Solar Energy Climatology of North Carolina

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ABSTRACT

A solar energy climatology for North Carolina was developed using radiation data from the six SOLMET stations in the state. The climatology provides information needed to design solar powered space and water heating systems, and evaluate their performance. It specifies the distribution of monthly average daily total radiation on a horizontal surface, relationships between radiation and temperature for an average heating season, and the variability of radiation within a season. The main features of the solar energy climatology can be explained by the synoptic climatology of the area. The absolute values of the SOLMET radiation data are questionable, although they are acceptable for system design purposes. Results are presented graphically, allowing the climatology to be easily related to system performance. Examples of the relationship are given for a typical active space and water heating system, using the F-Chart method to calculate performance.

1. Introduction

The increased interest in solar energy as an alternative energy source has increased demand for climatological information for use in system design and performance evaluation. Creation of the Hourly Solar Radiation–Surface Meteorological Observations (SOLMET) data file has provided the basic data with which a solar energy climatology can be developed. Such a climatology is presented here for North Carolina.

A useful solar energy climatology must be based on the information needs of system designers. Most designers use standard methods to solve the complex calculations needed to achieve best system sizing. Since these methods use ambient temperatures and total radiation on a horizontal surface as the climatic variables, only these parameters are considered.

A useful climatology must also be related to the potential performance of a system, to allow designers and clients to visualize system performance characteristics and the effects of design changes in the local climatic conditions. A performance emphasis also ensures that the climatology is presented at the level of detail that is significant for actual applications. Throughout this study the climatic effects are related, for illustrative purposes only, to performance calculated by the F-Chart method, for a typical active space and water heating system of the type described in Beckman *et al.* (1977). The system gains energy through a south-facing, flat-plate collector tilted at latitude plus 10° to the horizontal. The energy is transferred through a circulating anti-freeze solution to heat exchangers connected to the building's hot water and space heating systems. The building used is a medium sized well insulated house for a family of four. Auxiliary conventional heating systems ensure continuous availability of heat. The F-values presented represent the fraction of the total energy load that can be met from solar sources.

With these constraints, a climatology has been developed which provides information on three facets of solar energy generation:

1) Input data for system design by standard methods at any point in the state.
2) The relationship between temperature and radiation, for evaluation and graphical display of average system performance.
3) The temporal variability of radiation, for indications of short-term system performance.

2. The SOLMET data

The data needed to develop a solar energy climatology are available in the SOLMET data files (SOLMET, 1977). These files contain hourly values of total solar radiation on a horizontal surface, and simultaneous meteorological observations. The records are serially complete from 1952 to 1975. The meteorological data were obtained directly from National Weather Service (NWS) observations. Radiation values were rehabilitated from the original NWS radiation network results (SOLMET, 1979). These data are estimates based on measurements, and represent

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TABLE 1. SOLMET stations in North Carolina, their associated prime rehabilitation stations, SOLMET radiation averages for the heating season, and previously accepted heating season average radiation values.

		Radiation (MJ m^{-2}) (heating season average)	
Station	Associated prime station	SOLMET	Old values
Asheville	Nashville, TN	11.85	13.18
Cape Hatteras	Cape Hatteras	12.00	14.58
Charlotte	Nashville, TN	12.01	13.33
Cherry Point	Cape Hatteras	12.56	—*
Greensboro	Nashville, TN	11.86	12.32
Raleigh–Durham	Washington, DC/ Sterling, VA	11.52	12.66

* No values available for Cherry Point.

"the best presently available historical United States insolation values to use, when wide geographic coverage is desired" (Randall and Whitson, 1977). Six stations are available for North Carolina (Table 1). One station, Cape Hatteras, is a "prime" rehabilitation station, where actual measured values were directly corrected. The other stations are secondary, the values being derived by regression techniques from measurements of sunshine duration and cloud amount. The regression coefficients used were obtained from the nearest prime station with "climatically similar" conditions (SOLMET, 1979).

The climatology requires temporal resolution no finer than daily values. Hence the SOLMET hourly radiation values were summed to daily totals and hourly temperatures were averaged for each day. These daily values are used throughout the rest of the study.

An initial comparison of monthly average daily total radiation was made between SOLMET data and the older radiation values which have been widely used in solar energy system design. These previous estimates, conveniently summarized in Beckman *et al.* (1977), are uncorrected data, mainly obtained from the NWS network or from diverse short-period records. The SOLMET values, for the heating season (October to April), are 10% lower than the earlier ones (Table 1). Monthly differences vary from 0 to 20%, but show no systematic variation seasonally or spatially (Robinson and Easterling, 1980). The newer values decrease the predicted performance of a system. For the hypothetical system treated here, the annual F-value decreases by almost 20%.

