines appear. Figure 4 shows estimates of accumulated SKYRAD based solar radiation at individual stations plotted against the group mean of 25 stations from January 1977 through 1988. Midway through this period (1983), solar radiation based on SATRAD became available and is shown on the plot. The plot suggests that a single correction factor could be used to adjust the SATRAD values, making them consistent with the SKYRAD data and allowing the SATRAD values to be used in models whose parameters were calibrated using SKYRAD.

The ratio of mean annual values of SATRAD to SKYRAD in Table 2 for 30 stations is 1.07. Table 3 shows the monthly mean values for each of the 30 stations in Table 2. From Lindsey and Farnsworth (1993), the ratio of SUNP to SKYRAD is 1.08. Because SUNP gives an unbiased estimate of solar radiation, and the ratio of SUNP to SKYRAD is very similar to that of SATRAD to SKYRAD, we can infer that the change from the use of SKYRAD to the use of SATRAD will improve the PE estimates to be nearly unbiased.

CONCLUSIONS

Solar radiation estimated from the GOES satellite provides the greatest data availability with the least error for operational estimation of PE. These satellite estimates of solar radiation can be obtained for use with the Penman equation on a nationwide basis. Use of satellite based solar radiation is preferred for two basic reasons. The first is that the satellite estimates have a lower daily rms error than the solar radiation estimates based on percent sunshine. The percent sunshine data do produce better estimates of solar radiation than techniques using sky cover, but the satellite estimates are more accurate with daily rms ranging from 5 to 12 percent. Second, the uncertainty regarding data accessibility surrounding the continued measurement of percent sunshine makes that option less desirable. Although at some point an automatic sensor will be included at ASOS sites, the problems of maintaining data consistency during the transition from current data collection methods to implementation of ASOS and again from the current sensor to an automatic sensor have not yet been fully addressed.

Based on accuracy and data availability, we recommend that satellite estimates of solar radiation should replace other methods of estimating radiation for use in PE computations. The use of satellite estimates of solar radiation should produce PE estimates that are comparable to those based on direct measurements of solar radiation.

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Table 1. Comparison of daily solar radiation from pyranometers (MEAS) with estimates from percent sunshine (SUNP). Fifteen stations with 8 to 10 years of data were used.

Station Name	MEAS	SUNP	RMS	% RMS
Atlanta, GA	360.1	377.1	64.7	14.1
Boise, ID	403.1	376.7	56.8	20.1
Boston, MA	341.4	295.7	68.5	36.0
Burlington, VT	296.4	347.8	106.6	19.4
Cape Hatteras, NC	388.7	366.7	75.5	18.9
Charleston, SC	396.1	392.5	74.7	14.7
Greensboro, NC	361.6	360.6	53.0	22.5
Knoxville, TN	346.1	352.0	77.9	18.0
Lansing, MI	331.5	334.6	59.7	23.5
Little Rock, AR	376.2	399.2	88.4	14.5
Madison, WI	334.5	346.8	48.4	19.2
Portland, ME	315.8	339.3	60.6	23.0
Seattle, WA	309.6	314.1	71.3	14.4
Slt. St. Marie, MI	318.1	322.0	45.8	15.3
Tampa, FL	441.8	441.0	67.5	19.2
Average Values	354.7	357.7	68.0	19.4
Ratio SUNP/MEAS		1.00		

Table 2. Comparison of solar radiation values. SATRAD values are NESDIS estimates while SKYRAD values are from SYNTRAN (calculated using sky cover). All values in Langleys for 1983 to 1988.

Station Name	SATRAD	SKYRAD	SAT/SKY
Fort Smith, AR	359.6	349.4	1.03
Baton Rouge, LA	381.6	355.9	1.07
Springfield, MO	352.1	340.5	1.03
Newark, NJ	325.3	265.9	1.22
Allentown, PA	309.5	282.2	1.10
Knoxville, TN	351.9	349.0	1.01
Memphis, TN	368.5	361.7	1.02
Mobile, AL	385.0	364.9	1.06
Nashville, TN	350.6	344.9	1.02
Shreveport, LA	382.7	346.4	1.10
Little Rock, AR	369.8	354.9	1.04
Washington, DC	336.5	315.2	1.07
Wilmington, DE	321.1	295.6	1.09
Meridian, MS	380.5	342.6	1.11
Bristol, TN	335.3	333.3	1.01
Chattanooga, TN	358.9	340.7	1.05
Binghamton, NY	287.1	261.5	1.10
Bradford, PA	285.5	247.5	1.15
Philadelphia, PA	329.8	291.6	1.13
Richmond, VA	348.1	336.6	1.03
Roanoke, VA	345.2	332.6	1.04
Asheville, NC	358.7	345.9	1.04
Paducah, KY	358.8	344.4	1.04
Huntsville, AL	361.5	336.7	1.07
Lake Charles, LA	390.2	353.8	1.10
Jackson, MS	381.7	353.6	1.08
Harrisburg, PA	309.6	288.5	1.07
Wilkes-Barre, PA	303.4	255.7	1.19
Williamsport, PA	301.0	260.5	1.16
New Orleans, LA	386.5	338.3	1.14
Average of 30 Stations	347.20	323.01	1.07

Table 3. Comparison of solar radiation estimates derived from GOES satellite pictures (SATRAD) with estimates derived from sky cover (SKYRAD) by month for 1983-1988.

