USE OF DAILY POTENTIAL EVAPORATION IN THE NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM

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ABSTRACT

The accurate estimation of potential evaporation (PE), to derive estimates of evapotranspiration, is an important step in many hydrologic models. The National Weather Service (NWS) has used daily estimates of mean evapotranspiration in continuous rainfall-runoff models for river forecasting. The daily PE estimates have been derived mainly from meteorological data gathered on a regular basis throughout the country. Solar radiation is one of the required input variables. Because of its widespread availability, sky cover is now used almost exclusively by NWS to estimate solar radiation. Over a period of time, a bias has developed between the long-term mean PE computed using historical meteorological data and PE estimated operationally using real-time data. This bias was traced to the use of sky cover for the solar radiation estimates. The bias results in long-term means for PE which are significantly lower than values using corresponding direct measurements of solar radiation or estimates of solar radiation using percent sunshine. A standard has been established and verified to which long-term mean PE can be compared. PE estimates derived from sky cover can then be corrected to the standard using a ratio of long-term means. This procedure can be utilized to use a variety of solar radiation inputs for estimation of PE in a consistent fashion.

INTRODUCTION

Potential evaporation plays an important role in making accurate forecasts of river discharge, which are a major service of the hydrology program of the National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS).

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Experience has shown that in many areas of the country, continuous hydrologic models are required. The primary importance of potential evaporation (PE) to the hydrology program of the NWS is as an estimator to predict evapotranspiration (ET), which in turn is used in hydrologic models.

Ongoing estimates of mean ET at the basin scale are critical to most of these continuous conceptual models. For example, the Sacramento Soil Moisture Accounting model (SAC-SMA), used operationally by several of the NWS river forecast centers (RFC), models the runoff from rainfall based on levels of soil moisture. ET significantly influences the amount of soil moisture computed by the model. The "observed" PE is used as an input variable to derive ET. Since the accuracy of the final river runoff prediction depends to some extent on each of the variables used in computations, input variables, including PE should be as accurate as possible. NWS models which are oriented to single events use PE as an initial condition to obtain an index to seasonal soil moisture levels. These models are also dependent on unbiased values.

Values of PE for input into either continuous or event models can be obtained from pan evaporation measurements or from meteorological data that are gathered on a regular basis at many locations around the country.

Methods developed by the NWS for estimating PE for use in their hydrologic forecast models appeared to provide good results during model calibrations. However, over a period of time, runoff volume errors in the operational forecasts at several RFCs were traced to some significant bias between long-term mean PE estimates from calibration and PE estimated operationally with real-time data for operational forecasts. Possible explanations for this bias include a difference in the procedure used for developing PE. The resolution of these differences is critical for hydrologic modelers who use PE. This study reports on the background development of these PE estimates, the investigation to identify the differences, and the resulting conclusions.

Methods of Determining PE and use of PE in Models

In the past, the NWS has used two primary operational methods for determining daily estimates of PE for use in real-time hydrologic forecasting. The first is to use pan evaporation estimates, which can then be adjusted by a pan coefficient to obtain free water surface or potential evaporation. The second estimates PE from meteorological data. The NWS estimation technique uses an equation developed by Penman (1948), which requires input observations of air temperature, dew point temperature, wind travel, and net radiation.

The NWS River Forecast System (NWSRFS), the operational forecast software used by the NWS, contains the algorithms for estimating PE. In this algorithm, PE estimates can be obtained for input to rainfall/runoff models in one of two ways. The first method uses daily estimates computed from meteorological observations using Penman's equation as previously described. If daily estimates cannot be obtained, the second procedure is to utilize a climatological mean annual curve. These annual curves are based on long-term mean PE values computed from pan and/or meteorological data.

GENERAL PROBLEMS IN ESTIMATING POTENTIAL EVAPORATION

Estimates of PE based on both evaporation pans and on the Penman equation have certain shortcomings which will be discussed. It is because of these shortcomings that neither of these sources is uniquely preferred.

Evaporation Pan Networks

Evaporation pans generally provide the best estimate of evaporation over extended periods because they provide a direct measurement of the variable. They do, however, have several limitations that prevent their direct use in many parts of the country and cause errors in daily estimates of evaporation.

The major limitation of evaporation pans occurs in regions where freezing weather occurs. The pans can operate for only part of the year because freezing can damage the pans. Also, the PE measured during the change between the liquid and solid states does not necessarily represent the mean PE in the area. A second limitation is the effect of precipitation. Pan observations must be adjusted by the amount of precipitation received. Often bias exists between the precipitation catch of the evaporation pan and that of the nearby monitoring rain gage. This bias is then transmitted to the amount of pan evaporation measured at the site. Furthermore, there are a variety of possible errors in setting up pan sites and in making daily observations that can introduce error into the evaporation estimate.

Once an observation is made from a standard pan, there is additional likelihood for error in computing potential evaporation when the observation is multiplied by a "coefficient" to correct for energy exchange between the water in the pan and the adjacent environment.

On the basis of all of the limitations listed, but primarily because pan observations are not continuous throughout the year in many areas, pan measurements of evaporation are generally not used by NWS to obtain operational real-time estimates of PE on a daily basis.

Daily Estimation of PE Based on Meteorological Observations

Operational estimates of daily PE used at the RFCs are almost always based on the Penman equation computations because of the previously mentioned problems associated with pan measurements. The Penman method combines aerodynamic and energy balance procedures such that observations of the temperature measured right at ground level, which are not commonly available, are not required. The required input variables are, as noted earlier, daily average air and dew point temperatures (measured at the instrument shelter level), wind travel, and net radiation. Daily values of air and dew point temperatures and wind speed are observed and reported at over 250 weather stations.

Daily means of air temperatures and dew point temperatures are generally obtained by averaging a number of instantaneous measurements to compute a daily mean. The instantaneous temperatures are assumed to be representative of the mean for the time intervals before and after each observation.

Wind travel can be estimated from the observed values of the wind speed by assuming that the observations on the hour represent the mean wind for the 30 minutes before and after the hour. However, a problem exists in the use of the observed wind speeds because the observing station anemometers are not all at standard heights above the ground. Furthermore, the anemometer heights at individual stations have often been changed various times during the period of record.

The wind travel used in the NWSRFS estimating equation for PE is specified as that which would be observed two feet above the ground surface, a height used only for anemometers installed over evaporation pans. Anemometer heights where PE is estimated have varied from a height of twenty feet above the surface up to as high as a few hundred feet. Therefore, observed wind speeds at these stations must always be adjusted to estimate an equivalent wind at the two foot level. Calculations are often used which assume the winds to increase exponentially with height above the ground. Based on this assumption, wind travel at a height two feet above the ground can be estimated by simply assuming a form of logarithmic distribution. However, because buildings and surface roughness can modify this distribution, a logarithmic profile using an empirical exponent has been derived based on data from stations where wind movement was observed at both two feet above the ground and at some other anemometer height. The higher level anemometer is usually the official instrument for reporting the observed wind speed at the station.