The rehabilitation process does not easily allow estimates of accuracy, especially since there are at present no long-term high-quality direct observations for comparison. The SOLMET values, being corrections of previous measurements, are likely to be more accurate. In addition, most designers would prefer prediction on the conservative side, so that the risk of customer complaint of poor performance, is minimized. Hence, it is recommended in North Carolina that the SOLMET values be used for solar energy system design purposes.

3. Spatial distribution of input parameters

The basic input parameters for solar heating system design by standard methods are monthly averages of daily total radiation on a horizontal surface and monthly average temperature. These can be specified for the six SOLMET stations, but estimates for any point in the state are required. Consequently the first step of the climatology is to determine the spatial distribution of the parameters.

The six stations provide enough information to produce maps of the broad-scale features of the solar radiation distribution over the state. A set of maps of monthly average daily total radiation were produced. Four maps, indicating the significant features of the distribution and its variability with time, are reproduced here (Fig. 1). A two-part mapping procedure was used. The first stage was straightforward interpolation between the data points to establish the basic pattern. The second stage refined these maps through consideration of the climatology of the area.

The first stage utilized a standard computer mapping routine (SYMAP, 1977). This produced maps which revealed three distinct radiation regimes in the state, approximately corresponding to the major physical divisions: mountains, piedmont and coastal plain. These divisions provided the basis for the refinement.

The refinement stage emphasized the estimation of the location of the division boundaries by considering the synoptic climatology of the area. The refinement was intended to alter the basic, objectively obtained, SYMAP pattern as little as possible, but to produce a more climatologically realistic radiation distribution. This modification was accomplished within the SYMAP system by placing semi-permeable "barriers" to interpolation between data points, having the effect of varying the strength of the influence of one data point in a particular direction. Two barriers were used, one along the mountain foothills and one approximately parallel to the coast some distance inland. The strength of the barriers and their exact locations were developed by trial and error.

The local climatic variations which were considered in modifying these original maps were those that led to persistent excess or deficit of cloud amount in an area. For convenience, the piedmont, with few marked topographic features or contrasts in surface type, was treated as the control region. In the mountains, orographic effects are dominant. The wind direction in the area, however, is variable, and leads to frequent changes between windward and leeward ef-

