

RESEARCH ARTICLE

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Statistical analysis of cloud layers and solar irradiations for all seasons in Toyohashi city, Japan

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Abstract. Several solar irradiation forecasting methods are being developed toward economically efficient solar power generation. Among these, the method that utilizes all sky imagers to estimate the direction of cloud movement above certain observation points is able to forecast fluctuations in solar irradiation with localized temporal resolution (~ 30 min) through observation of shadows cast by clouds. The one-layered cloud is usually assumed in forecasting the direction of cloud movement. However, in reality, multilayered clouds may move in different directions in the sky. While such multilayered clouds may have effect on forecast accuracy, the extent to which multilayered clouds affect the solar irradiation and the generated solar power has never been reported. Therefore, the purposes of this study are (1) to give the dataset to know the effect of multilayered clouds and (2) to decide whether the multilayered clouds have to be considered in forecasting of solar irradiation. We analyzed the number of cloud layers and their effect on the solar irradiation, the generated solar power, and the clearness index through statistical analysis for all seasons in Toyohashi city, Japan. The dataset used to analysis includes data with 4381 h. The analytical results show that multilayered clouds were observed for $\sim 40\%$ of the daytime duration even in winter. In addition, the results show that multilayered clouds were observed even when the solar irradiation, the generated solar power, and the clearness index were high, which suggests that the effect of multilayered clouds must be considered. In addition, it will be shown that the maximum number of cloud layers to be considered is 3 from statistical analysis.

Keywords: Solar irradiation / clearness index / multilayered cloud / all sky imaging / statistical analysis

1 Introduction

The difference between forecasted and actual amount of generated solar power should be minimized to achieve economically efficient operation of solar power generation. In this context, an accurate forecasting of solar irradiation is necessary. Solar irradiation forecasting is performed by several methods [1–14] that use numerical weather prediction (NWP), satellite imaging, ground-based systems, which are characterized by temporal-spatial scales. NWP has an advantage that solar irradiation can be forecasted at any place up to more than one week. However, in prediction with NWP, it is difficult to forecast to variation of solar irradiation by clouds accurately because of the chaoticity in numerical prediction. The measurement with satellite imaging from the

space covers the large area on the Earth and can provide the information of the position of clouds, the thickness of clouds, and the motion of the clouds, allowing the forecasting of variation of solar irradiation by clouds. However, the accurate estimation of solar irradiation from the space is still a challenging issue. Ground-based systems forecast fluctuations by cloud shadows [3,4,7–11,15,16] in solar irradiation for short duration of ~ 30 min with the accurate solar irradiation measurement. The ground-based systems are divided into two types: the systems with pyranometer sensor networks [5,6] and the systems with all sky imagers (ASIs). The pyranometer sensor networks forecasts solar irradiations with one-dimensional data. On the other hands, the system with ASIs forecasts solar irradiations with two-dimensional data (sky images) as well as one-dimensional data. The systems with ASIs estimate the direction of cloud movements with optical flow [9,11–14]. In this context, the number of cloud layers is usually assumed to be unity [7].

