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Ground-based solar-radiation observations have rather high random errors, which were sourced from maintenance, calibration and/or inaccurate instruments in Turkey. Satellite-based radiation data obtained from the National Aeronautics and Space Administration (NASA) were compared with reliable ground observations, and it was found that the global solar incident insolation data of the NASA Surface Meteorology and Solar Energy (SSE) dataset is usable, with a rather low mean relative error of about 4%. Therefore, monthly and annual spatial distribution over Turkey and solar-radiation time series were analysed in order to detect the potential of solar radiation and to find out variations and trends, respectively.

1. Introduction

An accurate knowledge of global solar radiation on horizontal surfaces is required for many applications, from energy considerations to climate variability and change. Knowledge of solar radiation, which depends on ground measurements, is essential. The problems of ground measurements are the data quality and sparseness of stations in the area of interest.

A good example for data-quality problems is Turkey's experience of measurements of solar irradiation. Global solar radiation has been observed using actinographs at about 163 stations throughout the country since 1964 by the Turkish State Meteorological Service (TSMS). The data obtained from the actinographs were evaluated by Aksoy (1997a), and a rather high error rate with 14.7% annual and 42.1% monthly averages were found out. It was also determined that errors were independent of time, season and geographical conditions. Therefore, it was not possible to smooth these errors, as they were absolutely random. The TSMS started to modernize the measuring instruments. Within this conception, a new network, including pyranometers and pyrheliometers at 20 stations, has become operational to measure global and direct solar irradiation, respectively. However, only five of the stations could have reliable data for very short time periods. The problems of the data collected by the new network will be discussed in the following section. Therefore, it is not possible to map spatial distribution of solar radiation by only using the short data of five stations over Turkey, a country that covers an area of almost 800 000 km^2. This is another problem of the available ground measurements of this country.

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It is possible to obtain solar radiation at ground level from satellite images. Models developed for this can be gathered into two main groups: physical and statistical models. Physical models are usually based on determining the solar irradiation on horizontal surfaces by employing the radiative-transfer equation. The study of Gautier *et al.* (1980) is a good example of such a model. Statistical models depend on the regression between satellite count numbers or reflectance and corresponding ground measurements. The empirical model proposed by Cano *et al*. (1986) is well known in the literature. The estimation of solar irradiation on horizontal surfaces by using satellite data is well proven by many solar energy studies, which are summarized by Moradi *et al*. (2009).

The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) maintains solar-radiation studies through its working groups named The Satellite Application Facility on Land Surface Analysis (Land-SAF) (Geiger *et al*. 2008) and The Ocean & Sea Ice Satellite Application Facility (O&SI SAF) (OSI-SAF 2005). On the other hand, The European Centre for Medium-range Weather Forecasts (ECMWF) has a reanalysis model, which includes radiative-transfer processes, that is generally known as ERA-40 (Uppala *et al*. 2005). In addition, a satellite mission on solar radiation undertaken by the National Aeronautics and Space Administration (NASA) has been in operation since 1980s. The Surface Meteorology and Solar Energy (SSE) dataset of NASA covers the knowledge of irradiation incident on a horizontal surface (NASA 2009).

The aims of this study are two-fold. The first one is to identify the main knowledge on global solar radiation and its distribution over Turkey by employing the SSE dataset. This distribution knowledge covers mean monthly and annual bases. A validation study of monthly SSE data is also carried out by utilizing ground measurements. The second aim is to evaluate interannual variations on the annual time series of Turkey.

2. Data

The new network with pyranometers and pyrheliometers became operational at 20 stations in Turkey in the middle of 2003. Unfortunately, the locations were not evenly distributed to cover all the typical climates of the country, and some of them were installed at unsuitable locations. Moreover, some of the stations had communication and software problems in data logging, thus, their data were not available. A quality-control method of checking how the solar irradiation and bright sunshine hours correlate was applied to the remaining eight stations. It has been found that three of these stations exhibited completely different clusters from the general distribution trends. Therefore, they have been eliminated, and it was decided to use the data from only five ground stations for the period from January 2004 to December 2005 in the validation study of the satellite data. Ground measurements were carried out with CM11 Kipp & Zonen pyranometers (Delft, The Netherlands).

It has never been possible to detect solar energy potential and its distribution over Turkey with acceptable and well-tested accuracies because of the aforementioned problems of ground observations. Thus, to use satellite data for this aim is a necessity. The SSE dataset was preferred owing to the following reasons: (1) it is easy to obtain the dataset via the SSE web site; (2) its data format and unit are ready to use; and (3) the resolution of data is good enough, even with a coarse spatial and temporal resolution.

