LATITUDINAL VARIABILITY OF SURFACE SOLAR RADIATION IN MOLDOVA

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(Received 14 April 2008)

Abstract

Latitudinal variation of the level of solar radiation incident onto the ground surface over the territory of Moldova is analyzed. Combined solar radiation data from HelioClim-2 database comprising of datasets retrieved from METEOSAT satellite high resolution images and ground-based measurements at the Chisinau site from 2004 to 2007 are used in analysis. A simplified linear relationship between the surface solar irradiance and latitude is presented. Overestimation of solar irradiation data retrieved from METEOSAT satellite images relative to datasets from ground observations at the Chisinau site on the average amounts to 10.3%.

1. Introduction

Specific patterns of the atmosphere circulation and climatic characteristics both to regional and global scales are defined by solar radiation penetrating into the Earth's atmosphere. Before reaching the ground, surface solar radiation fallen on to the top of atmosphere is modified by absorption and scattering processes taking place in the Earth's atmosphere. The amount of solar radiation and its spectral distribution at the ground surface depends upon the atmosphere physical properties and components, such as aerosols, gases, and cloud structures, which undergo high temporal and spatial (in height, latitude, and longitude) variations. Each of components has a specific influence upon the radiation exchange and interaction processes. Solar radiation monitoring is carried out by a lot of individual ground-based stations and group of stations incorporated into the networks, which are irregularly spread on land around the world. These ground stations are of a particular interest for obtaining reliable arrays of data with the global, diffuse, and direct solar irradiances on the Earth's surface. At the same time, satellite platforms with spectral radiometers on-board give the unique opportunity to carry out solar radiation observations continuously with high time and spatial resolution over the large areas of land and oceans. Solar radiation data acquired at the ground stations are used as basic to validate satellite platform observations.

In this paper, longitudinal variability of surface solar irradiation levels across the territory of Moldova is investigated on the basis of data retrieved from satellite images and data available from ground observations. Solar radiation data from ground-based measurements at the Chisinau site are used to evaluate the METEOSAT satellite retrievals.

2. Approach and data compilation

Monthly mean solar flux data from HelioClim-2 database [1] on the Web SoDa services comprising of datasets from METEOSAT satellite platform from 2004 to 2007 are used in analysis of latitudinal variations of surface solar radiation levels. Solar radiation data are derived from satellite high resolution images of ground surface from METEOSAT platforms by using of the Heliosat-2 method [2-5]. The Heliosat-2 method was initially developed by Armines/Ecole des Mines de Paris in 2000-2001, within the framework of the project SoDa partly with the support of the European Commission. The Heliosat method converts ground surface images in the form of digital map of pixels acquired by meteorological geostationary satellite platforms, such as METEOSAT (Europe), GOES (USA) or GMS (Japan), into the data arrays and respective digital maps of solar radiation received at ground surface level. The Heliosat method was first proposed by Cano et al. [6]. Main idea of the method consists in determination of cloud index from time series of digital counts for pixels in Heliosat -1 version or from calibrated radiances for pixels in Heliosat-2 version scanned at visible channel of the METEOSAT platform. The cloud index represents a measure of the relative reflectivity of the clouds in the line site of METEOSAT. Then, cloud index is combined with an empirical clear sky model [7-9] to retrieve global solar irradiance at the ground surface. Spatial resolution for single pixel equals 5$'$ of arc angle or in size approx. 10 km at mid-latitude at the ground.

Ground surface solar radiation is measured at the ground-based solar radiation monitoring station equipped with the multifunctional radiometric complex [10, 11]. The station is situated in an urban environment at the Chisinau site with coordinates: φ=47.0013ºN, λ=28.8156ºE, h=205 m a.s.l. Radiometric complex was mounted on the roof of building of the Institute of Applied Physics, Academy of Sciences of Moldova. Automatic multifunctional complex consists of a set of the broadband radiometric sensors, datalogger CR10X with memory module SM 4M, electronics, stationary platform, and active sun tracking unit 2AP BD. This complex is intended to carry out long-term continuous monitoring of radiative properties of atmosphere and to acquire datasets with broadband solar radiation (global, diffuse, and direct components) in spectral wavelength region from UV-B to IR [10, 11]. In particular, global solar irradiance on horizontal plane is measured by solar sensor or pyranometer CM-11(Kipp&Zonen) in the wavelength spectral range from 308 nm to 2800 nm. Sample rate and interval of averaging for outputs from each of the sensors were 1 sec and 1 minute, respectively. Hourly, daily, monthly, and yearly levels of solar irradiation and irradiance, and their respective statistical means are deduced from these basic solar irradiance measurements with 1-minute resolution.

