

Resource Indicators of Solar Photovoltaic Plants in the Republic of Uzbekistan. Part 2. Verifying Satellite Actinometric and Reanalysis Data for Conditions in Uzbekistan

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Abstract—This work considers the current status of meteorological stations of actinometric observations in Uzbekistan. The data obtained from six modern ground-based meteorological stations in Uzbekistan are compared with the satellite observations and reanalysis data from NASA POWER, ERA5, and SARAHE. It is shown that the comparative deviations of the data of NASA POWER from the ground monthly amounts of solar radiation on the horizontal surface for most regions of Uzbekistan from April to September do not exceed 8%, which is quite acceptable for the design of solar power plants. The comparative deviations of the data of ERA5 and SARAHE for the same period of the year do not exceed 8 to 12%. According to the results of the calculation studies on verifying global horizontal solar radiation using the three aforementioned databases, these can be used in engineering calculations. When performing calculation studies, one can select any base depending on the required information, i.e. daily or hourly solar radiation values.

Keywords: actinometric data, satellite and ground observations, verification, meteorological stations, solar radiation, reanalysis, solar Atlas, database

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INTRODUCTION

The renewable energy sector is unevenly developed across different regions around the world. It is developed most intensively in countries dependent on energy resource imports. At the same time, the renewable energy sector can occupy a major niche in the foreseeable future in the power engineering of many countries, including those still rich in organic fuel reserves.

According to the 2018 results, the installed capacity of power plants operated on renewable energy sources (RES) around the world reached 2378 GW, which was 8.2% higher than in 2017 [1, 2]. The installed capacity of RES power plants at the end of 2018 amounted to about one third (33.4%) of the installed capacity of all of the world's power plants [1, 2]. Half of that capacity is related to hydroelectric power stations (HEPS) (1132 GW); the installed capacity of wind power stations is 591 GW, and the installed capacity of solar power plants is 502 GW (the installed thermal capacity of solar cell batteries adds another 480 GW). That said, the solar and wind power sectors are the fastest growing renewable energy sectors and employ about eleven million people around the world.

The capacity of the global market for photovoltaic modules in 2018 exceeded 100 GW and the capacity of solar cell batteries put in operation was about 33 GW [1, 2]. Global investments in renewable energy sources and fuels reached \$288.9 billion [3] in the same year. The worldwide scale of producing and using photovoltaic modules and solar cell batteries continues to expand.

The development of the renewable energy sector requires an evaluation of RES. These resources, including solar radiation, can be evaluated by statistical big data analysis and mathematical modeling of processes in power plants. These forecasts allow us to evaluate the economic and environmental efficiency of using such plants and optimizing their operation and their operational modes, depending on the time of the year, location, etc. [4, 5].

The modeling of solar energy conversion in photovoltaic and solar heat supply systems requires the use of reliable data on solar radiation falling on the solar plant surface. As a rule, this modeling is conducted in one-hour steps; thus hourly solar radiation sums are required [6–11]. The modeling results can be used in phases such as:

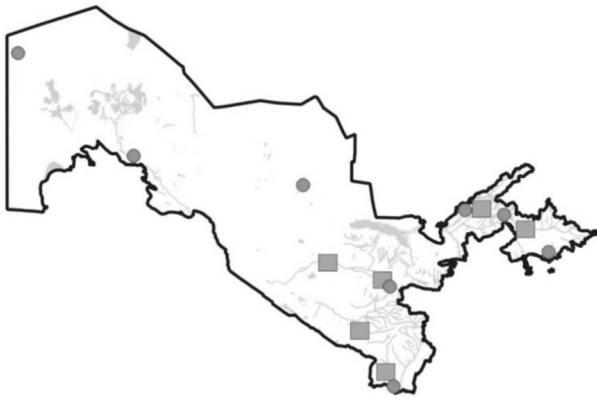


Fig. 1. Information on the location of automatic (squares) and non-automated (circles) weather stations in the Republic of Uzbekistan.

—planning (expected long-term values are defined as well as minimal attainable values in the case of a full-scale uncertainty study);

—operation (measured data allow us to analyze the efficiency of the operating system; the system's short-term productivity is forecast on the basis of weather forecasts for managing energy consumption and planning the interaction with the network).

The most reliable and, therefore, preferable sources of data on the solar radiation falling on the terrestrial surface are multiyear actinometric observations, whose results are presented in reference books and databases.