Net radiation is a difficult measurement to make on a routine basis. Solar radiation presents fewer problems and a national network of observing stations has existed for several decades. Net radiation over water is closely correlated with solar radiation because the albedo (or reflective characteristics of short wave energy from the water and pan surface below the water) is assumed to be relatively constant. Thus it is possible to develop empirical relationships to estimate net radiation for a water surface from solar radiation. These relationships are built into the Penman type equation used in NWSRFS to estimate PE.

While the direct measurement of solar radiation is preferred for estimating the net radiation input for computing PE, these measurements are rarely operationally available. The next level of preference in observed data are solar radiation estimates derived from hours of sunshine using the method developed by Hamon, Weiss, and Wilson (1954). Although there are more stations recording hours of sunshine than those which record solar radiation directly, the network is still limited and a movement toward automation of meteorological data collection leaves the availability of hours of sunshine data in question. However, there is a standard observation that exists that has some degree of correlation to solar radiation and is recorded at essentially all of the stations reporting real-time temperature and wind data to the NWS. That standard observation is sky cover. The estimation of solar radiation using sky cover follows a procedure developed by Thompson (1976).

Of the three sources of solar radiation used by NWS (direct measurement, estimation from minutes of sunshine, and estimation from sky cover), the least desired option is to estimate solar radiation from sky cover because of the subjectivity and the uncertainties involved in the manual observing procedures. But since it is the most readily available, it is generally the most used. Therefore, solar radiation is first estimated from sky cover or hours of sunshine. Then, various techniques are utilized which have been developed to convert solar radiation to net radiation. Finally, the Penman equation is used to estimate PE.

AVERAGE ANNUAL AND SEASONAL EVAPORATION

In the late 70's and early 80's, the NWS/Office of Hydrology (OH) staff developed long-term evaporation estimates for the United States. These estimates were further broken down into the annual average and the growing season average (May to October). For this project, 15 years of data (1956-1970) were collected and analyzed from as many sources as possible in the 48 contiguous United States. Even when all of the reporting pan stations were plotted, it was difficult to extrapolate the point estimates to many surrounding areas of the country. Therefore, estimates based on weather observations (using the Penman equation) were used along with interpolation schemes based on physiographic characteristics and topography to estimate values of evaporation in areas distant from pan stations. When all available data had been considered, isopleths of evaporation representing the best possible long-term estimates were drawn. These maps were published as NOAA Technical Report NWS 33 (NTR33) in 1982.

NOAA Technical Report NWS 34 (NTR34), also published in 1982, contains a comprehensive list of point PE data. These data cover the 15 year period used to produce the evaporation maps (1956 - 1970) for the PE estimates derived from meteorological data, and the entire period of record (to that time) for the pan data. The pan evaporation data and the PE estimates from meteorological data for various stations are given in terms of mean monthly, seasonal and annual evaporation in tabular form in NTR34 and can be used to develop mean annual curves for the included stations.

While computations from the Penman equation using observations from stations where both meteorological data and evaporation pans were maintained had been compared many times before with generally good agreement, the plotting of data from both pans and weather observations was considered a useful opportunity to check for regional biases between the two estimates. Therefore, the maps were analyzed with and without the meteorological data. The arithmetic difference between the two analyses is shown in Figure 7 of NTR33. Variations between the two methods were considered insignificant except in the southern part of the country between 100°W to 105°W, where the estimates based on the meteorological observations were significantly lower. This effect was duly but subjectively considered in drawing the isopleths on the map. However it is apparent that there is some significant part of the country where the estimates from pans are higher than those based on daily weather observations.

USE OF DAILY OBSERVED PE VERSUS MEAN VALUES IN FORECAST MODELS

As mentioned earlier, there are two ways in which PE estimates have been considered for use in NWS rainfall/runoff models. The first way is to use mean seasonal values and the second is to use computed daily estimates.

Climatological Mean Curves

In many cases long-term mean values of PE are used in NWS rainfall/runoff models to avoid the problems inherent in computing daily PE estimates for operational forecasting. This is done explicitly in the case of conceptual soil moisture accounting (SMA) models or implicitly in the case of most antecedent precipitation index (API) type models.

When explicitly using mean values, the seasonal variation in PE throughout the year is generally specified by the mean daily PE at the mid-point of each month. The monthly values are obtained from long-term averages of pan observations or from the values given in a NTR34 adjusted by the appropriate pan coefficient. The annual and seasonal means are checked against the map values in NTR33. Where differences exist, these values are adjusted to conform with the map values since much greater care went in to the development of the map values. The PE values are then multiplied by a value representing the seasonal changes in vegetative transpiration. The resulting curve represents potential ET, and is refined to account for available soil moisture during the modeling process. Factors which adapt the computed values to specific situations in the various basins are set during calibration.

Actual Daily PE Estimates

One of the major limitations in the use of a single annual curve is the wide variation of both evaporation and vegetative transpiration in the spring and fall of the year. Since these seasons appear to come early some years and late other years, significant errors in both potential evaporation and the resulting water budgets can occur during these times. Significant variations from the mean curve may occur, however, at any time of the year. During a rainy period in the middle of the summer, evaporation (and transpiration) is suppressed by lower temperatures and high humidity. In another year, hot dry periods may cause the PE to be very high. Both of these situations cause significant variation from the daily average curve. In addition, in some parts of the country there can be a significant variation in evaporation from one year to the next. For these reasons, daily estimates of PE, based on observed weather conditions, should provide an improvement in runoff calculations.

When used in NWS rainfall/runoff models, seasonal adjustment factors can be applied to the daily PE values to account for the variation in the activity of the vegetation. However, the seasonal adjustment curves currently used in NWSRFS models do not always account for variations in vegetation activity from year to year (e.g., trees leaf out at different times depending on weather conditions). Thus, without accounting for this effect, the amount of improvement that can be obtained by using daily PE estimates is reduced.

Comparison of Methods

In 1981, the NOAA/NWS/Hydrologic Research Laboratory (HRL) conducted a comparison using mean curves versus daily estimates in computing PE for use in the Sacramento Model. Mean curves were determined which gave the same long-term values as the daily PE estimates used in the original calibration of several basins. As a result of this study, advantages to using the daily values were judged to include:

1) Differences in PE from day-to-day are taken into account.
2) Deviations from normal PE lasting for weeks or months are included.

Disadvantages of using daily values were judged to include:

1) Inaccuracies in the meteorological variables used to compute PE primarily involving the relationship between sky cover or percent sunshine and radiation.
2) Operational inconsistencies that can arise because the data used to compute PE and the PE estimate itself are not frequently checked for consistency, thus possibly resulting in biased values.

The 1981 comparison study involved 3 basins: the Nuese River in North Carolina, the Leaf River in Mississippi, and Bird Creek in Oklahoma. When using daily PE estimates, the daily RMS error for these basins improved by 0.3, 1.7, and 5.3 percent and the monthly volume RMS error by 1.8, 5.0, and 29.0 percent, respectively. The standard deviation of annual PE for these areas was 23, 89, and 131 mm, respectively. Thus, the use of daily PE estimates didn't result in much improvement in a wetter and less variable climate like North Carolina, whereas the improvement was significant in a drier area with more variability in PE from year to year like Oklahoma.