2. Results of measurements

Table 1. List of sites where solar radiation datasets were retrieved from satellite images.

Site name	Coordinates (φ,λ) in degrees
Briceni	48.35 N, 27.70 E
Edineti	48.16 N, 27.30 E
Beltsy	47.76 N, 27.92 E
Codru	47.08 N, 28.25 E
Chisinau	47.00 N, 28.82 E
Comrat	46.30 N, 28.65 E
Cahul	45.90 N, 28.19 E
Vulcanesti	45.68 N, 28.40 E

Heights of sites range from 16 m to 205 m above sea level.

Latitudinal variation of surface ground solar irradiation levels over the territory of Moldova is analyzed. To this end, solar data retrieved from satellite images of the ground surface were used for specific sites in Moldova. List of these sites with coordinates is presented in Table 1. Datasets acquired at the ground-based solar radiation monitoring station (hereafter referred to as ARG) of the Institute of Applied Physics in Chisinau are also used for validation of respective ones retrieved from satellite images (HelioClim-2 database) [1]. Seasonal variability of mean monthly global solar irradiation $<Q_{gl,m}>$ observed at the Briceni, Chi-

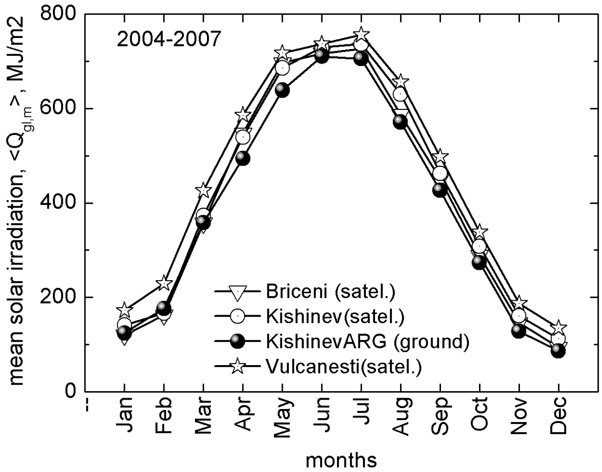

Figure 1. Seasonal variability of mean monthly global solar irradiation $\langle Q_{gl,m} \rangle$ retrieved from METEOSAT satellite images (HelioClim-2 database) at Briceni (north), Chisinau (Kishinev; central) and Vulcanesti (south) sites, and from ARG ground observations at the Chisinau site. Period of observations: 2004-2007.

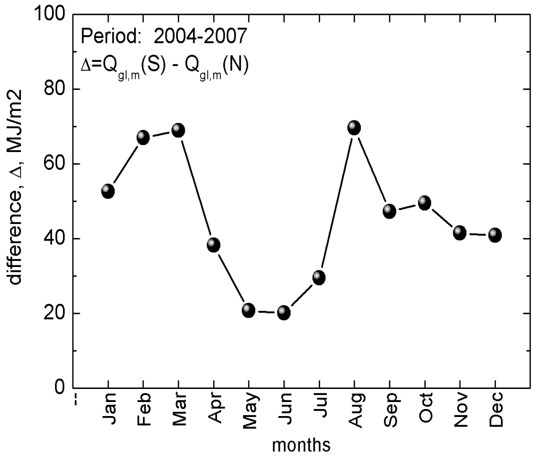

Figure 2. Seasonal variability of mean monthly latitudinal difference Δ between monthly global solar irradiations $Q_{gl,m}(S)$ and $Q_{gl,m}(N)$ observed at Vulcanesti and Briceni sites, situated at the south (S) and north (N) border of Moldova. Period of observations: 2004- 2007.

sinau, and Vulcanesti sites shows minimum and maximum values of $\langle Q_{gl,m} \rangle$ taking place in December and July, respectively (see Figure 1). Here are also presented datasets from ARG ground observations at the Chisinau site. All seasonal curves show good mutual resemblance. There can be clearly seen the existence of mean monthly latitudinal difference $\Delta = Q_{gl,m}(S) - Q_{gl,m}(N)$ between monthly global solar irradiations $Q_{gl,m}$ observed at Vulcanesti and Briceni sites, which are situated at the south (S) and north (N) border of Moldova, respectively. Seasonal variability of deduced difference is shown in Figure 2. It ranges from ~20 MJm^{-2} in June-July up to ~70 MJm^{-2} in February-March months. Meanwhile, mean annual value of Δ amounts to 45.5 MJm^{-2}.