GROUND-BASED WEATHER STATIONS IN UZBEKISTAN AND THEIR DATA

The Tashkent Observatory weather station was launched in Tashkent in December 1867 and became the first weather station in modern Uzbekistan. This facility has accumulated more than 150 years of climate data and is included in the World Meteorological Organization as well as in the list of weather stations used in the international exchange of weather information [12]. The first studies of atmospheric transparency in Central Asia were written by K.G. Trofimov and I.N. Yaroslavtsev. Regular actinometric observations were started in Tashkent in 1926 thanks to K.G. Trofimov, who was the head of the actinometric department of the Tashkent Geophysical Observatory until 1943 [13].

The former Soviet Union, Uzbekistan included, had 455 weather stations used for regular actinometric observations [14] between 1951 and 1989. The integrated program and procedure for processing and generalizing actinometric information were elaborated and used as the basis for publishing the Reference Book on the Climate of the Soviet Union and the Applied Research Reference Book on the Climate of the Soviet Union [15–17]. They contain a sufficiently broad range of data, including average monthly and

annual hourly and daily total solar radiation falling on the horizontal and vertical surface, as well as the total direct radiation falling on the surface normal to the beam in various cloudiness conditions. Unfortunately, this information is currently irrelevant (it only covers the period up to 1983 and is virtually unconverted to machine-readable form). The actinometric observation results for Uzbekistan found in the database of the World Radiation Data Center [18] only cover the data for Tashkent from 1964 to 1992. There are more than 80 weather stations in Uzbekistan but only eight of them (Qaraqalpaqia, Takhiatash, Tamdy, Samarkand, Termez, Tashkent, Kyzylcha, Fergana, see Fig. 1) are used in actinometric observations in three-hour intervals. The data are not digitized but are currently being converted to machine-readable form.

The available actinometric data do not meet current requirements for the reliable technical potential evaluation of Uzbekistan's solar energy resources.

Six modern automated weather stations have operated in Uzbekistan since February 2013. They were created with assistance from the Asian Development Bank as part of project UZBTA 8008: "Development of Solar Energy Utilization in Uzbekistan [19] and include Dagbid (Samarkand region), Qarmana (Navoi region), Guzar (Qashqadaryo region), Sherabad (Surxondaryo region), Pap (Namangan region), and Parkent (Tashkent region) (see Fig. 1). The results of actinometric and climate observations conducted at these stations are collected into databases. The Parkent weather station has special equipment and is used for measuring densities of total and scattered solar radiation on the horizontal surface, density of direct solar radiation on the Sun-tracking surface, ambient air temperature, relative humidity, wind speed and direction, maximal wind speed of gusts between measurements, atmospheric pressure, and precipitation in one-minute measurement periods. Uzbekistan also has small weather stations for farmers, laboratory weather stations for university students (Gulistan, Andijan), weather stations installed as part of technical assistance projects developed by Germany in Samarkand, and wind masts in Navoi. A weather station is being built as part of the USAID Power the Future program at the geosite of the Physical-Technical Institute of the Uzbekistan Academy of Sciences.

At the same time, the small number and uneven distribution of weather stations across the country do not allow us to use their data to create a complete map of the technical potential of solar energy for all of Uzbekistan's regions. That said, the extrapolation and interpolation of data from actinometric stations is hardly applicable because these measurements can be propagated with an acceptable inaccuracy at only 100 to 130 km from the weather station [20]. Moreover, there is no single data collection and processing center.

SATELLITE OBSERVATIONS AND REANALYSIS DATABASE

The techniques used in recent decades to cope with the insufficiency of terrestrial data on solar radiation input are the modeling and recovery of data using satellite observations and reanalysis [21, 22]. These techniques allow us to form long-term series of actinometric data for large zones of terrestrial surface.

Satellite models make use of measurements and images from geostationary- and polar-orbiting satellites to evaluate the radiation balance and properties of clouds [23, 24]. They have provided several solar radiation sums since the 1980s, with an hourly or daily time resolution and a spatial resolution of up to several kilometers. Not all of these data are global, and they remain unavailable in some regions.

Reanalysis relies on combining weather forecasting models with ground-based and satellite observations. The uncertainty of the results heavily varies in space because it depends not only on the characteristics of databases but also on the concrete conditions in the place of evaluation [25].

