SOLAR RADIATION AND THE DIVERSE RELIEF OF SLOVENIA

SONČNO OBSEVANJE V RELIEFNO RAZGIBANI SLOVENIJI

Matej Gabrovec

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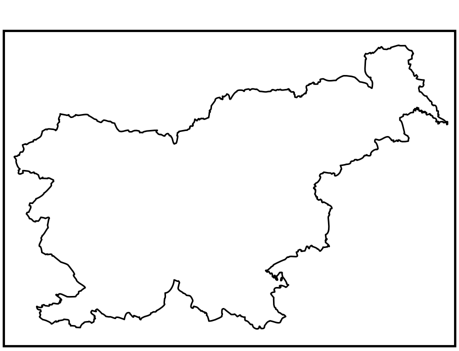


Abstract UDC: 551.52(497.4)

Solar Radiation and the Diverse Relief of Slovenia

The article presents the methods for the elaboration of the map of quasiglobal radiation in detail. The basis for the elaboration of the map is rastered Geographical Information System. Among meteorological data sources, the most important are those measuring the duration of solar radiation. We used mean ten-day period hour values in the period between 1961 and 1990 from twenty-four meteorological stations in Slovenia. The source of relief data is the 100 × 100 meter digital relief model from which we calculated the inclination, exposition, and level of shade. The final map clearly shows the differences in the annual energy of quasiglobal radiation at various relief positions and climate regions.

Izvleček UDK: 551.52(497.4)

Sončno obsevanje v reliefno razgibani Sloveniji

V članku so podrobneje predstavljene metode izdelave karte kvaziglobalnega obsevanja. Osnova za izdelavo karte je rasterski geografski informacijski sistem. Med meteorološkimi viri podatkov so najpomebnejše meritve o trajanju sončnega obsevanja. Uporabili smo povprečne dekadne urne vrednosti v obdobju 1961–1990 za 24 postaj v Sloveniji. Vir reliefnih podatkov je digitalni model reliefa 100 × 100 m, s pomočjo katerega smo računali naklon, ekspozicijo in osenčenost. Končna karta dobro prikazuje razlike v letni energiji kvaziglobalnega obsevanja na različnih reliefnih legah in klimatskih regijah.

Address – Naslov
dr. Matej Gabrovec
Geografski inštitut ZRC SAZU
Gosposka 13
1000 Ljubljana
Slovenia
Telefon: +386 (0)61 125 60 68/301
Fax: +386 (0)61 125 52 53
E-mail: Matej@zrc-sazu.si

Contents – Vsebina

1. Introduction

“The duration of solar radiation and its energy that reaches the soil are becoming ever more important climate data for various branches of economy from food production to the direct use of solar energy” (Petkovšek, 1982, 46). For this very reason not only are meteorologists involved in calculating the amount of solar radiation but also foresters, agronomists, geographers, and experts from other related fields. The latter have studied the importance of solar radiation for farming and forestry, and in their research they have studied in particular the importance of topographical elements for the intensity of solar radiation.

Slovenia measures only 20,256 square kilometers, but in spite of this we can divide its territory into three climate types: submediterranean, temperate-continental, and mountainous (Ogrin, 1996). However, the quantity of received energy of quasiglobal radiation is influenced more by various relief positions than by the different climate types. This is proven by the tables presented in the following chapters. For this reason we placed special emphasis on the influence of relief parameters in solar radiation in our study, which was only possible by the use of a digital relief model. In Slovenia, we have at our disposal a 100 × 100 meter digital relief model covering the territory of the entire country, an indispensable help in our research.

Relief influences solar radiation in two ways. Firstly, it influences the effective possible duration of solar radiation, that is, the period of sunshine in clear weather less than the period of shade due to relief obstacles (Kunz, 1983). Secondly, it influences through the inclination and exposition of the slopes on which the angle between the rays of the sun and the earth's surface depends, ultimately influencing the quantity of solar energy received. In Slovenia, the problem of effective possible duration of solar radiation was studied by Gams (1978), who developed a diagram of shade for individual typical days in a year for a selected settlement in a narrow alpine valley. Using the digital relief model, Anko (1983) calculated the exposition and inclination of the slopes of the village of Pernice in northern Slovenia, arranging the quantity of solar radiation on various sites according to Frank and Lee (1966).

In the mid 1980's, the elaboration of the 100 × 100 meter digital relief model of Slovenia was completed (Banovec, Hočevar, Kunaver, Petkovšek, 1972). This enabled the calculation of relief elements for the calculation of solar radiation. Several years earlier, the study *Distribution of Solar Energy in Slovenia* was finished (Hočevar, 1980) in which a model for the calculation of quasiglobal solar radiation was elaborated. In this study, which employed analyses of measurements of the duration of solar radiation at thirty-one stations in Slovenia and measurements of global solar radiation in Ljubljana and several towns in neighbouring countries (Klagenfurt, Trieste, and Zagreb), meteorological parameters (transmission coefficients of absorption and dispersion in the atmosphere) were calculated. In 1989, on the basis of meteorological model (Hočevar, Rakovec, 1977) and the use of the digital relief model, we developed a computer program for calculating quasiglobal solar radiation (authors Marko Krevs and Matej Gabrovec). The program was written in Pascal for Atari computers, and for the normal operation of the program in calculating radiation for a few dozen square kilometers of land a computer with four megabytes of internal memory was required.

The program was first tested in the calculation of quasiglobal radiation in the area of the Polhov Gradec hills. The calculation was elaborated for vegetation period in a 45 sq. km large territory in the central part of the hills. The aim of the study was an analyses of the adaptation of land use to natural conditions (Gabrovec, 1990). Later, we used the same program in the search for the laws governing the occurrence of summer snow-fields (Gabrovec, 1990 a). In the following years, the computer program was used in several physical geography dissertations. Žiberna (1992) studied the influences of the climate on the expansion of vineyards, and Ogrin (1995) calculated solar radiation of Slovene Istria. In 1995, the development of computer technology enabled us to calculate solar radiation over the entire country, since for this purpose we needed a personal computer with at least sixty-four megabytes of internal memory. In the following chapter I will present in detail the method used for elaborating the map of solar radiation in Slovenia. It was elaborated in 1996 for the *National Atlas of Slovenia* on the basis of methods developed in the second half of the 1980's (Gabrovec, 1990).

2. Method of Map Elaboration

The map is completely computer elaborated. The basis for its elaboration is the Geographical Information System being developed at the Geographical Institute ZRC SAZU (Perko, 1991). Basic processing is performed using the IDRISI computer program package (Eastman, 1992). The foundation of Geographical Information System is the 100 × 100 meter digital relief model that was basically prepared by the Surveying and Mapping Authority of the Republic of Slovenia and further improved under the auspices of the Geographical Institute ZRC SAZU. The hectare cell is thus the basic unit of the Geographical Information System, and all the calculations of solar radiation were made for each hectare cell. The computer program mentioned earlier was upgraded and adapted to work on IBM compatible computers and translated into Visual Basic. This work was done by Matjaž Skobir of the Institute for Geography in Ljubljana.

Calculations of quasiglobal radiation were elaborated according to Hočevar's model. Accordingly, the strength, more exactly surface density strength, of quasiglobal radiation is calculated according to the following formula (Hočevar, 1980):

$$j_k = \rho^2 I_0 \left(q_a q_s\right)^m D \sin p + 0{,}5 \rho^2 I_0 \cos^2\left(\frac{n}{2}\right) q_a^m \left(1 - q_s^m\right) \cos^{4/3} z \left(D + \left(1 - D\right) C\right)$$

The first part of the formula represents the strength of direct solar radiation; the second part, the strength of the diffused component of quasiglobal radiation.

With time integration from east to west, we calculate the daily energy, more exactly surface density day energy, of solar radiation:

$$E_k = \int_{vz}^{zh} j_k \, dt$$

where:

C is a factor dependent on the type of clouds and the zenith angle. For the summer period (April to September), we considered altocumulus (*Ac*) as the typical cloud and for the winter period, stratus (*St*). This factor is calculated according to the following formulae:

$$C(Ac) = 1.35 + 5.42 z - 3.38 z^2$$

$$C(St) = 0.35 + 4.49 z - 2.54 z^2$$

D: relative duration of solar radiation
E_k: energy of quasiglobal radiation
I_0: solar constant
j_k: strength of quasiglobal radiation
m: optical air mass, dependent on zenith angle of the sun
n: inclination of surface
p: angle between direction of sun's rays and surface
q_a: transmission coefficient relative to absorption
q_s: transmission coefficient relative to diffusion
ρ: relative distance between sun and earth
t: time, $t = 0$ at 12 noon
vz: sunrise ("vzhod sonca" in Slovene)
zh: sunset ("zahod sonca" in Slovene)
z: zenith angle of the sun, calculated according to the formula

$$\cos z = \sin\varphi \, \sin\delta + \cos\varphi \, \cos\delta \, \cos\omega t.$$

where the new symbols denote the following:
φ: geographical width
δ: declination of the sun
ω: circular frequency of daily cycle ($\omega = 360°/24$ hours)

Below I will cite the source of all meteorological and relief parameters in detail. All the calculations were made according to ten-day periods and hours. For the mean day in each ten-day period we first calculated the hourly values for the energy of quasiglobal radiation and from their sum got a daily value that we multiplied by ten, the number of mean days in a ten-day period, and thus received the ten-day period energy of radiation; with the sum of the ten-day period values we ultimately got the annual energy of quasiglobal radiation. All these calculations were elaborated for each hectare cell, of which there are over two million in Slovenia.