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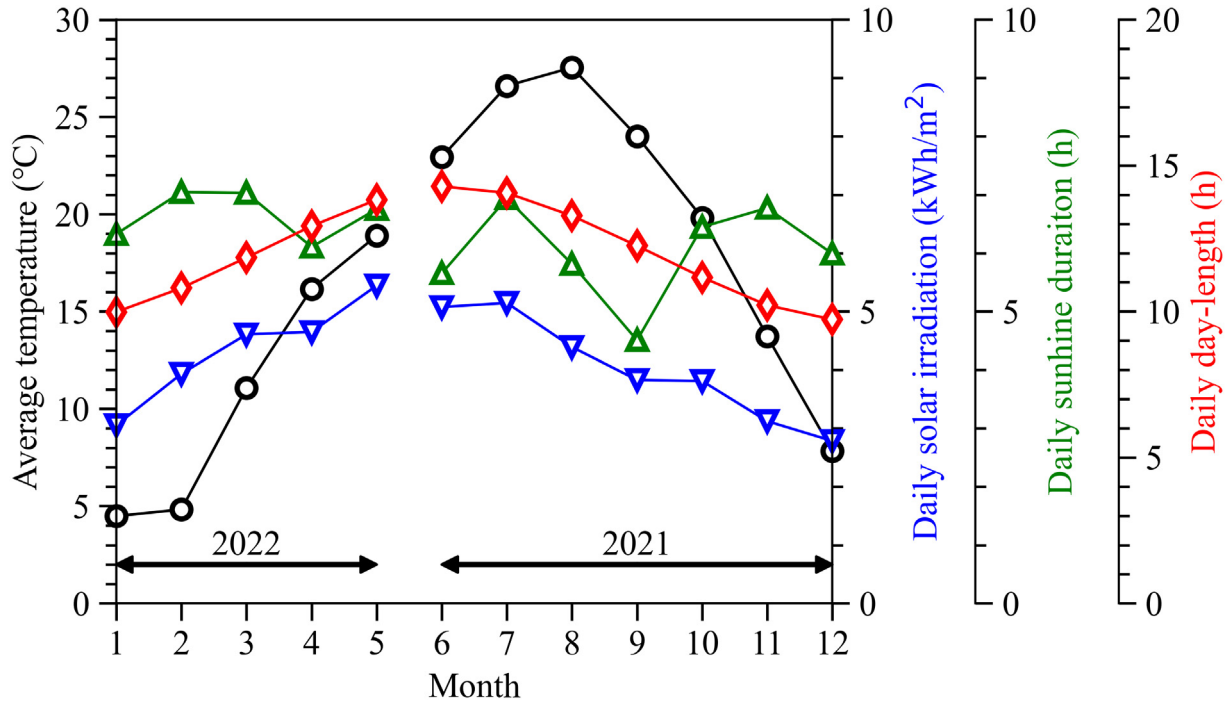


Fig. 1. Average temperature, daily GHI, daily sunshine duration, and daily day-length data for all months (2021/06–2022/05).

However, in reality, multilayered clouds may move in different directions. In fact, there are studies in which multilayered cloud conditions and the direction of cloud movements were investigated for solar irradiation forecasting, although the number is limited [4,8–10]. For example, Peng et al. [8] distinguished clouds using machine learning techniques and forecasted solar irradiances. B. Nouri et al. [4,10] valued the number of cloud layers with multi ASIs for probabilistic solar nowcasting. While multilayered clouds probably affect the accuracy of forecasting, effect of multilayered clouds on the solar irradiation and the amount of the generated solar power have never been reported.

The purposes of this study are (1) to give the dataset to know the effect of multilayered clouds and (2) to decide whether multilayered clouds have to be considered in forecasting of solar irradiation. We statistically analyzed the number of cloud layers and their effect on the solar irradiation, the generated photovoltaic (PV) power, and the clearness index for all seasons in Toyohashi city, Japan, which is located in East Asia. The results in this study show that multilayered clouds were observed even when the solar irradiation and the generated solar power are high, indicating considerable effect by multilayered clouds. In addition, it is shown that the direction of three-layered clouds should be considered in forecasting.

In Japan, the climate is diverse due to water vapor from the Pacific Ocean and the East Asian monsoon [17–19], and there is a rainy season along with spring, summer, fall, and winter seasons, making it an ideal case for statistical analysis of cloud layers. Note that statistical analysis of multilayered clouds and solar irradiation using data from satellites [14,20,21] has also been performed; however, it

lacks the great accuracy because of the observation from the space. Thus, analysis using ground-based observations in this study is more suitable.

The remainder of this paper is organized as follows: [Section 2](#) describes the ground-based measurement system and the analytical procedure to make the dataset. [Section 3](#) discusses the results of statistical analysis on cloud layers, the global horizontal irradiation (GHI), the generated PV power, and the clearness index. Finally, [Section 4](#) provides discussion and conclusions of this study.