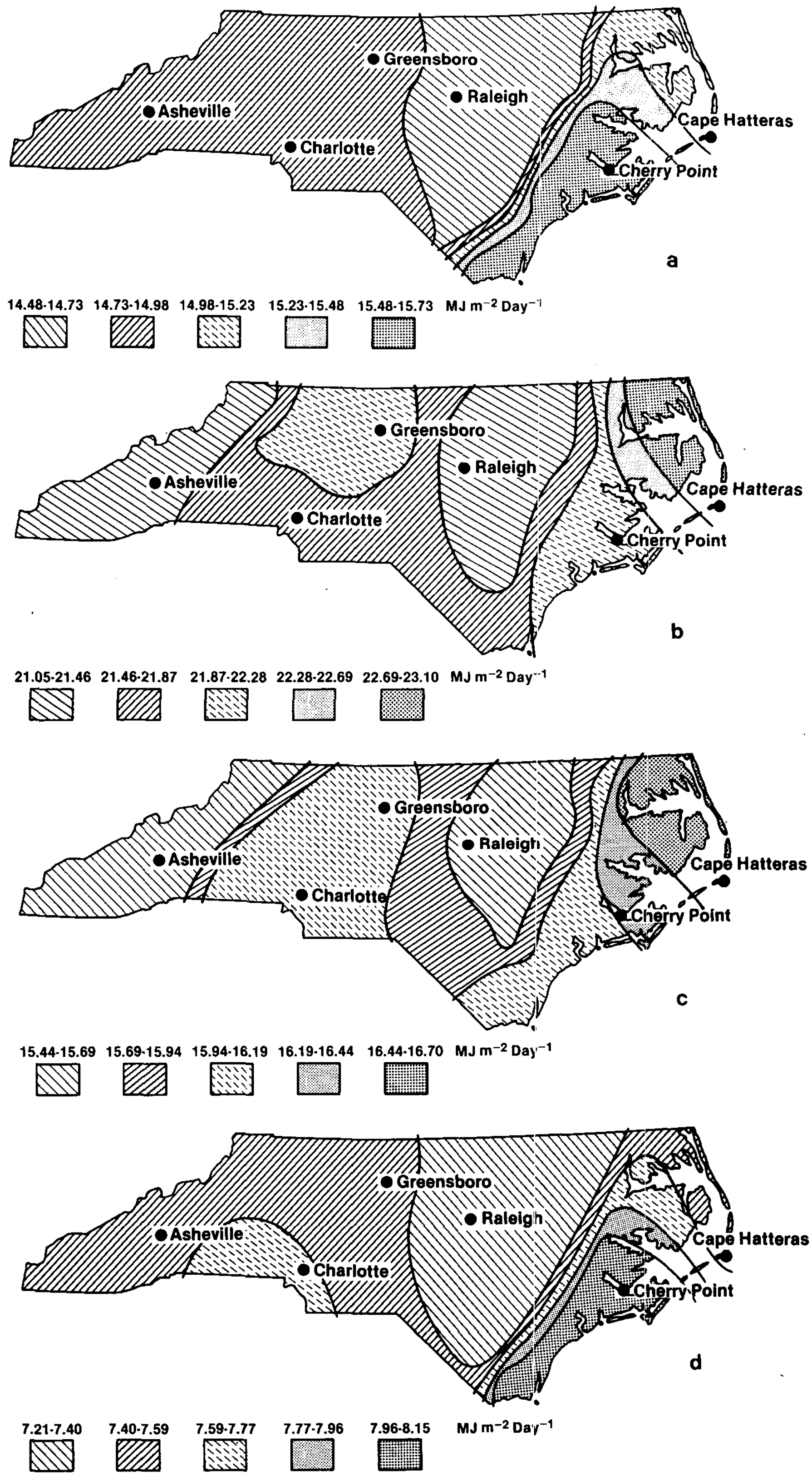

FIG. 1. Spatial distribution of monthly mean daily total solar radiation on a horizontal surface in North Carolina for (a) March, (b) June, (c) September, (d) December.

fects. The result is a small spatial variation in long-term average cloud amount, but more cloud than in the regions to the east. Unfortunately, the only SOLMET station in the region, Asheville, is in a broad basin, shielded on all sides, and may have anomalously low radiation values for the region. Hence, the SOLMET results may be somewhat atypical of the mountains, but in the absence of other data points, they must be accepted. An almost inpenetrable barrier was introduced approximately coincident with the eastern edge of the mountains. This forced the Asheville values to dominate the whole region, but with some piedmont influence being felt in the northern part of the state and at the extreme eastern edge of the mountains.

On the coastal plain, both depressions and sea breezes influence radiation receipts. Depressions in winter are more frequent northward of Cape Hatteras (Hayden, 1981) and lead to lower winter radiation totals in the northern coastal plain than in the southern portion (Fig. 1). The sea breeze effect is most marked in summer, but is also felt in spring and fall. Clouds are generated near the coast around noon and move inland during the afternoon; the influence on radiation is occasionally detected more than 60 km inland (W. Bach, Jr., personal communication, 1980). The two SOLMET stations, Cape Hatteras and Cherry Point, represent the northern and southern coastal plain conditions, respectively. The inland extent of these conditions was restricted by a semi-permeable barrier placed approximately 40 km from the mainland shore. This has the effect of severely limiting, but not eliminating, the inland extent of the coastal plain influences.

The use of the barriers in this fashion serves to emphasize, but not create, the spatial patterns which are similar to those which would be expected from synoptic climatological considerations alone. Minor variations between station values account for the small-scale pattern differences between months (Fig. 1). The only persistent unexplained feature is the region of low radiation totals in the eastern piedmont, centered on the Raleigh–Durham SOLMET station.

There are three possible explanations for this area of low values: a real spatial difference caused by mesometeorological effects; an apparent difference caused by the mapping technique; or a difference arising from the SOLMET rehabilitation process. The last seems most likely, since the maps were generated by standard procedures and there appears to be no physical reason, such as excess turbidity or cloud amount, why the eastern piedmont area should have these low values (Peterson *et al.*, 1981). The Raleigh–Durham SOLMET data, however, were derived from coefficients obtained for Sterling VA/Washington DC, while the other two stations in the theoretically similar situation, Greensboro and Charlotte, used the coefficients for Nashville (Table 1). Hence, it is possible that the difference arises because of the transfer of coefficients. Although this creates some uncertainty about the absolute accuracy of the SOLMET data, the differences are minor for system design requirements. For example, if the Greensboro radiation values are used in place of those of Raleigh–Durham for the hypothetical heating system, the annual F-value changes from 0.63 to 0.65. Such a difference would be of little consequence in any practical application.