2.1. Meteorological Parameters

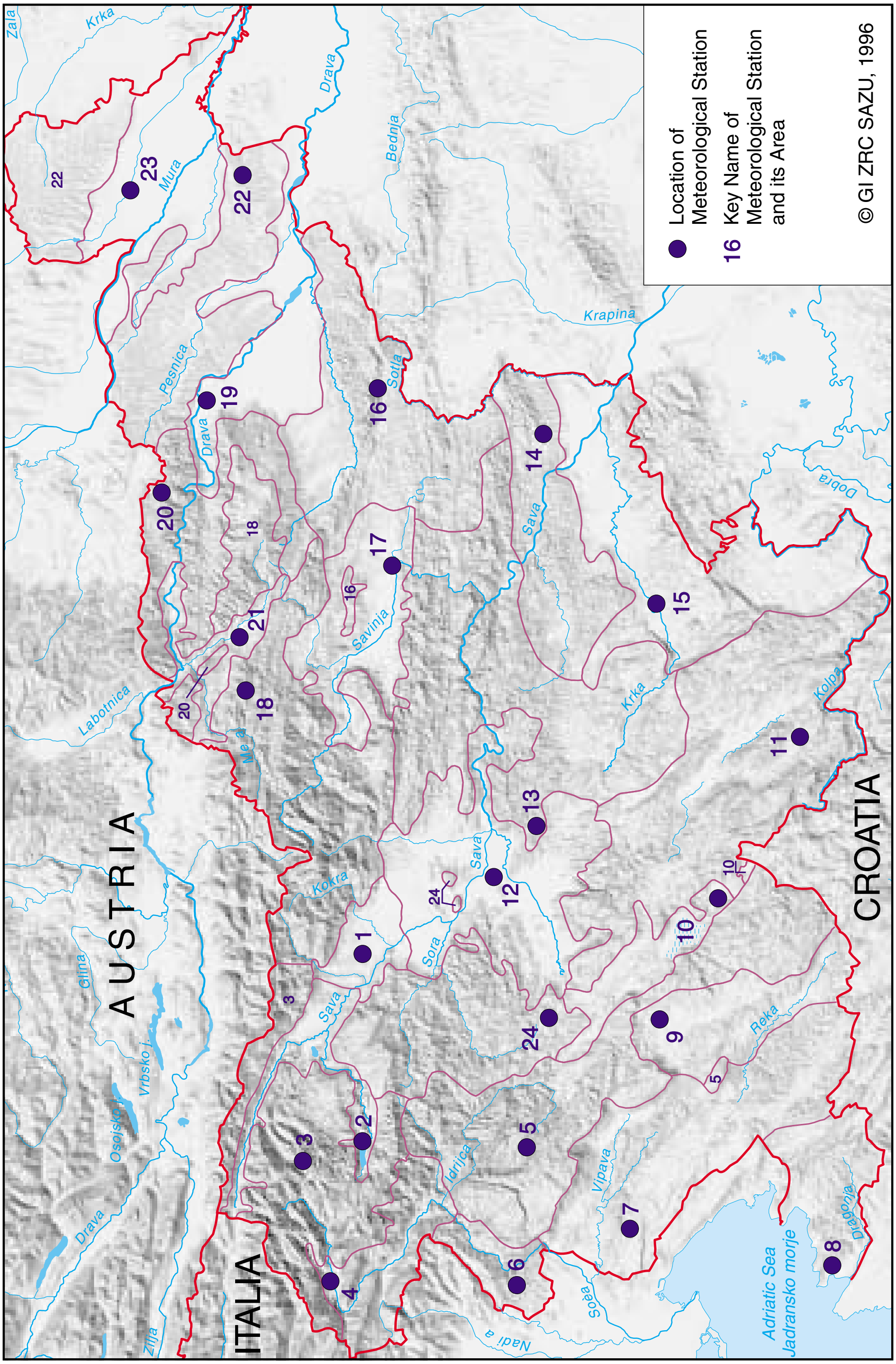
The transmission coefficients relative to absorption and dispersion were taken from the same study as the model. They were calculated on the basis of processing parallel sets of observations of global radiation and the duration of solar radiation. For their calculations the authors only had synchronous sets of both parameters available for Ljubljana, and in determining transmission coefficients for other places in Slovenia they took into consideration height above sea level and air pollution (Hočevar, 1980).

Data on mean ten-day period hour values for the duration of solar radiation was provided by the Hydrometeorological Institute of the Republic of Slovenia. In Slovenia, the duration of solar radiation is measured by Campbell-Stokes heliographs. These measuring instruments do not register the duration of solar radiation when the sun is lower than 3° above the horizon and are not accurate between the heights of the sun between 3° and 5°. The position of the heliographs at observation stations is such that obstacles block the sun (relief, trees, buildings) mainly in the morning and evening hours. Therefore in case when we want to use the measured values at the selected location as representative of wider areas, we must calculate them to a mathematical horizon to eliminate the influence of instrument error, relief, and other obstacles. For this kind of correcting the hour values for the duration of solar radiation, we must take into account differing weather situations and the fact that certain obstacles in the surroundings of the observatory stations are constantly changing (trees grow, new buildings appear, etc.). The hour values for the duration of solar radiation were corrected on the basis of data on the height of individual obstacles in different periods and on the basis of statistical analysis of the hour values for the duration of solar radiation. The hour values for the duration of solar radiation during the hours when obstacles were present were corrected to the maximum possible value for the duration of solar radiation when the previous (afternoon) or the next (morning) hour was clear. The mean ten-day period hour values for the duration of solar radiation were calculated on the basis of hour values calculated to a mathematical horizon (Kastelec, 1995).

We received data on the duration of solar radiation for twenty-four meteorological stations that are quite evenly dispersed across the entire country. The data covers the thirty-year period between 1961 and 1990. Regrettably, half of the stations were not in operation during the entire period, but none had been in operation for less than twenty years and only three were operational for less than twenty-five years. The list of the stations is shown in the first table.

Regrettably, the data cited on the duration of solar radiation is only valid for the specific measurement stations, and these are quite distant from each other. For our purpose we needed data on the duration of solar radiation for each hectare cell in Slovenia. Therefore we determined the area around each measurement station that would best correspond to the situation at the measurement point. In demarcating the areas of individual stations, we maintained two basic principles. Firstly, the boundaries of the areas must correspond to the boundaries of climate types in Slovenia. In this respect, we relied on Ogrin's typology (Ogrin, 1996). Secondly, the entire area must have a similar relief position as the meteorological station. Thus, the area of a basin station must be limited by the rim of the basin, the area of a mountain station must be totally within the higher elevations, and so forth.

Figure 1: Measurement stations of the duration of solar radiation and their areas (M 1 : 130,000).
Slika 1: Merilne postaje trajanja sončnega obsevanja in njihova območja (M 1 : 130,000).



Location of Meteorological Station
16 Key Name of Meteorological Station and its Area
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AUSTRIA
ITALIA
CROATIA
Adriatic Sea
Jadransko morje
Zala
Krka
Mura
Drava
Bednja
Pesnica
Sotla
Krapina
Dobra
Savinja
Sava
Labotnica
Kokra
Sora
Kolpa
Glina
Vrbsko j.
Osojsko j.
Zilja
Idrijca
Vipava
Reka
Dragonja

In some cases, the area of a meteorological station is not consistent, for example, where hills are divided into two parts by a wide valley or a basin, and we only had one measurement point at our disposal at a higher altitude above sea level. Of course, it was not possible to comply entirely with the two cited criteria because of the insufficient measurement network, but we believe that for the majority of Slovene territory the data on the duration of solar radiation is sufficiently representative. It is clear, however, that we were not able to take into consideration the influence of heavier fog in some smaller valleys and basins. The locations of the stations and their areas are shown in the first map.

TABLE 1: LIST OF STATIONS WITH MEASUREMENTS OF THE DURATION OF SOLAR RADIATION.
PREGLEDNICA 1: SEZNAM POSTAJ Z MERITVAMI TRAJANJA SONČNEGA OBSEVANJA.

