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Trends in Global Solar Radiation and Sunshine Duration in Past Two Decades in Japan

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Abstract

Global solar radiation (GSR) is an essential physical quantity for agricultural management and designing infrastructures. Because GSR has often been modeled as a function of sunshine duration (SD) and day length for a given set of locations and calendar days, analyzing interannual trends in GSR and SD is important to evaluate, predict or regulate the cycles of energy and water between geosphere and atmosphere. This study aimed to exemplify interannual trends in GSR and SD, which had been recorded from 2001 to 2022 in 40 meteorological stations in Japan, and validate the applicability of an SD-based model to the evaluation of GSR. Both the measured GSR and SD had increased in many of the stations in the study period with averaged rates of 0.252 [$W \cdot m^{-2} \cdot y^{-1}$] and 0.015 [$h \cdot d^{-1} \cdot y^{-1}$], respectively. The offset and the slope of the SD-based model were estimated by fitting the model to the measured data sets and were found to have been almost constant with the averages of 0.201[-] and 0.566[-], respectively, indicating that characteristics of the SD-GSR relation had not varied for the 22-year period and that the model and its parameter set can be stationarily applicable to the analyses and predictions of GSR in recent years. The stable trends in both parameters also implied that the upward trend in SD can be a main explanatory factor for that in the measured GSR. The upward trend in SD had coincided with the increase in the frequency of heavy-shortened rains, suggesting that the time period of each rainfall event had gradually decreased, which may be attributable to the obtained upward trend in SD. Further studies are required to clarify if there is some cause-effect relation between the changes in rainfall patterns and the standard level of solar radiation reaching the land surface.

Keywords

Angstrom-Prescott Model, Atmospheric Transmittance, Cloud Cover, Extraterrestrial Solar Radiation, Global Brightening, Hour Angle, Solar

Declination, True Anomaly

1. Introduction

Global solar radiation (GSR) is the sum of direct and diffused shortwave solar irradiance reaching to the earth's surface, and is the primary heat source for driving the cycles of energy and water between the geosphere and the atmosphere. Solar radiation in general is inevitable for plant growth where it promotes and/or regulates both photosynthetic activities in leaves and water-uptake activities in roots of the plants. At the same time, solar radiation is the principal factor in defining light- and temperature-environments for inner spaces and bodies of building structures. Thus, knowledge of any local GSR is essential for agricultural management and designing infrastructures.

Values of GSR have likely varied in the past decades. A well-known is the downward trend in solar radiation, called the "global dimming", which has happened in the period between around 1960 and around 1990. For instance, Dutton et al. (1991) presented a graph of the time series of annual average solar irradiance at the South Pole in which the solar irradiance had decreased steadily from 1967 to around 1983 by 15 [$W\cdot m^{-2}$], attributing to the interannual increasing trend in cloud cover. The graph also showed that the decreasing trend bottomed out after the mid-1980s, suggesting the possible reversal of the trends after those years. Liepert (2002) estimated that surface solar radiation worldwide decreased by 7 [$W\cdot m^{-2}$] from 1961 to 1990 while the decrease in the same period in the United States was 19 [$W\cdot m^{-2}$]. Stanhill and Cohen (2001) estimated the reduction in surface solar radiation from 1958 to 1992 and calculated that it could have amounted to 20 [$W\cdot m^{-2}$] or have proceeded with the rate of 0.514 [$W\cdot m^{-2}\cdot y^{-1}$], depending on methods of estimation.

On the other hand, it is also said that surface solar radiation has been increasing since the mid- or late-1980s. The analysis by Wild et al. (2005) suggested that the global downward trend in solar radiation did not continue after 1990, and the amount of sunlight has increased since the late 1980s. Pinker et al. (2005) confirmed the global trends in solar radiation by using satellite-based estimates and evaluated the increasing rate of 0.16 [$W\cdot m^{-2}\cdot y^{-1}$] for about 20 years from 1983.

These past trends in GSR can bring about an analysis of the post-dimming period in terms of the relationship between GSR and sunshine duration. And when the Angstrom-Prescott type model is to be used for the analysis, the following problems arise: 1) how the sunshine duration and GSR have varied with years, 2) how stationarily the model formulates the relation between sunshine duration and GSR, and 3) possible reasons behind the trends.

Therefore, this study aimed at exemplifying interannual trends in GSR and sunshine duration which had been measured from 2001 to 2022 in 40 meteorological stations over the Japanese archipelago, and validating the applicability of a sunshine-based atmospheric transmittance model.

2. Materials and Methods

2.1. Data Sets

A total of 40 weather stations of Japan Meteorological Agency, covering almost all over the country, were selected, where GSR Q [W·m^{-2}] and the sunshine duration n [h·d^{-1}] had concurrently been monitored. The latitudes, longitudes, and elevation heights from land surface of the stations were tabulated in Table 1. The measured values of Q [W·m^{-2}] and n [h·d^{-1}] on daily basis were collected from the database that are opened to the public by Japan Meteorological Agency (2022).

The Japan Meteorological Agency standardized the thermopile pyranometers used for measuring solar radiation at every meteorological station in the period between 1971 and 1974, after the uses of several types of pyranometer including Robitzsch-type pyranometers and Eppley-type pyranometers had mingled together. The measurement systems of sunshine duration had also been updated from Jordan sunshine recorders to rotating mirror sunshine recorders in the period from 1986 to 1990. Therefore, the measured data sets of GSR and sunshine duration obtained after these updates can be used for the analyses without any correction.

Values of daily precipitation, hourly-maximum precipitation, and cloud cover were also collected to characterize the interannual trends in GSR, sunshine duration, and the parameters of the atmospheric transmittance model. The stations where the cloud cover had been routinely measured throughout the study period were limited to 11 stations denoted in Table 1.

2.2. A Sunshine-Based Atmospheric Transmittance Model

Values of GSR Q [W·m^{-2}] in relation to sunshine duration n [h·d^{-1}] have often been expressed by the Angstrom-Prescott type model:

$$Q = Q_e \cdot \tau \tag{1}$$

where Q_e [W·m^{-2}] is the extraterrestrial solar radiation, and τ[-] is the atmospheric transmittance. Originally, the solar radiation expected in clear days Q_c [W·m^{-2}] had been adopted in place of Q_e [W·m^{-2}] (Angstrom, 1924; Prescott, 1940), but, later, the original model was modified into Equation (1) by replacing Q_c [W·m^{-2}] with Q_e [W·m^{-2}] as seen on Doorenbos and Pruitt (1977) and Allen et al. (1998).

Table 1. The locations of the 40 stations and their annually-averaged values of extraterrestrial solar radiation Q_{ea} [W·m^{-2}] and day length N_a [h·d^{-1}]. A station name marked with "*" indicates that the cloud cover had been monitored routinely at the station.

Station	Latitude	Longitude	Height [m]	Q_{ea} [W·m^{-2}]	N_a [h·d^{-1}]
Wakkanai	45˚24.9'N	141˚40.7'E	3	309.5	12.06
Sapporo(*)	43˚3.6'N	141˚19.7'E	17	319.7	12.05
Abashiri	44˚1'N	144˚16.7'E	38	315.6	12.06
Hakodate	41˚49'N	140˚45.2'E	35	325.0	12.05

Continued

Aomori	40˚49.3'N	140˚46.1'E	3	329.1	12.05
Akita	39˚43'N	140˚5.9'E	6	333.6	12.05
Morioka	39˚41.9'N	141˚9.9'E	155	333.7	12.05
Sendai(*)	38˚15.7'N	140˚53.8'E	39	339.4	12.04
Yamagata	38˚15.3'N	140˚20.7'E	153	339.4	12.04
Fukushima	37˚45.5'N	140˚28.2'E	67	341.3	12.04
Tsukuba	36˚3.4'N	140˚7.5'E	25	347.8	12.04
Utsunomiya	36˚32.9'N	139˚52.1'E	119	346.0	12.04
Maebashi	36˚23.2'N	139˚2.3'E	112	346.6	12.04
Tokyo(*)	35˚41.5'N	139˚45'E	25	349.2	12.04
Choshi	35˚44.3'N	140˚51.4'E	20	349.0	12.04
Kofu	35˚40'N	138˚33.2'E	273	349.3	12.04
Shizuoka	34˚58.5'N	138˚24.2'E	14	351.8	12.04
Nagoya(*)	35˚10'N	136˚57.9'E	51	351.1	12.04
Niigata(*)	37˚53.6'N	139˚1.1'E	4	340.8	12.04
Toyama	36˚42.5'N	137˚12.1'E	9	345.4	12.04
Fukui	36˚3.3'N	136˚13.3'E	9	347.8	12.04
Hikone	35˚16.5'N	136˚14.6'E	87	350.7	12.04
Osaka(*)	34˚40.9'N	135˚31.1'E	23	352.9	12.04
Nara	34˚40.4'N	135˚50.2'E	102	352.9	12.04
Hiroshima(*)	34˚23.9'N	132˚27.7'E	4	353.9	12.04
Takamatsu(*)	34˚19.1'N	134˚3.2'E	9	354.2	12.04
Matsuyama	33˚50.6'N	132˚46.6'E	32	355.9	12.04
Kochi	33˚34'N	133˚32.9'E	1	356.8	12.04
Shimonoseki	33˚56.9'N	130˚55.5'E	3	355.5	12.04
Fukuoka(*)	33˚34.9'N	130˚22.5'E	3	356.8	12.04
Oita	33˚14.1'N	131˚37.1'E	5	358.0	12.04
Nagasaki	32˚44'N	129˚52'E	27	359.7	12.04
Saga	33˚15.9'N	130˚18.3'E	6	357.9	12.04
Kumamoto	32˚48.8'N	130˚42.4'E	38	359.5	12.04
Miyazaki	31˚56.3'N	131˚24.8'E	9	362.4	12.04
Kagoshima(*)	31˚33.3'N	130˚32.8'E	4	363.7	12.03
Naha(*)	26˚12.4'N	127˚41.2'E	28	380.2	12.03
Miyako Island	24˚47.6'N	125˚16.7'E	39	384.1	12.03
Ishigaki Island	24˚20.2'N	124˚9.8'E	6	385.3	12.03
Minami-Daito Island	25˚49.7'N	131˚13.7'E	15	381.3	12.03
Ave.	-	-	-	349.8	12.04

In the Angstrom-Prescott type model, the atmospheric transmittance τ[-] is expressed as a function of sunshine duration as below:

$$\tau = a_0 + a_1 \cdot n/N \tag{2}$$

where N[h·d^{-1}] is the day length. The offset a_0[-] and the slope a_1[-] of this linear relation are likely to be site-specific. Even in cases of the original models, Angstrom (1924) showed the model with $a_0 = 0.22$[-] and $a_1 = 0.54$[-] while $a_0 = 0.25$[-] and $a_1 = 0.54$[-] were found on Prescott (1940). Therefore, these two parameters are determined by fitting the model outputs to data sets of Q[W·m^{-2}] and n[h·d^{-1}] obtained in a location of interest.