The SSE dataset originates from the NASA/World Climate Research Program and International Satellite Cloud Climatology project (ISCCP) summarized by Schiffer and Rossow (1985). The cloud-detection procedure of the ISCCP was based on the studies by Rossow and Schiffer (1991, 1999). In order to derive solar-radiation data, the SSE uses the outputs of some different projects such as the radiation data of the Surface Radiation Budget (SRB), the reanalysis temperature and moisture data of the Goddard Earth Observation System (GEOS), the total ozone column data of Total Ozone Mapping Spectrometer (TOMS) and the precipitation data of the Global Precipitation Climatology Project (GPCP). On the other hand, the SSE exploits the assimilation model, the Model of Atmospheric Transport and Chemistry (MATCH), of the National Center for Atmospheric Research (NCAR), with inputs from the Advanced High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) sensors (http://eosweb.larc.nasa.gov).

Radiation parameters have been derived originally on a 3-hourly temporal resolution for every day using an algorithm proposed by Pinker and Laszlo (1992). The 3-hourly values have been averaged into daily values using a normalization correction to account for the discretization of the solar cycle. Then, daily averages were used to obtain the monthly averages (SRB 2010). In this article, the monthly databases of release 6 of the SSE are taken, as they are available via the web site and no modification to the outlined procedure is considered. The SSE data depend on grid cells, and each map grid cell represents an area equal to that of 1° latitude by 1° longitude. The SSE database delivers monthly mean surface solar irradiance from July 1983 to December 2005. Turkey is covered with 85 grid cells of the SSE. The centre points of these cells and five selected ground stations are shown in figure 1. The monthly SSE dataset was downloaded and arranged as monthly and yearly time series.

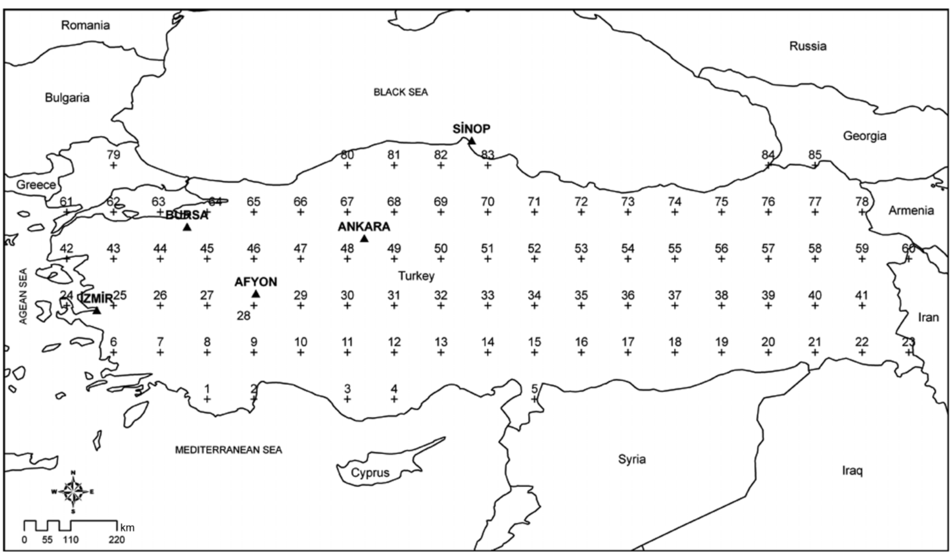

Figure 1. Location of the centre points of 85 NASA/SSE grid cells and five ground stations over Turkey.

3. Validation

Monthly SSE radiation values derived from 3-hourly temporal resolution data represent an area of about 10 000 km^2. These may seem rather low resolution, yet a temporal and spatial resolution higher than necessary might not be needed, especially for the average physical quantities in meteorological and geographical aspects. Moreover, the SSE dataset for a grid cell is not necessarily representative of a particular microclimate or any point within the cell because it covers a large area. Hence, the SSE datasets should be considered to be average values over the entire region of a grid cell. Studies on enhancing the geographical and time resolution of the SSE database might result in the aforementioned disadvantages (Perez *et al.* 2007). However, such a study is outside the scope of the present work's aim. Here, the SSE dataset is not intended to replace available and reliable ground measurements. The purpose is to augment the information on irradiation values for Turkey, which do not exist for acceptably higher spatial and temporal resolution.

On the other hand, there are studies on the accuracy of the SSE database. Whitlock *et al.* (2006) made a comparison between the SSE dataset and ground-site measurements on a global basis, and found that the biases varied from 13% to 16%. They found that the monthly biases were lower than the differences between the 3-hourly values. Stackhouse *et al.* (2008) compared the NASA SRB data to the National Solar Radiation Database (NSRDB) and revealed reasonably good agreement between the two datasets. Recently, a validation study has been published by Wahab *et al.* (2010). They compared two different satellite-based datasets, Helioclim-1 and SSE, to ground measurements for Algeria, Egypt, Libya and Tunisia. It was found that these two satellite-based databases exhibited similar and good performances, with a bias range from 1% to 7% for the average values. All validation studies show that the monthly SSE dataset is usable within acceptable accuracy levels.