Station Number	Station	Altitude in meters	Measurement Period
1	Brnik	384	1964–1990
2	Stara Fužina	547	1961–1990
3	Kredarica	2514	1961–1990
4	Bovec	425	1961–1990
5	Vojsko	1070	1963–1986
6	Vedrijan	258	1961–1990
7	Novelo pri Temnici	350	1961–1990
8	Portorož-Beli Križ	92	1961–1990
9	Postojna	533	1961–1990
10	Šmarata	590	1966–1990
11	Novi Lazi	545	1966–1990
12	Ljubljana-Bežigrad	299	1961–1991
13	Lipoglav	524	1962–1990
14	Sromlje	292	1971–1990
15	Novo mesto	220	1961–1990
16	Stojno selo	300	1963–1990
17	Celje	244	1961–1990
18	Uršlja gora	1696	1966–1990
19	Maribor	275	1961–1990
20	Duh na Ostrem vrhu	903	1967–1988
21	Šmartno pri Slovenjgradcu	452	1964–1990
22	Jeruzalem	345	1962–1984
23	Murska Sobota	184	1961–1990
24	Lavrovec	880	1964–1990

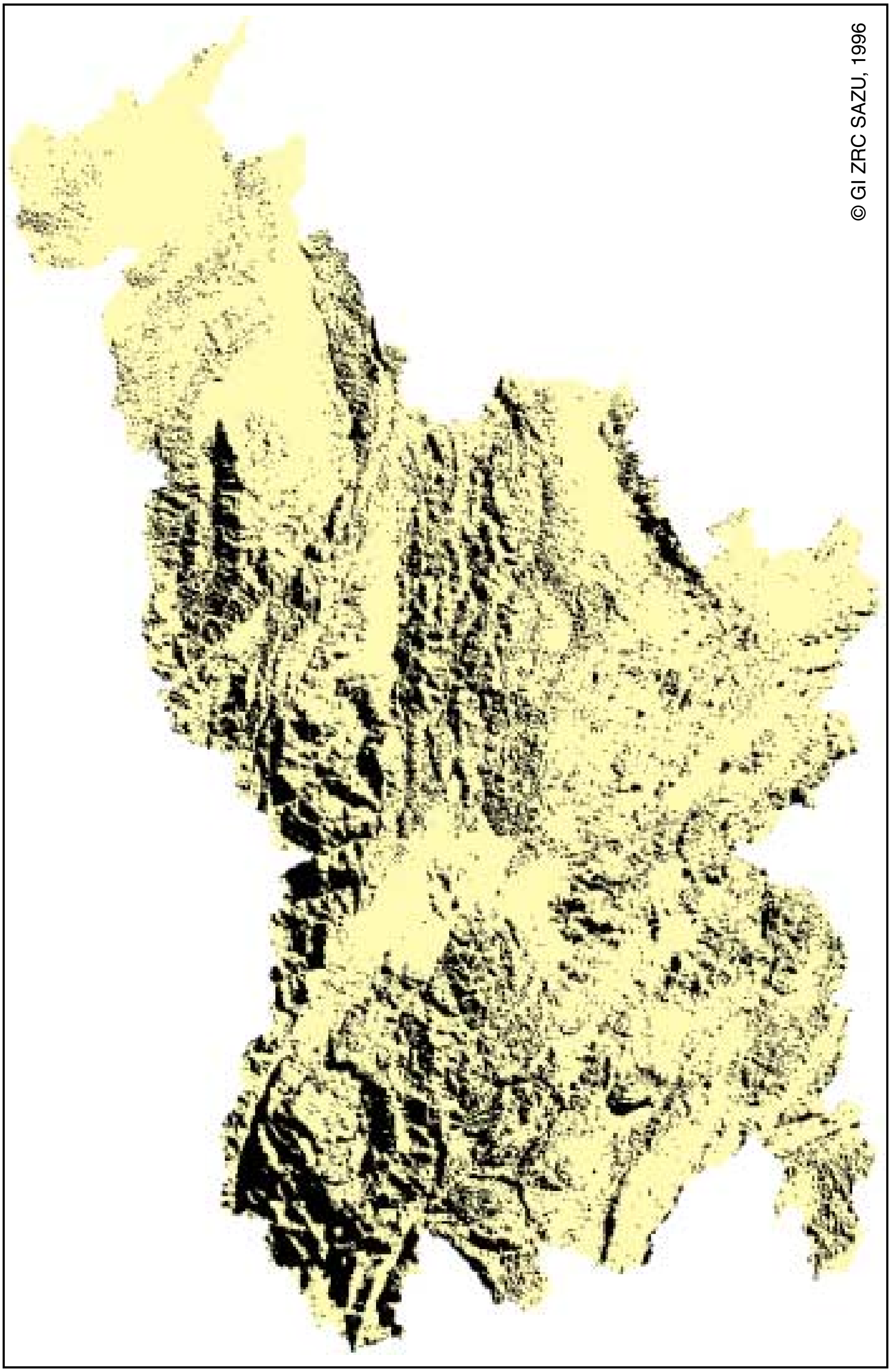
2.2. Relief parameters

Relief, as previously stated, influences solar radiation in two ways. Because of the various expositions and inclinations of the surface, the angle between the sun's rays and the surface changes and with it the amount of solar energy received. Secondly, various elevations function as obstacles to the sun's rays and surfaces in their shade in certain moments only receive a diffused portion of the solar radiation.

The source for the calculation of inclinations and expositions was the 100×100 meter digital relief model. Inclination was calculated from the corner points of each cell according to the following formula:

$$n = \arctan\left(a^2 + b^2\right)^{1/2}$$

Figure 2: Shade at 9:00. in the last ten-day period in December (M 1 : 130,000).
Slika 2: Osenčenost ob 9^h v zadnji dekadi decembra (M 1 : 130,000).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where a and b are coefficients for the regression of level ground that we calculate according to the following formulae:

$$a = \left(\frac{-h_1 + h_2 - h_3 + h_4}{200} \right) \qquad b = \left(\frac{-h_1 - h_2 + h_3 + h_4}{200} \right)$$

In the above formulae, h_1 to h_4 denote the heights above sea level of the corner points of a cell (Gabrovec, 1990). The exposition is calculated using the IDRISI software with the SURFACE module (Eastman, 1995).
For the calculation of direct solar radiation, we must calculate the angle between sun's rays and the surface for each hour in the day and for each ten-day period in the year for every cell. The formula for this calculation follows (Enders, 1976):

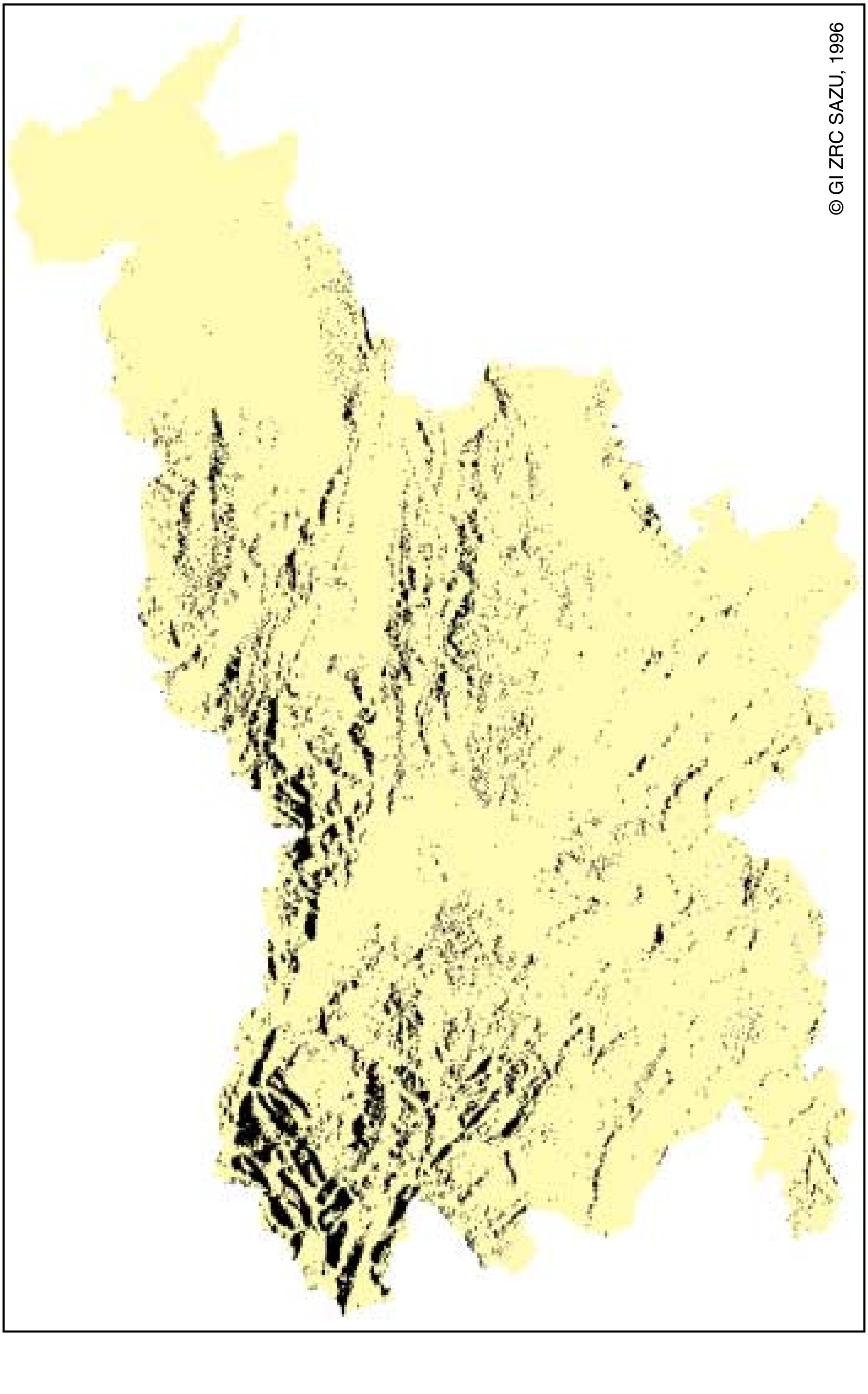
$$\sin p = (\sin\varphi \cos n - \cos\varphi \sin n \cos a)\sin\delta + (\cos\varphi \cos n + \sin\varphi \sin n \cos a)\cos\delta \cos\omega t + \sin n \sin a \cos\delta \sin\omega t$$

in which a is the exposition of the slope. The remaining symbols were explained in the beginning of Chapter 2.
The amount of shade was also determined using the digital relief model by calculating the relative height of cells in the path of the sun's rays. This was measured along a straight line perpendicular to the sun's rays. The shade of individual cells is determined on the basis of checking whether any of the cells in the path of the sun's rays had already surpassed its relative height. If this had happened, the cell was in the shade; otherwise, it was exposed to the sun (Krevs, 1996). The shade was calculated for all hours and decades. In the case that a cell was shaded, only the diffused portion of solar radiation is calculated for it in that hour. Figures 2 to 4 show the shade at 9:00 and 15:00 in the last ten-day period in December.

