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SOME ASPECTS OF NONRANDOM CLOUDINESS IN SOLAR ENERGY APPLICATIONS

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Abstract—In many geographical locations, daytime cloud patterns are nonrandom for certain periods of the year. This article discusses the general characteristics of daily nonrandom cloudiness and illustrates the use of satellite imagery to resolve nonrandom patterns over portions of the Rocky Mountain region of the United States. Results are presented in the form of cloud frequency figures that are derived from geostationary satellite data collected during the summer of 1986. These results are compared to surface-observed, solar radiation data. The implications of daily, nonrandom cloud patterns as a factor in solar energy applications are discussed.

1. INTRODUCTION

Most textbooks on solar energy acknowledge that, although it is customary to assume a random daily cloud distribution for solar engineering considerations, the actual distribution may be highly skewed due to various nonrandom patterns in cloudiness[1]. Those daily nonrandom patterns may be seasonal and can occur for a variety of reasons. Apparently, little attention is given to these biases in solar energy applications systems. Some discussions do include indexes for handling cloudiness when the bias is known[2]. However, the effect is typically ignored, since sufficient data for estimating the temporal and spatial variations in "actual radiation received" are sparse.

Since daily nonrandom cloudiness is a repetitive feature in terms of time of day, location, and/or season, the local impact on solar radiation should be easy to define. In this article, the authors discuss these nonrandom patterns for situations where such knowledge might be directly or indirectly useful in solar energy engineering. For example, such applications might include possible optimization of the azimuthal orientation of solar collectors or improved planning for summertime cooling needs. Climatological information about nonrandom cloudiness might also be useful to utility companies in the optimization of power load management. The data could be used to better understand and predict load power as affected by such variables as (1) changes in hourly air conditioning needs in summer, (2) varying power demands for heating in winter, or (3) hourly variations in power demand for building illumination.

This study evaluates, in a general manner, the characteristics of daytime, nonrandom cloudiness as it might affect solar energy applications. Characteristics of daily nonrandom cloudiness over the United States are discussed briefly in Section 2. Data analysis techniques and examples of satellite-derived daily nonrandom cloudiness along the eastern Rocky Mountains are given in Section 3. In Section 4, related features of surface measured solar radiation are evaluated and compared with results from Section 3.

2. DAILY NONRANDOM CLOUDINESS OVER THE UNITED STATES

Daily, nonrandom cloudiness is often linked to the diurnal cycle of ground heating and cooling. Thus, the distribution of cloudiness becomes highly skewed by hour for any given locale. Since different atmospheric processes are involved at different times of day, the resulting cloud types are different.

Morning fog or stratus cloudiness is typical in certain humid valleys due to condensation which forms from nocturnal cooling. Many portions of the United States, for example, are repeatedly covered with low stratus clouds and fog during the morning hours[3]. A typical example may be found along the Northern California shore area during the summer where onshore advection of marine stratus by the sea breeze produces a repetitive pattern of morning stratiform cloudiness[3]. Another example can occur when nocturnal land breezes along coastal areas initiate convection, which, in turn, result in a relatively high frequency of morning cloudiness. This type of cloudiness is typical during the winter along the eastern and southern coasts of the United States[4].

Most afternoon repetitive cloud cycles result from terrain-induced, thermal circulations such as the sea breeze (e.g., studies by [5, 6] for Florida) or the mountain/valley effect (e.g., studies by [4, 7, 8] for the Rocky Mountains). In both cases, convective clouds normally develop each day at about the same time in the afternoon, and over the same geograph-

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ical location. Preliminary results from the present study suggest that the coastal areas of Texas and the Great Lakes are also affected by nonrandom afternoon cloudiness during the summer.

3. SUMMER SATELLITE IMAGERY OVER THE EASTERN ROCKY MOUNTAINS

3.1 *Data and data processing systems*

Satellite data used for this study are from the Geostationary Operational Environmental Satellite (GOES). There were two types of data available for the study: 1 × 1 km resolution visual wavelength data (VIS), and 4 × 8 km resolution, thermal infrared wavelength data (IR). VIS and IR data are routinely available from GOES every 30 min. For this study, images were collected during June, July, and August 1987 over most of the contiguous United States and Gulf of Mexico at 1300, 1600, 1700, 1800, 1900, 2000, 2100, 2200, 2300, and 0000 GMT (Grenwich Mean Time). All digital data were collected and processed at the Colorado State University (CSU) direct readout satellite ground station.