2.3. Calculation of Day Length

The day length N[h·d^{-1}] in Equation (2) was calculated as below:

$$N = 2h_{ahd} \cdot (24/2\pi) \tag{3}$$

where h_{ahd} [rad] is the hour angle for half a day. The value of h_{ahd} [rad] was evaluated by using the following geometrically-derived equation:

$$\cos h_{ahd} = -\tan\varphi \cdot \tan\delta \tag{4}$$

where φ [rad] is the latitude of a location of interest in radian unit, δ [rad] is the solar declination, which is an angle of elevation from the plane of the earth's equator to the sun.

The solar declination δ [rad] was evaluated by using the following relation:

$$\sin\delta = \sin\delta_{max} \cdot \sin(1.5 \cdot \pi + f - f_{ws}) \tag{5}$$

where δ_{max} [rad] is the angle of the tilt of the rotation axis of the earth from the direction normal to the earth's orbital plane, being about 23.4393 in degree. f[rad] is the true anomaly of the earth for a given day of year (DOY). f_{ws} [rad] is the true anomaly of the earth on the day of the winter solstice in the northern hemisphere (DOY_{ws}).

The true anomaly f [rad] is the angle between the direction of the perihelion and that of the earth's position as seen from the sun and, thus, is the function of DOY. In this study, f[rad] was calculated in the following steps: 1) a mean anomaly M[rad] of the earth's position was determined for a given DOY; 2) an eccentric anomaly E[rad] of the earth's orbital position was derived from M[rad]; and 3) f [rad] was determined by E[rad]. In the step 1), the following relation was adopted:

$$M = 2\pi \cdot \left(\text{DOY} - \text{DOY}_{\text{ph}}\right) / T_{ty} \tag{6}$$

where DOY_{ph} is the day of the year on which the earth passes the perihelion in a year, T_{ty} [d] is the period of a tropical year (365.2422 days). In the step 2), M[rad] was converted into E[rad] by solving the Kepler's equation:

$$0 = M - E + e_o \cdot \sin E \tag{7}$$

where e_o[-] ($\fallingdotseq 0.01671$) is the eccentricity of the earth's orbit. The Newton-Raphson iteration was adopted to solve this equation. In the step 3), f[rad] was calculated from E[rad] by using the following geometrical relation:

$$f = \arctan\left(\sqrt{1-e_o^2} \cdot \sin E \Big/ \left(\cos E - e_o\right)\right) \tag{8}$$

Then, both f [rad] and f_{ws} [rad] were determined by applying Equation (6) through (8) for DOY and DOY$_{ws}$.

The values of N [h·d^{-1}] for the 40 stations were calculated for any date by making the series of Equations (3) through (8) work as a function of φ [rad] and DOY. Their annual averages for each year are tabulated in **Table 1**. The resultant values ranged from 12.03 to 12.06 [h·d^{-1}] with the mean of 12.04 [h·d^{-1}] among the 40 stations.

2.4. Calculation of Extraterrestrial Solar Radiation

The extraterrestrial solar radiation Q_e [W·m^{-2}] is a fraction of the solar radiation reaching the outer surface of the earth's atmosphere, namely the solar constant S_c [W·m^{-2}]. The solar constant S_c [W·m^{-2}] is likely to be about 1366 [W·m^{-2}] in a large time scale (Frohlich, 2009; Passos et al., 2007), though it is not a constant quantity. The difference between S_c [W·m^{-2}] and Q_e [W·m^{-2}] owes to the facts that the angle of incidence of the sun ray from the sky to the land surface varies with time in a day, and that the sun ray does not reach the land surface after dark in the day. Therefore, Q_e [W·m^{-2}] can be calculated by multiplying S_c [W·m^{-2}] with the integral of the sine of the solar elevation angle h_e [rad] with respect to the hour angle h_a [rad] in the domain of the day length ($-h_{ahd} \leqq h_a \leqq h_{ahd}$) divided by the hour angle for the period of one day (equal to 2π). In addition, a coefficient should also be multiplied as the correction factor for the varying distance between the sun and the earth as the earth orbits. The sine of h_e [rad] is related to the hour angle h_a [rad] by the following relation:

$$\sin h_e = \sin\varphi \cdot \sin\delta + \cos\varphi \cdot \cos\delta \cdot \cos h_a \tag{9}$$

Therefore, the integration and the multiplications mentioned above leads to:

$$\begin{cases} Q_e = \dfrac{S_c}{\pi} \cdot D \cdot \left(h_{ahd} \cdot \sin\varphi \cdot \sin\delta + \cos\varphi \cdot \cos\delta \cdot \sin h_{ahd}\right) \\ D = 1 + 2 \cdot e_o \cdot \cos M \end{cases} \tag{10}$$

The values of Q_e [W·m^{-2}] for the 40 stations were calculated for any date from Equation (10) with the aids of Equations (4) through (8). Thus, the input variables for determining Q_e [W·m^{-2}] were the same as for determining N [h·d^{-1}], φ [rad] and DOY. Their annual averages were tabulated in **Table 1**. The obtained values ranged from 309.5 to 385.3 [W·m^{-2}] with the mean of 349.8 [W·m^{-2}] among the 40 stations.

2.5. Data Processing

The pair of the parameters a_0[-] and a_1[-] in Equation (2) was determined for every year at every station by minimizing the sizes of least squared errors between values of daily-averaged Q [W·m^{-2}] evaluated by using Equation (1) and those measured daily in the year at the station. In order for clarifying interannual trends in Q

[W·m^{-2}] and n [h·d^{-1}], annually-mean values of these two quantities were determined for every station and every year in the study period.

3. Results and Discussion

3.1. Global Solar Radiation

Table 2 shows the annual mean values of GSR (Q_a [W·m^{-2}]) measured in each of the 40 stations. The series of Q_a [W·m^{-2}] for each station was averaged and named m_{Qa} [W·m^{-2}]. The obtained m_{Qa} [W·m^{-2}] tended to take a higher value for a station with lower latitude, ranging from the minimum of 130.4 [W·m^{-2}] for Abashiri in the northern most island Hokkaido to the maximum of 190.1 [W·m^{-2}] for Minami-Daito Island in the south-western sub-tropical region.

The interannual trend in Q_a [W·m^{-2}] was mostly upward in the 22-year period. When the values of Q_a [W·m^{-2}] for each of the stations were plotted against dominical years Y_d, the linear regression procedure applied to the Y_d - Q_a relation gave the rates $\mathrm{d}Q_a/\mathrm{d}Y_d$ [W·m^{-2} y^{-1}] as tabulated on Table 2. Counting the number of $\mathrm{d}Q_a/\mathrm{d}Y_d$ [W·m^{-2}·y^{-1}] with positive values indicated that Q_a [W·m^{-2}] had increased for the study period in 33 out of the 40 stations. Averaging the 40 values of $\mathrm{d}Q_a/\mathrm{d}Y_d$ [W·m^{-2}·y^{-1}] resulted in 0.252 [W·m^{-2}·y^{-1}], which is equivalent to the increase in Q_a [W·m^{-2}] by 5.5 [W·m^{-2}] in the 22-year period, representing the upward trend in GSR over the country.

Many of the stations with negative $\mathrm{d}Q_a/\mathrm{d}Y_d$ [W·m^{-2} y^{-1}] were found in the south-western region of the country with latitudes lower than 32[˚]. Since the values of GSR in that region are ordinarily in the possible highest levels, it can be difficult to expect additional increases in them, suggesting that the interannual trends in GSR found in that region might not have been downward but been effectively flat.

3.2. Sunshine Duration

Values of annually-averaged sunshine durations n_a [h·d^{-1}] were determined for each station (Table 3). The temporal means in the 22-year period m_{na} [h·d^{-1}] ranged from 4.07 to 6.17 [h·d^{-1}] among the values for the 40 stations, and had the spatially averaged value of 5.21 [h·d^{-1}]. The values of n_a [h·d^{-1}] also have increased in most of the stations. The rates of increase $\mathrm{d}n_a/\mathrm{d}Y_d$ [h·d^{-1}·y^{-1}] were 0.015 [h·d^{-1}·y^{-1}] in average and was 0.036 [h·d^{-1}·y^{-1}] at maximum. The value 0.015 [h·d^{-1}·y^{-1}] in $\mathrm{d}n_a/\mathrm{d}Y_d$ [h·d^{-1}·y^{-1}] implied that n_a [h·d^{-1}] had increased by 0.33 [h·d^{-1}] in the 22-year period.

A few negative $\mathrm{d}n_a/\mathrm{d}Y_d$ [h·d^{-1}·y^{-1}] were obtained mainly in the south-western region with low R^2 values, as some negative $\mathrm{d}Q_a/\mathrm{d}Y_d$ [W·m^{-2}·y^{-1}] (Table 2). These apparent coincidences found among Q_a [W·m^{-2}] and n_a [h·d^{-1}] induced us to estimate the extent to which the trend in n_a [h·d^{-1}] can explain that in the measured Q_a [W·m^{-2}]. Estimating this extent requires the values of the parameter a_1[-] in Equation (2). Thus, the relation between Q_a [W·m^{-2}] and n_a [h·d^{-1}] was analyzed in terms of Equation (2) in the next section.

Table 2. The annual mean values of GSR (Q_a [$W \cdot m^{-2}$]) measured in each of the 40 stations. The symbol "-" indicates that too many measurement errors had happened to determine the annual mean value. m_{Qa} [$W \cdot m^{-2}$] and σ_{Qa} [$W \cdot m^{-2}$] are the temporal mean and its standard deviation in Q_a [$W \cdot m^{-2}$]. The values of dQ_a/dY_d are the results of the linear regression applied to the Y_d-Q_a relations. R^2 is the deterministic coefficient of the linear regression.

