Impact of Landforms on the Spatial Distribution of Extraterrestrial Solar Radiation in the Months of March and September: A Geographical Approach

Romana, A.[1,2], Q. Xinfa[1], I. Ahmad[1,2], S. Sultan[3]

Abstract

Pakistan is subtropical country with substantial exposure to solar energy. To study various aspects of renewal solar energy and especially its spatial distribution over the diversified national territories is highly pertinent where our economy is already shaken by heavy oil imports. The surface geographical parameterization of solar radiation has been given least attention so far in Pakistan. In this paper, we have examined the spatial distribution of extraterrestrial solar radiations (ESR) in the months of March and September on experimental basis. The landform detail has been achieved from digital elevation model (DEM) and simulation of ESR has been done with the help of ArcGIS. The simulation of ESR in the months of March and September shows phenomenal variation, the landforms and latitudinal impact are the dominant controlling factors. The zonal distribution in Indus plains and landform induced pattern in mountains are obvious. The mountains, enclosed valleys, piedmonts and plains depict distinct variation of ESR. The Himalayas, Karakoram and Hindukush (HKH) mountains have more intershielding impact than any other part of the country. The experiment shows reasonable output. Referred to the situation in March, in northern rugged parts of the country, the amount of ESR varies between 788-1117 and 0-788 units on the southern and northern slopes respectively. The central rugged parts including Sulaiman lobe region receive ESR from 893 to 973 units while most of the plains and wide valleys are characterized by the range of 916-990 units. In southern parts especially the Makran Division lies in range of 999 to 1179 units. The Kirthar and central Brahui ranges have patches of ESR with units from 670-809, while most of the piedmonts in Balochistan reflects ESR between 916-899 units. Referred to the results in September, in northern parts, the southern slopes with maximum exposure to the sun receive wide range of ESR that varies from 894-1117 units. The slopes which are deeply influenced by the shadow impact come under the class of 0-661 units. In central zone, the dominant class of ESR is between 973-1030 units. The Sulaiman ranges, Toba Kakar ranges, the central Brahui ranges, Zarghoon, Takatoo and Murdar Ghar induce impact on the spatial distribution of ESR and estimated amount of ESR depicts 662-788 units. In southern zone, two dominant classes have been observed, first, the plains show 1031-1117 units and second the mountains have 662-973 units of ESR. However, in this zone the piedmonts obviously show patches of about 789- 894 units.

Key words: ESR, GIS, spatial distribution, rugged terrain.

Introduction

The availability of DEM through remotely sensed data and development of GIS has brought revolution in the development of distributed models which aim to explain meteorological and geographical spatial phenomenon and especially in the areas where we have no or inappropriate number of conventional meteorological observatories like in rugged and remote parts of Pakistan. Distributed modeling are actively applied in various sectors of agriculture (e.g. Meza and Varas, 2000; Spitters et al. 1986). Slope angle and mountain aspect are strong components inducing spatial variability in surface energy balance particularly in the rugged areas and control process like evaporation, melting of snow and glaciations (Barry, 1979; Essery, 2004). Pakistan is densely populated subtropical country with main dependency on agriculture; in this scenario, one can not deny the importance of renewable solar energy where our economy is already under the heavy burden of oil imports to meet the demand of energy in agriculture, housing and industry.

Measured sunshine duration may not be the true representative of vast regions, especially where topographic obstacle disturb its spatial distribution (Essery, 2004). Received at the surface, the direct solar radiation is the basic component of the global radiation; its measurement at the surface is given

[1] Nanjing University of Information Science & Technology, China.
[2] University of Balochistan, Quetta.
[3] Pakistan Meteorological Department.

complexity by the terrain interaction (Oliphant et al., 2003). Some of the well known researchers in this context (e.g Dozier and Qutcalt, 1979; Bouquet 1984; Stefanovic, 1985; Li and Weng, 1988) argue that distributed models are the best tools to explicate the relationship between solar radiation and complex rugged terrain. The terrain complexity remained a difficulty in computer models of extraterrestrial solar radiation, the terrain parameters acquisition were either neglected or simplified in the past, but the use and innovation in GIS has provided a strong support in this regard (He et al. 2003; De et al. 2003; Reddy 2003; Corripio 2003). The use of GIS based solar radiation models got tremendous momentum (Dubayah and Rich 1996), especially in the last two decades. Dozier and Frew (1990) argue that the use of DEM play fundamental role in distributed modeling especially in hydrological models. The geometry of the slopes has deep impact on the quantities of solar radiation received on the terrestrial surface (Fu, 1958, 1983). The slope and azimuth are found significant in the spatial distribution of direct solar radiation over the rugged territory of Yellow river basin in China (Zeng et al. 2005).