The majority of the significant differences between the two methods occurred during sizeable rainfall events. This is an indication that differences between daily values of PE and the annual curve of PE during, and immediately following periods of precipitation are more of a factor than differences during the weeks or months preceding a runoff event. This study made very clear the necessity to monitor the daily inputs and parameters to insure consistency so that any advantages from using daily estimates of PE can be realized. Consistent biases in the estimation can potentially produce worse results than use of mean annual curves.

Evolution of System Software

Before the NWS developed their comprehensive system, NWSRFS, the typical means of obtaining PE estimates was to use the NWS version of the Penman equation with percent sunshine as the input to estimate radiation. As NWSRFS first began to be implemented, daily PE estimates were derived from interpolated values of monthly means which were often from derived from pan data.

Calibration and Historical Data Analysis

Basin calibration software, known as the Synoptic Data Preprocessing program (SYNDPP) was used to estimate PE during the late 70's through the 80's. Estimation of PE with this software continued to be based on the Penman equation. Input was obtained from standard station observations of air temperature, dew point temperature and wind speed. However, because of the variety of sensors located at various stations, the software derived the estimate of solar radiation from one of three possible sources. The preferred source of daily solar radiation was pyranometer data. Second in preference was solar radiation estimated from percent sunshine. When neither of those sources was available, the solar radiation was estimated from sky cover.

In 1990, a replacement software program, the Synoptic Data Transfer program (SYNTRAN), was developed to compute PE estimates for calibrations. The only source of daily solar radiation accessed by SYNTRAN is the estimate from sky cover.

Operational PE Estimates

In early versions of operational forecast components of NWSRFS, solar radiation was generally estimated based on observations of percent sunshine.

In the current version of NWSRFS, because of greater availability, solar radiation estimates are generally based on sky cover.

INTRODUCTION OF BIASES INTO THE NWS SYSTEM

Differences between Evaporation Atlas (NTR33) and SYNTRAN

In recent years, NWS forecasters and researchers have noticed that both the (1) operational PE estimates and (2) those used in basin calibration using current software have been significantly lower than those shown in NTR33. This negative bias was noticeable even for areas where estimates based on meteorological data were supposed to be similar to the atlas values. The daily estimates of potential evaporation were in the range of 10 to 15 percent lower than the atlas indicated. This situation inspired the study that forms the basis for this report.

SEARCH FOR SOURCES OF CHANGE IN THE PE ESTIMATES

When it became apparent that there was a significant and rather consistent difference between the potential evaporation values being used for calibration and those in the maps, HRL staff began to look into the entire issue of PE estimates. They determined that the following questions required answers:

1. Are the maps in the evaporation atlas (NTR33) reproducible? Can they serve as a standard or do they contain detectible errors?

2. If the maps are correct, can there be an error in operational MAPE, the program to compute PE?

3. When differences are found between the Penman equation estimates and the pan values, do the differences result from the Penman model or from differences in input data?

4. If the differences are caused by data, is it related to air temperature, dew point temperature, observed wind or conversions to observed wind, or is the primary difference related to estimates of solar radiation?

5. If the differences are data related, is the effect uniform or are there local variations that should be accounted for?

6. If the above problems can be identified, can we make corrections to adjust the data to make them as accurate as possible? If such corrections exist, can they be applied to basin calibrations of hydrologic models that have been completed so as to correct the problem with relatively little effort?

Comparison of Inputs

A review of techniques used to develop NTR33 highlighted the fact that measured solar radiation and hours of sunshine observations were used for estimating PE in approximately 65 percent of the 225 first-order stations which made up the data base. However, in the operational procedures MAPE program, *sky cover is generally used for all stations.*

FINDINGS

The following are significant results of the study:

1. The data and programs used to create the base data for the evaporation maps were found and samples were rerun. The sample runs support the soundness and stability of the maps.

2. Checks were made between the output results of different programs with nearly identical results using similar input data.

3. The effect of air temperatures and dew point temperatures on PE show insignificant variation between the monthly mean data used to create the map and use of daily data. There were no significant differences resulting from these variables.

4. The observed data and corrections applied to the wind observations seem consistent and do not seem to be a source of problems.

5. **When estimates of solar radiation are made from pyranometer observations, hours of sunshine, and from sky cover at stations where all three observations were made, there seems to be a significant bias which varies according to location.**

Estimates of solar radiation from fifteen stations are tabulated in Table 1. These stations are located mostly in the eastern and northern United States, and recorded solar radiation, hours of sunshine and sky cover for the period 1965 to 1974. The averages of all 15 stations are shown along with the ratios of the pyranometer divided by percent sunshine estimates and pyranometer divided by sky cover estimates.

On the average, the estimates of solar radiation based on sky cover were 10 percent lower than those based on the pyranometer observations. Estimates of solar radiation based on percent sunshine averaged the same as the pyranometer observations although some significant variation did occur. The daily rms error (the difference between sky cover estimates and pyranometer data) averaged 28 percent. Figure 1 shows the data for the 15 stations with solar radiation estimated from both sky cover and percent sunshine plotted against pyranometer data. It is evident that solar radiation estimates based on percent sunshine are consistently higher than those based on sky cover.

In addition, data from 48 stations where only percent sunshine (SUNP) and sky cover (SKY) were observed are tabulated in Table 2. This table shows the daily averages and the ratio of SUNP/SKY. These ratios range from 0.96 to 1.19 with the average value of 1.08.

6. There is no significant difference between the data observed from 1956 - 1970 (period used to generate the maps in NTR33) and the total period of record. Using SYNTRAN,

evaporation from 1956 - 1970 was divided by the total period of record for each station (generally 1948-1988). These values are found in Table 3 and illustrated graphically in Figure 2. It was found that there is a variation no larger than 4 percent and an average variation around 1 percent between the two periods. Thus there are no significant climatic trends in the data. However, when comparing the magnitude of the computed PE it was found that SYNTRAN (which uses sky cover exclusively) produced annual evaporation values that averaged 14 percent lower than the maps.

CONCLUSIONS

1. The evaporation maps in NTR 33 give acceptable estimates of seasonal and annual evaporation for the entire period of data available for use in NWSRFS. There is no long term consistent trend in evaporation (See Figure 3).
2. Evaporation estimates based on sky cover observations are biased low. Double mass plots (not shown) were made for some of the stations by plotting the accumulated PE using observed solar radiation against PE using solar radiation computed from sky cover observations. These plots showed solar radiation estimates from sky cover to have a consistent negative bias compared to observed solar radiation.