Both reanalyses, NCEP and ERA, currently provide data on incident solar radiations on a high-resolution grid. The recovery of data on a regular grid using satellite observations was used to develop the global NASA POWER (NASA Prediction of World-wide Energy Resource) database broadly used in forecasting and design in solar power engineering [26]. The NASA POWER project has been in development since 2003 as a continuation and evolution of the NASA SSE project and is aimed at elaborating parameters for solar power engineering and other industries where solar energy is used. The NASA POWER project provides open access to daily values (including solar radiation at the upper atmospheric boundary and at the Earth's level, descending long-wave radiation, air and ground temperature, wind speed) with resolutions of $1^\circ \times 1^\circ$ and $0.5^\circ \times 0.5^\circ$ (only $1^\circ \times 1^\circ$ for solar radiation) for each day starting from July 1, 1983 up to the present. The inaccuracy in satellite actinometric data was found by comparison with the observation data from the ground-based weather stations included in the international BSRN (Baseline Surface Radiation Network). The inaccuracy reached about 20%, according to the developers.

A lot of actinometric data are found in the bases of the European System of Satellite Application Facility on Climate Monitoring (CM SAF) [27]), which includes climate and actinometric observations data from geostationary (SARAH base, 1983–2015, $\pm 65^\circ$ latitude, $\pm 65^\circ$ longitude, spatial resolution of $0.05^\circ \times 0.05^\circ$; SARAH-E, 1999–2016, $\pm 65^\circ$ latitude, 10° – 130° E, $0.05^\circ \times 0.05^\circ$) and polar satellites (CLARA-A, 1982–2015, global, $0.25^\circ \times 0.25^\circ$). Detailed climate and actinometric ERA reanalysis data are found in the bases of the European Centre for Medium-Range Weather Forecasts, ECMWF [28, 29]), in particular, hourly sums of total solar radiation on the horizontal surface (2000–2017, global data, $0.25^\circ \times 0.25^\circ$). The data

are provided by CM SAF and ECMWF from archives organized by time.

In addition, the Global Solar Atlas of the World Bank contains multiyear average annual sums of total, direct, and scattered solar radiation on the horizontal surface with a spatial resolution of $30''$ for Uzbekistan for 1999–2015 [30].

VERIFYING SATELLITE BASE AND REANALYSIS DATA

Available Works

When satellite and reanalysis databases are created, their data are compared with the data of actinometric terrestrial observations in certain points of support (the BSRN network has already been mentioned above). A major role in database formation is played by the verification of the modeling data on the components of incident solar radiation.

As a result of analyzing and evaluating the solar energy potential in Uzbekistan, we conducted preliminary studies [31, 32] for dividing the territory of Uzbekistan into five climate areas by solar radiation input. In addition, in [33–35] we analyzed the data obtained on the six automatic weather stations mentioned above. Papers [22, 25, 36] provide the results of verifying the data from SARAH, ERA5 and the data of reanalyzing the COSMO-REA6 model of the atmosphere according to the observational data from 41 weather stations of the BSRN around the world and 294 weather stations in Europe. Paper [37] compares the sums of radiation and light-reflecting power according to data from CLARA, SARAH, ERA5, and V2 Arctic System of Reanalysis (ASR) in a high-latitude area (Norway).

Earlier papers [20, 38, 39] provide the results of verifying data from NASA SSE according to terrestrial actinometric observations for Russia and the republics of Central Asia. The analytical comparison covered 25 active actinometric station in Central Asia and Russia, 17 of which are found in mountainous regions (the data of Uzbekistan's ground-based weather stations are taken from reference books [15–17]). In addition, distributions of the atmospheric brightness index for the territory of Russia [40–42] were considered according to the data from NASA POWER.

This paper is aimed at verifying the data available for Uzbekistan from NASA POWER, ERA5, and SARAH-E according to ground-based observation data from automatic weather stations for 2013–2017.

The local climate database for Uzbekistan, used to conduct the verification, has been developed as part of joint Russian–Uzbek project 18-58-41005 (MRU-FA-65/2017) of the Russian Foundation for Basic Research. This database covers the entire territory of Uzbekistan (between 37° and 45° N and 56° and 73° E) divided in 62 squares of $1^\circ \times 1^\circ$ by latitude and longitude and contains the results of ground-based observations from automatic weather stations as well as the data of the aforementioned bases.