Station	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	m_{Qa}	σ_{Qa}	dQ_a/dY_d	R^2
Wakkanai	126.9	131.7	139.0	131.1	134.3	127.9	132.8	130.7	126.5	126.2	126.1	125.6	125.9	136.8	125.5	126.0	130.1	130.1	134.0	131.3	137.6	131.9	130.4	4.15	0.029	0.002
Sapporo(*)	147.6	145.3	145.7	141.6	145.1	146.4	149.3	161.0	140.2	137.2	139.3	145.3	136.3	148.3	143.6	144.6	145.9	142.2	153.7	146.4	158.0	149.6	146.0	5.99	0.175	0.036
Abashiri	148.6	147.6	155.1	152.9	147.8	145.2	146.8	142.6	137.4	140.0	142.8	137.1	137.5	147.1	142.8	143.3	141.2	140.9	149.4	141.9	151.3	145.8	144.8	4.97	-0.224	0.085
Hakodate	139.4	139.1	137.4	136.1	139.2	134.0	139.7	136.0	142.7	136.9	139.6	140.0	135.1	149.6	144.1	143.4	143.7	137.9	149.6	137.4	147.1	148.4	140.7	4.70	0.424	0.343
Aomori	143.0	135.3	137.1	137.8	138.1	138.2	144.4	146.0	140.4	136.6	138.7	143.7	136.1	144.6	147.1	142.0	143.8	140.8	153.9	142.1	148.6	148.6	142.1	4.81	0.456	0.378
Akita	-	-	-	135.7	135.7	135.7	142.0	145.2	139.5	133.0	131.0	139.4	130.0	141.9	143.4	142.6	139.7	136.0	152.9	138.7	146.7	140.5	139.5	5.60	0.245	0.145
Morioka	149.4	140.3	140.6	142.1	143.2	140.6	144.5	147.4	141.1	138.1	142.4	146.8	138.2	149.6	151.8	148.6	143.5	146.4	155.1	138.1	148.1	147.3	144.7	4.70	0.252	0.121
Sendai(*)	145.4	146.6	135.5	153.7	145.7	136.1	146.0	140.2	142.4	147.3	152.5	149.6	146.3	159.0	159.6	150.2	149.0	152.3	156.5	145.0	152.4	151.1	148.3	6.37	0.515	0.275
Yamagata	149.2	145.2	139.1	150.2	145.8	141.7	141.8	144.0	143.0	140.7	148.4	148.1	147.3	148.6	149.7	149.1	143.2	152.4	153.9	142.4	151.8	153.3	146.8	4.32	0.326	0.240
Fukushima	146.2	145.4	134.9	147.6	146.8	137.0	143.4	142.2	143.2	146.7	151.6	144.7	148.0	148.4	147.7	148.6	147.3	152.2	151.6	143.0	149.5	151.6	146.3	4.43	0.384	0.316
Tsukuba	158.6	156.9	143.2	163.4	158.2	141.0	159.5	152.1	151.8	157.6	160.4	160.9	164.0	161.6	154.4	154.2	161.8	164.1	157.1	153.7	162.1	160.8	157.2	6.11	0.324	0.118
Utsunomiya	155.8	152.4	143.2	156.5	154.2	136.5	156.0	148.5	146.9	149.4	155.0	155.5	156.3	162.8	156.8	153.7	158.6	164.3	155.4	152.9	158.0	161.3	154.1	6.31	0.499	0.263
Maebashi	160.6	157.6	147.9	165.8	158.9	146.1	160.8	156.7	154.3	162.6	165.5	163.9	170.1	168.2	160.0	158.2	165.9	170.6	163.9	160.5	162.5	164.2	161.1	6.21	0.460	0.232
Tokyo(*)	147.2	147.5	137.0	156.1	148.0	132.0	151.3	145.7	144.0	153.6	158.2	159.6	163.9	159.2	150.6	146.8	156.7	161.2	152.3	150.1	157.9	157.8	151.7	7.88	0.637	0.276
Choshi	163.9	159.8	147.6	171.6	161.5	145.9	164.4	157.7	154.7	165.4	168.3	167.1	170.2	170.5	163.2	162.3	167.0	169.4	162.9	154.9	170.2	164.1	162.9	7.08	0.363	0.111
Kofu	172.7	169.8	156.9	174.1	171.5	157.0	171.9	174.4	174.7	178.0	174.1	174.9	179.1	173.6	174.3	175.2	182.1	184.8	175.0	172.7	175.1	176.7	173.6	6.35	0.534	0.298
Shizuoka	167.6	166.0	148.3	167.8	167.1	150.4	164.9	161.8	165.6	165.8	171.1	168.5	172.2	167.3	167.0	167.4	178.7	174.6	169.2	170.3	171.3	169.1	166.9	6.70	0.578	0.313
Nagoya(*)	164.7	162.3	149.8	165.5	164.8	154.2	166.6	166.4	167.2	163.9	163.6	163.2	173.6	170.0	163.6	167.5	170.4	174.9	169.7	167.7	162.3	171.3	165.6	5.67	0.479	0.301
Niigata(*)	152.6	146.6	139.0	148.4	144.7	139.7	141.4	148.1	144.5	138.9	147.9	146.8	140.6	146.3	145.9	145.3	142.3	146.6	154.0	143.4	152.6	151.6	145.8	4.43	0.191	0.079
Toyama	149.3	146.3	136.8	147.8	140.7	138.2	141.3	148.8	139.0	139.3	141.0	148.5	149.7	148.0	145.8	146.2	147.3	149.5	147.4	146.1	150.2	152.1	145.4	4.50	0.344	0.247
Fukui	150.8	146.8	136.3	148.7	143.7	142.0	145.6	150.7	144.8	143.0	147.0	148.7	149.8	151.3	144.6	151.3	150.2	154.8	150.4	148.0	153.8	157.1	148.2	4.68	0.444	0.379
Hikone	146.3	143.2	129.8	158.9	157.2	147.6	157.9	158.3	153.5	153.4	155.4	155.1	164.4	163.9	158.8	166.3	163.7	164.6	160.7	156.5	159.2	163.3	156.3	8.48	0.891	0.466
Osaka(*)	162.7	163.6	146.4	164.3	163.2	151.9	165.7	162.3	161.3	161.3	163.1	158.4	169.5	166.4	161.4	165.3	168.9	172.4	166.2	168.6	167.3	174.9	163.9	6.20	0.607	0.405
Nara	153.7	154.8	140.8	156.4	152.6	144.7	157.5	152.2	153.9	151.1	156.6	153.5	158.0	153.9	147.8	154.7	159.5	166.7	158.8	158.6	160.5	167.4	155.2	6.11	0.589	0.392
Hiroshima(*)	163.4	163.4	152.2	167.3	168.1	153.9	164.0	164.7	162.0	163.1	160.1	157.1	168.8	157.8	158.1	157.8	166.9	168.0	167.1	166.9	165.4	174.0	163.2	5.36	0.304	0.135
Takamatsu(*)	166.9	164.0	155.5	169.1	168.3	154.1	170.9	163.4	164.8	161.4	161.0	157.7	169.9	156.5	155.6	160.8	167.3	171.8	167.7	170.6	167.3	173.1	164.4	5.84	0.258	0.082
Matsuyama	160.9	163.1	154.1	169.6	164.6	151.9	166.5	165.1	162.6	161.4	162.6	156.4	169.1	160.5	157.9	160.3	167.1	169.2	164.3	170.2	165.8	171.9	163.4	5.28	0.340	0.175
Kochi	170.8	165.5	161.4	172.5	175.1	161.1	173.4	171.9	168.0	165.3	168.5	165.0	173.5	163.1	160.4	163.0	171.8	171.4	167.5	174.1	169.0	176.3	168.6	4.88	0.122	0.026
Shimonoseki	159.5	161.1	146.0	161.7	156.8	150.2	157.0	155.0	155.3	152.7	149.6	150.6	159.6	148.9	152.8	148.2	161.6	161.8	157.7	160.8	161.4	168.4	156.2	5.75	0.266	0.090
Fukuoka(*)	161.0	161.1	152.3	163.5	162.2	153.2	162.9	156.6	150.0	148.0	143.3	143.0	154.2	142.8	153.9	154.2	166.1	164.7	159.7	162.2	162.5	170.2	156.7	7.84	0.220	0.033
Oita	158.0	160.1	144.5	160.0	160.5	151.0	163.9	160.9	158.5	149.6	151.9	148.4	158.7	145.9	144.8	150.8	161.0	164.3	158.2	166.9	156.0	164.9	156.3	6.83	0.176	0.028
Nagasaki	164.3	159.8	152.4	169.0	166.6	158.4	165.3	162.1	163.4	156.5	154.5	152.2	160.9	149.1	147.5	150.5	163.5	164.9	162.8	163.6	163.0	169.1	160.0	6.43	-0.001	0.000
Saga	158.9	155.3	142.8	158.2	159.0	144.0	155.0	152.0	167.0	159.3	151.4	149.9	155.2	143.5	145.4	145.3	157.4	160.6	156.6	158.9	160.2	165.1	154.6	6.96	0.211	0.039
Kumamoto	169.1	168.5	160.3	174.5	168.6	159.5	170.6	165.4	165.5	158.6	159.2	156.8	168.2	155.3	154.0	156.7	167.0	170.0	167.5	171.3	169.7	173.5	165.0	6.25	0.038	0.002
Miyazaki	168.0	167.9	166.6	176.7	176.9	161.8	173.9	167.8	176.1	164.7	166.9	163.0	177.3	161.8	156.0	161.7	171.2	171.0	165.9	173.8	169.0	170.3	168.6	5.76	-0.098	0.012
Kagoshima(*)	169.1	166.7	165.7	177.3	170.8	165.0	171.8	166.7	170.4	158.6	151.4	144.2	168.4	155.0	149.2	157.8	163.3	164.7	161.0	162.9	165.5	167.8	163.3	7.94	-0.418	0.117
Naha(*)	168.9	175.2	178.2	173.5	166.8	164.7	170.4	174.4	180.1	159.6	163.8	158.3	173.5	170.1	175.3	170.4	166.8	177.4	166.2	167.7	176.2	162.0	170.0	6.10	-0.146	0.024
Miyako Island	172.7	176.8	177.8	172.6	166.8	168.5	171.7	172.2	180.3	163.5	158.7	164.4	174.6	174.3	178.1	174.8	171.3	177.3	168.0	172.8	183.7	164.0	172.1	6.07	0.023	0.001
Ishigaki Island	178.8	186.3	190.7	184.9	167.9	173.9	180.2	177.4	199.0	173.5	169.7	171.0	179.3	188.7	181.1	175.7	181.6	184.4	172.2	179.8	191.3	170.0	179.9	8.06	-0.119	0.009
Minami-Daito Island	190.1	196.0	202.3	190.8	181.8	193.3	184.7	186.6	198.5	185.1	185.4	174.1	191.1	186.2	198.8	192.8	190.8	200.3	189.8	185.5	195.5	182.0	190.1	6.89	-0.092	0.007
Ave.	158.5	157.5	150.5	160.4	157.2	149.4	158.4	157.0	156.8	153.7	154.9	153.9	159.1	157.4	155.5	155.8	159.9	162.3	160.1	158.0	161.9	162.1	157.3	3.41	0.252	0.231

Table 3. The annual mean values of sunshine duration (n_a [h·d⁻¹]) measured in each of the 40 stations. m_{na} [h·d⁻¹] and σ_{na} [h·d⁻¹] are the temporal mean and its standard deviation in n_a [h·d⁻¹]. The values of dn_a/dY_d are the results of the linear regression applied to the Y_d-n_a relations. R^2 is the deterministic coefficient of the linear regression.