REMEDIAL ACTIONS REQUIRED TO COMPENSATE FOR BIAS

Having established that biases do, in fact, exist in the NWS data, the means of making corrections must be devised for assessing the errors introduced into basin calibrations and for correcting them. The presence of a bias in the PE values used in forecasting a watershed is not critical provided that the values used operationally for making river forecasts are consistent with those used in the calibration of that river segment. However, considering the historical evolution in the computation of PE estimates that has just been discussed, it is likely that the PE values used operationally are biased relative to the values used for calibration. Of course, this is only a matter of concern where rainfall/runoff models use daily PE estimates (as opposed to a mean annual curve).

General Procedure

In order to overcome this problem, it is recommended that all daily PE estimates be adjusted to meet a standard. The accepted standard recommended by NWS's Office of Hydrology is the long-term mean free water surface evaporation values shown on Map 3 of the NTR33 evaporation atlas. The daily PE estimates generated for existing PE stations by NWSRFS or similar programs can be adjusted to fit this standard by applying an appropriate factor.

An adjustment factor to correct previously calibrated watersheds is calculated by:

$$PEADJ = \frac{PE_{calb}}{PE_{33}}$$

where:

$PEADJ$ = Rainfall/runoff model PE adjustment factor,

PE_{calb} = the long-term mean annual value of the PE time series used during calibration, and

PE_{33} = the weighted standard PE from Map 3 of NTR33 for the stations used to generate the operational time series.

For watersheds that were calibrated using PE computed from sky cover using the NWS procedure, no adjustment is necessary, unless sky cover is not be used to estimate solar radiation operationally. For other cases, the value of PE_{calb} would need to be known in order to obtain the proper PEADJ value.Examples of factors for selected stations are given in Table 3. All new calibrations will then use PE estimates that meet the standard. If new methods or data sources are used in the future, no further changes will be needed as long as the new PE estimates meet or are corrected to meet the standard.

SUMMARY

The manner in which potential evaporation (PE) has been estimated for input to hydrologic models has evolved based on available meteorological data. For operational river forecasting in the NWS hydrology program, sky cover estimates of solar radiation to obtain PE are now the primary source available. However, other sources of solar radiation have been utilized in the past, particularly as input for PE estimation in model calibrations using historical data. Recently, volume errors in operational runoff calculations have been discovered, as well as bias errors in PE estimates from both operational output and calibrations using current methods.

The errors have been traced to the use of sky cover in estimating solar radiation, which produces long-term means which are significantly lower than corresponding direct measurements of solar radiation or estimates obtained using percent sunshine. These biased values of solar radiation lead in turn to biased values of PE.

The NWS solution to this problem is to correct PE estimates derived from sky cover to an accepted standard. The standard which has been established in this case is the information on pan evaporation and meteorological PE estimates as contained in NTR33 and NTR34. Knowledge of the solar radiation inputs for calibration and those for operational forecasting allows for the correction of biased PE to the accepted standard using a ratio of the long-term means. This same procedure can be utilized by hydrologic modelers who have a variety of solar radiation inputs for the estimation of PE and who desire to use PE in a consistent fashion both in calibration and in real-time forecasting.

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Table 1. Comparison of solar radiation estimates (from 1965 to 1974) for 15 stations with pyranometer data (MEAS), percent sunshine data (SUNP), and sky cover data (SKY). RMS error relates SKY estimates to MEAS data.

Station Name	MEAS	SUNP	SKY	RMS (%)
Knoxville, TN	346.1	352.0	323.8	26.0
Little Rock, AR	376.2	399.2	337.3	27.0
Atlanta, GA	360.1	377.1	334.3	25.5
Charleston, SC	396.1	392.5	374.6	22.4
Tampa, FL	441.8	441.0	423.8	19.1
Greensboro, NC	361.6	360.6	331.0	24.2
Cape Hatteras, NC	388.7	366.7	361.5	24.2
Lansing, MI	331.5	334.6	294.6	40.9
Madison, WI	334.5	346.8	314.6	24.6
Boston, MA	341.4	295.7	248.2	37.1
Burlington, VT	296.4	347.8	273.6	36.7
Portland, ME	315.8	339.3	293.5	25.7
Seattle, WA	309.6	314.1	264.1	29.6
Boise, ID	403.1	376.7	362.6	20.3
Sault Saint Marie, MI	318.1	322.0	290.0	36.8
Average of 15 stations	354.7	357.7	321.8	28.0
MEAS/SUNP and MEAS/SKY		0.99	1.10	

Table 2. Comparisons of solar radiation computed using percent sunshine and sky cover for various stations.

Station Name and State	SUN	SKY	SUNP/SKY	Yrs.
Wilmington, NC	399.2	362.1	1.10	9
Windsor Locks, CT	305.0	260.9	1.17	10
Green Bay, WI	326.4	322.0	1.01	10
Duluth, MN	319.5	318.1	1.00	10
Minneapolis, MN	342.6	328.3	1.04	10
Buffalo, NY	284.1	262.6	1.08	10
Albany, NY	281.9	248.9	1.13	10
Cleveland, OH	294.8	271.9	1.08	10
Columbus, OH	288.8	289.1	1.00	10
Fort Wayne, IN	349.6	293.5	1.19	10
Jackson, MS	400.2	346.5	1.16	10
Chattanooga, TN	345.5	337.7	1.02	9
Nashville, TN	370.6	343.9	1.08	9
Shreveport, LA	375.1	339.9	1.10	9
Fort Smith, AR	380.1	333.5	1.14	9
Richmond, VA	361.3	332.4	1.09	9
Washington, DC	314.5	314.4	1.00	9
Charlotte, NC	396.1	346.7	1.14	9
Macon, GA	391.7	352.9	1.11	8
Norfolk, VA	362.9	345.6	1.05	8
Birmingham, AL	394.2	341.8	1.15	8
Jacksonville, FL	415.2	399.1	1.04	8
Memphis, TN	398.7	341.6	1.17	8
Montgomery, AL	356.1	347.3	1.03	8
Chicago, IL	330.2	324.8	1.02	10
Peoria, IL	353.9	326.6	1.08	10
Des Moines, IA	360.6	336.4	1.07	9
Louisville, KY	359.1	323.9	1.11	9
Asheville, NC	376.4	343.0	1.10	9
Savannah, GA	400.5	369.2	1.08	9
Binghamton, NY	285.9	243.2	1.18	10
Philadelphia, PA	308.2	272.5	1.13	10
Pocatello, ID	361.5	366.8	0.99	10
Portland, OR	316.0	294.6	1.07	10
Baltimore, MD	312.2	318.1	0.98	10
Dayton, OH	318.2	299.1	1.06	10
Evansville, IN	360.0	335.1	1.07	10
Indianapolis, IN	335.4	314.1	1.07	10
Quillayute, MI	257.4	226.5	1.14	10
Rockford, IL	290.4	301.5	0.96	10
Concord, NH	319.4	297.9	1.07	10
Harrisburg, PA	307.1	268.3	1.14	10
Providence, RI	293.4	269.9	1.09	10
Rochester, NY	288.3	257.6	1.12	10
Syracuse, NY	273.7	271.7	1.01	10
W-Barre/Scranton PA	300.6	255.0	1.18	10
Raleigh, NC	372.8	344.8	1.08	9
Average of 48 stations	332.0	307.1	1.08	