The SSE datasets were compared to the ground measurements. In this comparison study, the five SSE grid cells that cover the five ground stations have reliable surface measurements. As can be observed in figure 1, the numbers of these grid cells are 25, 28, 48, 64 and 83 for the stations İzmir, Afyon, Ankara, Bursa and Sinop, respectively. Monthly and annual data were extracted and arranged for the period 2004–2005. Firstly, satellite-derived monthly data was plotted against ground measurements, and the result is given in figure 2. The straight line in the figure shows the fine agreement between the two datasets, with a correlation coefficient (r^2) of 0.99. This result is a good beginning for the validation studies and further analysis. Then, the differences (BE), mean bias error (MBE), maximum and minimum biases, root mean square error (RMSE), relative error (RE) and correlation coefficients were computed, and are given in table 1 by using the following relations:

$$\mathrm{BE} = H_{\mathrm{ic}} - H_{\mathrm{im}}, \tag{1}$$

$$\mathrm{MBE} = \left[\sum_{i=1}^{n} \mathrm{BE}\right] \Big/ n, \tag{2}$$

$$\mathrm{RMSE} = \left\{\left[\sum_{i=1}^{n} (\mathrm{BE})^2\right] \Big/ n\right\}^{1/2} \tag{3}$$

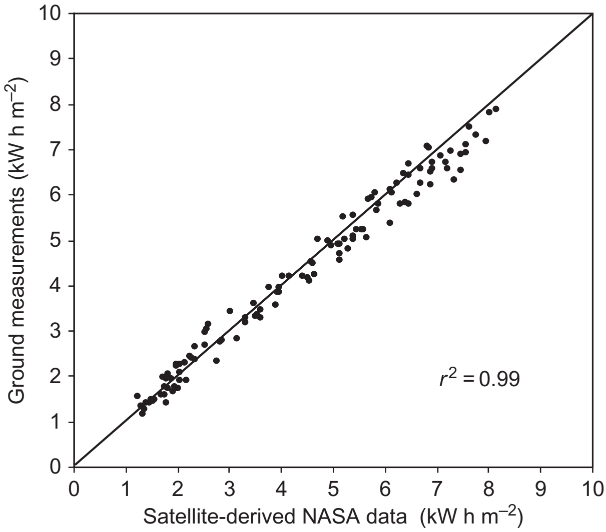

Figure 2. Scatter diagram of the satellite-derived and ground-based monthly global solar-radiation data for the period 2004–2005.

Table 1. Correlation coefficients, root mean square error (RMSE), mean bias error (MBE), bias analyses and relative error (RE) between the satellite-derived insolation data of NASA/SSE and ground data. The units of RMSE, MBE, maximum and minimum biases are in kWh m^{-2}.

Comparison test	Afyon	Ankara	Bursa	İzmir	Sinop	Average
Correlation coefficient	0.99	0.99	0.99	1.00	1.00	0.99
RMSE	0.36	0.39	0.31	0.25	0.34	0.33
MBE	0.13	0.31	0.13	−0.12	0.22	0.13
of winter	−0.05	0.19	−0.08	−0.20	0.04	−0.02
of spring	−0.08	0.16	0.06	−0.22	0.22	0.03
of summer	0.46	0.63	0.42	0.17	0.44	0.42
of autumn	0.14	0.24	0.11	−0.19	0.21	0.10
Maximum bias	0.80	0.94	0.76	−0.48	1.01	–
Minimum bias	−0.02	−0.01	0.00	−0.01	−0.02	–
Positive bias (%)	60.00	91.70	66.70	25.00	87.50	66.2
Negative bias (%)	40.00	8.30	33.30	75.00	12.50	33.8
RE (%)	3.00	7.50	3.30	2.50	5.90	4.4

and

$$\mathrm{RE} = \mathrm{BE} \times 100 \big/ \langle H \rangle, \tag{4}$$

where H_{ic} and H_{im} are the satellite-derived data and ground-measured data for the ith month, respectively, n is the total number of data and $\langle H \rangle$ is the mean value of the ground measurements.

According to table 1, all stations show overestimation, except İzmir station. The percentage of overestimations was computed to be 66.2% for the whole dataset of monthly values. There are only a few cases where the satellite-based data are considerably higher than the ground measurements. However, about 80% of them are inside the boundaries of ± 0.40 kW h m^{-2}. The mean relative error of almost 4% is a remarkable value due to the fact that some ground-observation instruments measure with higher error rates. Summer months gave the highest contribution to the MBE values. İzmir exhibits the lowest statistical error values, while Ankara station shows the highest values of RE, RMSE and MBE. This validation study shows a close agreement between SSE data and ground measurements. Therefore, these data are chosen for determining the distribution of solar radiation over Turkey.