Currently it is not possible to establish observatories for solar radiation in each remote valley as well as on each mountain slope in HKH and other mountains in the breadth and length of the country. Side by side owing to the lack of comprehensive system to record solar radiations and its various aspects based on ground stations at national level. Hence we are left with appropriate choice in the current national scenario to estimate different aspects of solar radiation like ESR and possible sunshine duration (PSD) (e.g Ambreen et al. 2011; Ambreen et al. 2010) through distributed modeling over the rugged terrains of Pakistan. In this study, our target is mapping of ESR in the months of March and September. Though we have sufficient north-south latitudinal extent, great variation in altitude, impact of ocean in the south of the country, the effect of western disturbances (WDs) in winter and the effect of Indian summer monsoon make the climate of Pakistan very complex (Ahmad, 2011). Generally, keeping in view the four seasonal-pattern in Pakistan, March is the commencing month of spring while September is the commencing month of autumn like other subtropical parts of the Northern Hemisphere. March and onward, the sunshine duration is progressive and further increases with the advent of warm half of the year while in September and onward it is on decline with the advent of cool half of the year because of the changing elevation angle of the sun with respect to location of Pakistan. In Pakistan, the astronomical analogue of solar radiation has remained under discussion (e.g. Raja and Doughar, 1991; Raja and Twidle, 1991; Nicol et al, 1999; Raja, 1994; Ilyas, 2004; Ahmad, 1989), but its surface geographical parameterization has been given least attention. In this scenario, the spatial distribution of ESR over the diversified lands of Pakistan based on theoretical approach and its simulation has been discussed for the first time in the months of March and September without the atmospheric attenuation.

Study Area and Detail of Landforms in Relevance to This Study

The role of landforms is significant in this study because elevation, orientation/aspect, angle of slopes, and trend of mountains and latitudinal extent are the basic parameter required in the distributed modeling of ESR. Pakistan is a country with substantial north-south extension and diversified landforms including high ramparts of mountains.

Various geological and geomorphologic agents have turned northern and western mountains of Pakistan into rugged complex. The landforms are ranging from coastal plains in the south up to the peak of K-2. Indus plains and coastline with Arabian Sea of about 1046 km Pakistan has variety of topography (Figure 1) including plains, plateaus, hills, piedmonts and lofty mountains with deep dissected valleys in the north. The height of landforms is increasing with respect to mean sea level (msl) as one proceeds from south to north as well as from east to west. The transitional zone of piedmonts exists in most of the cases between plains and mountains.

The Balochistan Plateau with average height between 600 and 900 meters above mean sea level (msl) shares about more than 42% area of the country. Other prominent physical features of Pakistan are northern lofty mountains comprised of HKH north of Peshawar valley and Potwar plateau. The western border ranges, Sulaiman range and Kirthar range are prominent physical features which substantially exert influence on the monthly ESR.