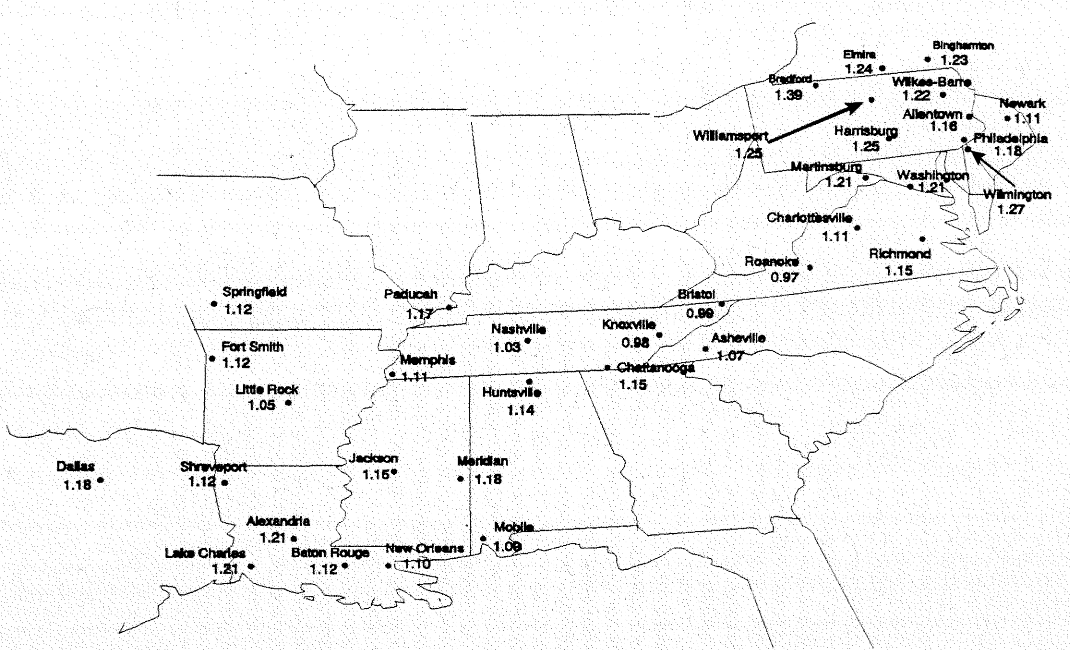

Figure 2. Map of SYNTRAN stations. Multipliers shown which remove bias from SYNTRAN PTPE estimates. These corrections can be used in MAPE and will correct the long-term mean PTPE from SYNTRAN to the evaporation atlas values.

Table 3. Comparison of evaporation from SYNTRAN at 35 stations with evaporation values from the evaporation atlas in NOAA Technical Report NWS 33.

				(1)	(2)		(3)		(4)	(5)	(6)						
			Period of Record	Annual Comparison						Summer Comparison		Ratios					
				Map 3	SYNTRAN Evaporation for:					May to Sept.	Map 1	(1)	(1)	(3)	(4)	(6)	(1)
Station Name		Sta. No.	(POR)	TR33	POR	yrs	56-70	yrs	83-88	SYNTRAN	TR33	/(3)	/(4)	/(2)	/(2)	/(5)	/(2)
Asheville	NC	3812	1948-1988	31.5	29.50	41	28.45	15	31.75	19.83	20.50	1.11	0.99	0.96	1.08	1.03	1.07
Paducah	KY	3816	1949-1988	40.5	34.65	19	33.33	15	34.75	25.45	28.20	1.22	1.17	0.96	1.00	1.11	1.17
Huntsville	AL	3856	1958-1988	37.5	32.95	30	34.28	12	35.76	22.81	26.50	1.09	1.05	1.04	1.09	1.16	1.14
Lake Charles	LA	3937	1962-1988	43.6	36.03	27	35.67	9	37.28	24.66	29.80	1.22	1.17	0.99	1.03	1.21	1.21
Jackson	MS	3940	1964-1988	42.0	36.68	25	36.23	7	36.99	25.42	29.00	1.16	1.14	0.99	1.01	1.14	1.15
Binghamton	NY	4725	1948-1988	27.8	22.55	41	21.69	15	24.72	17.32	21.50	1.28	1.12	0.96	1.10	1.24	1.23
Bradford	PA	4751	1957-1988	27.8	19.93	31	19.80	14	20.46	15.44	20.50	1.40	1.36	0.99	1.03	1.33	1.39
New Orleans	LA	12916	1948-1988	42.8	38.95	41	39.02	15	36.91	25.92	28.70	1.10	1.16	1.00	0.95	1.11	1.10
Philadelphia	PA	13739	1948-1988	35.0	29.77	41	29.19	15	31.29	21.24	25.50	1.20	1.12	0.98	1.05	1.20	1.18
Richmond	VA	13740	1948-1988	38.0	33.02	41	32.85	15	34.33	22.94	26.80	1.16	1.11	0.99	1.04	1.17	1.15
Roanoke	VA	13741	1948-1988	32.5	33.57	41	34.21	15	33.64	22.92	21.40	0.95	0.97	1.02	1.00	0.93	0.97
Washington	DC	13743	1948-1988	38.3	34.97	41	35.37	15	34.09	24.66	27.00	1.08	1.12	1.01	0.97	1.09	1.10
Wilmington	DE	13781	1948-1988	38.0	29.89	41	29.72	15	31.26	21.42	26.00	1.28	1.22	0.99	1.05	1.21	1.27
Meridian	MS	13865	1948-1988	41.0	34.63	33	34.51	15	34.05	23.69	27.80	1.19	1.20	1.00	0.98	1.17	1.18
Bristol	TN	13877	1948-1988	29.8	30.15	35	29.98	11	31.55	21.40	21.80	0.99	0.94	0.99	1.05	1.02	0.99
Chattanooga	TN	13882	1948-1988	37.0	32.13	41	32.03	15	33.82	22.62	25.00	1.16	1.09	1.00	1.05	1.11	1.15
Knoxville	TN	13891	1948-1988	32.5	33.32	41	32.61	15	34.25	23.61	23.00	1.00	0.95	0.98	1.03	0.97	0.98
Memphis	TN	13893	1948-1988	44.0	39.48	41	38.28	15	40.38	27.86	30.50	1.15	1.09	0.97	1.02	1.09	1.11
Mobile	AL	13894	1948-1987	41.9	38.53	40	37.89	15	39.17	25.44	28.00	1.11	1.07	0.98	1.02	1.10	1.09
Nashville	TN	13897	1948-1987	35.8	34.68	40	33.94	15	36.71	24.90	26.00	1.05	0.98	0.98	1.06	1.04	1.03
Shreveport	LA	13957	1948-1988	43.3	38.49	41	38.95	15	38.09	26.80	31.00	1.11	1.14	1.01	0.99	1.16	1.12
Little Rock	AR	13963	1948-1988	39.0	37.26	41	37.11	15	37.81	26.25	26.80	1.05	1.03	1.00	1.01	1.02	1.05
Fort Smith	AR	13964	1948-1988	41.3	37.00	41	36.36	15	37.86	26.36	29.30	1.14	1.09	0.98	1.02	1.11	1.12
Baton Rouge	LA	13970	1948-1988	42.8	38.21	41	37.08	15	38.47	25.66	29.00	1.15	1.11	0.97	1.01	1.13	1.12
Springfield	MO	13995	1948-1988	40.0	35.87	41	35.26	15	35.80	25.81	28.00	1.13	1.12	0.98	1.00	1.08	1.12
Newark	NJ	14734	1948-1988	33.5	30.16	41	30.59	15	31.44	21.51	24.50	1.10	1.07	1.01	1.04	1.14	1.11
Allentown	PA	14737	1948-1988	32.0	27.51	41	27.56	15	29.22	20.08	24.50	1.16	1.10	1.00	1.06	1.22	1.16
Harrisburg	PA	14751	1948-1988	34.3	28.30	41	28.40	15	29.30	20.42	26.00	1.21	1.17	1.00	1.04	1.27	1.21
Wilkes-Barre	PA	14777	1949-1988	30.3	24.88	40	25.32	15	24.34	18.74	22.90	1.20	1.24	1.02	0.98	1.22	1.22
Williamsport	PA	14778	1948-1988	31.0	24.75	35	24.52	11	25.12	18.12	23.10	1.26	1.23	0.99	1.01	1.27	1.25
Alexandria	LA	13935	1960-1977	42.6	35.22	16	34.69	8	****	24.60	29.50	1.23	****	****	****	1.20	1.21
Dallas	TX	13960	1948-1982	56.2	47.47	32	46.71	15	****	33.00	36.70	1.20	****	****	****	1.11	1.18
Charlottesville	VA	93736	1961-1964	36.0	32.53	4	****		****	22.00	24.00	****	****	****	****	1.09	1.11
Martinsburg	WV	13734	1949-1964	34.0	28.12	16	****		****	20.55	23.70	****	****	****	****	1.15	1.21
Elmira	NY	14748	1949-1954	27.5	22.15	6	****		****	17.37	21.50	****	****	****	****	1.24	1.24
Average Values				37.2	32.67		32.86		33.35	23.05	26.11	1.15	1.11	0.99	1.03	1.14	1.14