4. Spatial distribution

The time series obtained from NASA/SSE has been gridded by using the kriging method of the ARC-GIS software (ESRI, Redlands, CA, USA). Kriging with a linear variogram method for the gridding is very successful for the original climatic variables and their resultant statistics. Detailed descriptions of the kriging approach can be found in many publications, for example, Cressie (1991). A total of 13 solar-irradiation distribution maps are obtained for 12 months and annually. The geographical distribution of 22-year averages of annual global solar irradiation only is given in figure 3 because of the extent of the present article. The results of these distributions are given as follows.

The spatially coherent patterns with latitudes can be observed in all distribution maps. Consequently, solar irradiation increases from northern towards southern latitudes, as expected. On the other hand, the distribution of solar irradiation is closely related to synoptic-scale atmospheric circulation forms of the cloud regime. Classification of the depression tracks for Turkey was revealed by Karaca *et al.* (2000) and summarized by Türkeş (1998). They studied mean seasonal frequencies of the depressions with respect to the paths and mean seasonal distributions of all depressions. According to them, Turkey is affected mainly by four depressions that originate from the North Atlantic, Scandinavia, the Mediterranean Basin and the mid-Atlantic. The northern areas of Turkey are affected by about 80% of these depressions.

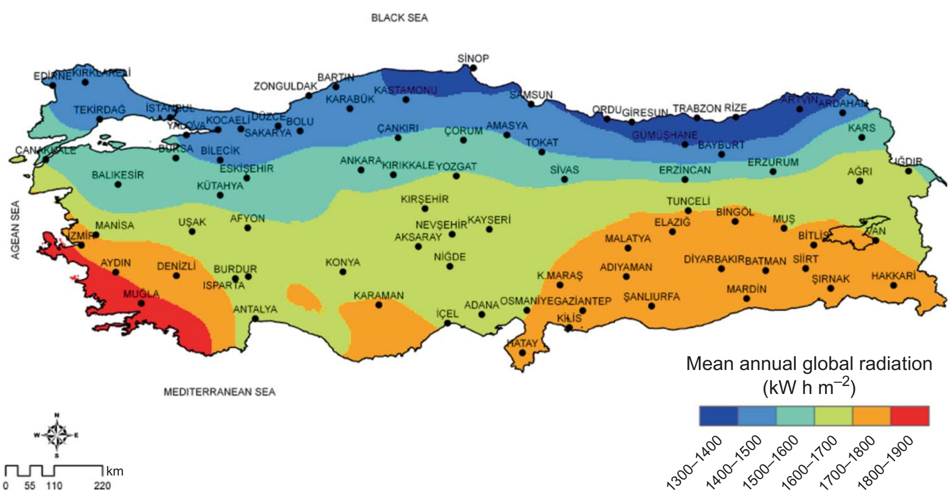

Figure 3. Geographical distribution of 22-year average of annual global solar irradiation based on NASA/SSE.

Furthermore, the southern extension of the cold fronts of the mid-latitude depressions also affects the northern part of the country. As a result of these, the depressions sourced in the north and northwest are more dominant in cloud and rainfall regime, which explains the low solar radiation over northern regions. The northern depressions also allow intrusions of cloud cover to plunge towards the south in the central area. Therefore, the distribution of solar radiation over Turkey can be characterized by a reverse seesaw between the southwest and the southeast. As a result of this, a disturbance appears in coherent patterns with latitudes on distribution maps in southern regions. Spatial distributions of monthly solar radiations are also similar to the annual distribution, except in winter months, which have a second cut-off over the continental interior of eastern Anatolia because of the winter depressions and their paths.

However, annual mean global solar irradiation varies between 3.6 and 5.1 kW h m^{-2}, with an average of 4.4 kW h m^{-2} in this work. Solar radiation exhibits a remarkable increase towards the south, and reaches its maximum value on the southwestern coast. Along the major part of the southern latitude zone, mean annual solar irradiation is above 4.6 kW h m^{-2}, while it is less than 4.0 kW h m^{-2} for the northern latitude belt. The extreme values of geographical distribution are 3.3 kW h m^{-2} at 84 grid cells covering the north side of the northeastern Anatolia and 5.3 kW h m^{-2} at 6 grid cells covering the west side of the southwest Anatolia. In evaluation of monthly mean solar irradiation, the lowest and highest values are detected as being 1.7 and 7.1 kW h m^{-2} for the months of December and June, respectively. In December, monthly solar irradiation ranges between 1.28 and 2.11 kW h m^{-2}. It is determined that the change in a rather wide scale from 5.87 to 8.34 kW h m^{-2} is current in June detected as another extreme month.