The data were processed through CSU's Interactive Research and Imaging System (IRIS). The main processor on the system is a VAX 11/780, and image processing is carried out on a two-station, COMTAL Vision One/20. Among other available functions, the system allows an operator to view imagery for quality control, "roam" imagery on the screen to ensure accurate navigation, and to alter picture element (pixel) brightnesses as required. For a more complete description of the CSU system refer to[9].

3.2 *Data analysis techniques*

To begin the data processing, the operator first renavigates all of the images to eliminate geographical mismatches due to satellite wobble, navigation parameter errors, etc. This is accomplished using a fiducial image, and various features of the COMTAL interactive processor. During this procedure, approximately 5% of the data were eliminated; namely, those images that were too cloudy to allow the operator to identify at least two landmarks over about a four-state area.

Once all of the images are matched, the digital counts at each location can be computer averaged. Three types of averages were produced. The first was a simple pixel-by-pixel average of all the VIS imagery for each month and by hour of the day. This type of average encompasses all brightnesses, from whatever cause, and may highlight regions of repetitively bright ground as well as regions having frequent clouds.

The second type of average was based on a scheme in which cloudy areas on each picture were turned pure white, and noncloudy areas turned pure black. Once this new image set was produced, averages were computed that represented the frequency of cloudiness at each location on the picture. An example of this type of average is shown in Fig. 1.

The third, and final, type of averaged image produced was again based on reprocessed, hourly imagery; this time altered to estimate regions having convective rainfall. These images will not be discussed here and are only mentioned for completeness. However, note that rainfall climatological information could be very useful in power load management problems.

3.3 *Illustration of satellite cloud imagery over Eastern Colorado*

Earlier satellite studies[7, 8] reveal that repetitive cloud cycles occur on a scale much too small to be resolved by the rather coarse network of solar radiation measurement sites in the United States. Figure 1 shows the frequency of cloudiness over the Colorado region at various times of day, during July 1986. When the details in Fig. 1 are compared with the topography illustration shown in Fig. 2, the direct relationship of cloudiness to terrain can easily be seen. The repetitiveness of this cloud cycle is as high as 75% for many elevated locations. Note, that in the early morning hours (Fig. 1a), before the diurnal heating has had a chance to be effective, the cloudiness, is more random in nature. However, by 1100 MST (Fig. 1c) the effect of the terrain has obviously begun to dominate. Figure 1 also shows the great variation in cloud frequency one might expect over very small regions. Measurements of "solar energy received" that are taken, for example, at Denver (D in Fig. 2), have very little application in nearby locations.

The data shown there is a great deal of cloudiness along and near the highest terrain features during the early part of the day, but almost no cloud activity over the plains of Eastern Colorado until mid to late afternoon. Thus, from a location such as Denver (D, Fig. 2), the view of the sun is routinely uninhibited for about the first half to two thirds of the day. It isn't until later that the very frequent cloudiness of late afternoon blocks the sun.

4. SURFACE HEMISPHERIC SOLAR RADIATION

4.1 *Radiation measurements along the eastern slopes of the Rocky Mountains*

July 22, 1986 was selected to illustrate the "typical" development of cloudiness over the eastern Rocky Mountain region during the summer. The case day is similar to the evolution discussed above, namely, a gradual eastward increase of cloudiness with time, which implies a consequent eastward reduction of incident radiation. This implication is confirmed by radiation data obtained from the Program for Regional Observing and Forecast Services (PROFS) sites in northeast Colorado. Figure 3 shows a time-dependent plot of the hemispheric solar radiation, (R_S), for this day as measured at locations *V*, *L*, *F*, and *W*. The