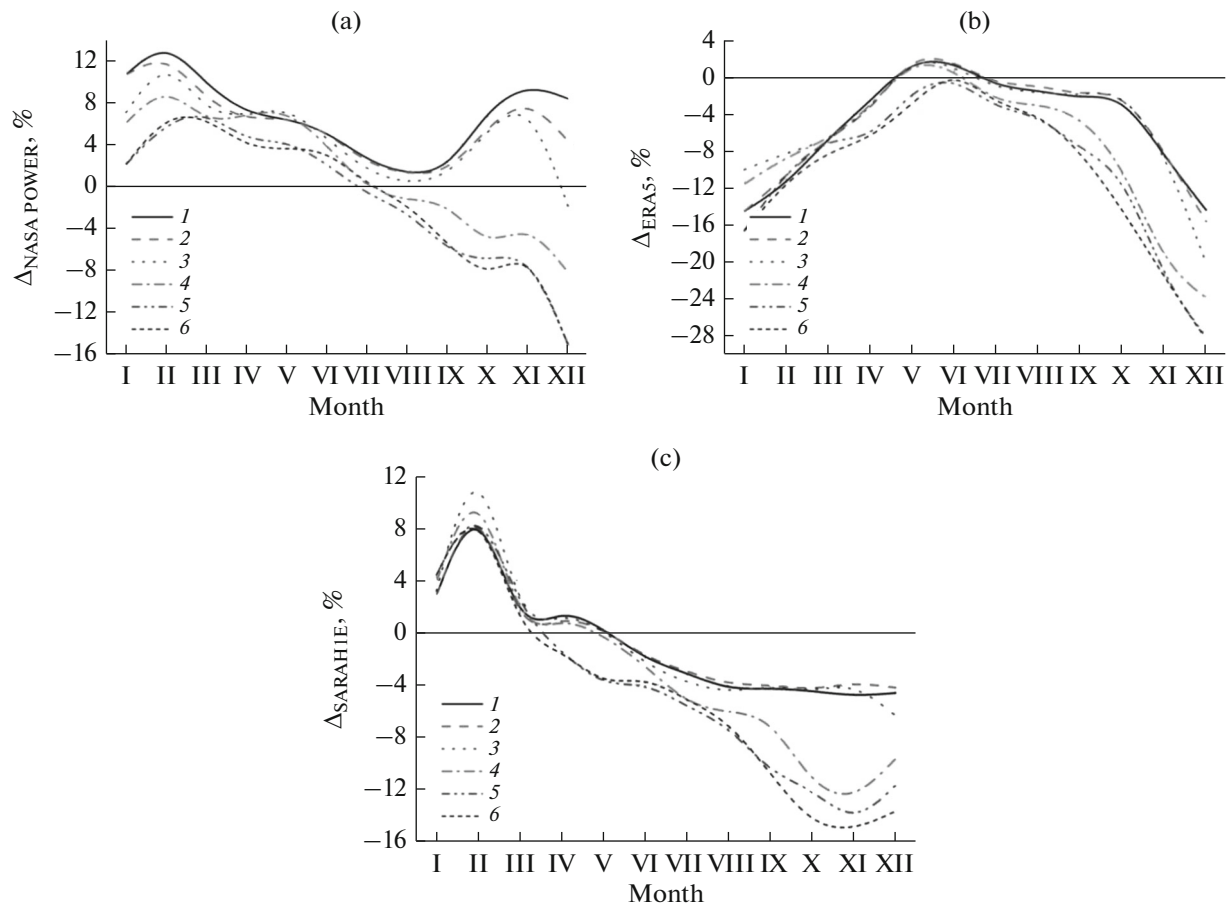


Fig. 2. Dependences of average relative error Δ on the time of the year ((a) is for NASA POWER; (b) is for ERA5; (c) is for SARAH-E; (1) is Parkent, (2) is Karman, (3) is Dagbit, (4) is Pap, (5) is Sherabad, (6) is Guzar).

MATERIALS AND METHODS

The main characteristic chosen in this paper for characterizing the deviation of the data from NASA POWER, ERA5, and SARAH-E from the ground-based observations is relative inaccuracy Δ of average daily sums of total solar radiation falling on the horizontal surface. This inaccuracy is recorded as

$$\Delta = \frac{\sum q_{db} - \sum q_{weather}}{\sum q_{db}}. \quad (1)$$

Here $\sum q_{db}$ and $\sum q_{weather}$ are the average monthly multiyear sums of data from NASA POWER, ERA5, and SARAH-E (db for the database) and ground-based measurements (weather), respectively. The inaccuracies in average monthly daily sums were analyzed for each actinometric station.