5. Interannual variability

The spatial distribution pattern of variability in annual mean solar-irradiation time series for each grid cell was examined by taking into account the coefficient of variation (CV). This measurement was used in order to determine interannual variability, which is calculated by computing the standard deviation as a percentage of the long-term average. The geographical distribution of computed CVs is given in figure 4. The CVs of mean annual solar irradiation vary between 2% and 5%. They have a mean value of 3%. The northern and southern latitude belts exhibit more variability with respect to the interior locations. The mid-latitudes of the country have CVs of about 3%, which is close to the mean value. The maximum CV of 5.19% is seen in the east part of southeastern Anatolia, while the west side of southwest Anatolia has the minimum value of 1.94%.

On the other hand, the Mann–Kendall rank correlation test proposed by Sneyers (1990) has been applied to the solar-irradiation time series to detect any possible trend. Therefore, it is possible to find out whether there is any statistically significant trend or not. This performance gives a hint on tendency of this time cycle, although it is not a sign of a secular trend because of the limited length of records with the 22-year data. The Mann–Kendall test statistic $u(t)$ is used to determine the sign and magnitude of the trend in a series. Moreover, short-term trends and the beginning of a trend in the series are investigated by using the time-series plot of $u(t_i)$ and $u'(t_i)$ values. The $u'(t)$ value is computed similarly to $u(t)$, starting from end of the series. In order to obtain such a time-series plot, sequential values of the statistics $u(t)$ and

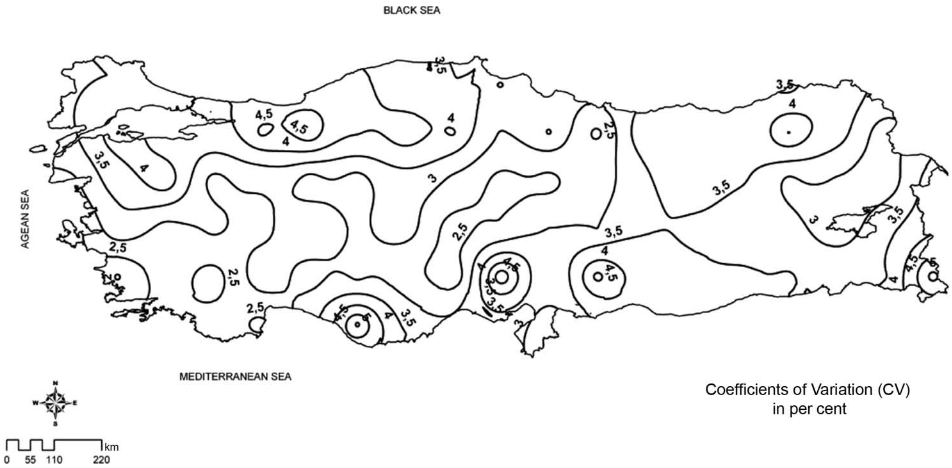

Figure 4. Geographical distribution of coefficients of variation for annual global solar radiation in Turkey.

$u'(t)$ are computed from progressive analysis of the Mann–Kendall test. The intersection of $u(t)$ and $u'(t)$ enables the beginning of a trend in the series to be located approximately.

The time-series plots obtained from the Mann–Kendall test and variations in annual mean global solar radiation for 85 grid cells have been prepared, but all cannot be presented here. The plots of 1 grid cell are given as an example in figure 5. The 1 grid cell shows an increasing trend like most of the other cells. The year-to-year variation of global solar radiation, their mean value and the smoothed line using a Gaussian filter for the 1 grid cell are given in figure 5(*a*). A remarkable increasing trend can be traced visually. Figure 5(*b*) shows the statistical meaning of the variation of the time series. The $u(t)$ and $u'(t)$ test statistics are given in figure 5(*b*), with critical significant

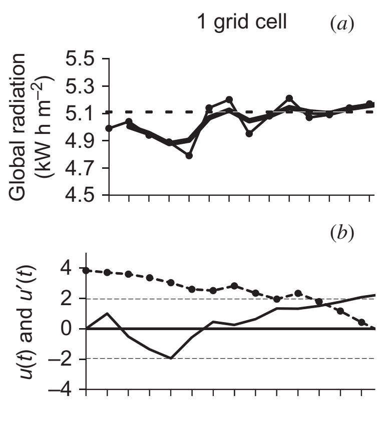

Figure 5. (*a*) Year-to-year variation of annual mean global solar radiation at 1 grid cell (thin line) with a smoothed line using a Gaussian filter (solid line) and long-term average (dashed line). (*b*) Trend from sequential values of the statistics of $u(t)$ (solid line) and $u'(t)$ (dashed line), with the critical significance values of ± 1.96 at the 0.05 level.