Station	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	m_{na}	σ_{na}	dn_a/dY_d	R^2
Wakkanai	3.7	4.0	4.6	4.2	4.3	3.9	4.2	4.2	3.8	3.9	3.9	3.7	3.8	4.5	3.9	3.8	4.1	4.0	4.3	4.2	4.5	4.1	4.1	0.26	0.004	0.011
Sapporo(*)	4.7	4.6	4.9	4.6	4.6	4.7	4.7	5.0	4.4	4.2	4.8	5.0	4.5	5.2	5.0	4.9	5.0	4.8	5.4	4.8	5.6	5.1	4.8	0.32	0.028	0.322
Abashiri	5.1	5.0	5.5	5.3	5.2	5.1	5.2	5.0	4.6	5.0	5.3	4.8	4.9	5.6	5.1	5.3	5.1	5.1	5.5	4.9	5.6	5.0	5.1	0.26	0.003	0.008
Hakodate	4.6	4.6	4.7	4.7	4.8	4.5	4.8	4.9	4.6	4.4	4.8	4.7	4.4	5.5	5.1	5.0	5.0	4.7	5.3	4.7	5.0	5.2	4.8	0.28	0.023	0.287
Aomori	4.3	4.0	4.1	4.1	4.1	4.0	4.6	4.5	4.3	4.0	4.2	4.6	4.1	4.7	4.7	4.4	4.5	4.5	5.1	4.4	4.8	4.6	4.4	0.30	0.031	0.457
Akita	4.0	3.9	4.0	3.9	3.8	4.0	4.3	4.4	4.2	3.9	4.0	4.6	4.0	4.5	4.7	4.6	4.3	4.2	5.0	4.2	4.8	4.5	4.3	0.34	0.036	0.481
Morioka	4.8	4.3	4.4	4.6	4.5	4.3	4.9	4.9	4.6	4.3	4.6	4.9	4.6	5.1	5.1	5.0	4.5	4.9	5.1	4.2	4.8	4.8	4.7	0.28	0.017	0.145
Sendai(*)	5.0	5.1	4.4	5.3	4.8	4.5	5.1	4.7	4.7	4.9	5.4	5.2	5.1	5.7	5.8	5.2	5.2	5.5	5.6	4.9	5.4	5.3	5.1	0.36	0.031	0.313
Yamagata	4.5	4.5	4.1	4.8	4.1	4.2	4.4	4.4	4.3	4.2	4.5	4.5	4.6	4.7	4.8	4.6	4.3	4.8	4.9	4.2	4.7	4.8	4.5	0.25	0.018	0.219
Fukushima	4.6	4.8	4.4	5.1	4.6	4.3	4.9	4.5	4.6	4.7	4.9	4.8	5.0	5.2	5.1	5.0	4.9	5.2	5.2	4.6	4.9	4.9	4.8	0.26	0.021	0.262
Tsukuba	5.8	5.7	4.8	6.1	5.7	4.6	5.7	5.2	5.1	5.5	5.9	6.0	6.1	6.1	5.6	5.4	5.8	5.9	5.4	5.4	5.9	5.7	5.6	0.41	0.016	0.066
Utsunomiya	5.6	5.5	4.8	5.7	5.5	4.5	5.6	5.2	5.0	5.1	5.6	5.7	5.8	6.0	5.5	5.3	5.6	5.9	5.3	5.4	5.7	5.7	5.5	0.36	0.019	0.113
Maebashi	6.0	5.9	5.3	6.3	6.0	5.2	6.1	5.7	5.5	5.9	6.1	6.1	6.4	6.4	5.8	5.8	6.1	6.5	5.9	5.8	6.1	6.0	5.9	0.33	0.016	0.106
Tokyo(*)	5.4	5.5	4.7	5.8	5.4	4.4	5.5	5.0	4.9	5.4	5.6	5.5	5.6	5.7	5.3	5.0	5.6	5.8	5.2	5.1	5.7	5.6	5.4	0.37	0.015	0.068
Choshi	5.7	5.5	4.6	5.9	5.5	4.7	5.7	5.4	4.8	5.6	6.0	6.0	6.1	6.2	5.6	5.5	5.9	6.0	5.6	5.2	6.2	5.6	5.6	0.46	0.026	0.141
Kofu	6.4	6.1	5.4	6.6	6.2	5.4	6.2	6.1	5.8	6.0	6.3	6.4	6.7	6.4	6.0	6.0	6.5	6.5	6.0	6.1	6.3	6.3	6.2	0.34	0.013	0.060
Shizuoka	6.0	5.9	5.0	6.2	6.2	5.1	5.8	5.7	5.7	5.9	6.5	6.2	6.3	6.0	5.8	5.7	6.4	6.1	5.8	6.1	6.3	6.1	5.9	0.37	0.021	0.136
Nagoya(*)	5.9	5.7	5.2	6.0	5.8	5.3	5.8	5.8	5.7	5.7	5.9	5.9	6.4	6.2	5.8	5.9	6.1	6.4	6.0	6.0	5.7	6.2	5.9	0.30	0.024	0.278
Niigata(*)	4.7	4.5	4.2	4.7	4.2	4.1	4.6	4.3	4.3	4.3	4.7	4.7	4.5	4.8	4.6	4.7	4.5	4.7	5.0	4.3	4.9	4.7	4.5	0.24	0.015	0.156
Toyama	4.7	4.5	3.9	4.7	4.1	4.2	4.5	4.5	4.3	4.3	4.4	4.8	4.9	4.8	4.7	4.6	4.8	4.9	4.8	4.5	4.8	4.8	4.6	0.27	0.024	0.344
Fukui	4.8	4.6	3.8	4.8	4.3	4.3	4.6	4.6	4.3	4.4	4.6	4.8	4.8	4.9	4.6	4.7	4.8	5.1	4.9	4.6	5.0	4.9	4.6	0.29	0.026	0.341
Hikone	5.2	5.1	4.4	5.4	5.1	4.7	5.2	5.1	4.9	5.1	5.1	5.1	5.7	5.4	5.1	5.5	5.3	5.6	5.3	5.2	5.4	5.4	5.2	0.29	0.025	0.310
Osaka(*)	5.9	5.6	5.0	6.1	5.7	5.1	5.8	5.5	5.5	5.6	5.9	5.6	6.3	5.9	5.5	5.8	6.0	5.7	5.7	5.9	6.0	6.4	5.7	0.33	0.022	0.181
Nara	5.2	5.1	4.4	5.4	4.9	4.6	5.2	4.8	4.9	4.9	5.1	4.8	5.5	5.1	4.8	5.2	5.2	5.6	5.1	5.1	5.3	5.6	5.1	0.31	0.020	0.170
Hiroshima(*)	5.8	5.7	5.3	6.1	5.9	5.3	5.8	5.7	5.4	5.6	5.4	5.4	6.2	5.4	5.3	5.2	5.7	6.0	5.8	5.9	5.7	6.0	5.7	0.28	0.007	0.023
Takamatsu(*)	5.8	5.7	5.1	6.1	5.7	5.1	5.9	5.4	5.4	5.6	5.6	5.5	6.3	5.4	5.4	5.5	6.0	6.1	5.7	5.9	5.8	6.1	5.7	0.32	0.017	0.116
Matsuyama	5.6	5.6	5.2	6.2	5.7	5.2	5.7	5.7	5.5	5.5	5.3	5.2	6.0	5.1	5.2	5.3	5.7	6.0	5.5	5.9	5.7	5.9	5.6	0.30	0.005	0.014
Kochi	6.1	5.7	5.7	6.2	6.3	5.6	6.1	6.0	5.8	5.7	5.8	5.6	6.5	5.7	5.7	5.7	6.1	6.2	5.8	6.3	6.1	4.9	5.9	0.34	-0.007	0.019
Shimonoseki	5.3	5.3	4.7	5.6	5.0	5.0	5.3	5.0	5.0	4.8	4.5	4.9	5.5	4.8	5.0	4.8	5.6	5.6	5.4	5.4	5.5	5.8	5.2	0.35	0.017	0.104
Fukuoka(*)	5.2	5.2	4.8	5.6	5.1	5.0	5.4	5.0	4.9	5.0	5.0	4.9	5.6	4.9	5.1	5.0	5.7	5.7	5.4	5.6	5.6	5.9	5.3	0.33	0.026	0.254
Oita	5.6	5.6	5.2	6.0	5.7	5.2	5.7	5.6	5.4	5.3	5.2	5.1	6.0	5.0	5.0	5.2	5.7	5.9	5.4	5.9	5.5	5.7	5.5	0.31	0.001	0.000
Nagasaki	5.3	5.1	4.9	5.6	5.3	5.1	5.3	5.1	5.2	4.8	4.7	4.7	5.5	4.8	4.8	4.8	5.3	5.5	5.3	5.3	5.3	5.5	5.1	0.29	0.005	0.012
Saga	5.6	5.5	5.0	5.9	5.6	5.1	5.7	5.4	5.3	5.1	5.1	5.1	5.8	5.1	5.1	5.1	5.6	5.8	5.6	5.7	5.8	6.0	5.5	0.32	0.012	0.061
Kumamoto	5.6	5.7	5.2	6.0	5.6	5.2	5.8	5.5	5.4	5.1	5.1	5.0	6.0	5.1	5.1	5.3	5.6	5.7	5.6	5.8	5.8	5.9	5.5	0.31	0.007	0.020
Miyazaki	5.7	5.7	5.8	6.2	6.3	5.5	6.2	5.9	5.9	5.2	5.6	5.5	6.6	5.6	5.4	5.6	6.1	6.0	5.6	6.0	5.9	5.7	5.8	0.32	-0.002	0.002
Kagoshima(*)	5.4	5.3	5.3	5.9	5.5	5.3	5.6	5.4	5.4	4.8	5.1	4.8	6.0	5.1	4.8	5.3	5.6	5.6	5.4	5.6	5.6	5.5	5.4	0.31	0.001	0.000
Naha(*)	4.4	4.7	5.1	4.9	4.3	4.4	4.7	4.9	5.1	4.1	4.4	4.2	5.0	4.8	4.9	4.8	4.5	5.1	4.5	4.7	5.1	4.4	4.7	0.31	0.005	0.012
Miyako Island	4.8	5.0	5.1	4.9	4.4	4.5	4.8	4.8	5.1	4.5	4.0	4.4	4.9	5.0	5.1	5.0	4.8	5.1	4.4	4.9	5.3	4.4	4.8	0.33	0.000	0.000
Ishigaki Island	5.1	5.3	5.5	5.3	4.7	4.0	4.8	4.9	5.4	4.7	4.3	4.4	5.0	5.6	5.2	5.0	5.2	5.5	4.8	5.3	5.8	4.6	5.0	0.45	0.011	0.027
Minami-Daito Island	5.8	6.1	6.3	5.8	5.4	5.9	5.6	5.5	6.2	5.5	5.3	4.9	5.8	5.7	6.4	6.0	5.9	6.2	5.7	5.6	5.9	5.3	5.8	0.37	-0.005	0.007
Ave.	5.2	5.2	4.9	5.5	5.1	4.8	5.3	5.1	5.0	5.0	5.1	5.1	5.5	5.3	5.2	5.2	5.4	5.5	5.3	5.2	5.5	5.4	5.2	0.20	0.015	0.237