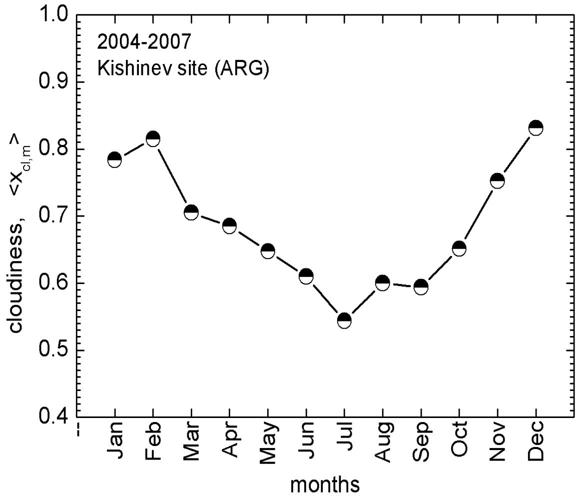

Figure 3. Seasonal variability of mean monthly total cloudiness $\langle x_{cl,m} \rangle$ observed at the Chisinau site. Cloudiness scale: 0.0 indicates a clear sky and 1.0 (or 8/8) indicates a completely covered sky. Period of observations: 2004-2007.

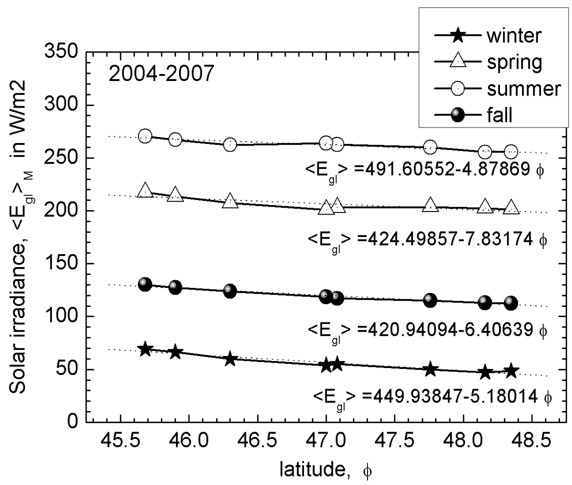

Figure 4. Latitudinal variability of mean global solar irradiances $\langle E_{gl} \rangle$ averaged for seasons- winter (Dec-Jan-Feb), spring (Mar-Apr-May), summer (Jun-Jul-Aug), and fall (Sep-Oct-Nov). Period of observations: 2004-2007.

Large values of latitudinal difference Δ between monthly global solar irradiation $Q_{gl,m}$ in late fall-winter-early spring seasons observed at north and south sites may be attributed to influence of total cloudiness upon the measured irradiation levels at these sites. For example, seasonal variability of mean monthly cloudiness $\langle x_{cl,m}\rangle$ observed at the Chisinau site from 2004 to 2007 is shown in Figure 3. Sky cover is reported here in eighths, so that 0.0 indicates a clear sky and 1.0 (or 8/8) indicates a completely covered sky. Minimum value of cloudiness $\langle x_{cl,m}\rangle\sim 0.54$ is observed in July. Large values of $\langle x_{cl,m}\rangle\sim 0.7$–$0.8$ are typical of the end of fall, winter and early spring seasons as is seen from Figure 3, and these seasons are considered as cloudy ones. The most cloudy month in this period of observations was December 2007 with $\langle x_{cl,m}\rangle\sim 0.98$. Solar datasets and total cloudiness were averaged over period of observations from 2004 to 2007.