Sta. #	3812		3816		3856		3937		3940	
Name	Asheville		Paducah		Huntsville		Lake Charles		Jackson	
State	NC		KY		AL		LA		MS	
Lat.	35		37		35		30		32	
Long.	83		88		87		93		90	
	SATRAD	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**
Jan.	203.0	198.6	157.9	164.5	183.4	181.0	227.9	210.3	213.0	198.5
Feb.	246.4	222.1	206.2	206.7	236.0	208.8	274.5	247.6	256.4	229.8
March	349.2	321.1	335.4	299.1	336.8	300.9	384.4	342.4	386.5	345.5
April	427.3	417.9	425.6	420.3	422.6	406.1	453.8	410.5	449.7	433.4
May	481.2	454.2	502.2	463.3	479.5	428.1	509.3	435.0	505.0	444.7
June	518.4	498.8	557.4	502.0	541.6	475.3	534.7	462.8	534.6	481.2
July	499.9	482.6	555.8	505.4	530.0	486.8	523.1	470.6	525.6	481.3
Aug.	457.9	420.8	499.6	476.5	495.2	444.6	496.1	452.4	486.9	440.7
Sept.	404.9	395.5	422.7	406.8	422.3	407.9	446.1	413.2	449.6	428.8
Oct.	316.1	319.8	301.4	308.1	314.2	312.0	372.4	348.9	342.5	330.4
Nov.	227.3	228.0	204.4	204.0	223.0	219.1	272.0	253.0	253.9	238.4
Dec.	193.9	191.5	164.4	175.7	174.8	170.2	209.4	198.9	198.9	190.4
Totals	360.5	345.9	361.1	344.4	363.3	336.7	392.0	353.8	383.6	353.6

Sta. #	4725		4751		13739		13740		13741	
Name	Binghamton		Bradford		Philadelphia		Richmond		Roanoke	
State	NY		PA		PA		VA		VA	
Lat.	42		42		40		38		37	
Long.	76		79		75		78		80	
	SATRAD	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**
Jan.	107.6	102.8	107.6	93.1	143.9	134.5	167.4	180.0	173.3	172.5
Feb.	139.6	149.4	148.1	136.5	199.2	176.3	218.5	213.1	222.7	207.0
March	252.0	231.2	252.5	226.2	306.5	272.5	329.5	313.1	329.7	298.5
April	311.6	281.4	322.7	277.2	355.8	302.7	383.7	381.1	399.9	383.9
May	411.7	356.7	429.4	353.2	453.9	375.8	479.6	437.4	462.6	436.0
June	494.9	446.9	501.4	432.0	534.3	453.3	543.1	494.7	524.1	496.7
July	480.1	425.2	485.8	407.5	513.1	440.7	529.2	476.6	508.1	474.9
Aug.	442.7	389.8	435.1	354.3	479.1	411.8	476.9	448.1	463.8	443.9
Sept.	329.5	310.5	321.9	289.7	382.8	357.2	396.4	382.9	393.0	390.3
Oct.	226.5	220.2	214.0	197.1	271.7	263.7	292.9	311.2	298.5	310.8
Nov.	144.2	130.8	135.6	119.9	193.7	175.9	212.3	215.8	214.3	206.5
Dec.	104.2	92.6	94.6	83.1	153.5	135.2	167.2	185.2	172.6	170.8
Totals	287.1	261.5	287.4	247.5	332.3	291.6	349.7	336.6	346.9	332.6

Sta. #	13743		13781		13865		13877		13882	
Name	Washington		Wilmington		Meridian		Bristol		Chattanooga	
State	DC		DE		MS		TN		TN	
Lat.	39		40		32		36		35	
Long.	77		76		89		82		85	
	SATRAD	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**
Jan.	153.3	158.7	134.3	137.4	213.9	195.8	178.2	163.8	182.8	186.4
Feb.	202.3	196.9	169.2	181.1	259.5	226.3	222.7	193.6	235.7	217.0
March	313.8	290.1	292.6	276.4	383.1	327.1	328.2	297.2	332.4	312.2
April	364.9	347.0	351.4	305.4	452.5	424.2	393.8	385.3	423.2	411.9
May	467.6	414.0	448.3	376.5	501.9	431.6	437.2	443.2	489.3	452.9
June	531.0	476.7	525.5	463.5	532.3	459.7	497.8	513.8	543.7	494.8
July	525.8	465.8	513.0	452.1	532.7	462.1	483.0	491.5	515.1	476.5
Aug.	473.9	428.2	474.3	416.1	480.6	428.1	422.4	432.9	474.5	438.6
Sept.	391.0	375.6	375.4	361.4	440.6	410.4	384.9	396.2	411.1	392.0
Oct.	276.2	282.3	264.9	264.2	339.4	324.7	296.7	311.8	317.8	314.2
Nov.	199.7	191.0	186.4	174.6	252.0	233.1	221.1	205.7	223.5	218.6
Dec.	156.4	156.2	146.6	137.9	200.1	187.8	163.8	164.4	178.9	173.2
Totals	338.0	315.2	323.5	295.6	382.4	342.6	337.0	333.3	360.7	340.7

Table 3. (cont.)