3. Main Characteristics of the Distribution of Quasiglobal Solar Radiation in Slovenia

The first glance at the map of the annual energy of quasiglobal radiation shows us very large differences within short distances. These differences are the result of various expositions and levels of shade. The consequence of this is that the variability within an area of a particular climate type is larger than the variability between climate types. Table 2 shows the mean values of annual energy of quasiglobal radiation according to climate types, and the table 3 shows the mean values according to various expositions irrespective of inclination. Flat land is there, where inclination of a cell is below haf degress. In dividing Slovenia by climate types we relied on the Ogrin typology and divided Slovenia into Submediterranean, Temperate-continental, and Mountainous climates. The temperate-continental type, which encompasses the largest part of Slovenia, is further divided into the temperate-continental subtypes of western and southern Slovenia, central, and eastern (subpannonian) Slovenia (Ogrin, 1996).
A look at the tables above reveals that there is larger difference relative to solar radiation between northern and southern expositions (3472 and 4448 MJ/m^2) than between the two extreme climate types, that is, between the mountainous and submediterranean climates (3713 and 4375 MJ/m^2). With expositions, the standard deviations are larger on sunless slopes, with shade influencing larger differences. With climate types, the standard deviations are larger where the relief is more diverse. Therefore, the standard deviation is small in flat and hilly subpannonian Slovenia. The standard deviation is very small on sunny slopes and flatland in spite of the fact they occur in all climate types.

Figure 3: Shade at 12:00 in the last ten-day period in December (M 1 : 130,000).
Slika 3: Osenčenost ob 12^h v zadnji dekadi decembra (M 1 : 130,000).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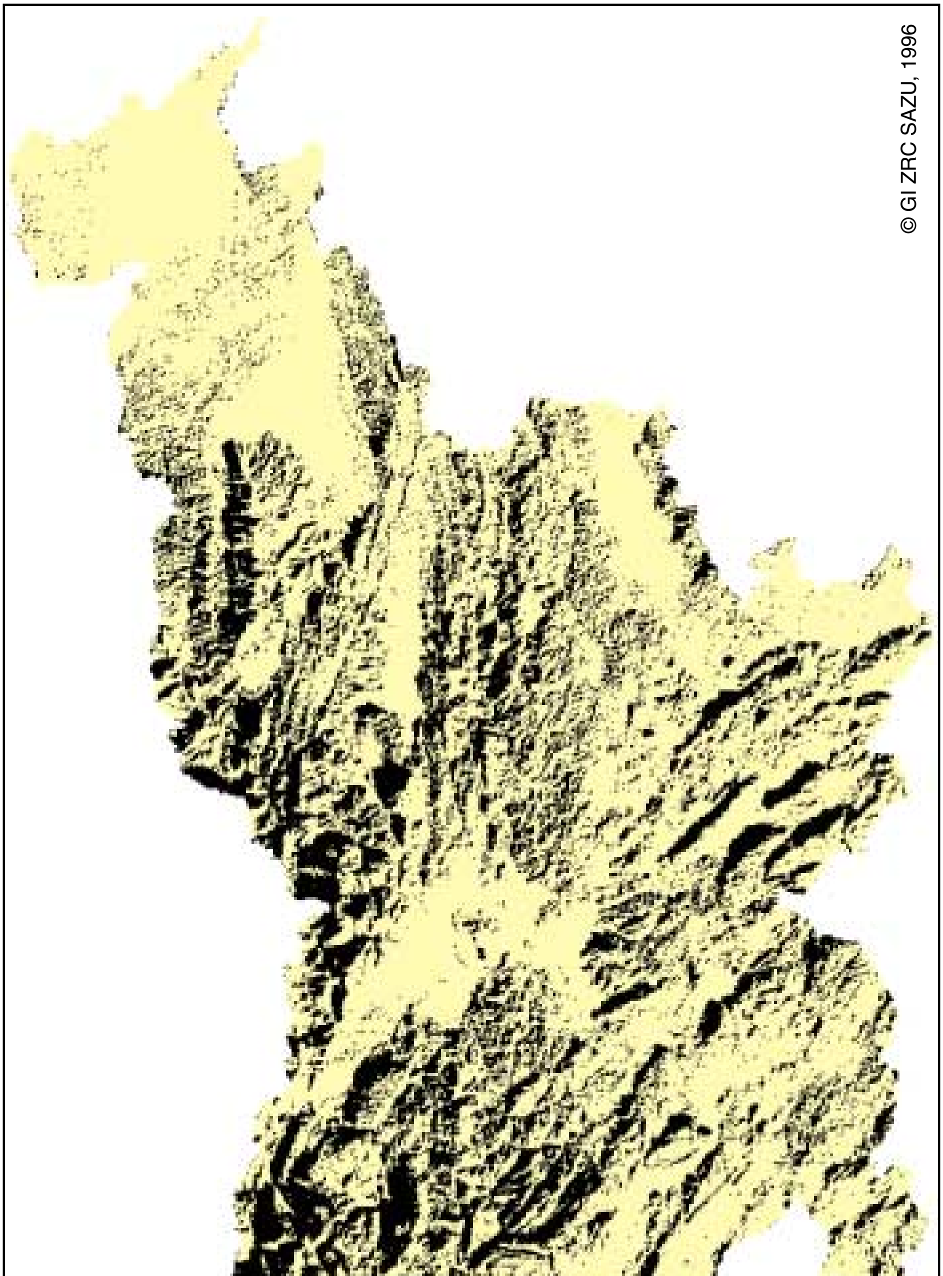
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Table 2 and Figure 7 reveal that the annual amount of quasiglobal radiation is by far the largest in submediterranean Slovenia where it surpasses the national average by around 10%. Sunny positions stand out even more so here. Another extreme is mountainous Slovenia where the influence of increased cumulus-cloudiness occurs during the summer. Otherwise, the amount of solar energy increases from west to east and is linked with the decrease in cloudiness and the amount of rainfall in the same direction. The map of quasiglobal radiation in the last ten-day period in June roughly shows a similar distribution of energy as the annual map, while the December map is decidedly different. Then we can clearly see a larger quantity of solar radiation in the mountainous world in the north of the country, while on the other hand there are basins with very little sun with temperature inversions and fog, and sunless slopes on which in winter the sun frequently does not shine at all, this confirms older findings (Hočevar, 1980; Petkovšek, 1982).

TABLE 2: ENERGY OF QUASIGLOBAL SOLAR RADIATION BY CLIMATE TYPE IN MJ/SQ. M.
PREGLEDNICA 2: ENERGIJA KVAZIGLOBALNEGA SONČNEGA OBSEVANJA PO PODNEBNIH TIPIH V MJ/M^2.

Climate type	Mean annual energy	Standard deviation	Daily Energy of 3rd ten-day period in June	Daily Energy of 3rd ten-day period in December
Submediterranean	4375	446	20.89	2.84
Temperate-continental western and southern Slovenia	3955	479	18.50	2.70
Temperate-continental central Slovenia	4013	409	19.27	2.54
Subpannonian	4135	289	19.39	2.59
Mountain	3713	759	16.10	3.34