values of ±1.96 and ±2.58 at 0.05 and 0.01 significance levels, respectively. The beginning year of a trend in the series of the 1 grid cell was found to be 1995 by taking into consideration the intersection of the $u(t)$ and $u'(t)$ lines in figure 5(*b*). Moreover, $u(t)$ values show a statistical significance of the trend of whether $u(t)$ is bigger than the critical significant values or not. According to figure 5(*b*), the 1 grid cell has a significant positive trend statistically at the 0.05 and 0.01 levels because the $u(t)$ value (3.83) is bigger than both the critical values. This statistical study was applied to all the grid cells. The latitude and longitude of the centre points of the grid cells, the $u(t)$ values with their statistical significances and intersection years for all cells are given in table 2.

Results from the Mann–Kendall test for the 85 grid cells and visual interpretation of the time-series plots are summarized as follows. (a) The majority of grid cells are considerably similar to each other in terms of the year-to-year variability and trend patterns. According to the statistical tests, long-term variations in global solar irradiation are explained with a significant increasing trend, especially over the last 10-year period. (b) Global solar-radiation series generally tend to increase, except for five of the cells that are situated in the north and northeast of the country. Variations and trends are not statistically significant in these five cells, exhibiting downward tendencies. A statistically significant positive trend for 73% of the grid cells was detected, while no significant variation was observed for 27% of them. In other words, any statistically significant negative trend was not found in 27%. (c) The beginning year of a trend in the series was detected for each grid cell by taking into consider the intersection of $u(t)$ and $u'(t)$ values. Many plots from the Mann–Kendall tests demonstrate a discernible increase in the radiation time series starting from the period 1995–1997. 1991 is also noted as a second remarkable starting year.

A study on variations and trend in global solar radiation for Turkey was carried out by Aksoy (1997b). In that study, Aksoy used the outputs of a ground-based statistical model (Aksoy 1997a) of the data of 34 meteorological stations for the period 1960–1994, and found that significant negative trends of the annual means were observed with 71% of the stations. It is of course not possible to connect these two datasets due to the differences of their sources. However, some comments on interpreting both results could be carried out. In the first study, a general downward trend started from the early 1960s and continued to the early 1990s. A stationary and even increasing tendency was apparent after the 1990s in that study. In present study, the stability of time series at the beginning of the 1990s is clear, as can be seen in figure 5, while a remarkable increasing trend starts in the middle of the 1990s. When a comparison is carried out among the locations in both studies, it was detected that the locations have the warmer weather conditions in second study. The trend sign of locations that had negative trends in early study have converted into no or positive trends in present study. The stations also showed no significant change in the old study have turned into positive trends in this study. Wahab *et al.* (2010) also studied long-term variations for 11 stations of four nations, Algeria, Egypt, Libya and Tunisia. The data periods of some of the stations almost covered both study periods of those of Aksoy. According to Wahab *et al.*, there is a clear decreasing trend between early 1970 and early 1990, while a stability and/or an increasing tendency occurs between the mid-1990s and 2005. Their findings are compatible with both studies of Aksoy. However, the variations are clearer and statistically significant in the present study.

Table 2. The results of trend analyses.