Sta. #	13891		13893		13894		13957		13963	
Name	Knoxville		Memphis		Mobile		Shreveport		Little Rock	
State	TN		TN		AL		LA		AR	
Lat.	36		35		31		32		35	
Long.	84		90		88		94		92	
	SATRAD	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**
Jan.	168.5	174.9	189.5	196.8	226.9	227.2	217.3	204.0	190.5	200.6
Feb.	219.6	208.4	230.0	224.6	267.9	249.6	262.1	231.6	236.3	232.4
March	323.9	308.6	343.1	320.4	391.5	362.7	371.9	329.5	349.9	322.5
April	397.4	396.4	423.3	422.3	470.5	447.0	444.4	409.5	415.0	413.4
May	484.8	470.7	489.3	457.1	511.2	473.0	498.2	421.5	491.7	444.4
June	545.1	534.1	554.4	525.0	517.2	460.5	545.9	461.4	564.5	504.2
July	522.6	508.1	554.9	526.9	525.2	471.9	549.9	491.5	567.3	522.4
Aug.	477.6	462.6	509.2	490.9	464.5	431.4	523.9	472.3	511.6	486.9
Sept.	404.6	410.9	435.4	437.6	441.1	426.9	435.5	411.6	437.7	422.1
Oct.	307.8	321.6	321.6	326.8	354.2	356.6	330.3	307.3	306.9	305.7
Nov.	217.6	217.2	221.2	230.6	262.7	264.5	241.9	233.5	219.9	228.4
Dec.	172.3	174.7	169.0	181.3	210.3	207.2	190.6	182.8	165.2	175.8
Totals	353.5	349.0	370.1	361.7	386.9	364.9	384.3	346.4	371.4	354.9

Sta. #	13964		13970		13995		14734		14737	
Name	Fort Smith		Baton Rouge		Springfield		Newark		Allentown	
State	AR		LA		MO		NJ		PA	
Lat.	36		31		37		41		41	
Long.	94		91		93		74		75	
	SATRAD	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**
Jan.	188.6	193.6	221.2	211.2	169.5	181.6	144.4	124.5	131.3	126.9
Feb.	227.8	231.7	253.3	228.9	214.6	214.1	195.8	173.3	172.0	179.6
March	331.3	303.5	387.1	352.7	320.4	280.1	303.6	252.9	285.7	264.6
April	416.3	393.6	455.7	441.4	406.3	393.1	350.6	275.5	337.4	290.4
May	472.5	439.5	506.1	454.6	482.4	438.7	445.5	336.6	427.9	371.1
June	562.7	494.1	517.2	454.4	555.5	489.4	527.3	416.2	516.0	457.3
July	562.1	543.8	522.1	457.4	557.9	529.9	504.2	388.1	491.9	428.4
Aug.	503.9	499.3	475.8	433.8	506.3	490.3	476.2	373.0	464.7	397.4
Sept.	405.9	414.5	445.2	423.6	405.9	408.2	369.8	331.5	358.7	341.6
Oct.	290.6	294.0	356.8	358.7	273.9	283.7	258.8	240.4	249.5	245.9
Nov.	208.3	211.8	259.0	255.5	200.6	213.4	182.8	157.6	173.0	162.4
Dec.	164.3	172.9	201.3	198.6	150.2	163.5	144.0	120.8	133.9	120.3
Totals	361.2	349.4	383.4	355.9	353.6	340.5	325.3	265.9	311.8	282.2

Sta. #	14751		14777		14778		12916		13897	
Name	Harrisburg		Wilkes-Barre		Williamsport		New Orleans		Nashville	
State	PA		PA		PA		LA		TN	
Lat.	40		41		41		31		36	
Long.	77		76		77		90		87	
	SATRAD	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**	**SATRAD**	**SKYRAD**
Jan.	134.2	130.3	125.5	109.1	120.4	112.7	222.8	207.5	165.8	171.9
Feb.	161.1	175.1	162.6	151.9	158.4	154.7	257.0	238.8	221.4	206.5
March	287.1	271.4	273.0	233.8	272.0	244.5	380.4	356.4	324.8	296.3
April	345.4	304.7	327.8	272.4	332.2	274.3	454.3	434.8	406.2	403.2
May	445.7	379.6	427.6	347.5	427.3	357.0	496.8	445.0	459.1	442.4
June	516.7	461.8	509.8	420.1	512.1	439.0	485.9	387.8	532.2	497.9
July	514.9	451.9	484.6	395.0	491.7	425.1	490.6	408.0	546.8	527.7
Aug.	464.3	393.0	451.1	379.0	456.0	375.0	413.2	386.3	452.0	477.6
Sept.	369.6	350.7	349.0	314.2	348.3	295.0	412.7	396.6	425.8	435.6
Oct.	257.2	258.7	243.3	225.8	239.3	220.2	391.3	330.2	297.0	310.0
Nov.	182.8	165.4	162.6	136.7	160.3	128.8	236.2	257.3	206.3	201.1
Dec.	137.5	119.1	123.6	100.1	119.9	99.7	201.2	196.8	154.5	161.6
Totals	318.0	288.5	303.4	257.1	303.2	260.5	370.2	337.1	349.3	344.3