Latitudinal variability of mean monthly global solar irradiance $\langle E_{gl}\rangle$ averaged for winter (Dec-Jan-Feb), spring (Mar-Apr-May), summer (Jun-Jul-Aug), and fall (Sep-Oct-Nov) seasons for specific sites on the territory of Moldova (see Table 1) are shown in Figure 4. Linear relationship $\langle E_{gl}\rangle = a + b\varphi$, where φ (in degrees) is the latitude of site, is used to approximate seasonal latitudinal variability of ground surface solar irradiances. Longitudinal variability of global solar irradiances $\langle E_{gl}\rangle$ shows different rates of decreasing *b* for seasons: it ranges from –7.83 $Wm^{-2}\cdot deg^{-1}$ in spring to –4.88 $Wm^{-2}\cdot deg^{-1}$ in summer months. This discrepancy in rates of decrease of the incoming solar radiation may be attributed to various total cloudiness levels at these latitudes during the seasons.

Latitudinal variability of yearly totals of global solar irradiation Q_{gl} retrieved from METEOSAT satellite images for series of sites (see Table 1) situated from north to south border of Moldova and values of Q_{gl} deduced from ARG ground observations at the Chisinau site are shown in Figure 5.

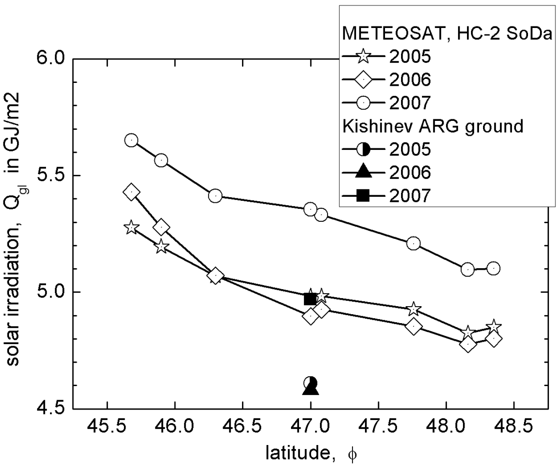

Figure 5. Latitudinal variability of yearly totals of global solar irradiation Q_{gl} (φ) retrieved from METEOSAT satellite images for specific sites over the territory of Moldova and from ARG ground observations at the Chisinau (Kishinev) site.

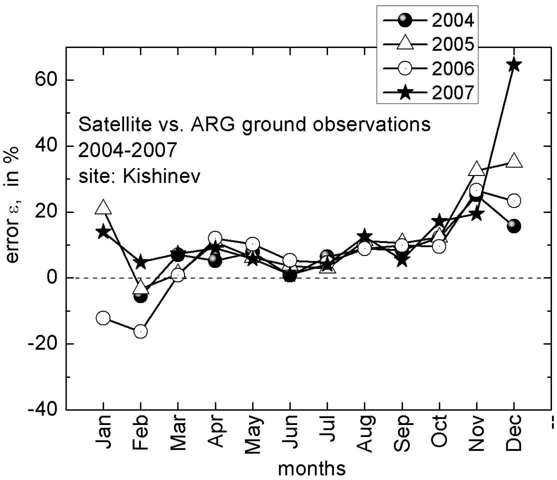

Figure 6. Seasonal variability of relative difference between monthly totals of global solar irradiations $Q_{gl,m}$ deduced from METEOSAT satellite images and from ARG ground based observations at the Chisinau (Kishinev) site.

There is clearly seen the resemblance of curves for yearly totals of global solar irradiation Q_{gl} versus φ, which, in general, show distinct latitudinal decreasing of incoming solar radiation. Decrease is not uniform and, on the average, the rate of decreasing ranges from –14 $GJm^{-2}\cdot deg^{-1}$ in 2005 to –0.30 $GJm^{-2}\cdot deg^{-1}$ in 2006. Such discrepancies in yearly dependences of $Q_{gl}(\varphi)$ may be connected with variable levels of total cloudiness at the site latitudes. It should be noted that yearly sum of global solar irradiation Q_{gl} observed in 2007 was noticeably larger than total irradiation levels registered during other years. In other words, it may be said that the year of 2007 was "brighter" than other ones due to less cloudiness (on the average) taking into account that yearly mean total cloudiness $\langle x_{cl} \rangle$ took on values of ~ 0.69, 0.67, and 0.66 in 2005, 2006, and 2007, respectively. Discrepancy between yearly sum of global solar irradiation level $Q_{gl}(\varphi)$ registered in 2007 year and irradiation levels $Q_{gl}(\varphi)$ observed in 2005 and 2006 can be characterized by value of difference deduced between them for all sites. On the average, this difference is positive and it amounts to ~0.33 GJm^{-2} for each of the years. Values of yearly totals of global solar irradiation Q_{gl} from ARG ground observations are shown in Figure 5 and marked with separate symbols, such as filled triangle, square, and semi-filled circle. Respective differences between METEOSAT and ARG data from observations at the Chisinau site have positive values. Overestimation of METEOSAT totals of global solar irradiation data relatively ARG data consists of 8.1% in 2005, 6.9% in 2006, and 7.7% in 2007. It may be due to inaccurate accounting of total cloudiness and value of surface albedo in applied computational algorithm.