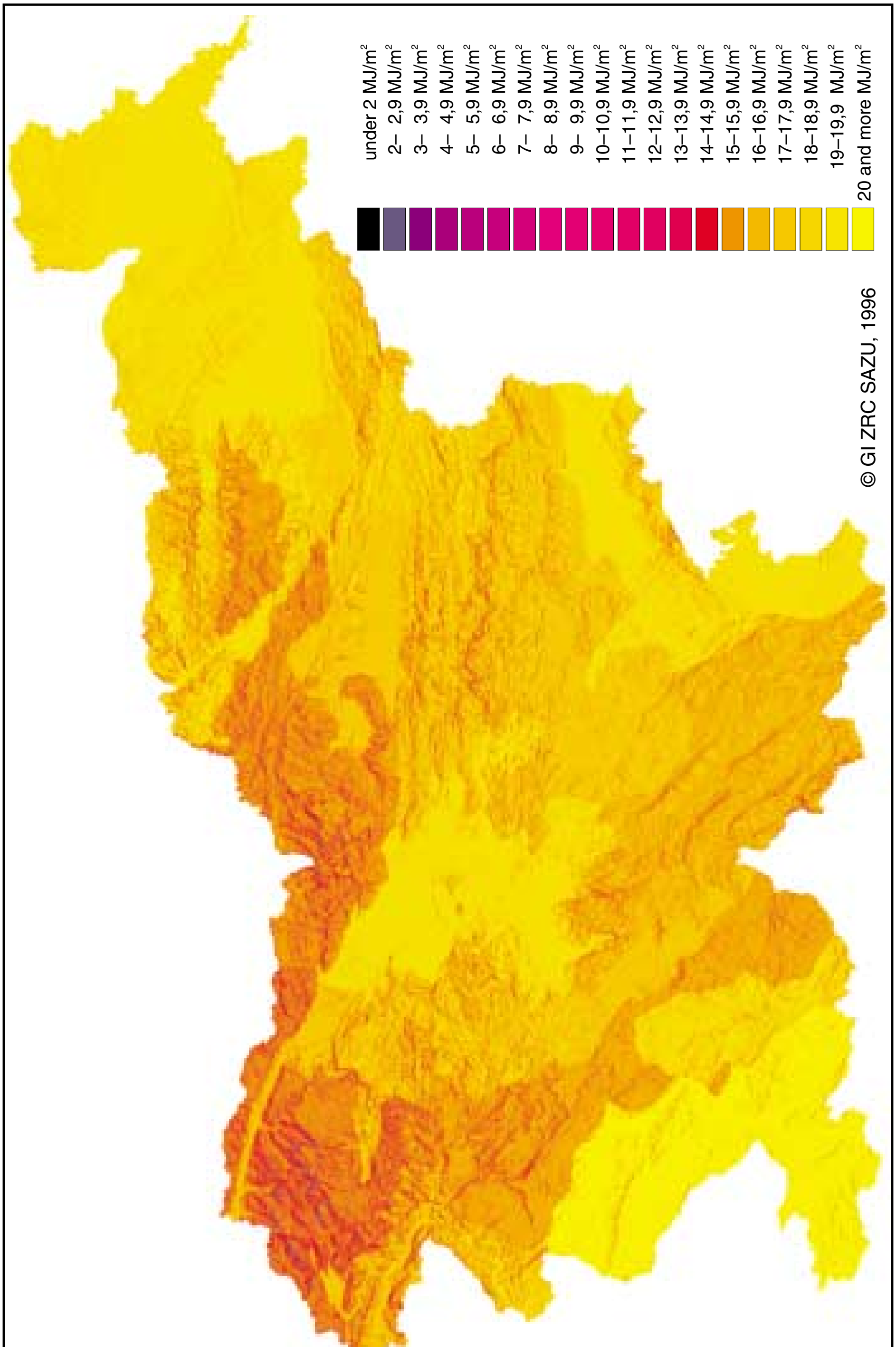
TABLE 3: ANNUAL ENERGY OF QUASIGLOBAL SOLAR RADIATION RELATIVE TO EXPOSITION IN MJ/SQ. M.
PREGLEDNICA 3: LETNA ENERGIJA KVAZIGLOBALNEGA SONČNEGA OBSEVANJA GLEDE NA EKSPOZICIJO V MJ/M^2.

Exposition	Mean annual energy	Standard deviation
North	3472	600
Northeast	3647	469
Northwest	3590	554
East	3998	272
West	4002	330
Southeast	4313	186
Southwest	4342	211
South	4448	226
Flatland	4175	68

4. Conclusion

The innovation of the new map is that it shows the quasiglobal radiation for the entire country and simultaneously takes into consideration the relief characteristics of each hectare cell individually. The elaboration of such maps was not previously possible since digital relief models for the entire country were not available and we did not have enough computers capable of performing the calculations within a reasonable time. The calculation of the annual quantity of energy of quasiglobal radiation for all of Slovene territory took approximately one week of computer time on a 586/133 Mhz IBM compatible computer with sixty-four megabytes of internal memory. Therefore, the majority

Figure 4: Shade at 15:00 in the last ten-day period in December (M 1 : 130,000).
Slika 4: Osenčenost ob 15^h v zadnji dekadi decembra (M 1 : 130,000).



under 2 MJ/m2
2– 2,9 MJ/m2
3– 3,9 MJ/m2
4– 4,9 MJ/m2
5– 5,9 MJ/m2
6– 6,9 MJ/m2
7– 7,9 MJ/m2
8– 8,9 MJ/m2
9– 9,9 MJ/m2
10–10,9 MJ/m2
11–11,9 MJ/m2
12–12,9 MJ/m2
13–13,9 MJ/m2
14–14,9 MJ/m2
15–15,9 MJ/m2
16–16,9 MJ/m2
17–17,9 MJ/m2
18–18,9 MJ/m2
19–19,9 MJ/m2
20 and more MJ/m2
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of researchers had so far calculated the quasiglobal radiation only for southern sites of various inclinations without consideration of shade (Hočevar, 1980; Seifert, 1990). Those studies were primarily undertaken for the needs of planning the exploitation of solar energy, while the present maps also allow the determination of optimal locations for farming and forestry.

To conclude, I also present a graph of the frequency distribution of annual energy of quasiglobal radiation. This shows a very large span between minimal and maximal values of 811 and 5333 MJ/m^2 respectively. The ratio between them is as much as 1:6.5. Without the influence of relief, that is, theoretically supposing that all the cells were level and invariably exposed to the sun, the ratio would only be 1 : 1.19. The minimal and maximal values in this case would be 3876 and 4596 MJ/m^2 respectively. The frequency distribution is distinctly asymmetrical, the consequence of shade. Average northern sites in Slovenia receive a good 15% less solar energy than level sites while the most sunless positions receive about a fifth of the energy of average cell in level elevations. All this data proves beyond doubt that in a country as small as Slovenia, relief is the decisive factor in the distribution of the energy from quasiglobal radiation.

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Figure 5: Mean daily energy of quasiglobal radiation in the last ten-day period in June (M 1 : 130,000).
Slika 5: Poprečje dnevne energije kvaziglobalnega obsevanja v zadnji dekadi junija (M 1 : 130,000).

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6. Povzetek – Summary

Sončno obsevanje v reliefno razgibani Sloveniji

Matej Gabrovec

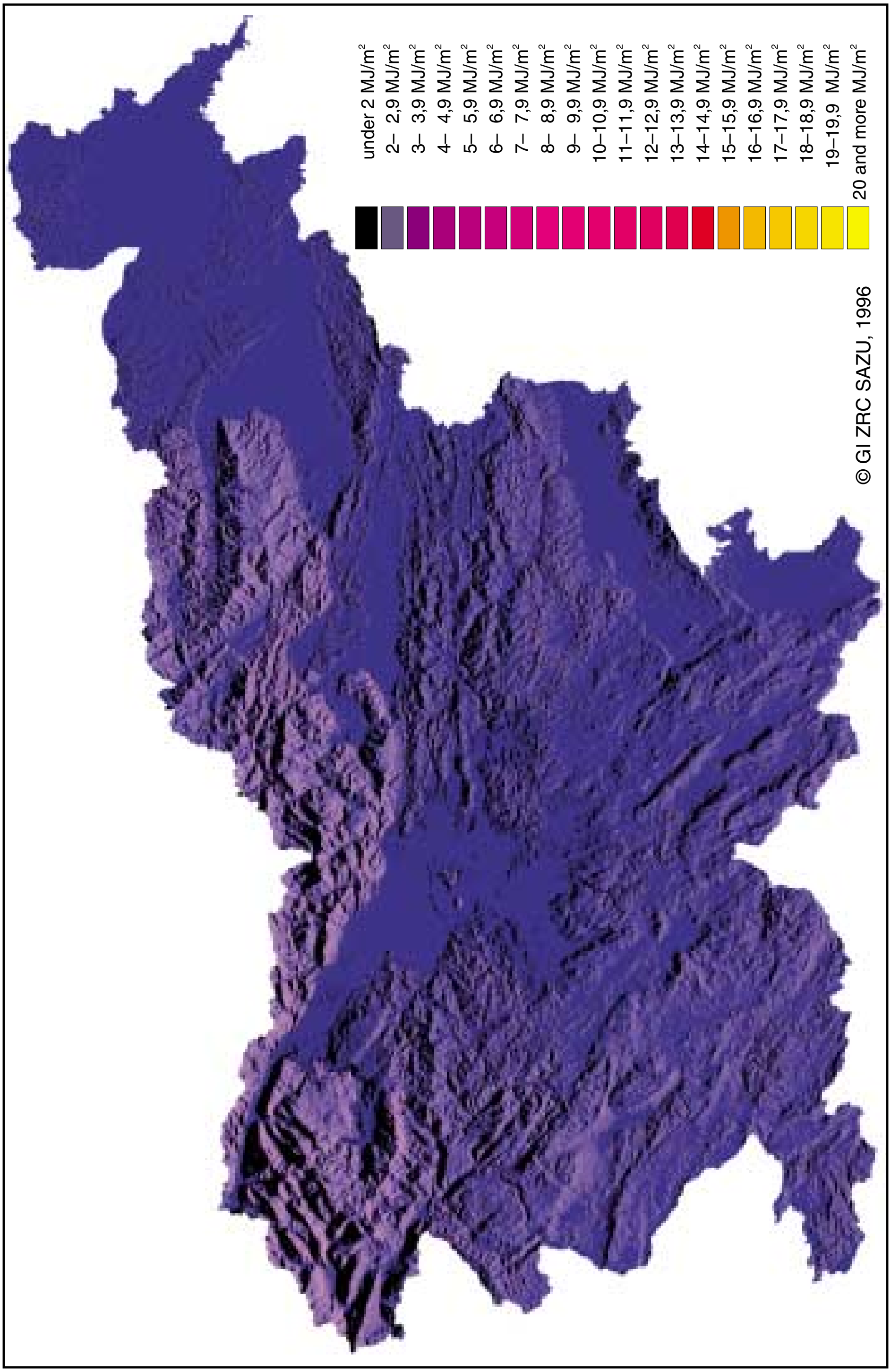
"Trajanje sončnega obsevanja in njegova energija, ki pride do tal, postajata vse pomembnejša klimatska podatka za razne gospodarske panoge od pridelave hrane, do neposredne izrabe sončne energije." (Petkovšek, 1982, 46). Prav zato se z izračunavanjem količine sončnega obsevanja ne ukvarjajo zgolj meteorologi, ampak tudi gozdarji, agronomi, geografi in strokovnjaki drugih sorodnih strok. Slednji so proučevali pomen sončnega obsevanja za kmetijstvo in gozdarstvo, v svojih raziskavah pa so proučevali zlasti vpliv topografskih elementov na jakost sončnega obsevanja.