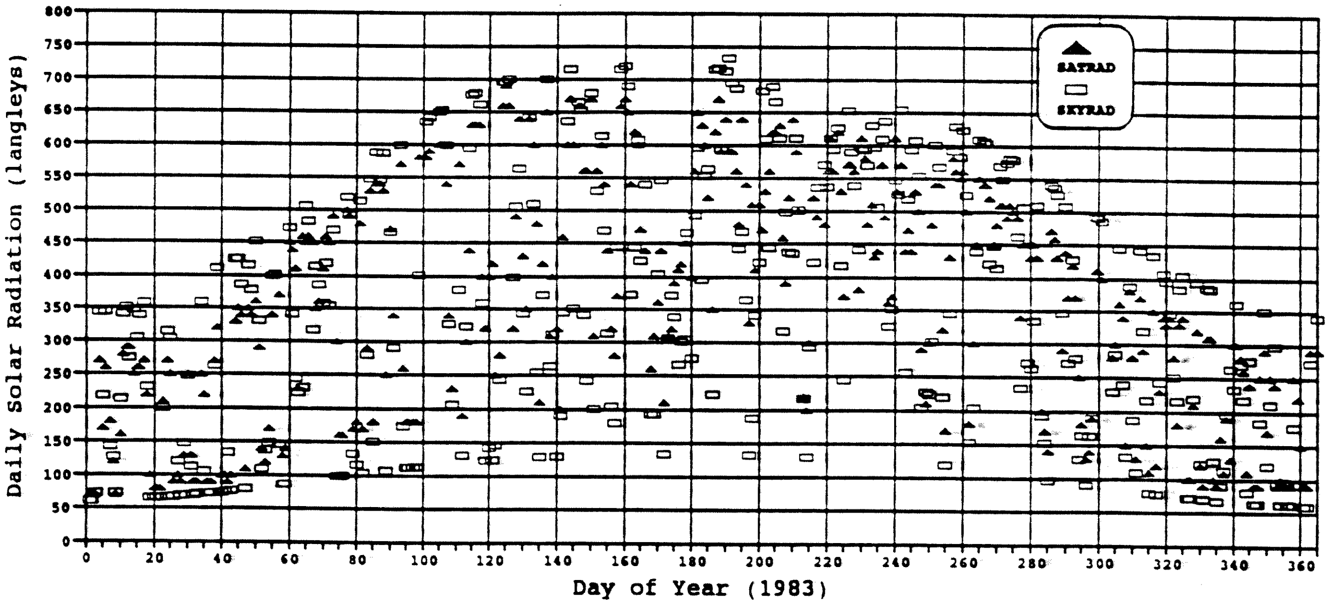

Figure 1. Comparison of daily solar radiation estimates using sky cover and satellite imagery at Jackson, MS for the year 1983.