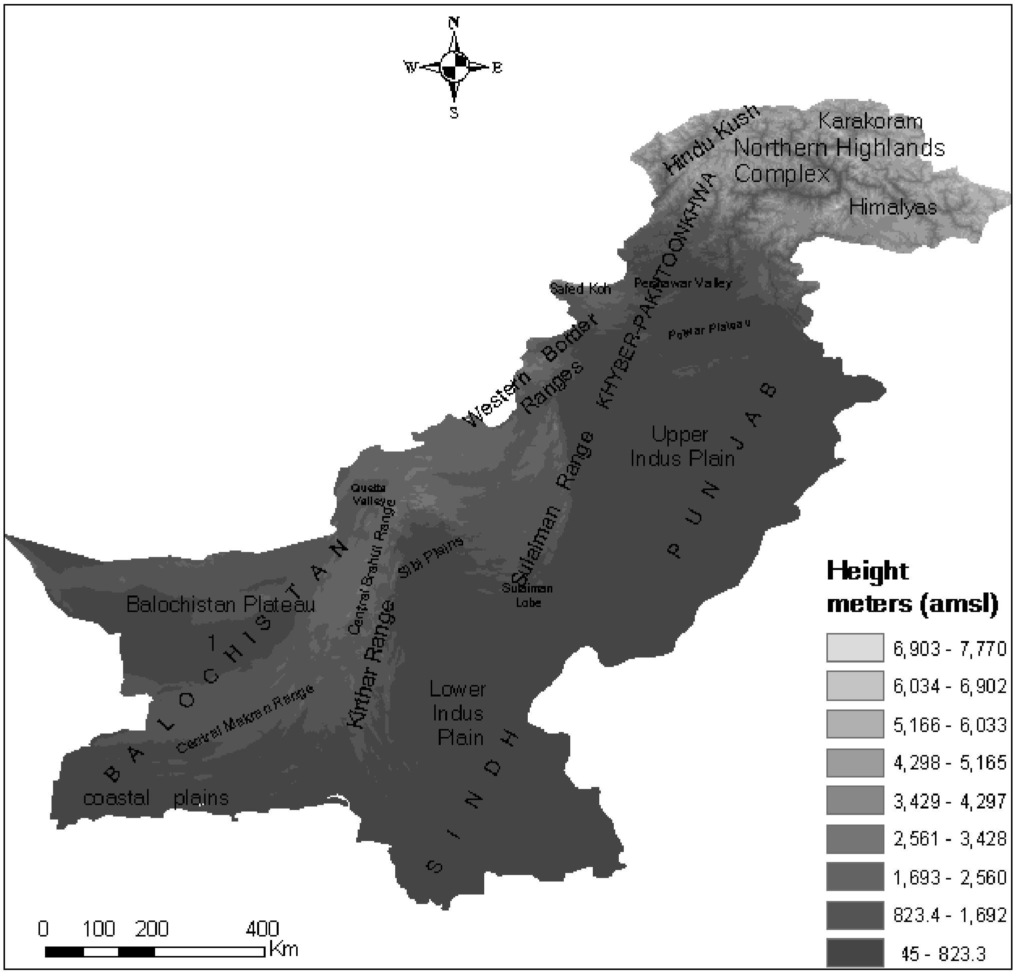

Figure 1: Physiographic detail of Pakistan in relevance to this study

Data and Methodology

We consider spatial distribution of ESR in Mega Joule/m^2 (MJ.m^{-2}) over the diversified lands of Pakistan. Hereafter the unit (units) refers to MJ.m^{-2}. The amount of ESR is dependent on the path and elevation angle of the sun in the sky and added by the surface topographical factors including slope angles, height and its aspect; in this paper we follow Qiu et al. (2005) who developed the ESR model for China. For the experiment, we have chosen the months of March and September. We use the DEM input into ArcGIS with spatial resolution of 90 meter × 90 meter. The DEM data was obtained from Shuttle Radar Topography Mission (SRTM) (Jarvis et al. 2008). The Arc GIS has been used as platform for the mapping of ESR over the diversified landforms of the study area.

The latitude, slope, and aspect of slopes and sun elevation angles are the important parameters which determine the amount of ESR in the rugged parts of the country. For the PSD the range of integration, that is sunrise and sunset has been used. Thus, the slopes will receive ESR from sunrise to sunset in the time T equals to 1440 minutes for the whole day. The sun declination angle (δ) and earth-sun distance correction factor can be measured by using Fourier series (Zuo et al. 1991). The daily calculated PSD would give us the amount of ESR. It is very difficult to have the theoretical expression of the incident of solar radiation over the complicated profiles of the ridges. Thus for practical purpose the topographical features were obtained from the DEM. The monthly amount of ESR was accumulated from daily ESR for each grid. The calculated ESR is based on the following formula.

$$W_o\alpha\beta = \frac{T}{2\pi}\left(\frac{1}{2}\right)^2 I_o \left\{u\sin\delta\left[\sum_{i=1}^{m}\left(w_{ssl} -_{wsrl}\right)\right] + v\cos\delta\left[\sum_{i=1}^{m}\left(\sin w_{ssl} - \sin w_{srl}\right)\right] u\sin\delta\left[\sum_{i=1}^{m}\left(w_{ssl} -_{wsrl}\right)\right]\right.$$

$$\left. + v\cos\delta\left[\sum_{i=1}^{m}\left(\sin w_{ssl} - \sin w_{srl}\right)\right] - w\cos\delta\left[\sum_{i=1}^{m}\left(\sin w_{ssl} - \sin w_{srl}\right)\right]\right\}$$

Where:

$W_o\alpha\,\beta$ is the daily quantity of ESR on the grid,

I_o is solar constant,

δ is the solar declination angle,

u, v and w representing geographical/topographical factors:

$$u = \sin\varphi\cos\alpha - \cos\varphi\sin\alpha\cos\beta$$
$$v = \sin\varphi\sin\alpha\cos\beta + \cos\varphi\cos\alpha$$
$$w = \sin\alpha\sin\beta$$

w_{srl} denotes sunrise hour angle,

w_{ssl} represents sunset hour angle.