This comparison calculation also illustrates the fact that the maps are more than adequate in spatial resolution and detail to provide the information needed to determine the appropriate radiation values for solar heating system design calculations throughout the state. Values near the borders are the least reliable because stations in adjacent states were not used in the development of the maps. However, the influence of these stations on most of the border regions would have been minor, since the interpolation procedure favors the nearer, internal stations. The small potential increase in accuracy gained did not warrant the extra effort.

Information concerning the monthly average temperature, the other basic input parameter, is readily available for a large number of sites in the monthly and annual issues of *Climatological Data*, North Carolina edition, available from the National Climatic Center, Asheville, NC. Comparison of the average temperatures calculated from the SOLMET files for the entire period of record with the climatic normals (Knapp *et al.*, 1980), which refer to a slightly different period, indicated that the differences were minor, and not significant for solar energy system design. Hence, maps of temperature distribution were not produced, since designers can readily use the published values from their local station.

For any point in the state, the basic input parameters for design calculations can be estimated from the radiation maps and the temperature tabulations. In general, the small spatial variation of both parameters across the state allows interpolations between data points which are likely to produce estimates adequate for design calculations. Such estimates, especially in the mountains, must be made with caution.

4. Temperature and radiation relationships

System performance is dependent on the relationship between incoming radiation, which controls the energy available, and ambient temperature, which largely determines the amount of energy needed by a building. To examine this relationship, a graphical approach, using daily data for the heating season, was adopted (Fig. 2). This approach provides further insight into the solar energy climatology, and allows a designer and potential purchaser to visualize the familiar local weather conditions in a way that can be related to system performance.