The verification of the average monthly values of daily sums of total radiation falling on the horizontal surface and direct radiation falling on the surface normal to the beam included the calculation of a set of quantities. The most broadly applied indicator in the average square deviation. The average absolute deviation (root mean square or RMS) is used as an additional measure in the evaluation. The propagation and

general correlation of data sets with ground-based measurements are evaluated using Pearson's correlational and dot plots.

It should be noted that, since there were no data for NASA POWER and ERA5, the values of daily sums of direct radiation, falling on the surface normal to the beam, according to those databases were verified using design formulas from [6].

RESULTS AND DISCUSSION

One of the main parameters used for comparison was relative inaccuracy Δ in the total solar radiation coming to the horizontal surface. The inaccuracy was analyzed by both individual observation points and all points for certain time spans (year, warmer part of the year, months). Uzbekistan has a small area, and, therefore, the points have little difference in latitude. This is why the relations of the average relative inaccuracy to the geographical latitude of the weather stations were not considered. However, the average relative inaccuracies heavily depends on the time of the year. For the dependence of the average relative inaccuracy on the time of the year for individual weather stations see Fig. 2.

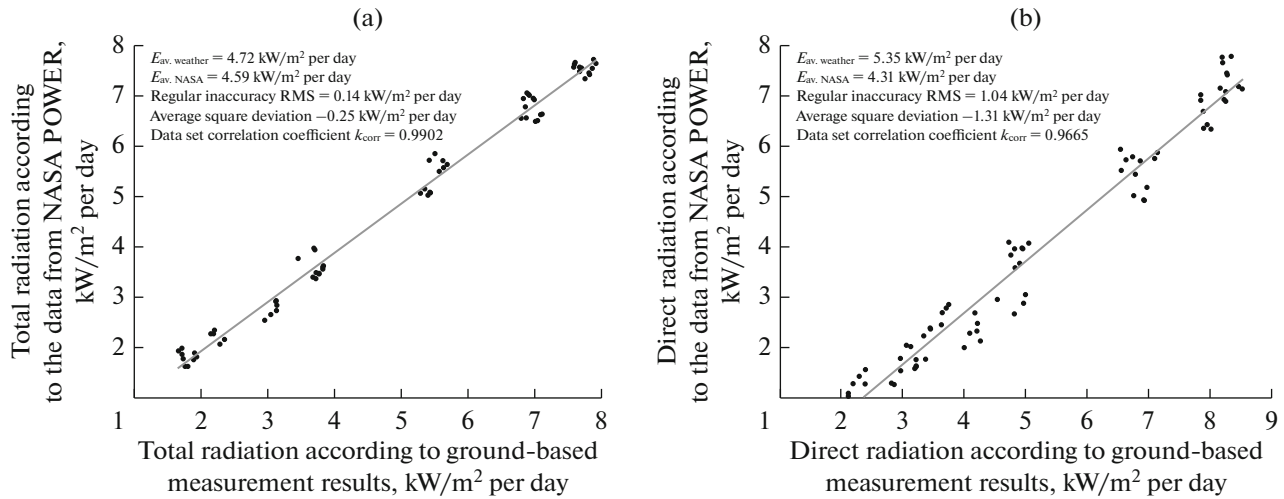


Fig. 3. Scattering diagrams of incident solar radiation according to the data from NASA POWER as related to the ground-based actinometric observations ((a) is for average monthly daily sums of total solar radiation falling on the horizontal surface; (b) is for average monthly daily sums of direct solar radiation on a surface normal to the beam), kW/m² per month.