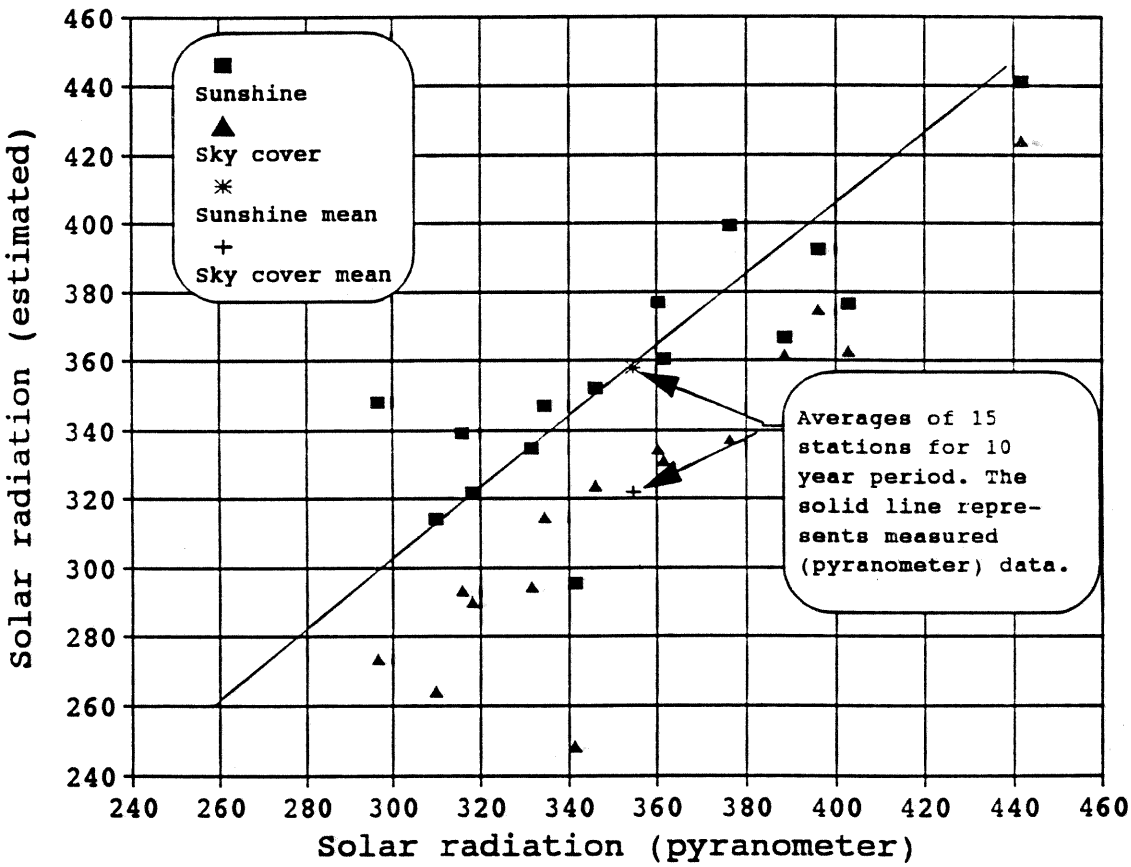

Figure 2. Comparison of estimated solar radiation values (from sky cover and from percent sunshine) to pyranometer data for 15 stations for the period 1965-1974.

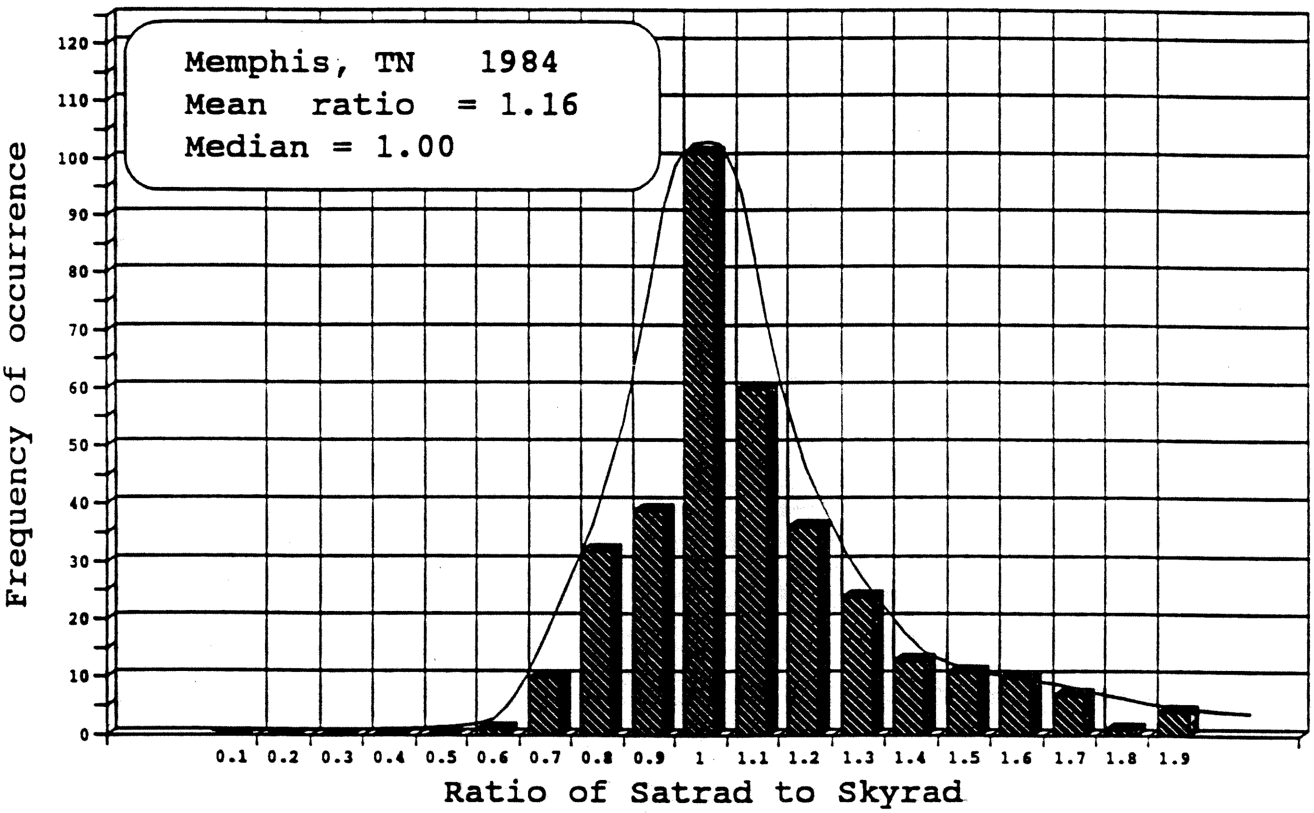

Figure 3. Frequency distribution of the daily ratios of satellite radiation (SATRAD) to sky cover radiation (SKYRAD) for 1984 in Memphis, TN.