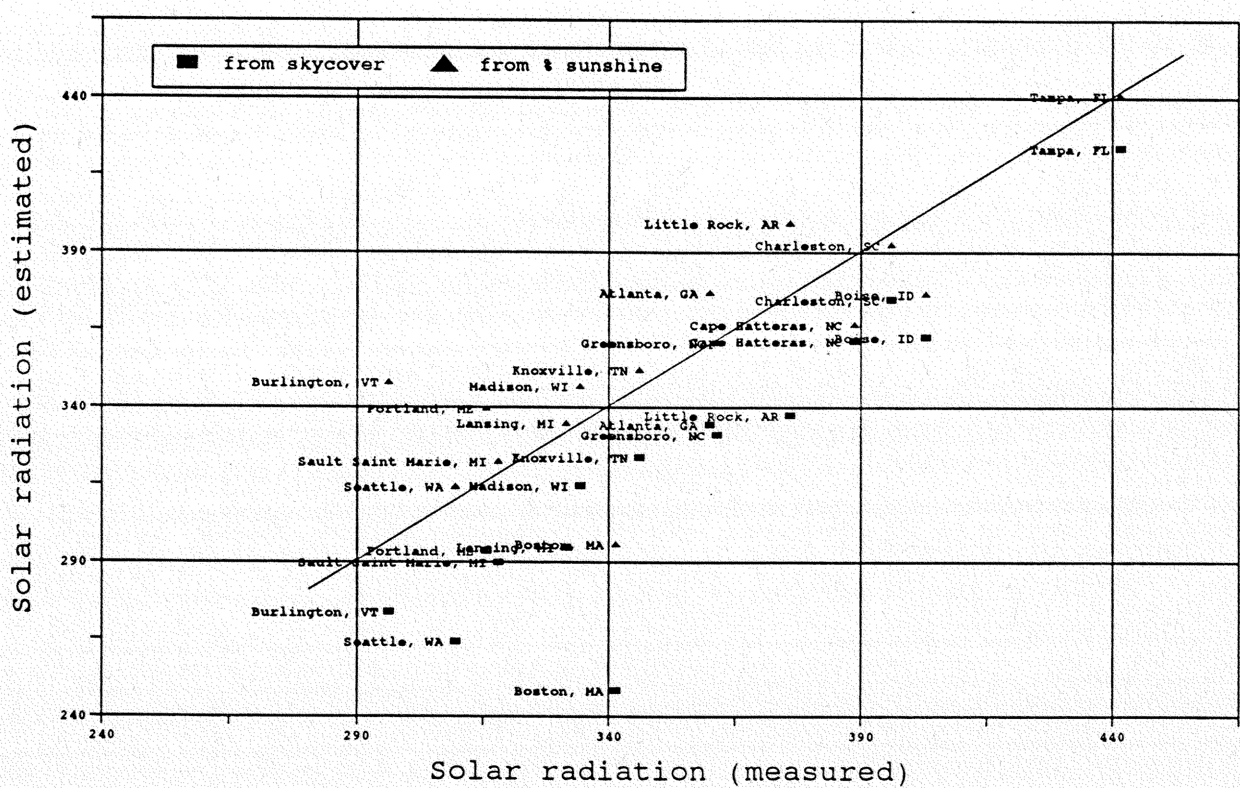

Figure 1. Plot of values from Table 1 showing solar radiation estimates from percent sunshine and sky cover versus pyranometer data for 15 stations for 1965 to 1974.