Table 2. Mean values of monthly and yearly totals of global solar radiation $\langle Q_{gl} \rangle$ (in MJm^{-2}) retrieved from METEOSAT satellite images in SoDa Web services, HelioClim-2 (HC-2) database and ground based measurements (ARG) at the Chisinau site. Multiyear mean relative error $\langle \varepsilon \rangle$ is derived for HC-2 data relatively ARG data from 2004 to 2007. Chisinau SHMS represents data observed at the Chisinau station from the State Hydrometeoro-logical Service (SHMS) and averaged over 1954-1980. Period of observations for METEOSAT and ARG data: from 2004 to 2007.

	Chisinau (satel.) HC-2	Chisinau SHMS ground [12]	Chisinau, ARG ground	$\langle \varepsilon \rangle$, %
Jan	141	126	124	7.5
Feb	166	176	176	-5.1
Mar	373	335	358	4.1
Apr	539	478	494	9.3
May	686	629	639	7.5
Jun	729	696	711	2.7
Jul	737	734	705	4.5
Aug	630	624	571	10.4
Sep	463	444	426	8.6
Oct	308	285	273	12.8
Nov	161	121	128	25.9
Dec	112	84	87	34.7
Year	5045	4732	4693	10.3

Seasonal variability of relative error $\varepsilon = (Q_{gl,m}[HC\text{-}2] - Q_{gl,m}[ARG])/Q_{gl,m}[ARG]$ deduced for monthly totals global solar irradiation levels $Q_{gl,m}$ retrieved from METEOSAT satellite images (HC-2) and from ARG ground based observations at the Chisinau site from 2004 to 2007 is shown in Fig. 6. On the average, multiyear mean relative error $\langle \varepsilon \rangle$ between METEOSAT and ARG datasets is positive and amounts to ~10.3%, or METEOSAT data retrieved from satellite images are represented as overestimated values relative to ARG data from ground observations. For individual years, deduced yearly mean relative errors were also positive and ranged from ~6.9% in 2006 to ~13.8% in 2007. It can be clearly seen that the greatest discrepancy takes place in late fall and winter months for each year; e.g., in December 2007 relative error reached up to 64.7%. During this period of observations, monthly mean direct and global solar irradiances reached anomalously low values, $\langle E_{dir} \rangle$ ~1.4 Wm^{-2} and $\langle E_{gl} \rangle$ ~18.8 Wm^{-2} ever registered at the Chisinau site. This month was characterized as the most cloudy one with monthly mean of total cloudiness $\langle x_{cl,m} \rangle$ of ~0.98. During January and February months mean relative error ε was negative and reached –16.3%, or METEOSAT retrieving gave underestimated values relative to ARG ground data. In both cases, with over- and underestimation, values of relative error between retrieved METEOSAT data and directly measured ARG data may be attributed to inaccuracy in cloudy index calculation and in selection of surface albedo in retrieving of solar irradiation levels from satellite high resolution images with utilizing of HelioSat2 algorithm [2-5].