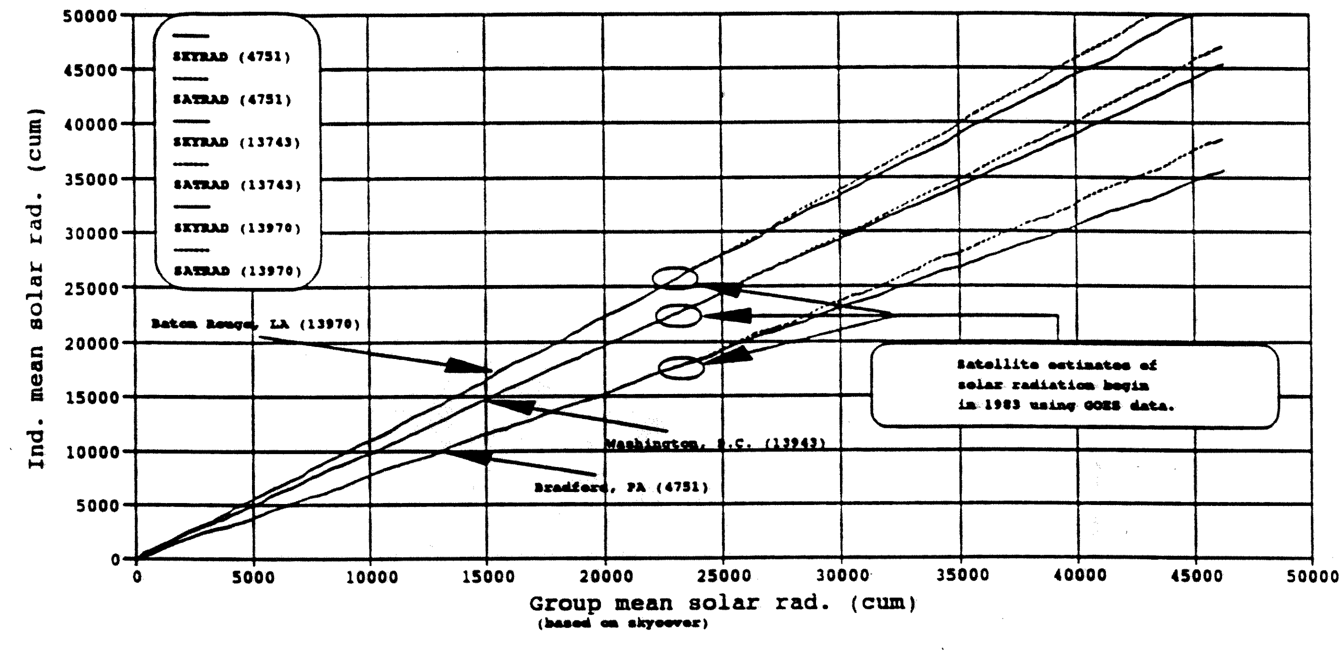

Figure 4. Double-mass plot of solar radiation from satellite and sky cover estimates. Sky cover radiation for selected stations shown for the period 77-88 with satellite data shown from 83-88.