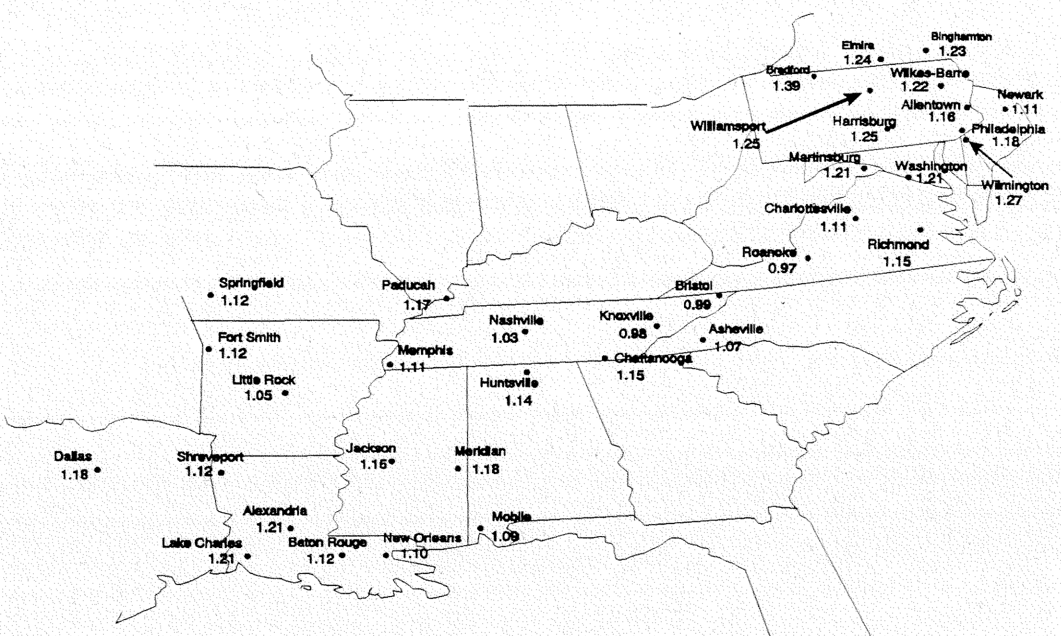

Figure 2. Map of SYNTRAN stations. Multipliers shown which remove bias from SYNTRAN PTPE estimates. These corrections can be used in MAPE and will correct the long-term mean PTPE from SYNTRAN to the evaporation atlas values.

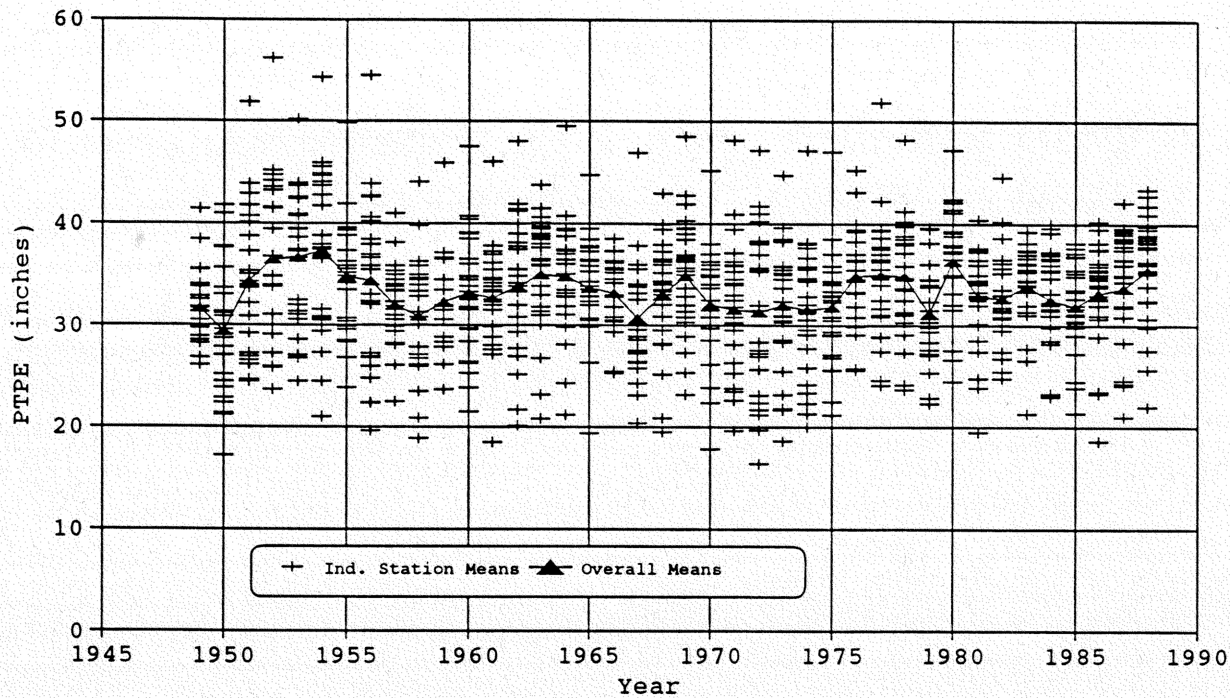

Figure 3. Annual means of PE for individual SYNTRAN stations shown with the mean of all stations for the time period 1948 to 1988.