The amount of ESR is imposed over the diversified topography of Pakistan with the help of different colors (tones) as classified by ArcGIS. The various colors and their different tones explicitly mark the spatial distribution of ESR in the study domain with regional variation. Figures 2 and 3 depict the monthly amount of ESR in the months of March and September respectively. Their distinct zones of ESR have been described in accordance with appropriate regional details.

Results and Discussion

In March, the gradual progress of ESR from south to north and in September a gradual retreat of ESR from north to south is obvious as the sun declination angle is progressive in March and on decline in September with respect to Pakistan. Owing to the north-south territorial extent of Pakistan, the latitudinal impact remains important where the zonal impression in the plains and landform induced pattern of ESR in the mountainous parts of the country can be seen as salient feature. The influence of mountains is more obvious in northern and western national territories. The HKH area is found with paramount influence on the amount of ESR and its spatial distribution, second is Sulaiman Lobe and Quetta region, and third is central Brahui, Kirthar and Makran hilly areas. The results support that the slopes facing the sun have large amount of monthly ESR than their opposite counterparts.

Spatial Distribution of ESR in the Month of March

Referred to Figures 2, in March the three major distinct zones including the northern, central and southern zones are obvious. The southern parts of the country including Balochistan, Sindh with latitudinal extent of about 24° to 29° N latitudes, the central zone is extending from about 29° to about 34° N latitude embracing the areas of northwestern Balochistan, Punjab excluding its southern parts, tribal areas, Khyber-Phakhtunkhwa (KPK) except its northwestern parts. Northern zone is stretching predominantly over northern rugged parts of the country including HKH Mountains.

Spatial distribution of ESR in the northern zone

The northern zone is the most discrete zone where the landform impact is more prominent than any other part of the country. It is assumed that this zones starts from north of Peshawar valley and Potwar Plateau. This zone embraces lofty HKH mountains of Gilgit-Baltistan (GB), Azad Kashmir (AK), and northern parts of KPK mostly comprised of Hindukush mountains. The amount of ESR has high variation due to the role of slopes by casting shadow and intershielding influence. In this zone, the southward slopes receive substantially more ESR than the northward sloping aspects. The southward slopes have the ESR units from 788-1117. The northward slopes have ESR units ranging from 0-788.