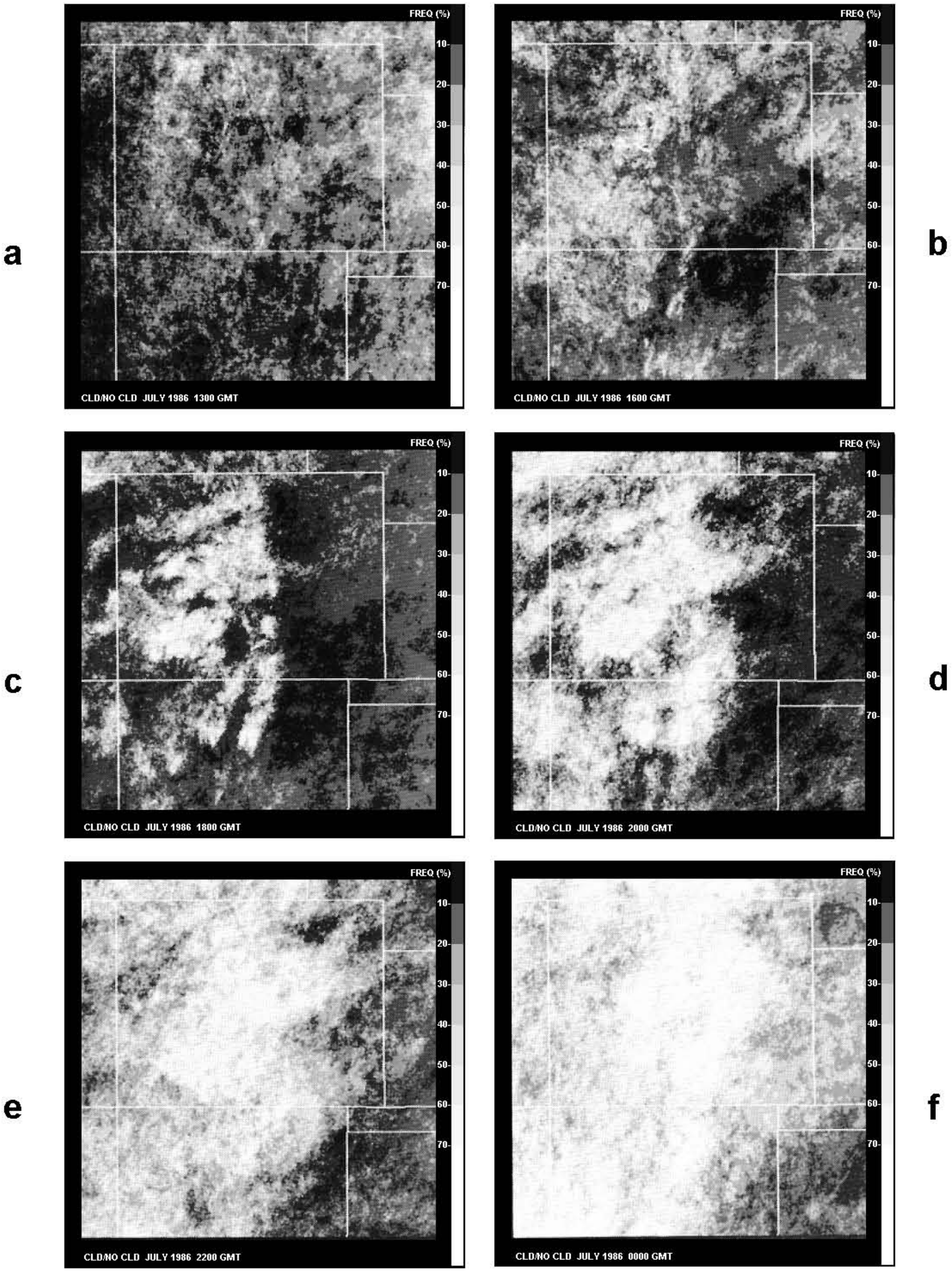

Fig. 1. Composite satellite imagery depicting cloud frequency over Colorado and surrounding region for July 1986. Method of calculating frequencies is described in text. Times shown are (a) 0600 mountain standard time (MST), (b) 0900 MST, (c) 1100 MST, (d) 1300 MST, (e) 1500 MST, and (f) 1700 MST.

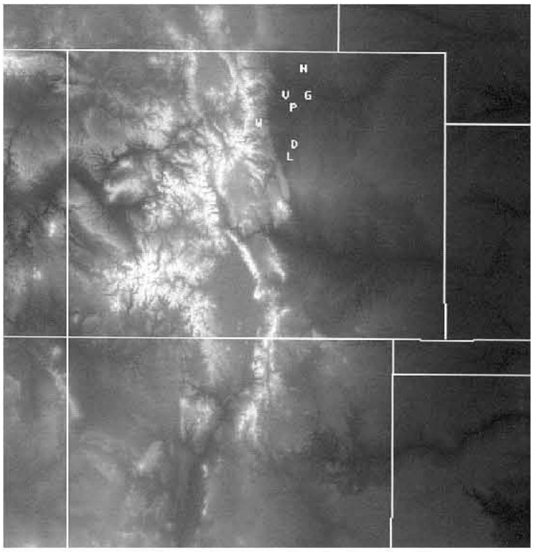

Fig. 2. Image depicting topography for the same region shown in Fig. 1. Brightness is proportional to terrain height. Highest (brightest) point in Colorado is 4400 m (Mt. Elbert in central CO along the Continental Divide)—the lowest is 1032 m (along the Arkansas River Valley in extreme southeast CO).

data provides site specific confirmation of the climatological results.