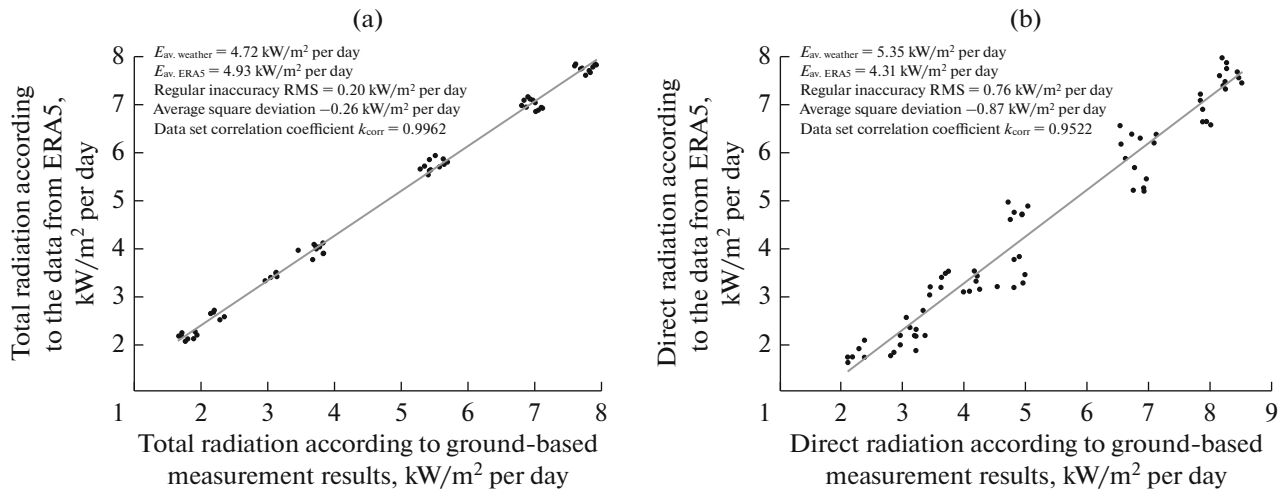


Fig. 4. Scattering diagrams of incident solar radiation according to the data from ERA5 as related to the ground-based actinometric observations ((a) is for average monthly daily sums of total solar radiation falling on the horizontal surface; (b) is for average monthly daily sums of direct solar radiation on a surface normal to the beam), kW/m² per day.

The average relative inaccuracy according to the data from NASA POWER (Fig. 2a) varies from 0 to 16%, depending on the time of the year. High Δ values are usually observed in winter (December–February) (2 to 16%), whereas from March to November Δ varies from 0 to 8%. The lowest inaccuracy is observed in summer (0 to 4%).

Figures 2b and 2c show the yearly variations in the average relative inaccuracy according to the data from ERA5 и SARAH1E. The inaccuracy varies from 0 to 12% from March to October and from 4 to 28% from November to February. The highest average relative inaccuracy in the whole year is shown by ERA5.

Proceeding from the change in the average relative inaccuracy according to the three databases, we can

conclude that all of the three can be used for the period from March to October (a similar inaccuracy for all of the bases is observed in summer and reaches up to 4%). However, because of their lower average relative inaccuracies, the data from NASA POWER are better suited than the data from the other bases.

For the diagram of scattering of the data from NASA POWER, ERA5, and SARAH1E see Figs. 3 to 5, respectively.

In terms of total solar radiation on the horizontal surface the data from NASA POWER, ERA5, and SARAH1E are much closer to the ground-based observation results than the data on direct solar radiation on the Sun-tracking surface.