3.3. The Parameters of the Sunshine-Based Model

The values of a_0[-] in Equation (2) were determined for each of the stations in the series of years (**Table 4**). m_{a0}[-] denotes the interannual average of a_0[-] obtained for each of the stations. The values of m_{a0}[-] ranged from 0.163 to 0.239 with their mean of 0.201. σ_{a0}[-] denotes the standard deviation of a_0[-] associated with m_{a0}[-], whose values ranged from 0.006 to 0.017, and with the nation-wide value of 0.004. No obvious interannual trend was found among the series of a_0[-] values. The signs of $\mathrm{d}a_0/\mathrm{d}Y_d$ [y^{-1}] varied from positive to negative throughout the 40 stations, resulting in the mean of $\mathrm{d}a_0/\mathrm{d}Y_d$ [y^{-1}] being 0.00006. And their sizes were less than 0.001 in most cases. These features suggested that a_0[-] had been practically constant for the study period.

Table 4. The values of a_0 in Equation (2) "$\tau = a_0 + a_1\, n/N$" determined for each of the stations in the series of years. The symbol "-" in the table indicates that the value was not obtained because of the shortages of measured global solar radiation data. m_{a0}[-] and σ_{a0}[-] are the temporal mean and its standard deviation in a_0[-]. The values of $\mathrm{d}a_0/\mathrm{d}Y_d$ are the results of the linear regression applied to the Y_d-a_0 relations. R^2 is the deterministic coefficient of the linear regression.

Station	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	m_{a0}	σ_{a0}	$\mathrm{d}a_0/\mathrm{d}Y_d$	R^2
Wakkanai	0.217	0.217	0.227	0.217	0.217	0.229	0.219	0.219	0.209	0.209	0.209	0.219	0.219	0.219	0.209	0.199	0.199	0.209	0.219	0.209	0.209	0.219	0.214	0.008	-0.00053	0.209
Sapporo(*)	0.227	0.227	0.217	0.207	0.217	0.229	0.219	0.279	0.219	0.219	0.199	0.219	0.199	0.209	0.209	0.209	0.209	0.199	0.229	0.219	0.229	0.219	0.218	0.017	-0.00048	0.036
Abashiri	0.227	0.236	0.236	0.236	0.227	0.229	0.229	0.249	0.219	0.219	0.209	0.219	0.209	0.219	0.219	0.199	0.219	0.209	0.229	0.219	0.219	0.239	0.223	0.012	-0.00074	0.168
Hakodate	0.187	0.197	0.197	0.187	0.197	0.199	0.189	0.179	0.199	0.199	0.199	0.219	0.199	0.209	0.189	0.199	0.199	0.189	0.209	0.209	0.219	0.199	0.199	0.010	0.00075	0.242
Aomori	0.217	0.207	0.217	0.217	0.227	0.229	0.219	0.239	0.229	0.219	0.219	0.219	0.209	0.219	0.229	0.219	0.219	0.209	0.219	0.219	0.219	0.219	0.220	0.007	-0.00007	0.004
Akita	-	-	-	0.197	0.207	0.199	0.209	0.229	0.199	0.189	0.189	0.189	0.179	0.199	0.199	0.189	0.189	0.189	0.199	0.199	0.199	0.189	0.197	0.011	-0.00070	0.138
Morioka	0.207	0.197	0.207	0.197	0.197	0.209	0.199	0.219	0.199	0.199	0.189	0.209	0.189	0.209	0.219	0.199	0.209	0.199	0.219	0.209	0.209	0.199	0.204	0.009	0.00029	0.046
Sendai(*)	0.167	0.167	0.177	0.187	0.177	0.169	0.179	0.179	0.179	0.189	0.189	0.199	0.169	0.189	0.179	0.179	0.169	0.169	0.179	0.179	0.169	0.179	0.178	0.009	0.00005	0.002
Yamagata	0.227	0.217	0.207	0.217	0.227	0.209	0.209	0.219	0.219	0.219	0.229	0.229	0.199	0.219	0.219	0.219	0.209	0.219	0.219	0.219	0.219	0.219	0.218	0.007	0.00004	0.001
Fukushima	0.207	0.187	0.177	0.187	0.207	0.189	0.189	0.199	0.199	0.199	0.209	0.199	0.199	0.199	0.189	0.199	0.199	0.189	0.199	0.199	0.199	0.199	0.196	0.008	0.00029	0.060
Tsukuba	0.197	0.197	0.197	0.187	0.207	0.209	0.209	0.209	0.219	0.209	0.209	0.199	0.209	0.189	0.189	0.199	0.209	0.209	0.209	0.199	0.199	0.219	0.204	0.009	0.00029	0.045
Utsunomiya	0.207	0.187	0.187	0.197	0.207	0.189	0.199	0.199	0.199	0.209	0.209	0.209	0.209	0.199	0.199	0.209	0.209	0.209	0.209	0.199	0.189	0.209	0.202	0.008	0.00046	0.138
Maebashi	0.197	0.187	0.187	0.197	0.187	0.189	0.189	0.199	0.199	0.199	0.209	0.199	0.199	0.189	0.179	0.199	0.199	0.199	0.199	0.199	0.199	0.209	0.196	0.007	0.00049	0.195
Tokyo(*)	0.177	0.167	0.177	0.177	0.187	0.179	0.179	0.179	0.189	0.189	0.199	0.189	0.209	0.179	0.169	0.179	0.189	0.189	0.189	0.179	0.169	0.189	0.183	0.010	0.00032	0.044
Choshi	0.207	0.217	0.217	0.217	0.217	0.199	0.209	0.209	0.219	0.209	0.209	0.209	0.209	0.199	0.209	0.219	0.199	0.209	0.199	0.209	0.199	0.229	0.210	0.008	-0.00021	0.029
Kofu	0.197	0.207	0.197	0.207	0.217	0.209	0.209	0.219	0.219	0.219	0.209	0.209	0.219	0.209	0.209	0.219	0.219	0.219	0.219	0.209	0.209	0.209	0.212	0.007	0.00045	0.180
Shizuoka	0.197	0.197	0.187	0.197	0.197	0.199	0.209	0.199	0.219	0.199	0.189	0.199	0.219	0.199	0.199	0.209	0.219	0.219	0.219	0.199	0.189	0.199	0.203	0.010	0.00051	0.103
Nagoya(*)	0.197	0.197	0.177	0.187	0.197	0.189	0.199	0.199	0.199	0.189	0.189	0.189	0.199	0.199	0.189	0.199	0.199	0.189	0.199	0.189	0.189	0.199	0.194	0.006	0.00014	0.022
Niigata(*)	0.217	0.197	0.197	0.197	0.207	0.199	0.199	0.219	0.219	0.199	0.209	0.209	0.189	0.199	0.229	0.199	0.199	0.199	0.209	0.219	0.209	0.219	0.206	0.010	0.00038	0.058
Toyama	0.197	0.197	0.197	0.187	0.197	0.189	0.189	0.209	0.199	0.199	0.189	0.199	0.189	0.189	0.189	0.209	0.189	0.189	0.199	0.209	0.189	0.209	0.196	0.008	0.00020	0.030
Fukui	0.197	0.207	0.207	0.187	0.197	0.199	0.189	0.209	0.209	0.189	0.199	0.199	0.199	0.209	0.189	0.209	0.199	0.199	0.199	0.199	0.199	0.219	0.200	0.008	0.00026	0.046
Hikone	0.187	0.177	0.167	0.197	0.197	0.199	0.209	0.209	0.209	0.189	0.209	0.189	0.199	0.219	0.199	0.209	0.209	0.199	0.199	0.199	0.199	0.219	0.200	0.012	0.00101	0.279
Osaka(*)	0.187	0.207	0.187	0.177	0.197	0.189	0.209	0.209	0.209	0.189	0.179	0.189	0.199	0.209	0.199	0.199	0.199	0.189	0.209	0.209	0.199	0.209	0.198	0.010	0.00060	0.138
Nara	0.177	0.197	0.177	0.177	0.197	0.189	0.189	0.199	0.199	0.179	0.189	0.199	0.189	0.199	0.189	0.189	0.209	0.199	0.209	0.209	0.199	0.219	0.195	0.011	0.00122	0.489
Hiroshima(*)	0.187	0.197	0.167	0.177	0.197	0.179	0.189	0.199	0.199	0.199	0.199	0.199	0.189	0.199	0.189	0.199	0.209	0.179	0.199	0.189	0.179	0.219	0.193	0.012	0.00063	0.125
Takamatsu(*)	0.197	0.217	0.197	0.197	0.197	0.189	0.219	0.209	0.219	0.199	0.199	0.199	0.199	0.199	0.189	0.199	0.199	0.199	0.209	0.219	0.219	0.219	0.204	0.010	0.00044	0.080
Matsuyama	0.187	0.197	0.177	0.167	0.187	0.169	0.199	0.199	0.199	0.189	0.199	0.199	0.189	0.209	0.199	0.189	0.189	0.189	0.199	0.199	0.199	0.209	0.193	0.011	0.00088	0.276
Kochi	0.197	0.187	0.177	0.197	0.187	0.179	0.199	0.199	0.199	0.189	0.199	0.189	0.179	0.189	0.179	0.179	0.199	0.179	0.189	0.179	0.189	0.199	0.189	0.008	-0.00016	0.016
Shimonoseki	0.187	0.207	0.167	0.177	0.197	0.179	0.199	0.199	0.189	0.189	0.189	0.189	0.179	0.189	0.189	0.179	0.189	0.169	0.189	0.179	0.199	0.199	0.188	0.010	-0.00003	0.000
Fukuoka(*)	0.187	0.197	0.187	0.177	0.207	0.179	0.199	0.189	0.179	0.169	0.159	0.169	0.169	0.159	0.169	0.169	0.189	0.169	0.169	0.179	0.179	0.189	0.179	0.013	-0.00080	0.169
Oita	0.167	0.187	0.158	0.167	0.197	0.169	0.189	0.169	0.179	0.169	0.179	0.169	0.159	0.169	0.169	0.169	0.179	0.169	0.169	0.179	0.179	0.189	0.174	0.010	0.00010	0.005
Nagasaki	0.207	0.197	0.177	0.187	0.197	0.189	0.199	0.189	0.189	0.189	0.189	0.189	0.179	0.179	0.169	0.169	0.189	0.179	0.179	0.179	0.199	0.199	0.187	0.010	-0.00052	0.115
Saga	0.167	0.167	0.148	0.167	0.177	0.149	0.169	0.159	0.189	0.179	0.169	0.159	0.149	0.159	0.149	0.149	0.169	0.149	0.159	0.159	0.169	0.169	0.163	0.011	-0.00028	0.026
Kumamoto	0.207	0.207	0.197	0.207	0.197	0.189	0.199	0.189	0.209	0.189	0.189	0.189	0.189	0.189	0.179	0.179	0.199	0.189	0.189	0.189	0.199	0.209	0.195	0.009	-0.00047	0.115
Miyazaki	0.187	0.197	0.187	0.207	0.207	0.199	0.189	0.189	0.209	0.199	0.199	0.189	0.179	0.179	0.169	0.179	0.199	0.189	0.189	0.199	0.189	0.199	0.192	0.010	-0.00036	0.052
Kagoshima(*)	0.207	0.197	0.197	0.217	0.197	0.199	0.199	0.199	0.219	0.189	0.179	0.179	0.189	0.179	0.169	0.169	0.189	0.179	0.179	0.179	0.189	0.199	0.191	0.014	-0.00124	0.351
Naha(*)	0.217	0.246	0.236	0.217	0.227	0.209	0.219	0.239	0.239	0.209	0.209	0.209	0.229	0.209	0.229	0.219	0.219	0.219	0.219	0.209	0.219	0.209	0.221	0.011	-0.00071	0.162
Miyako Island	0.227	0.227	0.236	0.207	0.207	0.219	0.219	0.209	0.219	0.199	0.219	0.219	0.229	0.219	0.229	0.219	0.219	0.219	0.219	0.219	0.239	0.209	0.219	0.010	0.00008	0.003
Ishigaki Island	0.227	0.236	0.246	0.217	0.227	0.229	0.239	0.199	0.269	0.229	0.229	0.229	0.229	0.239	0.229	0.219	0.229	0.219	0.219	0.219	0.239	0.219	0.229	0.013	-0.00042	0.042
Minami-Daito Island	0.236	0.246	0.256	0.227	0.227	0.239	0.239	0.249	0.239	0.229	0.249	0.249	0.239	0.229	0.239	0.239	0.229	0.259	0.249	0.229	0.239	0.229	0.239	0.010	-0.00011	0.006
Ave.	0.200	0.203	0.196	0.196	0.203	0.197	0.203	0.207	0.208	0.199	0.200	0.201	0.197	0.199	0.196	0.197	0.202	0.196	0.203	0.200	0.201	0.208	0.201	0.004	0.00006	0.009