4.2 *July averaged hemispheric radiation*

Available monthly averaged hemispheric radiation, (R_S), for July 1982, 1985, and 1986 at Fort Collins, CO, show an asymmetric pattern around the midmonth local noon hour (Fig. 4). The ratio of total hemispheric radiation after noon compared to that before noon is 0.86 for 1982, 0.76 for 1985, and 0.72 for 1986. This asymmetry agrees with results obtained by the satellite study described above. Moderation of the ratio at this specific site is caused by (1) appearance of some random cloudiness associated with large scale meteorological systems which occurred on several days of the study period and (2) suppression of the afternoon cloudiness on other days.

5. DISCUSSION

This study provides a general discussion, along with a specific example for using satellite data, to evaluate the impact of daily nonrandom cloudiness on solar energy. As discussed above, the occurrence

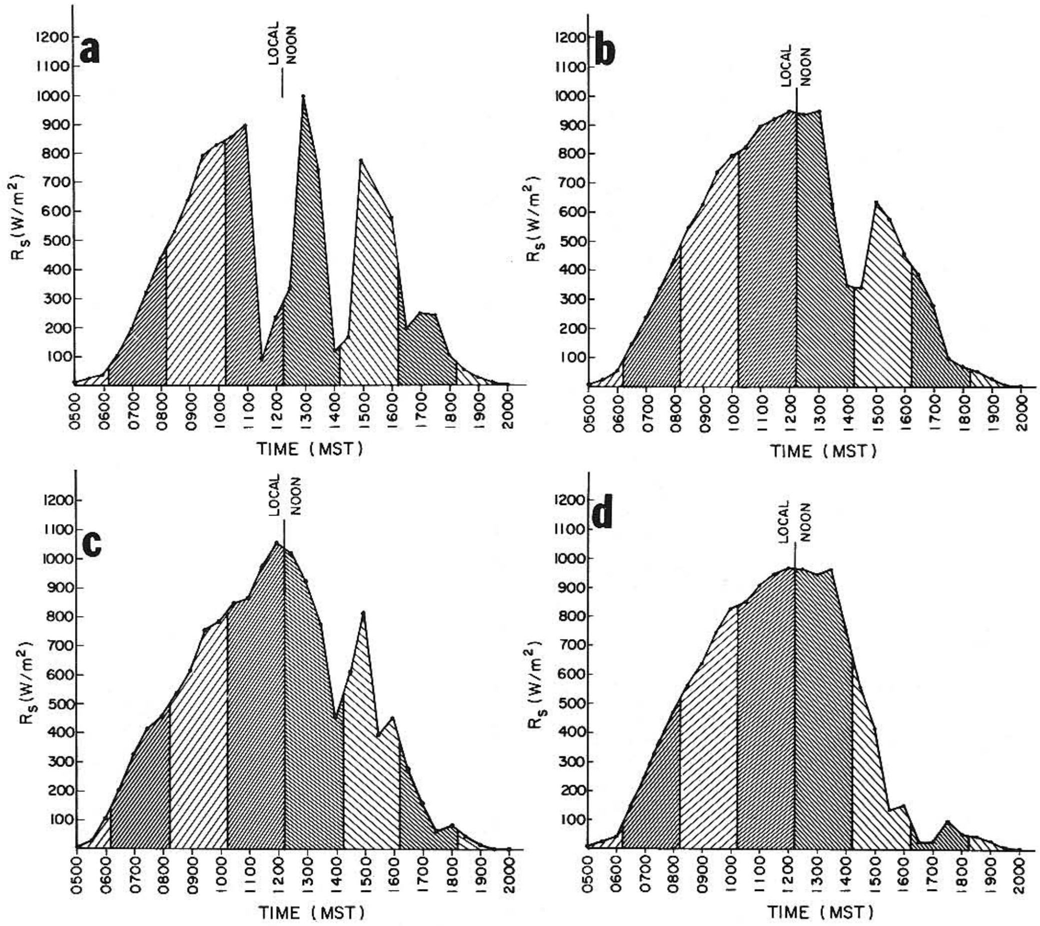

Fig. 3. Daily time-dependent hemispheric radiation, (R_S), for four of the sites indicated in Fig. 2 on July 22, 1986. Values shown are the highest 5-min average for the 15 min surrounding the plotted times. Sites shown are (a) Ward, CO (W), (b) Loveland, CO (V), (c) Littleton, CO (L), and (d) Nunn, CO (N).