The climatology is summarized by two parameters

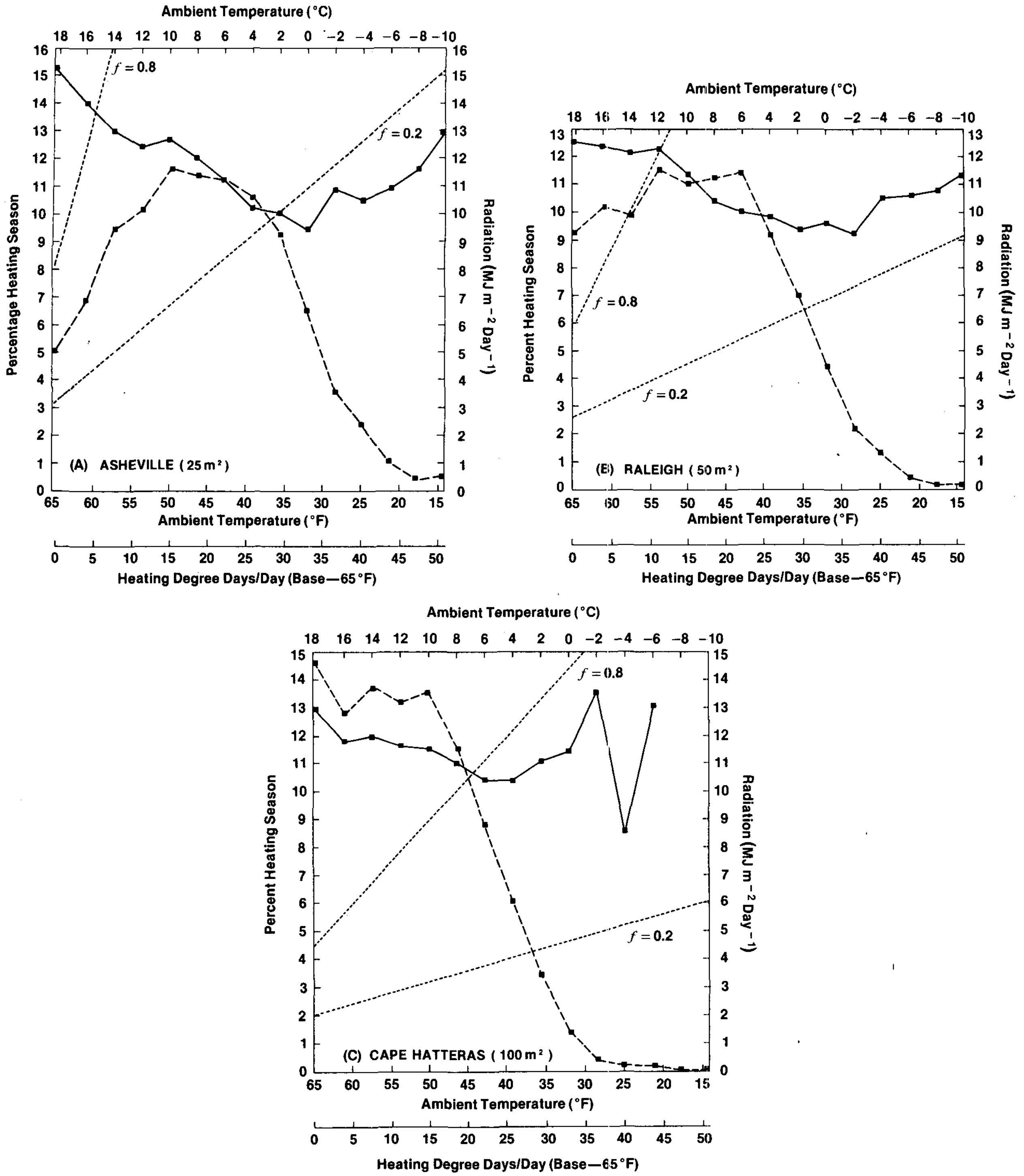

FIG. 2. The relationship between ambient temperature and 1) average daily total radiation on a horizontal surface (solid line), 2) frequency of occurence in the heating season (long-dashed line) and 3) solar energy required to obtain the specified performance from a hypothetical system (short-dashed line) for (A) Asheville with a system collector area of 25 m^2, (B) Raleigh with 50 m^2, and (C) Cape Hatteras with 100 m^2.

displayed as functions of ambient temperature: average daily total radiation and percent of heating season. Following Baer and Merrill (1977), graphs are presented with energy demand increasing, and thus temperatures decreasing, to the right. The relationship between daily total radiation and temperature

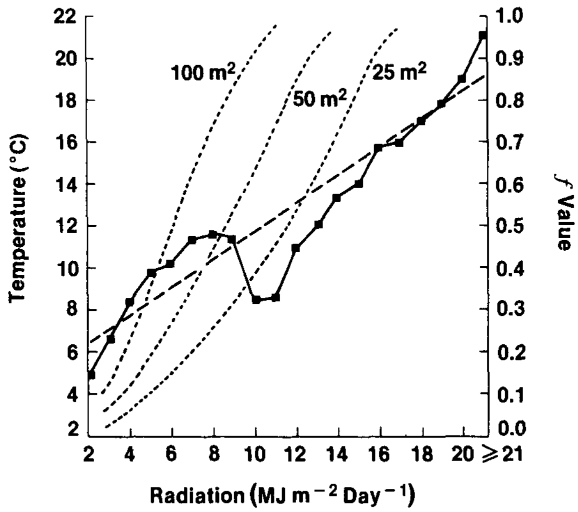

FIG. 3. The relationship between daily total radiation and 1) average ambient temperature for the heating season at Raleigh (solid line), with a linear approximation of the relationship (long-dashed line), and 2) f-values for various collector sizes used in system performance calculations (short-dashed lines).

was obtained by dividing temperatures into 2°C intervals, and calculating the average radiation in each interval. The highest temperature interval was 16–18.3°C, to include the maximum temperature at which space heating is required. No attempt was made to portray variability about the average, although the low temperature results for Cape Hatteras, obtained with very few days data, indicate this variability. The resulting curve thus displays the relationship for an average of many heating seasons. When long-term performance is the prime concern, such averages are appropriate.

In order to display the frequency of occurrence of each temperature, the percentage of the heating season in each interval was found by a similar method. Again, the curve represents the distribution in an average of many seasons.

These two curves together indicate the climatology without regard to a particular solar energy system. The overall patterns can be explained by the synoptic climatology of the area. The high radiation totals during the coldest periods in winter result from invasions of cloud-free Canadian Arctic air. The highest temperatures of the heating season occur in spring and fall when anticyclonic situations associated with the offshore Bermuda High give clear conditions favorable for high radiation totals. The effects of these conditions are apparent at extreme temperatures. At intermediate temperatures, they are overshadowed by the dominance in all seasons of southerly air flows. These are either humid flows from the southeast which contain stratus clouds resulting from slow orographic uplift as they move inland, or air from the southwest with its embedded depressions which causes frequent changes from clear to cloudy conditions. In winter these southerly airflows are cool and give low radiation totals. In the intermediate seasons there is an increase in both temperatures and radiation associated with the longer days and higher sun angles.