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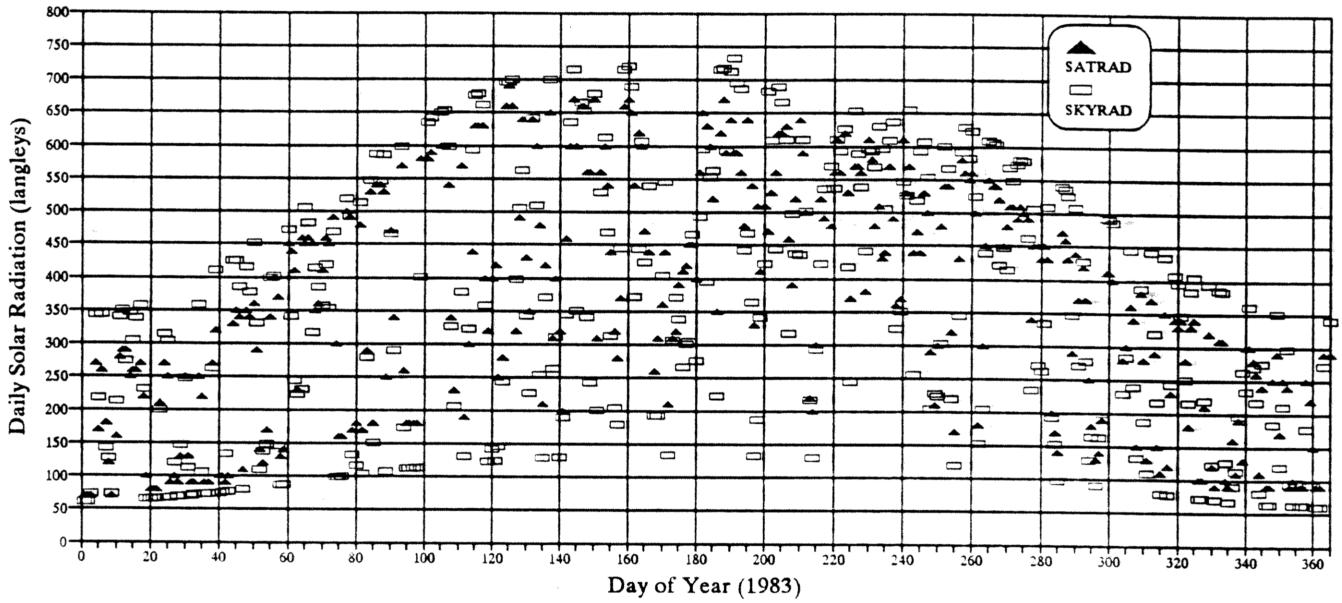
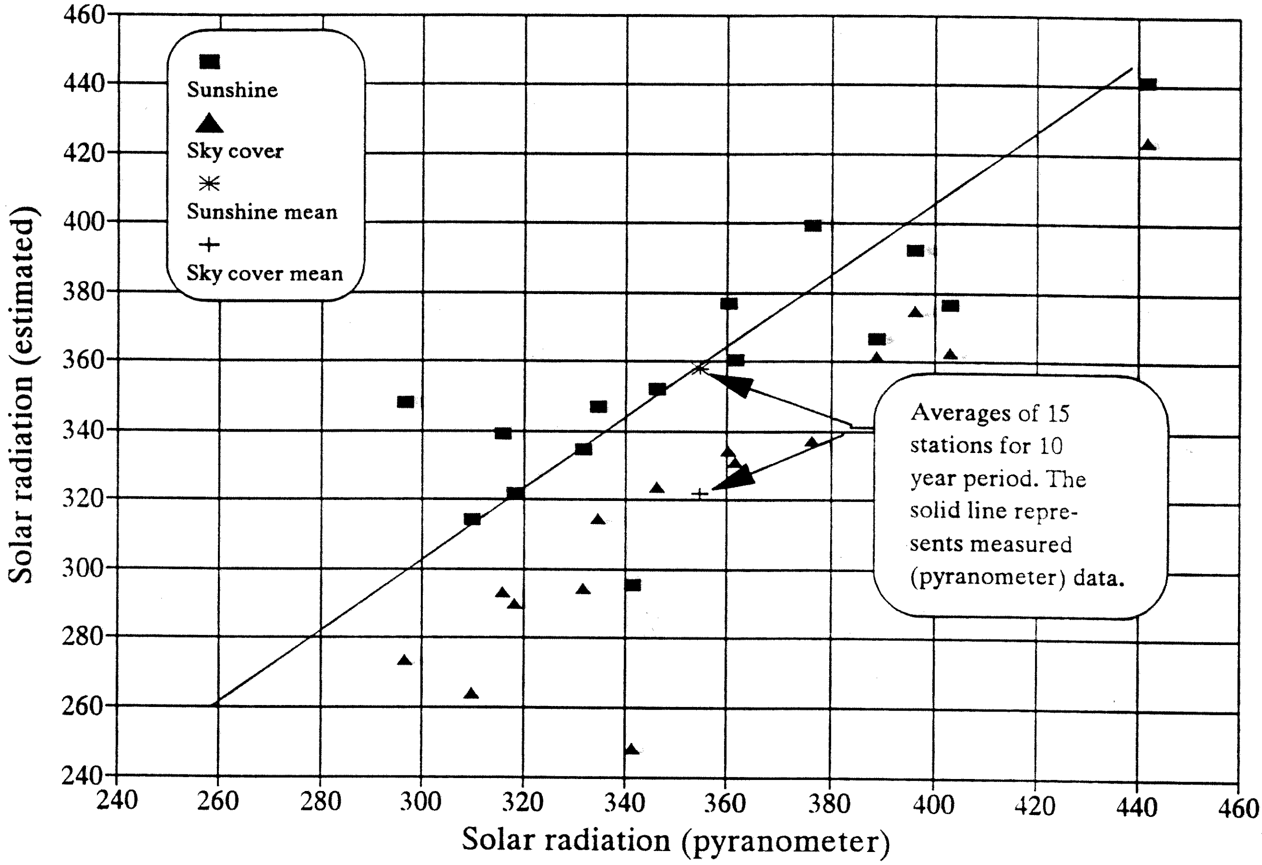
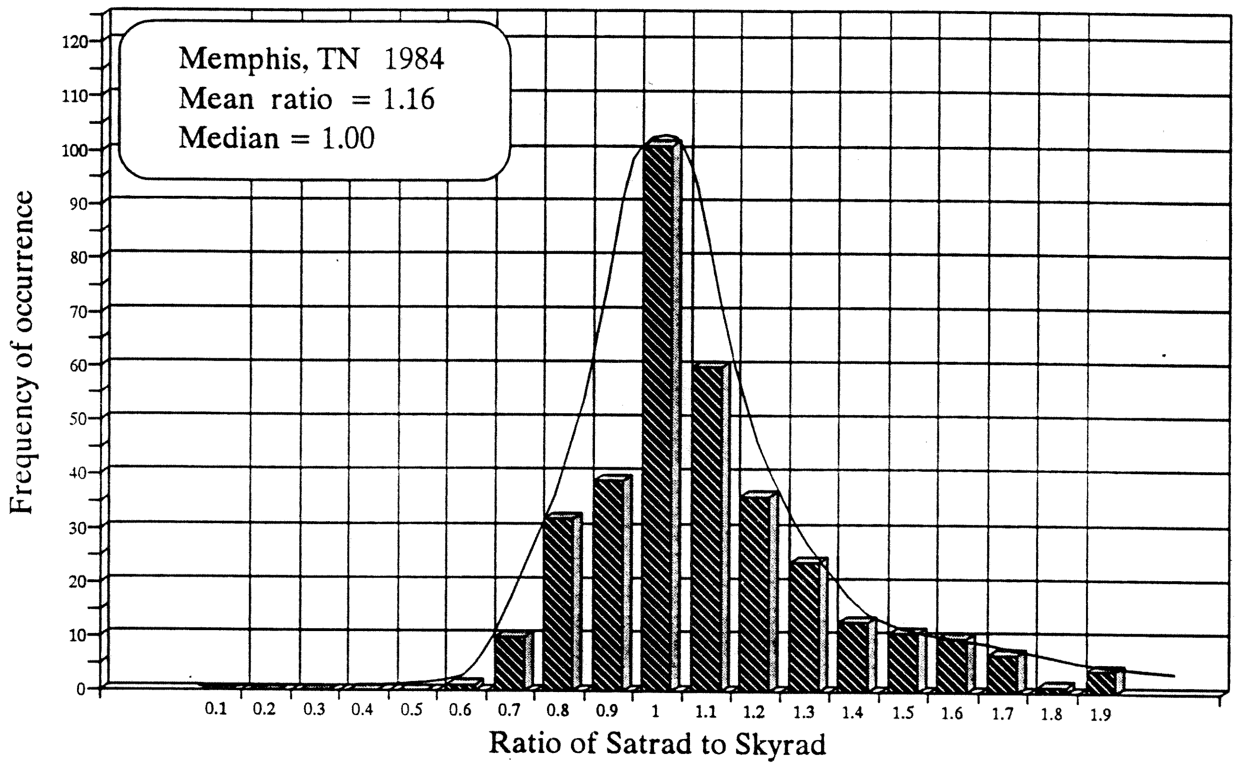