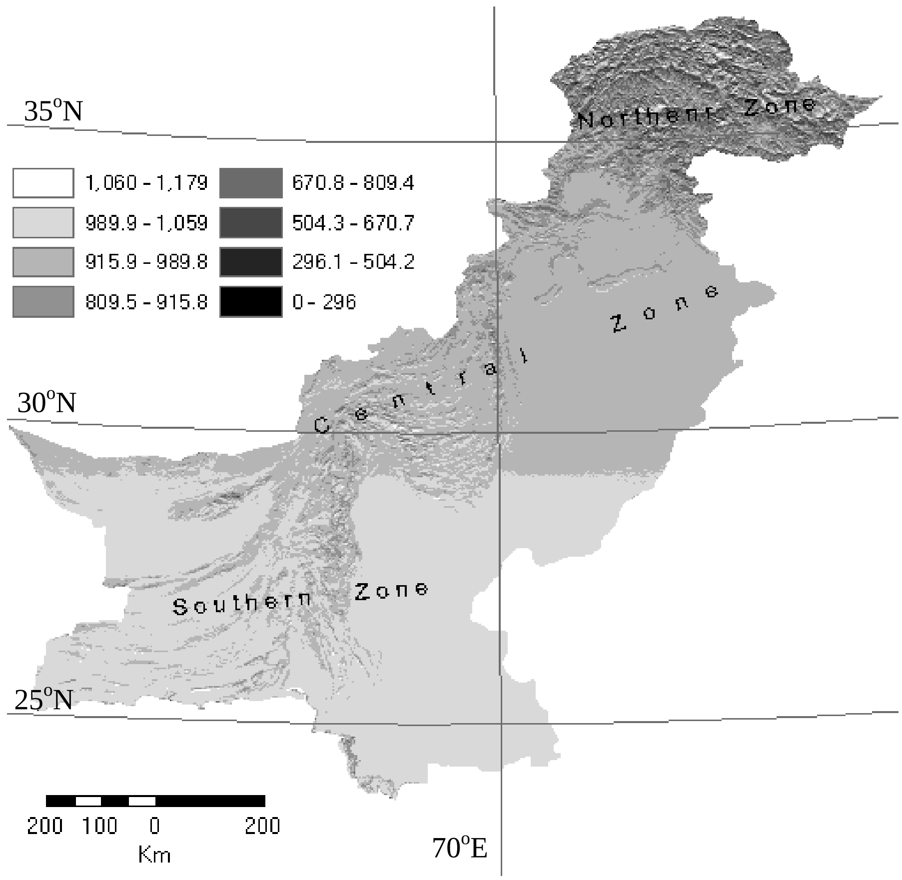

Figure 2: Spatial distribution of ESR (unit: $MJ.m^{-2}$) in Pakistan in the month of March.

Some of the northward slopes with high angle remain under predominant shadow eventually receive the lowest range from 0-306 units.

Spatial Distribution of ESR in the Central Zone

The central zone of ESR in March is restricted to the Punjab plains, Potwar plateau, Peshawar valley, northwestern Balochistan, Sulaiman Ranges and rugged terrains of tribal areas. In this zone, the western rugged parts and eastern plains show obvious bifurcation. The Safed Koh, Kurram valley and its proximity, Waziristan hills and Sulaiman ranges receive less ESR than the Punjab plains, Potwar region, southern KPK and flat areas of northwestern Balochistan. The mentioned rugged parts of the central zone depicts units of ESR from 508 to 788 units but the southward slopes especially in the Sulaiman lobe region receive ESR from 893 to 973 units. Most of the plains and wide valleys are characterized by the range of 916-990 units.

Spatial Distribution of ESR in the Southern Zone

Spatial distribution of ESR in the southern zone is profoundly disrupted by the rugged topography of Balochistan plateau and surrounding mountains in March. The obvious difference of ESR can be figured out in Kirthar, central Brahui ranges, coastal Makran and central Makran ranges. Most of the Sindh, Sibi plains, central Balochistan basin area and plains in the Makran Division lie between 999 to 1179 units of ESR. The Kirthar and central Brahui ranges have patches of ESR with units from 670-809 where the height and angle of the slopes are comparatively high, while most of the piedmonts in Balochistan exhibit ESR between 916-899 units.

Spatial Distribution of ESR in the Month of September

Referred to Figures 3, we have three obvious zones of ESR in September the northern, central and southern zones. Approximately the northern zone extends from 34° - 37° N latitude occupies most of the high altitudes in northern Pakistan, the central zone is extensive comparatively and extends from 27° N to 34° N and southern zone stretches over from 24° N to 27° N latitude. The highest amount of ESR per unit area is received in the southern zone and maximum filtering impact by landforms is obvious in the HKH zone of the northern highland of rugged complex.