The values of a_1[-] in Equation (2) were also determined for each of the stations (Table 5). This table has the same format as Table 4. The values of m_{a1}[-] varied between 0.521 and 0.609, and can be averaged at 0.566, while $\mathrm{d}a_1/\mathrm{d}Y_d$ [y^{-1}] took 0.00038 as the nation-wide average and ranged between −0.00122 and 0.00183 among the 40 stations. These figures implied that a_1[-] had been stable in the 22-year period.

Table 5. The values of a_1 in Equation (2) "$\tau = a_0 + a_1\, n/N$" determined for each of the stations in the series of years. The symbol "-" in the table indicates that the value was not obtained because of the shortages of measured global solar radiation data. m_{a1}[-] and σ_{a1}[-] are the temporal mean and its standard deviation in a_1[-]. The values of $\mathrm{d}a_1/\mathrm{d}Y_d$ are the results of the linear regression applied to the Y_d-a_1 relations. R^2 is the deterministic coefficient of the linear regression.

Station	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	m_{a1}	σ_{a1}	$\mathrm{d}a_1/\mathrm{d}Y_d$	R^2
Wakkanai	0.581	0.571	0.542	0.542	0.551	0.538	0.567	0.558	0.587	0.577	0.587	0.548	0.567	0.567	0.577	0.597	0.607	0.587	0.567	0.587	0.577	0.577	0.571	0.019	0.00151	0.276
Sapporo(*)	0.551	0.561	0.551	0.581	0.571	0.558	0.567	0.538	0.577	0.577	0.577	0.548	0.577	0.558	0.558	0.567	0.558	0.597	0.538	0.567	0.548	0.567	0.563	0.015	0.00003	0.000
Abashiri	0.571	0.561	0.542	0.551	0.542	0.538	0.538	0.498	0.558	0.548	0.558	0.538	0.548	0.538	0.548	0.567	0.548	0.558	0.528	0.558	0.548	0.528	0.546	0.016	-0.00025	0.011
Hakodate	0.601	0.591	0.551	0.571	0.571	0.567	0.577	0.468	0.617	0.577	0.577	0.528	0.567	0.538	0.577	0.567	0.567	0.587	0.548	0.558	0.538	0.567	0.564	0.030	-0.00088	0.036
Aomori	0.551	0.571	0.532	0.542	0.532	0.548	0.548	0.528	0.538	0.558	0.558	0.528	0.558	0.528	0.528	0.548	0.538	0.567	0.548	0.558	0.538	0.538	0.544	0.013	-0.00007	0.001
Akita	-	-	-	0.601	0.571	0.587	0.577	0.548	0.597	0.607	0.577	0.548	0.577	0.567	0.558	0.587	0.587	0.597	0.587	0.587	0.567	0.577	0.579	0.017	-0.00009	0.001
Morioka	0.591	0.611	0.581	0.591	0.601	0.597	0.577	0.558	0.577	0.597	0.607	0.558	0.587	0.558	0.548	0.597	0.567	0.597	0.567	0.587	0.577	0.587	0.583	0.018	-0.00078	0.084
Sendai(*)	0.611	0.611	0.611	0.591	0.620	0.637	0.597	0.617	0.617	0.597	0.577	0.567	0.617	0.597	0.607	0.617	0.617	0.617	0.607	0.617	0.637	0.607	0.609	0.016	0.00034	0.018
Yamagata	0.532	0.542	0.561	0.542	0.551	0.587	0.548	0.548	0.558	0.538	0.528	0.518	0.577	0.538	0.528	0.548	0.567	0.548	0.548	0.548	0.558	0.558	0.548	0.016	0.00017	0.005
Fukushima	0.551	0.581	0.591	0.561	0.571	0.597	0.567	0.587	0.587	0.577	0.577	0.567	0.558	0.548	0.567	0.577	0.577	0.587	0.567	0.577	0.587	0.587	0.575	0.013	0.00023	0.013
Tsukuba	0.551	0.551	0.561	0.561	0.551	0.558	0.548	0.558	0.548	0.548	0.538	0.548	0.538	0.558	0.558	0.567	0.558	0.538	0.558	0.567	0.567	0.538	0.553	0.010	0.00005	0.001
Utsunomiya	0.551	0.571	0.601	0.561	0.551	0.587	0.567	0.577	0.577	0.548	0.548	0.538	0.538	0.577	0.577	0.567	0.577	0.558	0.567	0.577	0.597	0.577	0.568	0.017	0.00038	0.020
Maebashi	0.551	0.561	0.571	0.561	0.561	0.567	0.567	0.558	0.567	0.577	0.558	0.567	0.567	0.567	0.587	0.558	0.567	0.548	0.567	0.567	0.567	0.558	0.565	0.008	0.00011	0.007
Tokyo(*)	0.551	0.561	0.571	0.561	0.542	0.577	0.567	0.597	0.577	0.567	0.558	0.597	0.558	0.587	0.587	0.597	0.577	0.567	0.587	0.597	0.617	0.587	0.577	0.018	0.00183	0.416
Choshi	0.561	0.532	0.551	0.551	0.542	0.577	0.548	0.558	0.577	0.567	0.548	0.548	0.558	0.567	0.567	0.558	0.577	0.558	0.567	0.558	0.567	0.528	0.558	0.014	0.00034	0.026
Kofu	0.571	0.551	0.581	0.551	0.542	0.567	0.567	0.577	0.597	0.607	0.577	0.567	0.548	0.558	0.597	0.587	0.587	0.577	0.577	0.587	0.577	0.587	0.575	0.017	0.00110	0.173
Shizuoka	0.561	0.561	0.591	0.551	0.561	0.577	0.558	0.577	0.548	0.577	0.567	0.567	0.538	0.558	0.597	0.577	0.567	0.567	0.558	0.577	0.587	0.577	0.568	0.014	0.00052	0.054
Nagoya(*)	0.551	0.551	0.591	0.571	0.561	0.587	0.567	0.577	0.577	0.577	0.577	0.567	0.548	0.558	0.587	0.567	0.567	0.577	0.567	0.587	0.587	0.567	0.572	0.013	0.00043	0.050
Niigata(*)	0.542	0.571	0.571	0.571	0.571	0.577	0.548	0.528	0.548	0.538	0.548	0.528	0.567	0.538	0.498	0.548	0.548	0.558	0.548	0.538	0.548	0.538	0.548	0.019	-0.00122	0.179
Toyama	0.561	0.571	0.581	0.581	0.571	0.587	0.577	0.558	0.567	0.548	0.567	0.558	0.577	0.577	0.567	0.548	0.577	0.558	0.558	0.558	0.597	0.548	0.568	0.013	-0.00051	0.060
Fukui	0.551	0.532	0.571	0.571	0.571	0.577	0.577	0.558	0.558	0.567	0.558	0.548	0.558	0.538	0.567	0.558	0.567	0.558	0.567	0.567	0.567	0.538	0.560	0.013	-0.00015	0.006
Hikone	0.512	0.522	0.542	0.561	0.571	0.577	0.558	0.558	0.548	0.567	0.548	0.577	0.558	0.558	0.587	0.567	0.577	0.558	0.567	0.567	0.577	0.538	0.559	0.019	0.00130	0.206
Osaka(*)	0.551	0.532	0.542	0.561	0.551	0.577	0.548	0.548	0.548	0.577	0.577	0.558	0.538	0.538	0.567	0.558	0.558	0.577	0.548	0.558	0.567	0.548	0.556	0.014	0.00046	0.047