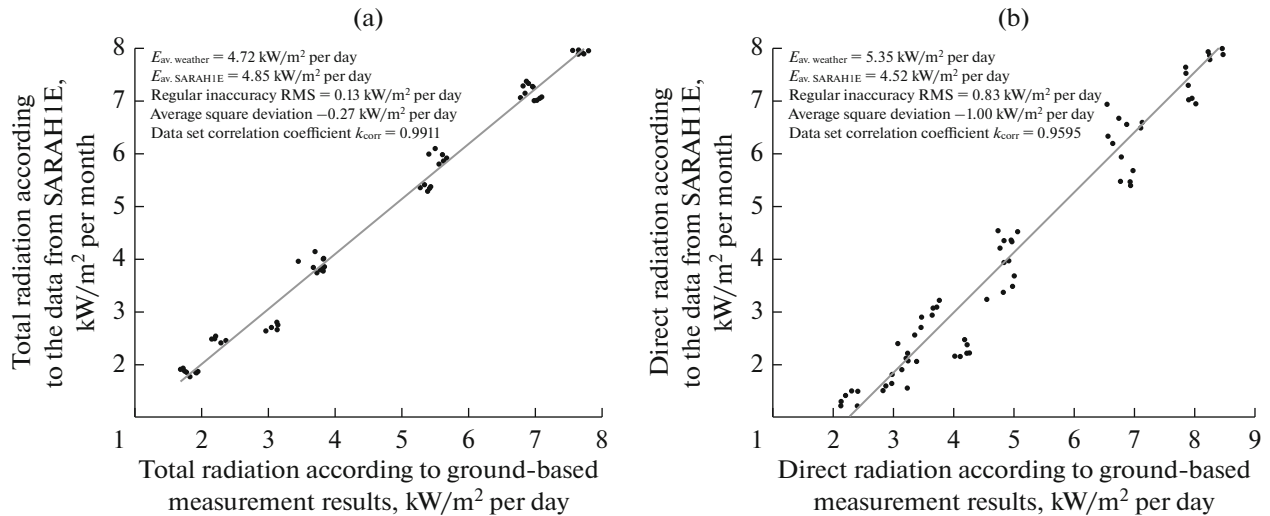


Fig. 5. Scattering diagrams of incident solar radiation according to the data from SARAH1E as related to the ground-based actinometric observations ((a) is for average monthly daily sums of total solar radiation falling on the horizontal surface; (b) is for average monthly daily sums of direct solar radiation on a surface normal to the beam), kW/m² per day.

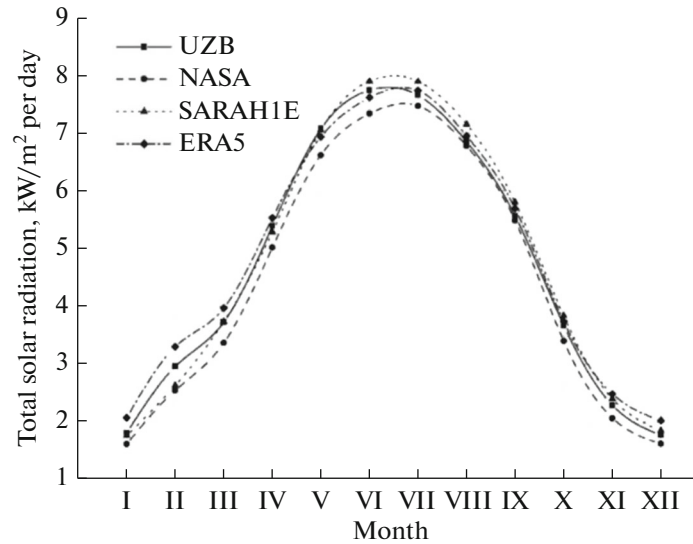


Fig. 6. Average daily sums of total solar radiation according to NASA POWER, ERA5, SARAH1E and ground data of Uzbekistan (2013–2017)

The data from NASA POWER, ERA5, and SARAH1E were analyzed for reliability in detail using the actinometric measurements from the Parkent weather station (Fig. 6).

The biggest difference in weather data is observed in the colder part of the year (November–March), though it does not exceed 15%.

The satellite data (NASA POWER and SARAH1E) and the reanalysis data (ERA5) are close to one another, which means that the data from the weather stations in Uzbekistan and the geographic locations close to it were not considered while forming the databases.

CONCLUSIONS

As shown by verifying the data from NASA POWER, ERA5, and SARAH1E according to the results of the ground-based observations from six automatic weather stations in Uzbekistan, the relative deviations of the data from NASA POWER from the terrestrial monthly sums of solar radiation on the horizontal surface for most of Uzbekistan's regions do not exceed 8% from April to September, which is quite acceptable when designing solar power plants. The relative deviations of the data from ERA5 and SARAH1E for the same period did not exceed 8–12%.

The consistent inaccuracy and the average square deviation of monthly sums of solar radiation on the

horizontal surface for NASA POWER (0.14 and 0.25 kW/m² per day), ERA5 (0.2 and 0.26 kW/m² per day), and SARAHE (0.13 and 0.27 kW/m² per day) are very close to each other. The average monthly sums of direct solar radiation on the surface normal to the beam from the three databases show a greater difference from the ground-based measurements than the sums of radiation on the horizontal surface.

The results of the calculation studies aimed at verifying the global horizontal distribution of solar radiation according to the three aforementioned databases allow us to use them in engineering calculations. A calculation study can be conducted using any chosen base, which depends on the information required, i.e., daily or hourly solar radiation amounts.

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