	Centre of cell					Centre of cell			
N	Latitude (°)	Longitude (°)	$u(t)$	YI	N	Latitude (°)	Longitude (°)	$u(t)$	YI
1	36.5	29.5	3.83**	1995	44	39.5	28.5	1.86	–
2	36.5	30.5	2.14*	1991	45	39.5	29.5	0.79	–
3	36.5	32.5	4.54**	1997	46	39.5	30.5	1.92	–
4	36.5	33.5	4.15**	1997	47	39.5	31.5	1.49	–
5	36.5	36.5	1.10	–	48	39.5	32.5	2.45*	1997
6	37.5	27.5	0.59	–	49	39.5	33.5	2.45*	1997
7	37.5	28.5	3.58**	1995	50	39.5	34.5	2.48*	1992
8	37.5	29.5	1.92	–	51	39.5	35.5	2.51*	1991
9	37.5	30.5	3.07**	1989	52	39.5	36.5	1.95	–
10	37.5	31.5	2.90**	1992	53	39.5	37.5	2.68**	1991
11	37.5	32.5	2.26*	1998	54	39.5	38.5	2.23*	1997
12	37.5	33.5	3.05**	1997	55	39.5	39.5	3.19**	1997
13	37.5	34.5	0.37	–	56	39.5	40.5	3.47**	1996
14	37.5	35.5	3.16**	1999	57	39.5	41.5	1.58	–
15	37.5	36.5	2.88**	1997	58	39.5	42.5	0.68	–
16	37.5	37.5	3.52**	1997	59	39.5	43.5	−0.93	–
17	37.5	38.5	3.07**	1997	60	39.5	44.5	−1.47	–
18	37.5	39.5	3.44**	1996	61	40.5	26.5	3.27**	1992
19	37.5	40.5	3.19**	1996	62	40.5	27.5	2.23*	1989
20	37.5	41.5	3.36**	1996	63	40.5	28.5	0.03	–
21	37.5	42.5	3.47**	1996	64	40.5	29.5	1.41	–
22	37.5	43.5	3.81**	1995	65	40.5	30.5	3.10**	1997
23	37.5	44.5	4.37**	1994	66	40.5	31.5	3.21**	1998
24	38.5	26.5	2.43*	1995	67	40.5	32.5	2.20*	1997
25	38.5	27.5	2.71**	1991	68	40.5	33.5	3.44**	1997
26	38.5	28.5	2.31*	1991	69	40.5	34.5	4.00**	1997
27	38.5	29.5	3.10**	1991	70	40.5	35.5	2.96**	1997
28	38.5	30.5	2.31*	1991	71	40.5	36.5	3.38**	1995
29	38.5	31.5	2.74**	1991	72	40.5	37.5	2.74**	1996
30	38.5	32.5	2.85**	1996	73	40.5	38.5	3.55**	1994
31	38.5	33.5	3.38**	1997	74	40.5	39.5	2.45*	1992
32	38.5	34.5	2.37*	1996	75	40.5	40.5	1.41	–
33	38.5	35.5	1.92	–	76	40.5	41.5	2.45*	1992
34	38.5	36.5	2.00*	1996	77	40.5	42.5	1.13	–
35	38.5	37.5	2.82**	1997	78	40.5	43.5	2.11*	1991
36	38.5	38.5	2.26*	1991	79	41.5	27.5	1.72	–
37	38.5	39.5	3.05**	1996	80	41.5	32.5	−0.31	–
38	38.5	40.5	2.79**	1995	81	41.5	33.5	−1.33	–
39	38.5	41.5	3.16**	1996	82	41.5	34.5	−1.33	–
40	38.5	42.5	2.68**	1994	83	41.5	35.5	2.79**	1998
41	38.5	43.5	3.44**	1995	84	41.5	41.5	0.28	–
42	39.5	26.5	3.38**	1992	85	41.5	42.5	2.14*	1996
43	39.5	27.5	2.71**	1992					

Notes: N is the grid cell number, $u(t)$ is the Mann–Kendall test statistic with its significance at the 0.05 level (*) and 0.01 level (**) and YI intercept year means the beginning of the trend in the time series.

6. Conclusions

The main conclusions of the study are summarized as follows.

Global solar-radiation data obtained from actinographs in Turkey are not reliable because they have rather high random errors. Thus, up until now, it has never been possible to obtain solar irradiation over Turkey with acceptable levels of accuracy. Recently, a new network with a greater number of stations has been launched in order to observe solar irradiation; however, some problems still exist.

The NASA/SSE dataset was downloaded to find the solar energy potential of Turkey. Data of 85 grid cells over the country, covering the period from July 1983 to December 2005 was collected. After an examination of validation using the measured data of five ground stations for the period 2004–2005, it was observed that the SSE data had a good agreement with the measured values, with a mean relative error of about 4%.

Spatial distributions of monthly and annual global solar-irradiation data obtained from NASA/SSE over Turkey were examined using the kriging method. Annual mean values varied between 3.6 and 5.1 kW h m^{-2}, and had an average of 4.4 kW h m^{-2}. The extreme months were detected as December, with an average of 1.7 kW h m^{-2} and June, with an average of 7.1 kW h m^{-2}.

Annual global solar-irradiation time series of NASA/SSE has been analysed from 1984 to 2005 at 85 grid cells of the country in order to detect year-to-year variations. For this aim, the CV was used and Mann–Kendall time-series analyses implemented to detect whether any trend existed. It was found that the time series have an average variation of 3% and that the 62 grid cells exhibit a significant increasing trend statistically. The beginning year of trends in the series was detected to be the middle of the 1990s.

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References

Aksoy, B., 1997a, Estimated monthly average global radiation for Turkey and its comparison with observation. *Renewable Energy*, **10**, pp. 625–633.

Aksoy, B., 1997b, Variations and trends in global solar radiation for Turkey. *Theoretical and Applied Climatology*, **58**, pp. 71–77.

Cano, D., Monget, J.M., Albuisson, M., Guillard, H., Regas, N. and Wald, L., 1986, A method for the determination of the global solar radiation from meteorological satellite data. *Solar Energy*, **37**, pp. 31–39.

Cressie, N., 1991, *Statistics for Spatial Data* (London: John Wiley).