Slovenija meri le 20256 km^2, kljub temu pa lahko njeno ozemlje razčlenimo na tri podnebne tipe, to je na submediteransko, zmernokontinentalno in gorsko (Ogrin, 1996). Vendarle pa na količino prejete energije kvaziglobalnega obsevanja bolj vplivajo različne relefne lege kot različni podnebni tipi. To dokazujeta preglednici 2 in 3. Prav zato smo v tej raziskavi dali poseben poudarek vplivu reliefnih parametrov na sončno obsevanje, to pa je bilo možno le z uporabo digitalnega modela reliefa. V Sloveniji imamo za ozemlje celotne države na razpolago digitalni model reliefa 100 × 100 m, ki je bil nepogrešljiv pripomoček v naši raziskavi.

Relief na sončno obsevanje vpliva na dva načina. Prvič vpliva na tako imenovano efektivno možno trajanje sončnega obsevanja, to je čas sijanja sonca pri jasnem vremenu, zmanjšan za čas osenčenosti zaradi reliefnih ovir (Kunz, 1983). Drugič vpliva z naklonom in ekspozicijo pobočij, od česar je odvisen kot med sončnimi žarki in zemeljsko površino, ki končno vpliva na količino prejete sončne energije. V Sloveniji se je s problemom efektivnega možnega trajanja sončnega obsevanja ukvarjal Gams (1978), ki je za vas Sočo izdelal diagram osenčenosti za posamezne značilne dni v letu. Anko (1983) je s pomočjo digitalnega modela reliefa izračunal ekspozicijo in naklon pobočij vaškega zemljišča Pernic v severni Sloveniji, količino sončnega obsevanja na različnih legah pa je priredil po Franku in Leeju (1966).

Sredi osemdesetih let je bila končana izdelava digitalnega modela reliefa Slovenije 100 × 100 m (Banovec, Hočevar, Kunaver, Petkovšek, 1972). Ta nam je omogočil izračun reliefnih elementov za izračun sončnega obsevanja. Nekaj let prej je bila končana raziskovalna naloga Razporeditev potenciala sončne energije v Sloveniji (Hočevar, 1980), v kateri je bil izdelan model izračunavanja kvaziglobalnega sončnega obsevanja. V tej študiji so bili s pomočjo analize meritev trajanja sončnega obsevanja na 31 postajah v Sloveniji in meritev globalnega sončnega obsevanja v Ljubljani in v nekaterih mestih v sosednjih državah (Celovec, Trst in Zagreb) izračunani meteorološki parametri (tran-

Figure 6: Mean daily energy of quasiglobal radiation in the last ten-day period in December (M 1 : 130,000).
Slika 6: Poprečje dnevne energije kvaziglobalnega obsevanja v zadnji dekadi decembra (M 1 : 130,000).


under 2 MJ/m²
2– 2,9 MJ/m²
3– 3,9 MJ/m²
4– 4,9 MJ/m²
5– 5,9 MJ/m²
6– 6,9 MJ/m²
7– 7,9 MJ/m²
8– 8,9 MJ/m²
9– 9,9 MJ/m²
10–10,9 MJ/m²
11–11,9 MJ/m²
12–12,9 MJ/m²
13–13,9 MJ/m²
14–14,9 MJ/m²
15–15,9 MJ/m²
16–16,9 MJ/m²
17–17,9 MJ/m²
18–18,9 MJ/m²
19–19,9 MJ/m²
20 and more MJ/m²
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smisijski koeficienti absorbcije in razpršitve v atmosferi). Leta 1989 smo na osnovi meteorološkega modela (Hočevar, Rakovec, 1977) in ob uporabi digitalnega modela reliefa izdelali računalniški program za računanje kvaziglobalnega sončnega obsevanja (avtorja Marko Krevs in Matej Gabrovec). Program je bil napisan v Pascalu za Atarijeve računalnike, za normalno delovanje programa pri izračunavanju obsevanja za nekaj deset km^2 ozemlja je bil potreben računalnik s 4 megabyti notranjega pomnilnika. Program smo prvič preizkusili ob računanju kvaziglobalnega obsevanja na ozemlju Polhograjskega hribovja. Izračun smo naredili za vegetacijsko dobo na 45 km^2 velikem osrednjem delu hribovja. Cilj raziskovalne naloge je bila analiza prilagoditve rabe tal naravnim razmeram (Gabrovec, 1990). Kasneje smo isti program uporabili, ko smo iskali zakonitosti pojavljanja poletnih snežišč (Gabrovec, 1990 a). V naslednjih letih je bil računalniški program uporabljen v nekaterih fizičnogeografskih razpravah. Žiberna (1992) je proučeval vpliv klime na razširjenost vinogradov, Ogrin (1995) pa je izračunaval sončno obsevanje slovenske Istre. Razvoj računalniške tehnologije nam je v letu 1995 omogočil izračunavanje sončnega obsevanja na ozemlju celotne države. V ta namen smo namreč potrebovali osebni računalnik z vsaj 64 megabyti notranjega pomnilnika. V nadaljevanju podrobneje prikazujem metodo izdelave karte sončnega obsevanja Slovenije. Ta je bila izdelana v letu 1996 za Nacionalni atlas Slovenije, v osnovi pa so bile uporabljene metode, ki smo jih razvili v drugi polovici osemdesetih let (Gabrovec, 1990).

Karta sončnega obsevanja je v celoti izdelana računalniško. Temelj za njeno izdelavo je geografski informacijski sistem, ki ga razvijamo na Geografskem inštitutu ZRC SAZU (Perko, 1991). Osnovne obdelave delamo s pomočjo programskega paketa IDRISI (Eastman, 1995). Temelj geografskega informacijskega sistema je digitalni model reliefa 100 × 100 m, ki ga je v osnovi pripravila Republiška geodetska uprava in smo ga v okviru Geografskega inštituta ZRC SAZU še izpopolnili. Hektarska celica je tako osnovna enota geografskega informacijskega sistema, vsi izračuni sončnega obsevanja so narejeni za vsako hektarsko celico. Zgoraj omenjeni računalniški program je bil izpopolnjen in prilagojen za delo na IBM kompatibilnih računalnikih ter preveden v Visual Basic. To delo je opravil Matjaž Skobir z Inštituta za geografijo v Ljubljani.

Izračuni kvaziglobalnega obsevanja so narejeni po Hočevarjem modelu. Po njem je moč, natančneje ploskovna gostota moči, kvaziglobalnega obsevanja izračunana po naslednji formuli (Hočevar, 1980):

$$j_k = \rho^2 I_0 (q_a q_s)^m D \sin p + 0{,}5 \rho^2 I_0 \cos^2\left(\frac{n}{2}\right) q_a^m \left(1 - q_s^m\right) \cos^{4/3} z \left(D + (1 - D) C\right)$$

Prvi del formule predstavlja moč direktnega sončnega obsevanja, drugi del pa moč difuzne komponente kvaziglobalnega obsevanja.

S časovno integracijo od vzhoda do zahoda izračunamo dnevno energijo, natančneje ploskovno gostoto dnevne energije, sončnega obsevanja:

$$E_k = \int_{vz}^{zh} j_k \, dt$$

pri čemer je:

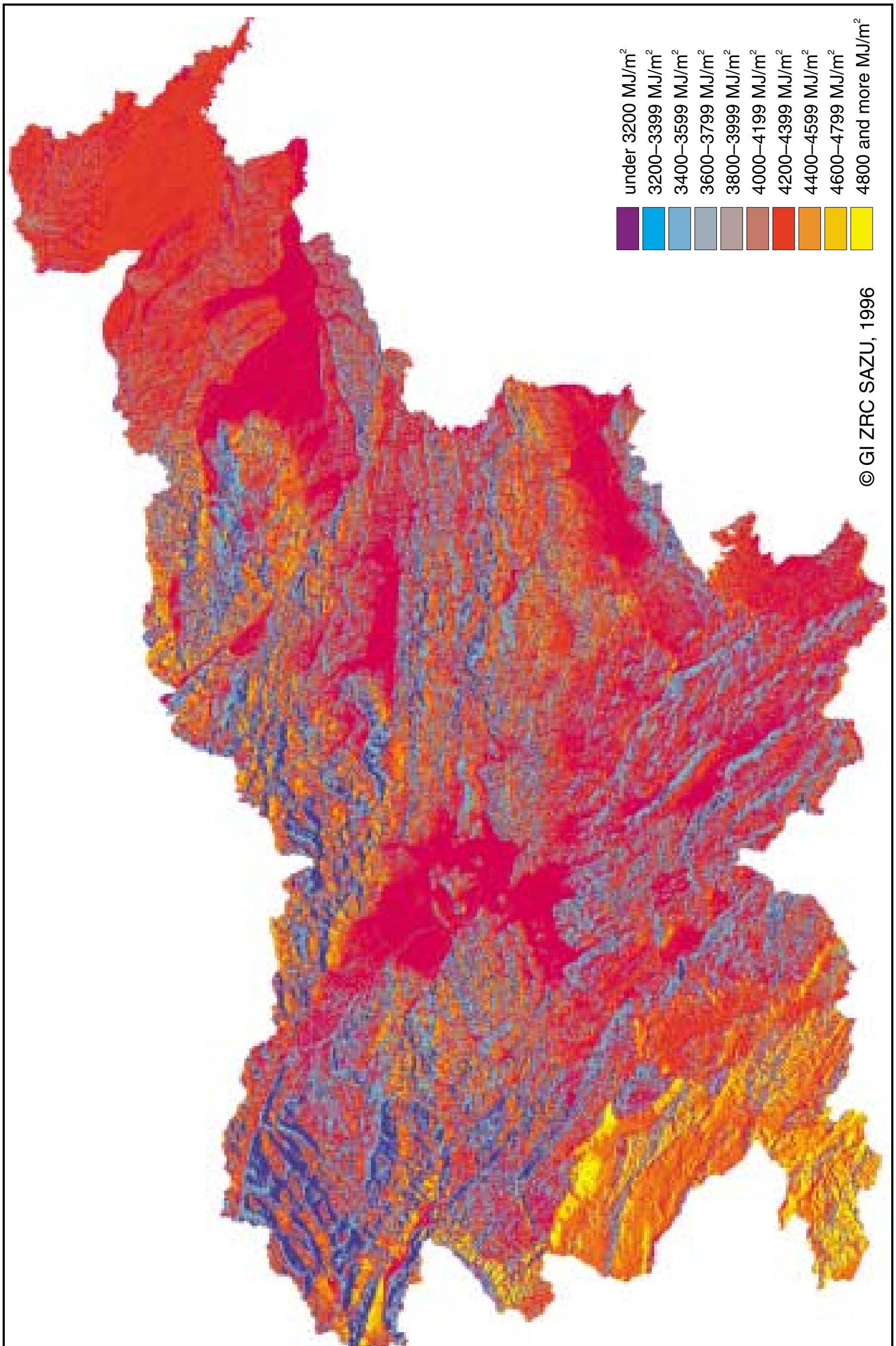
C: faktor, odvisen od rodu oblakov in zenitnega kota. Za poletni čas (od aprila do septembra) smo kot tipičen oblak vzeli altokumulus (*Ac*), za zimski čas pa stratus (*St*). Faktor je izračunan po naslednjih formulah:

$$C(Ac) = 1{,}35 + 5{,}42 z - 3{,}38 z^2$$

$$C(St) = 0{,}35 + 4{,}49 z - 2{,}54 z^2$$

D: relativno trajanje sončnega obsevanja
E_k: energija kvaziglobalnega obsevanja
I_0: solarna konstanta
j_k: moč kvaziglobalnega obsevanja

Figure 7: Mean annual energy of quasiglobal radiation (M 1 : 130,000).
Slika 7: Povprečna letna energija kvaziglobalnega obsevanja (M 1 : 130,000).


under 3200 MJ/m^2
3200–3399 MJ/m^2
3400–3599 MJ/m^2
3600–3799 MJ/m^2
3800–3999 MJ/m^2
4000–4199 MJ/m^2
4200–4399 MJ/m^2
4400–4599 MJ/m^2
4600–4799 MJ/m^2
4800 and more MJ/m^2
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m: optična zračna masa, odvisna od zenitnega kota Sonca
n: naklon površja
p: kot med smerjo sončnega žarka in površjem
q_a: transmisijski koeficient glede na absorbcijo
q_s: transmisijski koeficient glede na razpršitev
ρ: relativna oddaljenost med Soncem in Zemljo
t: čas, $t = 0$ ob 12^h
vz: vzhod sonca
zh: zahod sonca
z: zenitni kot sonca, ki ga izračunamo po enačbi:

$$\cos z = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega t.$$

kjer novi simboli pomenijo naslednje:
φ: geografska širina,
δ: deklinacija sonca,
ω: krožna frekvenca dnevnega cikla ($\omega = 360°/24ur$).

V nadaljevanju bom podrobneje navedel vire vseh meteoroloških in reliefnih parametrov. Vse izračune smo delali po dekadah (desetdnevnih razdobjih) in urah. Za srednji dan v vsaki dekadi smo izračunali najprej urne vrednosti energije kvaziglobalnega obsevanja, z njihovim seštevkom smo dobili dnevno vrednost, ki smo jo pomnožili z 10 oziroma s številom dni v dekadi in tako dobili dekadno energijo obsevanja, s seštevkom dekadnih vrednosti pa smo končno dobili letno energijo kvaziglobalnega obsevanja. Vsi ti izračuni so bili narejeni za vsako hektarsko celico, teh pa je v Sloveniji preko dva miljona.

Transmisijski koeficienti glede na absorbcijo in razpršitev so povzeti iz iste študije kot model. Izračunani so na podlagi obdelave paralelnih nizov opazovanj globalnega obsevanja in trajanja sončnega obsevanja. Avtorji so imeli za izračun na razpolago sinhrona niza obeh parametrov le za Ljubljano, pri določitvi transmisijskih koeficientov za druge kraje Slovenije pa so upoštevali nadmorsko višino in onesnaženost zraka (Hočevar, 1980).

Podatke o povprečnih dekadnih urnih vrednosti trajanja sončnega obsevanja nam je posredoval Hidrometeorološki zavod Republike Slovenije. V Sloveniji trajanje sončnega obsevanja merimo s Campbell-Stokesovimi heliografi. Merilni inštrumenti ne beležijo trajanja sončnega obsevanja, kadar je sonce nižje od 3° nad obzorjem, med višinama Sonca 3° in 5° pa niso točni. Lega heliografov na opazovalnih postajah je tudi taka, da so predvsem v jutranjih in večernih urah pred Soncem ovire (relief, drevje, poslopja). Zato je potrebno v primeru, ko želimo merjene vrednosti na izbrani lokaciji uporabiti kot reprezentativne za širše območje, preračunati na matematični horizont – odpraviti vpliv napake merilnih inštrumentov, reliefa in drugih ovir. Pri tovrstnem popravljanju urnih vrednosti trajanja sončnega obsevanja moramo upoštevati različne vremenske situacije in dejstvo, da se nekatere ovire v okolici opazovalnih postaj neprestano spreminjajo (drvesa rastejo, pojavljajo se nova poslopja…). Urne vrednosti trajanja sončnega obsevanja so bile popravljene na osnovi podatkov o višini posameznih ovir v različnih obdobjih in na osnovi statistične analize urnih vrednosti trajanja sončnega obsevanja. Urne vrednosti trajanja sončnega obsevanja v urah, v katerih so bile prisotne ovire, so bile popravljene na maksimalno možno vrednost trajanja sončnega obsevanja v primeru, če je bila predhodna (popoldan) ali naslednja (dopoldan) ura jasna. Povprečne dekadne urne vrednosti trajanja sončnega obsevanja so izračunane na osnovi urnih vrednosti preračunanih na matematični horizont (Kastelec, 1995). Podatke o trajanju sončnega obsevanja smo dobili za 24 meteoroloških postaj, ki so dokaj enakomerno razporejene po ozemlju celotne države. Podatki so za 30-letno razdobje 1961–1990. Žal polovica postaj ni delovala v celotnem razdobju, vendar nobena ni delovala manj kot 20 let, le tri pa so delovale manj kot 25 let. Seznam postaj prikazuje prva preglednica.

Žal pa navedeni podatki o trajanju sončnega obsevanja veljajo le za konkretno merilno postajo, te pa so med seboj precej oddaljene. Za naše namene smo potrebovali podatek o trajanju sončnega obsevanja za vsako hektarsko celico v Sloveniji. Tako smo okoli vsake merilne postaje določili območje, ki naj bi čim bolj ustrezalo razmeram na merilni točki. Pri razmejitvi območij posameznih postaj smo se držali dveh temeljnih načel. Prvič se morajo meje območij ujemati z mejami podnebnih

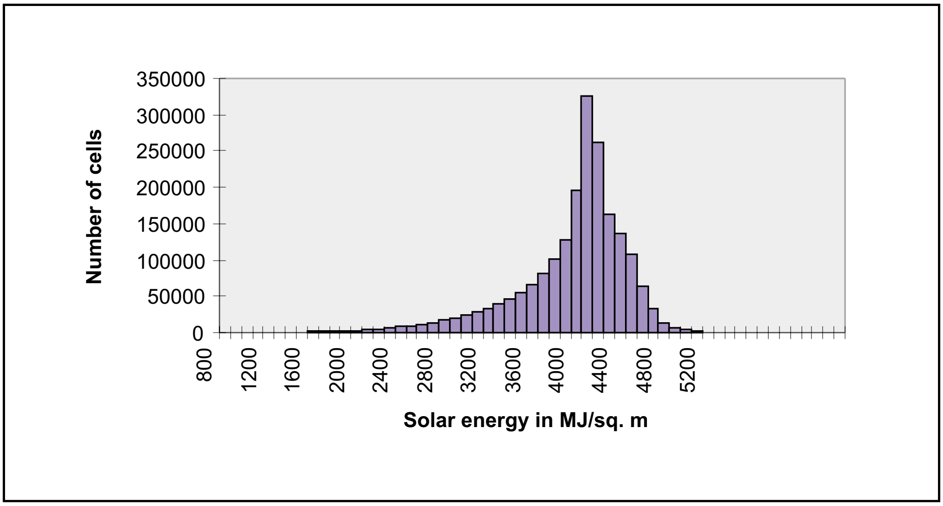

Figure 8: Frequency distribution of mean annual energy of quasiglobal radiation.
Slika 8: Frekvenčna distribucija povprečne letne energije kvaziglobalnega obsevanja.