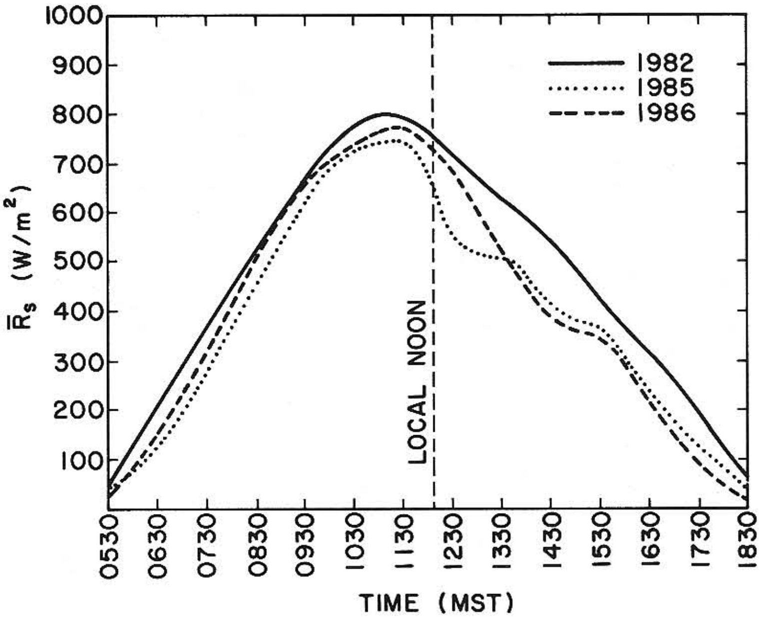

Fig. 4. Time-dependent July averaged hemispheric radiation, $\langle R_S \rangle$, for Fort Collins, CO, for 1982 (from [10]), 1985 (from [11]), and 1986 (from data archived at the Colorado Climate Center, CSU).

of daily, nonrandom cloudiness due to sea breezes, mountain valley breezes, etc., is not a new idea and that is not the point of this article. The present, ongoing study simply illustrates a method for evolving greater detail in the climatological database. Obviously, cloud frequency data from a single summer does not constitute a "climatology." However, similar data from other years[7, 8], as well as the June and August data from the present study (not shown), reveal the same tendencies, and data collection is continuing and expanding over the regions discussed. With such cautions in mind, it can be said that the evaluations presented here qualitatively illustrate how cloud frequency data from satellite could have importance in several applications. For the specific case illustrated in this paper, several applications might be suggested.

1. A more effective solar collector azimuth through some eastward bias in orientation. This bias would allow a more direct exposure to radiation during the first part of the day, which is the sunny time for many locations along the eastern slopes of the Rockies.
2. More effective power load management. Summertime afternoon hours in the region illustrated are likely to experience some drop in electrical power demand for air conditioning. Although there may be a slight increase in power demand for lighting at these times, normally a drop in power consumption is recorded.
3. The optimization of passive solar energy systems. Passive solar designs might profit somewhat by considering the temporal and spatial features of nonrandom cloudiness.

Hourly surface observations have been made at several hundred sites nationwide for many years. Thus, point specific cloud climatologies could easily be constructed. However, this study points out the severe spatial variation that might occur in daily expected cloud cover. Realistic data bases demand higher spatial resolution. Such resolution is possible using the geostationary satellite sensors.

The use of satellite data for establishing a regional computation of solar radiation has been carried out for specific cases in the past (e.g., [12–15] among others). The time and spatial resolution currently available for geostationary satellite imagery makes it an ideal study tool for point-specific solar evaluations. Although no quantitative results were presented here (they were not within the intended scope of the original study), such calculations are possible and would be useful to carry out for specific purposes.

Other studies for other months of the year are being planned, and even though problems exist (e.g., discriminating clouds from snow in winter) none of these problems is insurmountable. Eventually it is hoped that such climatological information is available globally, for all times of the year.

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