Gautier, C., Diak, G. and Masse, S., 1980, A simple physical model to estimate incident solar radiation at the surface from GOES satellite data. *Journal of Applied Meteorology*, **19**, pp. 1005–1012.

Geiger, B., Meurey, C., Lajas, D., Franchistéguy, L., Carrer, D. and Roujean, J.-L., 2008, Near real-time provision of downwelling shortwave radiation estimates derived from satellite observations. *Meteorological Applications*, **15**, pp. 411–420.

Karaca, M., Deniz, A. and Tayanç, M., 2000, Cyclone track variability over Turkey in association with regional climate. *International Journal of Climatology*, **20**, pp. 1225–1236.

Moradi, I., Mueller, R., Alijani, B. and Kamali, G.A., 2009, Evaluation of the Heliosat-II method using daily irradiation data for four stations in Iran. *Solar Energy*, **83**, pp. 150–156.

National Aeronautics and Space Administration (NASA), 2009, Surface meteorology and solar energy. Available online at: http://eosweb.larc.nasa.gov/(accessed 15 October 2009).

OSI-SAF, 2005, Surface solar irradiance, product manual, Version 1.5, Meteo, France. Available online at: http://www.osi-saf.org/(accessed 26 May 2009).

Perez, R., Kmiecik, M., Wilcox, S. and Stackhouse, P., 2007, Enhancing the geographical and time resolution of NASA SSE time series using microstructure patterning. In *Proceedings of the Solar 2007 Conference (American Solar Energy Society)*, R. Compbell-Howe (Ed.), 8–13 July, Cleveland, OH (West Chester, OH: Curran Associates).

Pinker, R.T. and Laszlo, I., 1992, Modeling surface solar irradiance for satellite applications on a global scale. *Journal of Applied Meteorology*, **31**, pp. 194–211.

Rossow, W.B. and Schiffer, R.A., 1991, ISCCP cloud data products. *Bulletin of the American Meteorological Society*, **72**, pp. 2–20.

Rossow, W.B. and Schiffer, R.A., 1999, Advances in understanding clouds from ISCCP. *Bulletin of the American Meteorological Society*, **80**, pp. 2261–2287.

Schiffer, R.A. and Rossow, W.B., 1985, ISCCP global radiance data set: a new resource for climate research. *Bulletin of the American Meteorological Society*, **66**, pp. 1498–1505.

SRB, 2010, Surface Radiation Budget project of NASA/GEWEX program. Available online at: http://gewex-srb.larc.nasa.gov/ (accessed 15 October 2009).

Sneyers, R., 1990, *On the Statistical Analysis of Series of Observations*. WMO Technical Note No. 143, (World Meteorological Organization: Geneva), pp. 6–11.

Stackhouse, P.W., Zhang, T., Chandler, W.S., Whitlock, C.H., Hoell, J.M., Westberg, D.J., Perez, R. and Wilcox, S., 2008, Satellite based assessment of the NSRDB site irradiances and time series from NASA and SUNY/ALBANY algorithms. In *Proceedings of the Solar 2008 Conference (American Solar Energy Society)*, 3–8 May, San Diego, CA.

Türkeş, M., 1998, Influence of geopotential heights, cyclone frequency and southern oscillation on rainfall variations in Turkey. *International Journal of Climatology*, **18**, pp. 649–680.

Uppala, S.M., Kållberg, P.W., Simmons, A.J., Andrae, U., Da Costa Bechtold, V., Fiorino, M., Gibson, J.K., Haseler, J., Hernandez, A., Kelly, G.A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R.P., Andersson, E., Arpe, K., Balmaseda, M.A., Beljaars, A.C.M., Van De Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B.J., Isaksen, L., Janssen, P.A.E.M., Jenne, R., Mcnally, A.P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N.A., Saunders, R.W., Simon, P., Sterl, A., Trenberth, K.E., Untch, A., Vasiljevic, D., Viterbo, P. and Woollen, J., 2005, The ERA-40 reanalysis. *Quarterly Journal of the Royal Meteorological Society*, **131**, pp. 2961–3012.

Wahab, M.A., El-Metwally, M., Hassan, R., Lefevre, M., Oumbe., A. and Wald, L., 2010, Assessing surface solar irradiance and its long-term variations in the northern Africa desert climate using Meteosat images. *International Journal of Remote Sensing*, **31**, pp. 261–280.

Whitlock, C.H., Chandler, W.S., Hoell, J.M., Westberg, D.J., Zhang, T. and Stackhouse, P.W., 2006, *January 2006 Accuracy Status for NASA Buildings-related Climate Parameters over the Globe*. A[P1] Special Report for the ASHRAE Technical Committee 4.2 on Climatic Information ASHRAE 2006 Winter Meeting and EXPO, 21–25 January, Chicago, IL.