The importance of the southerly airflow is seen when average temperatures for particular radiation values are calculated (Fig. 3). This figure, obtained in a manner similar to Fig. 2, but with temperature replacing radiation as the dependent variable, shows an approximately linear temperature increase with radiation. This reflects the overall dominance of conditions associated with the southerly airflow throughout the heating season.

The synoptic conditions influence the state approximately uniformly. Hence, the major difference between representative stations in each climatic division (Fig. 2) arises from the temperature variations across the state, which is a direct response to altitudinal variations. These cause the percent of heating season curve to shift toward higher temperatures from west to east. The radiation curves for all stations have a similar shape, except for the variable values at low temperatures at Cape Hatteras.

Inferences concerning refinement of the solar energy climatology for any point in the state follow from the analysis of Fig. 2. For a particular point away from the SOLMET stations, the radiation curve could be shifted up or down the vertical axis to reflect the total radiation received at the point, as indicated by the proceeding maps. Similarly, the percent of heating season curve could be moved about the horizontal axis to compensate for the temperature difference between the point and the SOLMET station. Unless the point of interest is in an unusual climatic situation, however, the minor spatial variations suggested by the analysis are unlikely to have practical consequences and such refinement is unnecessary. In most cases reference to the nearest SOLMET station is likely to provide the required visual impression of the solar energy climatology.

The two curves for each station considered so far specify the solar energy climatology in general terms. Connections between them and system performance must be made for a specific system. A direct connection between climatology and performance can be made by expressing the heating requirements at a particular temperature in terms of the solar radiation on a horizontal surface needed to satisfy the requirement at that temperature for that system. Such values can be obtained by performing a standard F-Chart calculation backward. Numerous assumptions are involved in this process, so that the results can only be regarded as rough guides, even for the specific system. For each station of Fig. 2, two performance curves are presented, showing the radiation amount needed to provide 20% (f = 0.2) and 80% (f = 0.8) of the load demanded by the given ambient temperature. These values were chosen to represent low and high performance characteristics, since F-Chart gives unreliable estimates at more extreme values. In each case, the system used was the hypothetical one mentioned earlier. The different curves for each station were created by changing only the size of the collector area. Since the curves are independent of station, they can be transferred between stations to assess the effects of system size changes. They are presented separately here to preserve figure clarity.

The complete diagrams give a direct visual impression of the performance of a particular system under the meteorological situations likely to be encountered in the state. They provide a quantitative impression of performance levels at a particular temperature and the frequency with which that condition occurs. They demonstrate, for example, that a 50 m^2 system will provide more than 80% of the required load for approximately 40% of the heating season in Raleigh, and that even on the coldest days more than 20% of the required energy will be provided. Once the temperature is below freezing, the increase in radiation as temperature decreases ensures that an approximately constant fraction, somewhat more than 20%, of the load can be generated from solar sources.

5. Temporal variability of radiation

For an analysis of the temporal variability of radiation in a solar energy climatology, the emphasis must be on the frequency of occurrence of extended periods with low radiation totals. When such periods occur, a solar heating system will not be able to meet the load requirements either from the current input energy or from energy drawn from storage. Variability information is complimentary to that obtained from the radiation and temperature analysis, since it specifically considers day-to-day variations within an average heating season. A similar graphical approach can be adopted, first establishing the basic climatology and then relating it to performance. However, the relationship between climatology and performance is complex, and does not allow simple illustration. Hence, two approaches were used. The first is a simple presentation of the number of extended periods per season with low radiation totals, allowing a designer and client to obtain an overall impression of temporal variability (Fig. 4). The second approach is more appropriate for use with performance estimates, since it allows incorporation of system energy storage and the effects of temperature (Fig. 5).