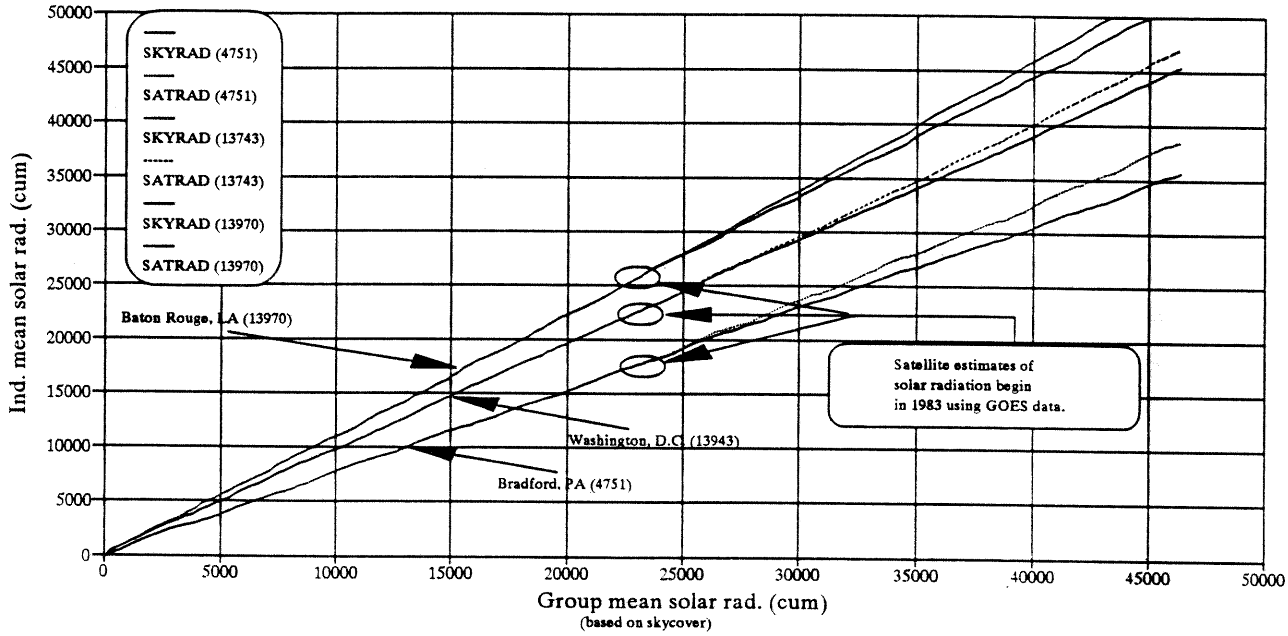
SATRAD
SKYRAD
Daily Solar Radiation (langleys)
Day of Year (1983)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360



Sunshine
Sky cover
Sunshine mean
Sky cover mean
Averages of 15 stations for 10 year period. The solid line represents measured (pyranometer) data.
Solar radiation (estimated)
Solar radiation (pyranometer)
240
260
280
300
320
340
360
380
400
420
440
460



Memphis, TN 1984
Mean ratio = 1.16
Median = 1.00
Frequency of occurrence
0
10
20
30
40
50
60
70
80
90
100
110
120
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
Ratio of Satrad to Skyrad



SKYRAD (4751)
SATRAD (4751)
SKYRAD (13743)
SATRAD (13743)
SKYRAD (13970)
SATRAD (13970)
Baton Rouge, LA (13970)
Washington, D.C (13943)
Bradford, PA (4751)
Satellite estimates of
solar radiation begin
in 1983 using GOES data.
Ind. mean solar rad. (cum)
Group mean solar rad. (cum)
(based on skycover)
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000