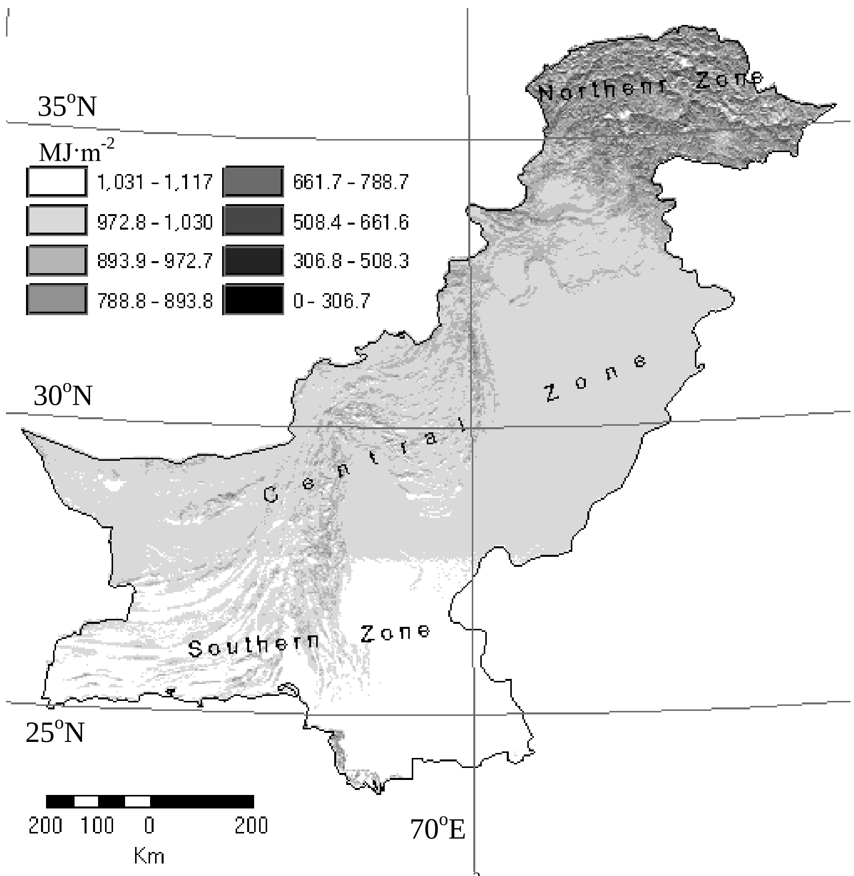

Figure 3: Spatial distribution of ESR (unit: $MJ.m^{-2}$) in Pakistan in the month of September.

Spatial Distribution of ESR in the Northern Zone

In the southern zone more or less the spatial distribution of ESR apparently looks analogous to that found in March but the shadow impact of slopes is more prominent in March than the shadow impact of slopes in the month of September The slopes with maximum exposure to the sun receive a variety of range of ESR amount that varies from 894-1117 units. The slopes which are deeply influenced by the shadow impact come under the class of 0-661 units. Another category of rugged terrain is between the highest and lowest class which has average ESR units from 662-893 in the month of September.

Spatial Distribution of ESR in the Central Zone

In central zone, the dominant class of ESR varies between 973-1030 units in September. The prominent impact of slopes has been measured in the Sulaiman ranges, the area dominated by Toba Kakar ranges in northwestern Balochistan, the central Brahui ranges, Zarghoon, Takatoo and Murdar Ghar in the Quetta region. The shadow impact is obvious in these mountainous terrains, the ESR amount has been estimated from 662-788 units. While the other slopes and piedmonts of the zone depict the amount of ESR approximately from 789-894 units.

Spatial Distribution of ESR in the Southern Zone

Being close to the tropics the southern zone in Pakistan receives highest amount of ESR per unit area in September if compared with central and northern zones. There are two dominant classes in this zone. First, the plains have ESR from 1031-1117 units second the mountains have 662-788 units. The rugged territory depicts variation that is the mountains with north-south trend shows little impact on the ESR than the mountains with east-west trend. The high slopes of Kirthar range have obvious more impact while the rest of the mountains in the southern zones are with low heights therefore there impact is not much obvious. However, the ranges in the southern zone depict ESR of 662-973 units with predominant patches of 789-894 units over the piedmonts.

Conclusion

The model supports that ESR over the diversified national territories considerably vary in the months of March and September at regional scale from north to south and east to west in the country. Landforms play instrumental role in the determination of amount of ESR in the rugged territories. The height, angle and orientation of slopes are the key factors that are giving shape to the spatial distribution and amount of ESR. The HKH Mountains prominently interrupt the distribution of ESR controlled by their height and slope angles. The plains show less variation and predominantly reflect latitudinal impact. The mountains with moderate height in Balochistan, KPK and Tribal Areas show less screening impact on the ESR if compared with the high HKH Mountains. The amount of ESR found on the piedmonts stand as distinct patches especially in Balochistan. The results support that ArcGIS is the compatible tool to map the spatial and temporal dimensions of solar energy over the complex landforms of Pakistan in the absence of a comprehensive system for solar radiation data. Solar energy is the cheap and renewable source of power. Its determination is difficult without knowing its geographical accessibility and spatial distribution especially where most of our country is dominated by rugged topography except the Indus plains. Therefore, this study can be efficiently utilized as base line study and could be highly pertinent for the determination of geographical accessibility and spatial distribution of solar energy potential in the difficult and inaccessible national territories.

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