The simple presentation displays the number of occurrences per season of periods when radiation was below a given value (Fig. 4). This was obtained by searching the record and counting the number of periods in each season when two consecutive days had radiation below a specified value. The average over all seasons was then calculated. Two days was chosen as the minimum for an extended period, since the effect of isolated, single, low-radiation days will be compensated by the energy storage built into any system. Similar searches for three and four days were undertaken, and the results for all displayed as cumulative frequency distributions. Since the value of

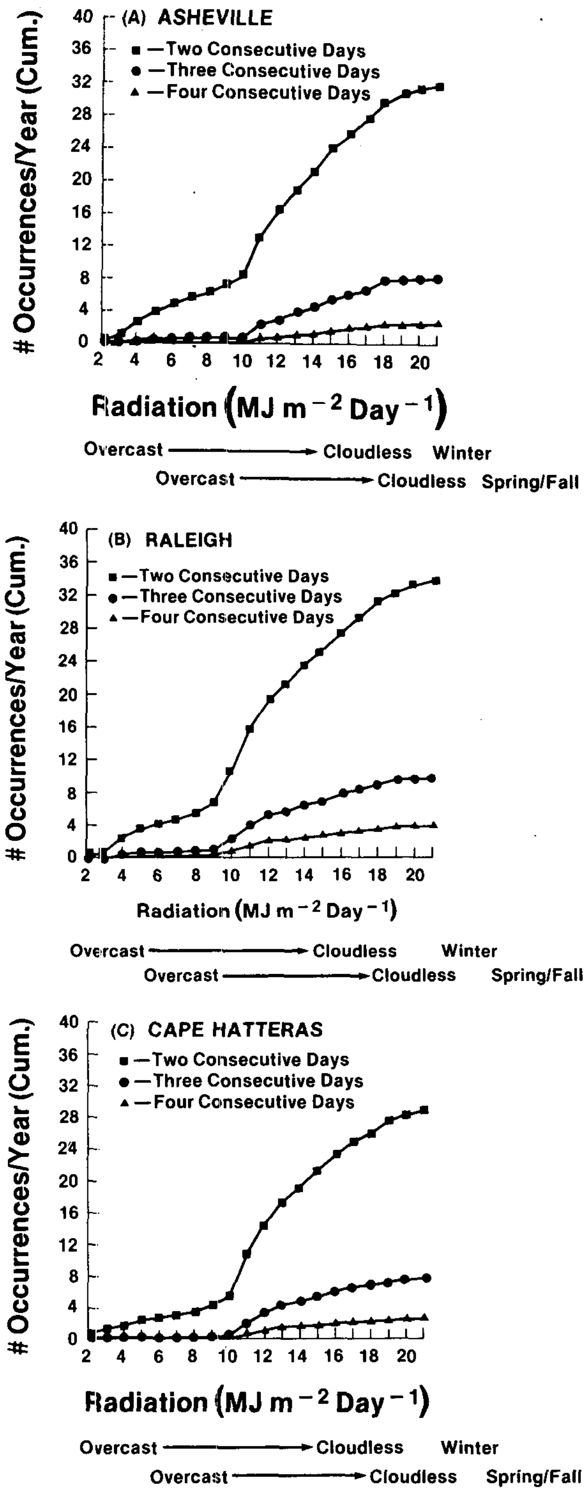

FIG. 4. Cumulative frequency of number of occurrences per heating season of successive days with radiation totals below specified values, for (A) Asheville, (B) Raleigh, and (C) Cape Hatteras.

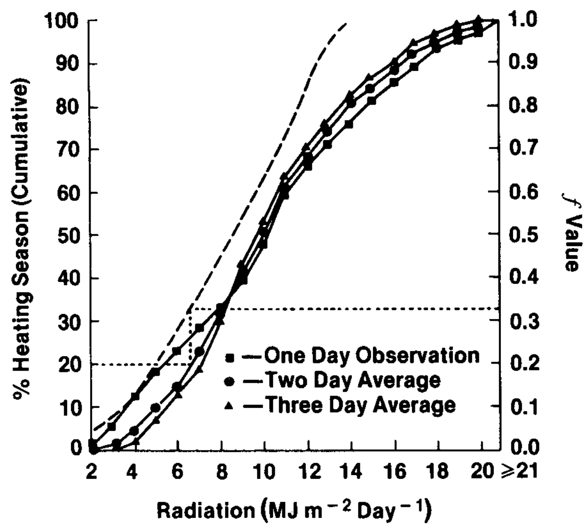

FIG. 5. Cumulative frequency of percent of heating season with successive days having average radiation below specified values (solid lines), and f-values for a hypothetical system with a 50 m^2 collector area operating under average ambient temperature conditions at these radiation values (dashed line). The method of relating the percent of the heating season to the f-value is indicated by the short-dashed line.

the display is in answering questions such as "How frequently do we get four consecutive completely cloudy days?" in a manner that is related to energy availability, indications of the conditions associated with various radiation amounts were included on the diagram.