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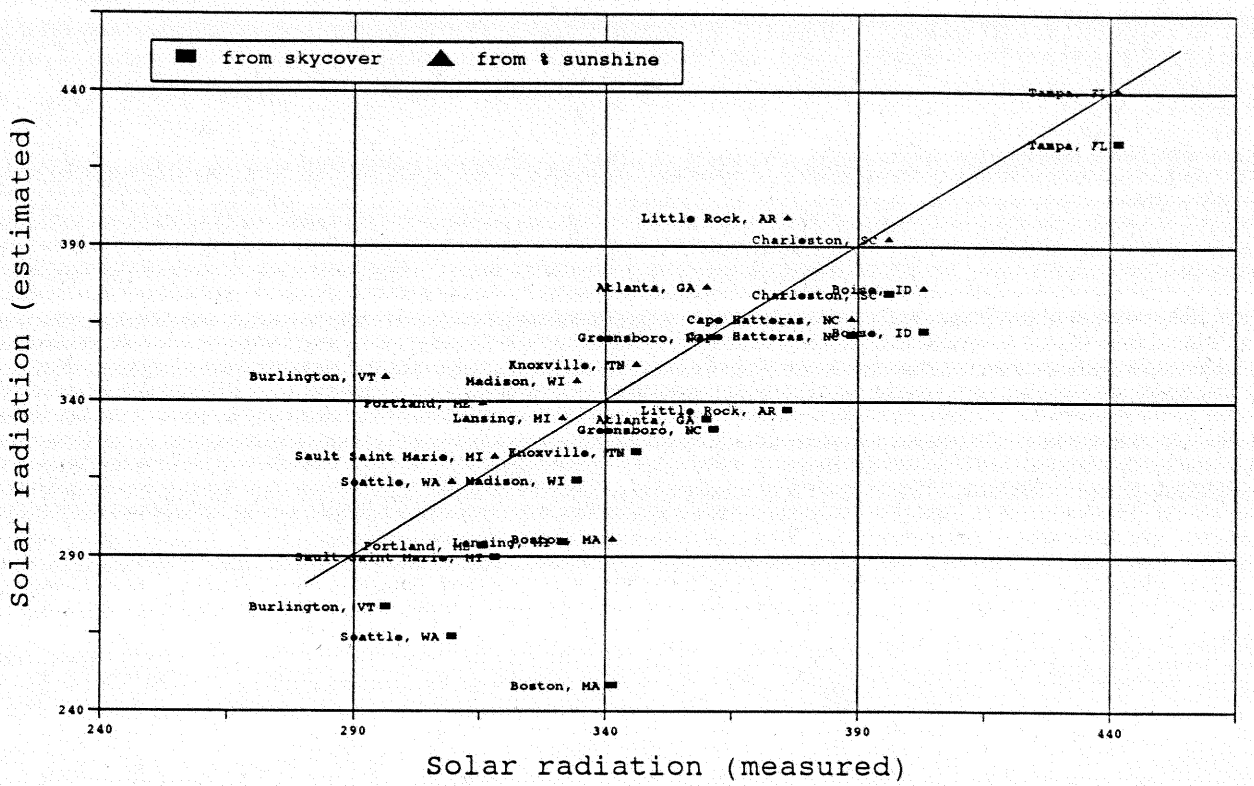
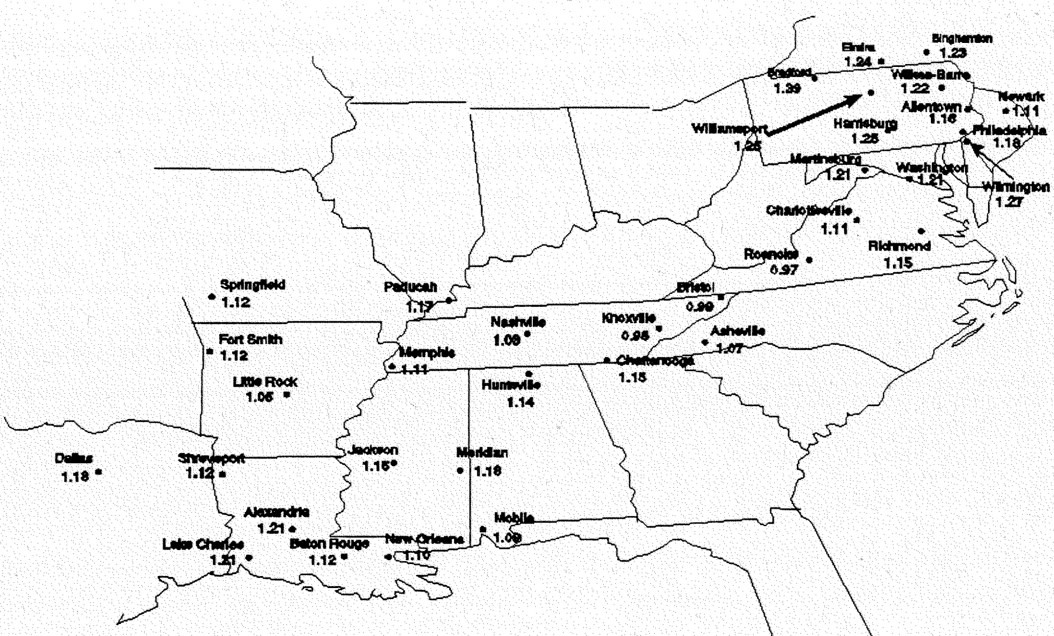
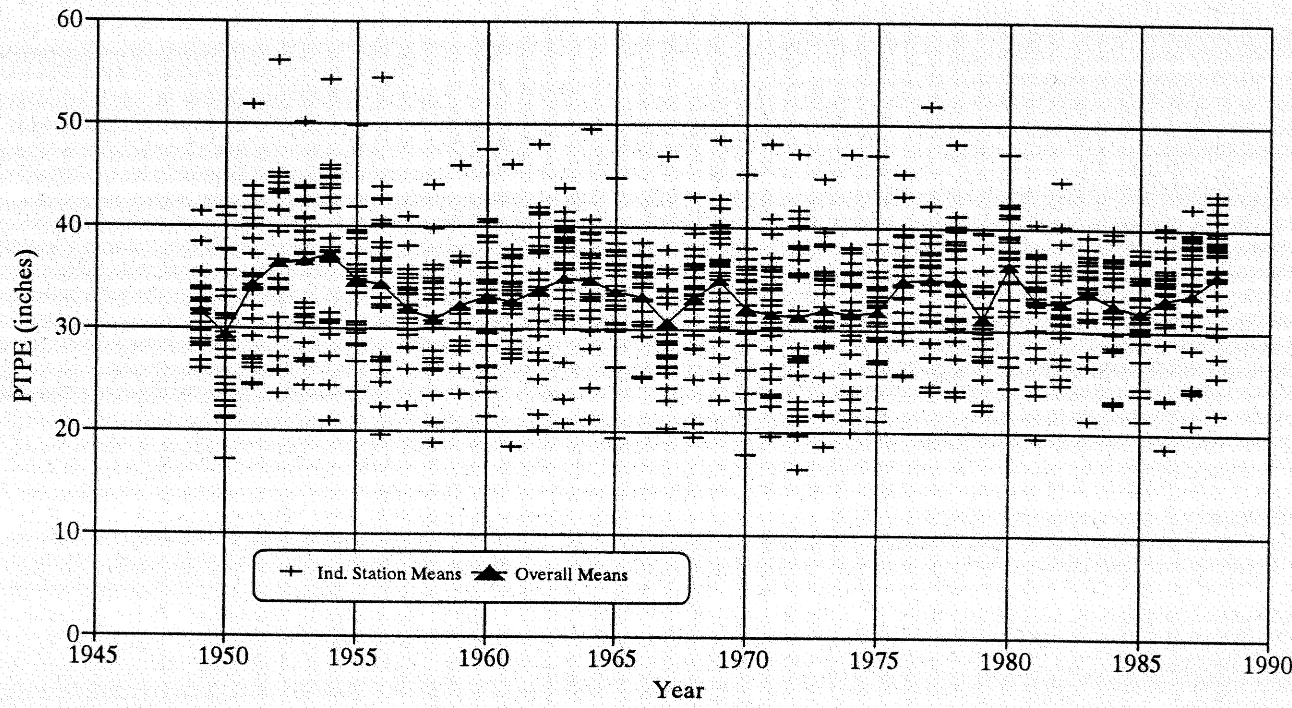


from skycover
from % sunshine
Solar radiation (estimated)
Solar radiation (measured)
240
290
340
390
440
Tampa, FL
Little Rock, AR
Charleston, SC
Atlanta, GA
Boise, ID
Cape Hatteras, NC
Greensboro, NC
Knoxville, TN
Burlington, VT
Madison, WI
Portland, ME
Lansing, MI
Sault Saint Marie, MI
Seattle, WA
Boston, MA



Binghamton 1.23
Elmira 1.24
Bradford 1.39
Wilkes-Barre 1.22
Newark 1.11
Allentown 1.16
Williamsport 1.25
Harrisburg 1.25
Philadelphia 1.18
Martinsburg 1.21
Washington 1.21
Wilmington 1.27
Charlottesville 1.11
Richmond 1.15
Roanoke 0.97
Bristol 0.99
Springfield 1.12
Paducah 1.17
Nashville 1.09
Knoxville 0.95
Asheville 1.07
Fort Smith 1.12
Memphis 1.11
Chattanooga 1.15
Little Rock 1.05
Huntsville 1.14
Dallas 1.18
Shreveport 1.12
Jackson 1.15
Meridian 1.18
Alexandria 1.21
Mobile 1.09
Lake Charles 1.21
Baton Rouge 1.12
New Orleans 1.10



60
50
40
30
20
10
0
PTPE (inches)
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
Year
Ind. Station Means
Overall Means