Nara	0.581	0.551	0.591	0.571	0.561	0.587	0.587	0.577	0.577	0.607	0.597	0.587	0.558	0.558	0.577	0.577	0.558	0.567	0.558	0.567	0.587	0.558	0.575	0.015	-0.00057	0.059
Hiroshima(*)	0.551	0.542	0.581	0.581	0.551	0.587	0.567	0.558	0.567	0.558	0.567	0.538	0.558	0.548	0.567	0.567	0.548	0.587	0.558	0.577	0.597	0.558	0.564	0.016	0.00042	0.029
Takamatsu(*)	0.551	0.512	0.561	0.551	0.561	0.577	0.538	0.548	0.538	0.548	0.558	0.548	0.538	0.548	0.558	0.538	0.558	0.558	0.548	0.538	0.528	0.538	0.547	0.014	-0.00036	0.030
Matsuyama	0.551	0.542	0.581	0.581	0.551	0.587	0.558	0.558	0.558	0.577	0.577	0.558	0.567	0.567	0.567	0.577	0.587	0.567	0.558	0.567	0.567	0.558	0.567	0.012	0.00028	0.021
Kochi	0.561	0.581	0.601	0.561	0.581	0.607	0.577	0.577	0.577	0.587	0.587	0.607	0.577	0.577	0.587	0.587	0.567	0.587	0.587	0.597	0.587	0.587	0.584	0.012	0.00045	0.057
Shimonoseki	0.571	0.542	0.591	0.571	0.551	0.577	0.558	0.558	0.577	0.567	0.587	0.567	0.577	0.577	0.577	0.567	0.558	0.587	0.558	0.587	0.558	0.567	0.570	0.013	0.00025	0.016
Fukuoka(*)	0.581	0.571	0.581	0.581	0.551	0.597	0.558	0.587	0.567	0.577	0.567	0.558	0.548	0.577	0.607	0.607	0.567	0.587	0.607	0.587	0.587	0.577	0.579	0.017	0.00080	0.091
Oita	0.581	0.542	0.581	0.561	0.522	0.587	0.567	0.607	0.577	0.567	0.567	0.577	0.567	0.577	0.577	0.567	0.567	0.587	0.607	0.587	0.577	0.577	0.574	0.018	0.00104	0.134
Nagasaki	0.561	0.561	0.591	0.591	0.571	0.597	0.577	0.597	0.597	0.607	0.597	0.587	0.577	0.587	0.597	0.597	0.587	0.597	0.607	0.617	0.577	0.587	0.590	0.014	0.00102	0.219
Saga	0.581	0.561	0.581	0.561	0.551	0.587	0.558	0.577	0.617	0.637	0.597	0.607	0.587	0.577	0.597	0.597	0.577	0.607	0.597	0.597	0.587	0.577	0.587	0.020	0.00114	0.132
Kumamoto	0.551	0.542	0.571	0.561	0.561	0.587	0.567	0.587	0.558	0.587	0.587	0.587	0.558	0.577	0.587	0.577	0.567	0.597	0.587	0.597	0.577	0.558	0.574	0.016	0.00113	0.217
Miyazaki	0.581	0.561	0.581	0.542	0.542	0.558	0.577	0.577	0.567	0.567	0.577	0.577	0.558	0.587	0.597	0.587	0.548	0.577	0.587	0.567	0.587	0.577	0.572	0.015	0.00086	0.133
Kagoshima(*)	0.561	0.571	0.581	0.532	0.571	0.577	0.567	0.587	0.558	0.607	0.548	0.548	0.558	0.597	0.597	0.597	0.567	0.587	0.587	0.587	0.587	0.577	0.575	0.019	0.00117	0.159
Naha(*)	0.591	0.542	0.532	0.561	0.561	0.587	0.567	0.528	0.528	0.607	0.587	0.577	0.538	0.577	0.548	0.567	0.567	0.567	0.567	0.577	0.567	0.577	0.565	0.021	0.00063	0.036
Miyako Island	0.542	0.532	0.512	0.561	0.581	0.548	0.548	0.577	0.567	0.597	0.558	0.558	0.538	0.548	0.538	0.548	0.548	0.558	0.577	0.558	0.538	0.567	0.554	0.019	0.00045	0.024
Ishigaki Island	0.542	0.542	0.522	0.571	0.453	0.577	0.548	0.577	0.538	0.558	0.558	0.558	0.548	0.528	0.548	0.548	0.538	0.548	0.548	0.548	0.518	0.548	0.544	0.025	0.00014	0.001
Minami-Daito Island	0.512	0.502	0.492	0.542	0.522	0.518	0.518	0.508	0.528	0.548	0.528	0.478	0.528	0.538	0.518	0.518	0.538	0.498	0.518	0.538	0.538	0.538	0.521	0.018	0.00087	0.102
Ave.	0.561	0.556	0.567	0.564	0.557	0.577	0.563	0.562	0.569	0.576	0.568	0.558	0.560	0.562	0.570	0.571	0.567	0.573	0.567	0.574	0.572	0.564	0.566	0.006	0.00038	0.159

The trends that both a_0[-] and a_1[-] had not significantly changed with years were obvious when their nation-wide averages were plotted against Y_d (**Figure 1**), and suggested that the upward trend in n_a [h·d^{-1}] can be a main explanatory factor for that in the measured Q_a [W·m^{-2}]. For instance, because the sunshine duration n_a [h·d^{-1}] had increased by 0.33 [h·d^{-1}] in the period between 2001 and 2022 while the parameter a_1[-] took almost consistently 0.566[-] in that period(**Table 5**), the increase in GSR during that period can be calculated as 5.38 [W·m^{-2}], by using Equation (2) with the values of Q_e [W·m^{-2}] of 349.8[W·m^{-2}] and N[h·d^{-1}] of 12.04 [h·d^{-1}] in average (**Table 1**). This calculated value is very similar in size with the increase in the measured GSR for the same 22-year period of 5.5 [W·m^{-2}]. Certainly, the interannual increase in the sunshine is likely to explain the major portion of the increase in the measured GSR in recent years.

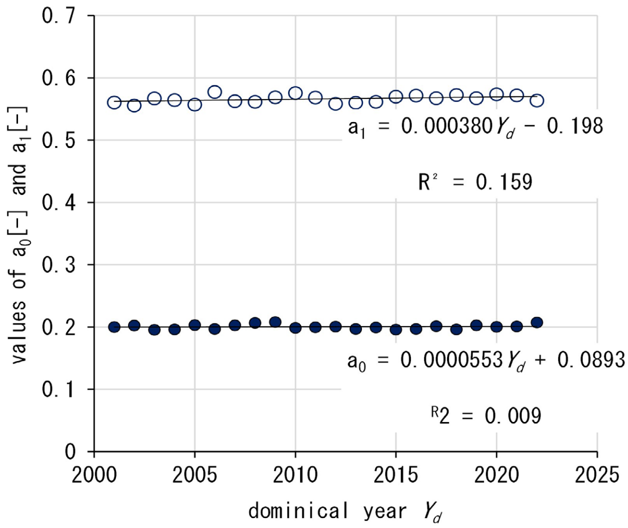

Figure 1. The interannual trends in the nation-wide averages of a_0 and a_1 in Equation (2) "$\tau = a_0 + a_1\, n/N$".

3.4. Possible Factors for the Increase in Sunshine Duration

The observed increase in sunshine duration allowed to assume that patterns of precipitation and of cloud cover have changed so that the number of rainy days or the daily cloud cover have decreased. Thus, these two quantities were analyzed as follows.

Figure 2 shows the annual total of rain days per year [d·y^{-1}]. The rain days were counted up among the days with rainfall of more than 0 [mm·d^{-1}] observed in each station. Then, each plot on the graph was obtained by averaging the values for the 40 stations. The annual total of rain days had varied with the rate of 0.096 [d·y^{-2}], suggesting that it was almost constant around 138 [d·y^{-1}] or slightly increased for the 22-year period.