The diagrams for the three stations are very similar. All indicate a significant change in conditions at radiation values around 9 or 10 MJ m^{-2} day^{-1}. This is likely to be a response to the change from overcast to broken cloud with some direct radiation, when these values are exceeded in spring and fall. At values below 9 MJ m^{-2} day^{-1} only the two-day period has a significant number of occurrences, with Asheville having the greatest number, and Raleigh and Cape Hatteras being approximately equal. Nevertheless, the entire state generally has a uniform climatology in this respect.

These simple diagrams, unfortunately, cannot be easily related to system performance, since they ignore both the effects of temperature on energy demand and the effects of storage within the system on energy supply. An alternative approach, which is more complex, can be used to provide a general relationship between radiation variability and performance. This is illustrated here using Raleigh–Durham data. First, the effects of storage on smoothing the effects of day-to-day radiation variations are introduced by utilizing running means for radiation. These, obtained by a method similar to that for Fig. 4, are expressed as average daily totals and are displayed as a function of percentage of the heating season (Fig. 5). The effects of storage can be seen by comparing the three curves. Incorporation of one day's storage markedly decreases the percentage of the heating season when low radiation totals are encountered. An additional day's storage has a much less pronounced effect. The diagrams thus provide a clear demonstration of the effects of storage size changes.

The next step in relating climatology to performance was to incorporate temperature effects. An assumption was introduced to make the calculation tractable and allow transfer of the method between stations. It was assumed that the average relationship between radiation and temperature shown in Fig. 3 held throughout the heating season. This was a deliberate simplification, since it is likely that the synoptic situation, creating extended low radiation periods, also creates temperatures different from average. A further simplification was made by using a least-squares linear approximation for the radiation versus temperature relationship (Fig. 3). The f-value was then calculated for each radiation and temperature combination for the hypothetical system with three different collector sizes (Fig. 3). These curves could then be transferred onto Fig. 5 to allow performance estimates. Only the 50 m^2 curve is transferred here.

The method of estimating the performance of a system on a day-to-day basis throughout an average heating season from Fig. 5 is shown by example. This indicates, assuming a 50 m^2 system with one day's storage, that 20% of the heating season will have an f-value less than 0.32. The effect of storage size changes can be seen directly by using the appropriate frequency curve. Similarly, use of another size curve from Fig. 3 would provide information on the effect of collector size changes. Again, the performance is limited to the system for which the F-Chart calculations were made.

6. Conclusions

The SOLMET data files can be used to produce a solar energy climatology of North Carolina. This climatology can be used to provide the basic input parameters needed to design solar energy systems at any point in the state, and can be related to system performance to illustrate, for both designers and purchasers, the effects of climate on systems of various configurations.

The major uncertainty in the climatology is the validity of the absolute SOLMET radiation values. These values are ~10% lower than those commonly used previously in solar energy system design, significantly decreasing estimated system performance. The SOLMET values probably are more accurate, being corrections of older data. This fact, combined with the more conservative performance estimates they yield, indicates that they are the most suitable values to use in solar energy calculations.

Circumstantial evidence for the relative accuracy of the SOLMET data between stations is provided by the spatial distribution of radiation across North Carolina. The data network is sufficiently dense, and the topography sufficiently homogeneous, to produce maps of monthly average radiation for the state. Since most of the resulting patterns can be explained by the synoptic climatology of the area, it is likely that the relative accuracy of the data are adequate for system design purposes. The major anomaly can be attributed to the process used to produce the SOLMET values. Although the differences in radiation caused by this anomaly are not significant for system design purposes, they raise questions about the absolute accuracy of the data.

The radiation maps suggest that the spatial variation of radiation receipt across the state is sufficiently small for reliable solar heating system performance estimates to be made at any point. These estimates, combined with the more readily available monthly temperature normals, provide the first portion of the solar energy climatology, the basic parameters for input to solar heating system designs.

The second aspect of the climatology is the estimation of potential performance. Performance for a particular system depends on the relationship between temperature and radiation, and on the short-term variability of radiation. The SOLMET data can be used to obtain temperature and radiation relationships for an average heating season, and estimates of the frequency of extended periods of low radiation totals within an average season. These can be explained by the synoptic climatology of the area.

The climatology was designed to be related directly to system performance in a manner that could be understood and used by designers and their clients. Since performance is dependent on the particular system under consideration, the approach adopted here was to display the climatology graphically. Performance estimates for a particular system were then added as examples of the use and interpretation of the climatological information.

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