tipov v Sloveniji. V tem pogledu smo se naslonili na Ogrinovo tipologijo (Ogrin, 1996). Drugič pa mora imeti celotno območje podobno reliefno lego kot meteorološka postaja. Tako mora biti območje kotlinske postaje omejeno z robom kotline, območje višinske postaje mora biti v celoti v višjih legah in podobno. V nekaterih primerih območje meteorološke postaje ni sklenjeno, ker je bilo na primer hribovje razdeljeno na dva dela s širšo dolino ali kotlino, na razpolago pa smo imeli samo eno merilno točko na večji nadmorski višini. Seveda se navedenima kriterijema zaradi preredke merilne mreže ni dalo v celoti ugoditi, menimo pa, da so za večino slovenskega ozemlja podatki o trajanju sončnega obsevanja dovolj reprezentativni. Jasno pa je, da nismo mogli upoštevati vpliva povečane megle v nekaterih manjših dolinah in kotlinah. Lokacije postaj in njihova območja so prikazana na prvi sliki.

Relief, kot je bilo že rečeno, vpliva na sončno obsevanje na dva načina. Zaradi različne ekspozicije in nagnjenosti površja se spreminja kot med sončnimi žarki in površjem in s tem količina prejete sončne energije. Drugič pa različne vzpetine delujejo kot ovira sončnim žarkom, površine v senci zato v tistem trenutku prejmejo le difuzni del sončnega obsevanja.

Vir za izračunavanje naklonov in ekspozicije je bil digitalni model reliefa 100 krat 100 m. Naklon je bil izračunan iz vogalnih točk vsake celice po naslednji formuli:

$$n = \arctan\left(a^2 + b^2\right)^{1/2}$$

pri čemer sta a in b koeficienta regresijske ravnine, ki ju izračunamo po naslednjih formulah:

$$a = \left(\frac{-h_1 + h_2 - h_3 + h_4}{200}\right) \qquad b = \left(\frac{-h_1 - h_2 + h_3 + h_4}{200}\right)$$

h_1 do h_4 pomenijo v zgornjih formulah nadmorske višin voglanih točk celice (Gabrovec, 1990). Ekspozicija je izračunana s pomočjo programa IDRISI z modulom SURFACE (Eastman, 1995).

Za izračun direktnega sončnega obsevanja moramo za vsako uro v dnevu in dekado v letu in za vsako celico izračunati kot med sončnim žarkom in površjem. Formula za ta izračun je naslednja (Enders, 1976):

$$\sin p = \left(\sin\varphi \cos n - \cos\varphi \sin n \cos a\right)\sin\delta + \left(\cos\varphi \cos n + \sin\varphi \sin n \cos a\right)\cos\delta \cos\omega t + \sin n \sin a \cos\delta \sin\omega t$$

pri čemer je a ekspozicija pobočja, ostali simboli pa so razloženi zgoraj.

Osenčenost smo prav tako ugotavljali s pomočjo digitalnega modela reliefa. Ugotavljali smo jo tako, da smo v smeri potovanja sončnega žarka izračunavali relativno višino celic. To smo merili na premici, ki je pravokotna na sončne žarke. Osenčenost posamezne celice ugotavljamo na podlagi preverjanja, če je katera izmed celic v smeri potovanja žarka že presegla njeno relativno višino. Če se je to zgodilo, je celica v senci, sicer je osončena (Krevs, 1996). Osenčenost smo izračunali za vse ure in dekade. V primeru, da je celica osenčena, v tisti uri ni direktne komponente sončnega obsevanja zato računamo le difuzni del sončnega obsevanja. Slike 2 do 4 nam prikazujejo osenčenost ob 9^h, opoldne in ob 3^h popoldne v zadnji dekadi decembra.

Prvi pogled na karto letne energije kvaziglobalnega obsevanja (slika 7) nam pokaže zelo velike razlike na kratke razdalje. Te razlike so posledica različnih ekspozicij in osenčenosti. Posledica tega je, da je variabilnost znotraj območja posameznega podnebnega tipa večja kot pa variabilnost med njimi. Preglednica 2 kaže povprečno letno energijo kvaziglobalnega obsevanja po podnebnih tipih, preglednica 3 pa povprečja po različnih eskpozicijah ne glede na naklon. Ravnina je tam, kjer je naklon celice manjši od pols stopinje. Pri razdelitvi Slovenije na podnebne tipe smo se oprli na Ogrinovo tipologijo in delili Slovenijo na submediteransko, zmernokontinetalno in gorsko. Zmernokontinentalni tip, ki obsega največji del Slovenije, pa smo delili še naprej na zmernokontinentalni podtip zahodne in južne Slovenije, osrednje ter vzhodne (subpanonske) Slovenije (Ogrin, 1996).

Preglednici 2 in 3 nam lepo pokažeta, da je večja razlika med severno in južno ekspozicijo (3472 in 4448 MJ/m^2) kot med ekstremnima podnebnima tipoma glede na sončno obsevanje, to je med gorskim in submediteranskim podnebjem (3713 in 4375 MJ/m^2). Pri ekspozicijah so standardni odkloni večji na osojnih pobočjih, tu na večje razlike vpliva različna osenčenost. Pri podnebnih tipih so večji standardni odkloni tam, kjer je reliefno bolj razgiban svet. Zato je majhen standarden odklon v ravninski in gričevnati subpanonski Sloveniji. Zelo majhen je standarden odkon na prisojnih pobočjih in ravninah, kljub temu da so ta v vseh podnebnih tipih.

Preglednica 2 in slika 7 nam kaže, da je letna količina kvaziglobalnega obsevanja daleč največja v submediteranski Sloveniji, kjer za okoli 10 % presega državno popreče. Še posebej izstopajo tamkajšnje prisojne lege. Drug ekstrem je gorska Slovenija, kjer se kaže vpliv povečane kopaste oblačnosti v poletnem času. Sicer pa energija sončnega obsevanja narašča od zahoda proti vzhodu, kar je povezano z zmanjševanjem oblačnosti in količine padavin v isti smeri. Karta kvaziglobalnega obsevanja v zadnji dekadi junija (slika 5) nam kaže v grobem podoben razpored energije kot letna karta, bistveno drugačna pa je decembrska karta (slika 6). Takrat lepo vidimo večjo količino sončnega obsevanja v gorskem svetu na severu države, medtem ko so na drugi strani zelo slabo osončene kotline s temperaturno inverzijo in meglo ter osojna pobočja, na katera pozimi pogosto sploh ne posije sonce, kar potrjuje ugotovitve prejšnjih raziskav (Hočevar, 1980; Petkovšek, 1982).

Novost predstavljene karte je, da za celotno državno ozemlje Slovenije prikazuje kvaziglobalno obsevanje ter pri tem upošteva reliefne značilnosti vsake hektarske celice posebej. Izdelava takih kart doslej ni bila mogoča, ker nismo imeli na razpolago digitalnih modelov reliefa za ozemlja celotnih držav niti nismo imeli dovolj zmogljivih računalnikov, ki bi lahko izračune opravili v doglednem času. Za izračun letne količine energije kvaziglobalnega obsevanja celotnega slovenskega ozemlja je bilo potrebno približno en teden računalniškega časa IBM kompatibilnega računalnika s 64 megabyti notranjega pomnilnika 586/133 Mhz. Zato je večina avtorjev doslej izračunavala kvaziglobalno obsevanje le za južne lege različnih naklonov brez upoštevanja osenčenosti (Hočevar, 1980; Seifert, 1990). Te študije so bile narejene predvsem za potrebe planiranja izkoriščanja sončne energije, medtem ko pričujoče karte omogočajo tudi ugotavljanje optimalnih leg za kmetijstvo in gozdarstvo.

Za zaključek prikazujem še graf frekvenčne distribucije letne energije kvaziglobalnega obsevanja (slika 8). Ta nam kaže zelo velik razpon med minimalno in maksimalno vrednostjo, ki znašata 811 oziroma 5333 MJ/m^2. Razmerje med njima je torej kar 1:6,5. Brez vpliva reliefa, to je ob teoretični predpostavki, da bi bile vse celice ravne in stalno osončene, bi bilo to razmerje samo 1 : 1,19. Minimalna in maksimalna vrednost bi bili v tem primeru 3876 oziroma 4596 MJ/m^2. Frekvenčna distribucija je izrazito asimetrična. To je posledica osenčenosti. Povprečne severne lege v Sloveniji prejmejo dobrih 15 % manj sončne energije kot ravnine, najbolj senčne lege pa prejmejo le okoli petino energije povprečne celice na ravnini. Vsi ti podatki nam nedvomno dokazujejo, da je na majhnem ozemlju, kot je Slovenija, odločilen faktor pri razporeditvi energije kvaziglobalnega obsevanja relief.