Figure 3 shows annual mean values of cloud cover plotted against the dominical year. Any of the values of annual mean cloud cover was of spatially averaged among the 11 stations marked in **Table 1**. The values were in the international synoptic code, having converted from those recorded originally in the Japanese synoptic code. The cloud cover had likely been stable. The temporal average of the plotted values in the entire period was 5.7[-] (between "cloudy" and "mostly cloudy") with a standard deviation of 0.116[-]. And the slope of its trend obtained from the linear regression of the plots was 0.00418 [y^{-1}]. This kind of trend was also found on each of the 11 stations, implying that the cloud cover had also commonly been stable or barely increased over the country.

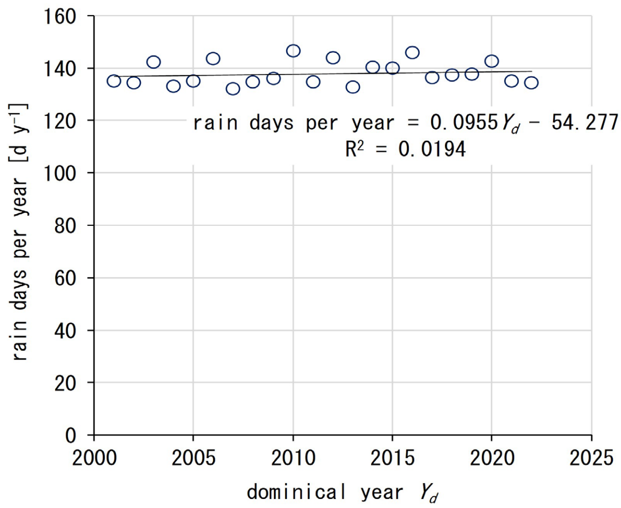

Figure 2. The annual rain days [$d \cdot y^{-1}$] (the number of days with daily rainfall more than 0 [$mm \cdot d^{-1}$]) for the 22-year period. Each value was the average of the 40 stations.

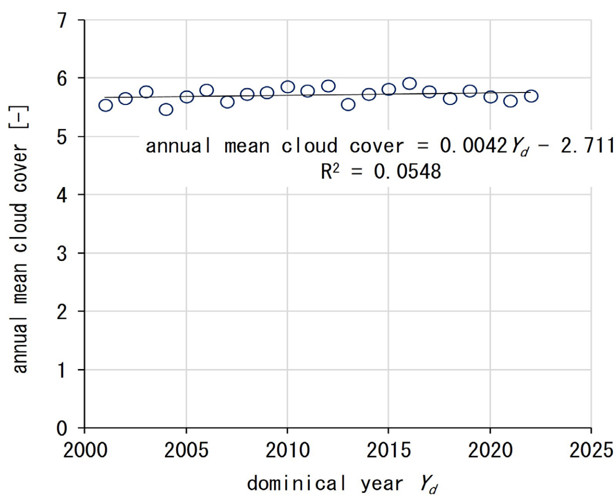

Figure 3. The annual mean values of cloud cover spatially averaged among the 11 stations.

The fact that both the number of rainy days and daily cloud cover had been almost constant or even increased for the 22-year period implied that the upward trend in the sunshine duration in the study period was attributable to shortening of rainfall duration in each rain event or to faster development and elimination of thick clouds such as cumulus or nimbus rather than cirrus. This means that the rainfall pattern had changed so that heavy rainfalls with short duration are occurring more frequently. One evidence that can support this implication was that the number of heavy rain days with more than 20 [mm·h^{-1}] had increased in the whole country (**Figure 4**). Its average was 5.32 [d·y^{-1}] for the 22-year period with the increasing rate of 0.0821 [d·y^{-2}]. This upward trend in heavy rainfall frequency was found at 35 out of the 40 stations during the study period, indicating that strong rain day numbers had commonly increased over the country. In addition, the upward trend in heavy rainfall frequency was found regardless of rainfall intensity. According to the rainfall intensity scale of Japan Meteorological Agency, these heavy rain days can be classified into such four mutually-exclusive categories as the kinds of days with more than 1) 20 [mm·h^{-1}], 2) 30 [mm·h^{-1}], 3) 50 [mm·h^{-1}], and 4) 80 [mm·h^{-1}]. And, when the number of days for each category was counted up for each year at every station, the number of days for all the categories showed positive slopes of 0.0507, 0.0273, 0.0027, and 0.0013 [d·y^{-2}] for category 1), 2), 3), and 4), respectively. These facts suggest the necessity of further studies confirming possible mechanisms behind the relation between the increase in sunshine duration and the shortening in rainfall duration.

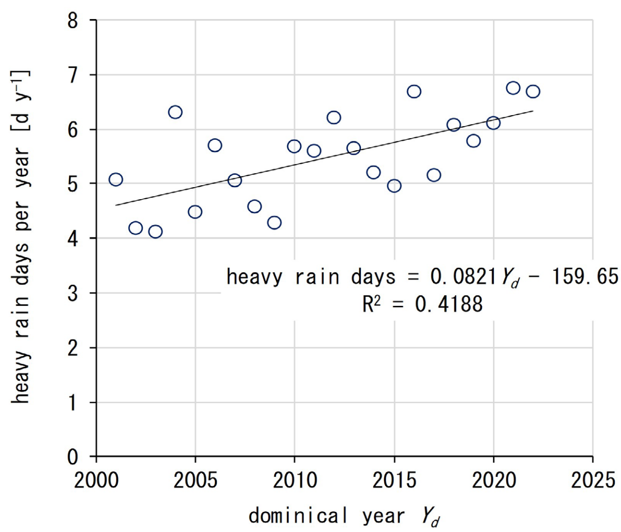

Figure 4. The number of heavy rain days (days on which rainfall(s) with more than 20 [mm·h^{-1}] were recorded) at each station for the years.

3.5. Applicability of a Simple Sunshine-Based Model

In this study, the measured relation between GSR and sunshine duration allowed the sunshine-based model to perform well. However, since cloud cover and aerosols in the atmosphere can directly affect atmospheric transmittance, the sunshine-based model may perform better in general by taking both factors into account. Among the factors, cloud cover was sometimes suggested to be the major factor for the better estimation of solar radiation (Feng & Wang, 2021). At the same time, even in a case that a thorough long-term investigation successfully found out an upward trend in cloud cover occurring coincidently with a downward trend in solar radiation, it is not always easy for researchers to successfully confirm a statistical significance between the two trends (Yamasoe et al., 2021). These findings imply the difficulty and subtleness in identifying the relation between solar radiation and cloud cover.

Contrarily, another study proposed a simple model in which solar radiation is expressed by a logarithmic function of atmospheric aerosol concentration (Hu et al., 2017), rather than a function of cloud cover. At first glance, there are some contradictive discussions among the past studies concerning with the possible factors for solar radiation. However, they may not be in disagreement but may hold together when some site-specific conditions are considered. For instance, aerosols' detrimental effect on solar radiation is likely to be found in regional scale rather than a national scale (Xie et al., 2021), suggesting that importance of each factor may differ depending on spatial and/or temporal scales of interest. In other words, it may be possible to make a model more detailed by taking into account larger number of factors while the enhancement of the specialized use of the model at a specific site in a certain time period may prevent it from being applied to a general purpose in larger scales. Therefore, it can be expected that a sunshine-based model with a simpler form will commonly be used, while further investigations are still necessary with the accumulation of reliable data sets to clarify the applicability of a simple sunshine-based model from the viewpoints of temporal and spatial scales in which the model would be used.

4. Conclusions

This study analyzed interannual trends in global solar radiation (GSR) and sunshine duration which had been measured from 2001 to 2022 in 40 meteorological stations over the Japanese archipelago, and exemplified the applicability of the Angstrom-Prescott atmospheric transmittance model to the analysis and prediction of GSR.

The annually-averaged GSR Q_a [W·m^{-2}] had increased in 33 out of the 40 stations with dominical years Y_d for the study period. The rate $\mathrm{d}Q_a/\mathrm{d}Y_d$ [W·m^{-2}·y^{-1}] was 0.252 [W·m^{-2}·y^{-1}] in average, implying that the nation-wide increase in Q_a [W·m^{-2}] amounted to 5.5 [W·m^{-2}] for the 22-year period. The stations with negative $\mathrm{d}Q_a/\mathrm{d}Y_d$ [W·m^{-2}·y^{-1}] were found mostly in the south-western region of the country. However, the apparently-downward trends in Q_a [W·m^{-2}] found in that region might have been effectively flat.

The annually-averaged sunshine durations n_a [h·d^{-1}] had also increased with the rate $\mathrm{d}n_a/\mathrm{d}Y_d$ [h·d^{-1}·y^{-1}] of 0.015 [h·d^{-1}·y^{-1}] in average among the 40 stations, equivalent to the increase in n_a [h·d^{-1}] of 0.33 [h·d^{-1}] for the 22-year period. A few negative $\mathrm{d}n_a/\mathrm{d}Y_d$ [h·d^{-1}·y^{-1}] were found in the stations located in the south-western region of the country, as for $\mathrm{d}Q_a/\mathrm{d}Y_d$ [W·m^{-2}·y^{-1}], suggesting that the interannual increase in GSR can be explained mainly by the increasing trend in sunshine duration.

The offset a_0[-] and the slope a_1[-] of the Angstrom-Prescott model were estimated by fitting the model to the measured data sets of Q_a [W·m^{-2}] and n_a [h·d^{-1}]. The resultant parameter values indicated that both the offsets and slopes had almost been constant with the nation-wide averages of a_0 = 0.201[-] and a_1 = 0.566[-], implying that characteristics of the atmospheric transmittance had almost been stationary for the 22-year period, and that the model and its parameter set can be applied to the analyses and predictions of GSR in recent years.

The trends that both a_0[-] and a_1[-] had not significantly changed with years also indicated that the upward trend in n_a [h·d^{-1}] can be a main explanatory factor for that in the measured Q_a [W·m^{-2}]. In fact, the parameterized sunshine-duration model evaluated the increase in GSR as 5.38 [W·m^{-2}] for the increase in sunshine duration of 0.33 [h·d^{-1}] and the stable parameter a_1[-] of 0.566[-] found in this study, reproducing well the increase in the measured GSR of 5.5 [W·m^{-2}] for the same 22-year period.

The upward trend in sunshine duration coincided with the increase in the frequency of heavy, shortened rains. This coincidence suggested that time period of each rainfall event had gradually decreased so that sunshine duration hours in each date had relatively increased in the two decades. Therefore, further studies are required to clarify if there is some cause-effect relation among the changes in rainfall patterns and in standard level of solar radiation reaching the land surface.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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