Mean values of monthly and yearly totals of global surface solar irradiation $<Q_{gl}>$ retrieved from METEOSAT satellite high resolution images at the HelioClim-2 database [1] and ARG ground based measurements at the Chisinau site are presented in Table 2. Chisinau SHMS datasets are represented as ones observed at the Chisinau station from the State Hydrometeorological Service (SHMS). SHMS datasets were averaged over period from 1954 to 1980. Mean monthly totals of global solar irradiation $<Q_{gl,m}>$ retrieved from satellite images for the Chisinau site were averaged for the period of observations from 2004 to 2007. Large value of mean relative error $<\varepsilon>$ ~12.8% is typical of late fall-winter and winter months. This was due to large total cloudiness $<x_{cl,m}>$~0.81 observed during these months at the Chisinau site. Meanwhile, value of $<\varepsilon>$ deduced from spring-summer-early fall months of observations, on the average, was ~6.7% due to less total cloudiness $<x_{cl,m}>$~0.63. Multiyear mean relative error was ~10.3%. These facts indicate overestimation in solar radiation data retrieved from satellite images in comparison with the ARG data from direct ground-based measurements carried out at the Chisinau site. Discrepancies in yearly dependences of $Q_{gl}(\varphi)$ may be connected with variable levels of total cloudiness at the site latitudes.

There should be noted a very good resemblance between data with mean values of monthly totals of global solar radiation $<Q_{gl}>$ observed at the ARG ground station at the IAP during the period from 2004 to 2007 and data acquired at the Chisinau ground station under operation of the State Hydrometeorological Service from 1954 to 1980. Mean relative error between mean monthly and yearly totals of global solar radiation $<Q_{gl}>$ observed at these stations amounts to ~0.11% and ~0.83%, respectively.

4. Summary and conclusions

The present paper shows latitudinal variation of the ground surface solar irradiation levels across the territory of Moldova. For this purpose, a set of sites situated from the north to south border of Moldova was chosen. Solar irradiation data at these sites were retrieved from METEOSAT satellite high resolution images with using HelioSat-2 algorithm developed in Centre d'Energétique, France. Analysis of latitudinal variability was based on continuous series of observations fulfilled from 2004 to 2007. Additionally, ground observations of solar radiation carried out at the Chisinau site are used. Seasonal variability of mean monthly global solar irradiations $<Q_{gl,m}>$ at Briceni, Chisinau and Vulcanesti sites reveals mutual resemblance with minimum and maximum values of $<Q_{gl,m}>$ taking place in December and July, respectively. Difference between mean monthly totals of global solar irradiation $<Q_{gl,m}>$ observed at Vulcanesti and Briceni sites, situated in the south and north parts of Moldova, respectively, ranges from ~20 MJm^{-2} in June-July up to ~70 MJm^{-2} in February-March months. Annual mean value of Δ amounts to ~45.5 MJm^{-2}.

Latitudinal variability of mean global solar irradiance $<E_{gl}>$ averaged for winter, spring, summer, and fall seasons for specific sites was approximated with linear relationship $<E_{gl}>=a+b\varphi$, where φ (in degrees) is the latitude of site. Rates of decreasing b of global solar irradiance for seasons ranged from –7.83 $Wm^{-2}\cdot deg^{-1}$ in spring to –4.88 $Wm^{-2}\cdot deg^{-1}$ in summer. This discrepancy may be connected with various total cloudiness levels at these latitudes during the seasons. Latitudinal variability of yearly totals of global solar irradiation $<Q_{gl}>$ retrieved from METEOSAT satellite images for series of sites ranged from north to south of Moldova, and values of $<Q_{gl}>$ deduced from ARG ground observations at the Chisinau site show latitudinal decrease: on the average, the rate of decreasing ranges from –0.14 $GJm^{-2}\cdot deg^{-1}$ in 2005 to –0.30 $GJm^{-2}\cdot deg^{-1}$ in 2006.

METEOSAT solar radiation data retrieved from satellite images of high resolution give overestimated values relative to datasets from ARG ground based observations at the Chisinau site from 2004 to 2007. Multiyear mean relative error between METEOSAT and ARG datasets is positive and amounts to $\langle\varepsilon\rangle_Y$ ~10.3%. Mean monthly relative errors $\langle\varepsilon\rangle$ ~12.8% and ~6.7% are typical of late fall-winter and spring-summer-early fall months with total cloudiness $\langle x_{cl,m}\rangle$ ~0.81 and ~0.63%, respectively. This may be connected to inaccuracy in cloudy index calculation and in selection of surface albedo in retrieving of solar irradiances from satellite images with utilizing of HelioSat2 algorithm.

Acknowledgements

The author thanks Prof. Lucien Wald, Ecole des Mines de Paris (France) for his contribution to our disposal of solar radiation data from the SoDa HelioClim-2 database for the set of sites at the territory of Moldova.

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