2 Ground-based measurement and procedure to make dataset

Herein, we made observations on the rooftop of a building of the Toyohashi University of Technology (Toyohashi city, Aichi Prefecture; 34.7° latitude and 137.4° longitude). The Toyohashi University of Technology is located 40 m above the sea level. [Figure 1](#) shows monthly the average temperatures, the average daily GHI, the daily sunshine duration, and the daily day-length in Toyohashi city during the analysis (from June 2021 to May 2022). The month with the longest daily day-length was June while that with the highest average temperature was August. Because the temperature is high in summer (July and August), the atmosphere in summer is unstable and is prone to cloud formation. Here, the data for the average temperature and the average GHI were acquired by our research group. The data for the sunshine duration, which is the sum of durations for which the direct solar irradiation was $\geq 0.12 \text{ kW/m}^2$, was obtained from the Automated



Fig. 2. Sky images from camera with a viewing angle of (a) 98° and (b) 195° on 2021/08/01 10:01.

Meteorological Data Acquisition System (AMeDAS) provided by the Japan Meteorological Agency. The day-length is the sum of durations for which solar altitude angle was ≥ 0 , calculated from the formula presented in [Appendix A](#).

In making the dataset, we replaced all data as data over an hour. That is, we evaluated the maximum number of observations over an hour for clouds, the amount of the integrated GHI over an hour, the amount of the integrated PV power over an hour, and the average of the clearness indices over an hour. The division of one hour starts at every hour on the hour. For example, the integrated solar irradiation for 12:00 is calculated by integration between 12:00 and 13:00. The details of measurement and analysis are shown below.

Sky images were taken by ASIs with viewing angles of 98° and 195° to the sky. Because sky images obtained from a viewing angle of 98° have little distortions, they are well suited for analysis of cloud movement directions. On the other hand, because sky images obtained from a viewing angle of 195° capture a wide area, they are suited for analysis of the number of cloud layers. [Figure 2](#) shows the sky images obtained from viewing angles of 98° and 195° taken simultaneously. Sky images were taken from June 2021 to May 2022 with five-second intervals. These images were combined to create hourly videos, and the maximum number of layers over an hour was analyzed. Two technologists determined the number of cloud layers. In cases where more than two layers of clouds were observed and cloud movements differed at angles $\geq 30^\circ$, they were considered to be moving in “different directions”. The analyzed duration was from sunrise to sunset. Because the analyzed duration was divided into one-hour segments, segments with the time of sunrise/sunset should be treated carefully. In this study, if the time of sunrise (sunset) was 30 min earlier (later), the one-hour segment was analyzed. During the analyzed duration, the total hours were 4,400 h. Among these hours, the ASIs were not available for 19 h due to equipment maintenance, which is equivalent to 4.3% of the analyzed duration; thus, the analyzed duration in dataset for only ASIs was the remaining 4,381 h.

The GHI was measured using a pyranometer (MS-601) manufactured by Eko Instruments Co. Ltd. Solar panel to generate the PV power was a polycrystalline silicon PV cell with an area of 32.8 m² and a rated direct current output of 4.86 kW. The installation inclination angle of the solar panel was 35° and the azimuth was 171°. The GHI and the generated power by the solar panel were hourly integrated

with one-second sampling. The ASIs and the measurement system for the GHI operated separately with different maintenance schedules. Thus, the analyzed duration in dataset for the GHI and the generated PV power with the ASIs reduced to 4,252 h from 4,381 h with only ASIs.

If only the GHI is analyzed, variation of solar irradiation in the meridian passage due to the change of the Sun’s declination and the change of distance between the Sun and Earth would be incorporated along with fluctuations in solar irradiation by clouds. Thus, herein, the clearness index [\[15\]](#) is also utilized. The clearness index is obtained as a ratio of the GHI and the extra-terrestrial solar irradiance on a horizontal surface. The clearness index cancels the effect of the above changes on the GHI. The evaluation method for the clearness index is presented in [Appendix A](#). For the clearness index, a one-hour average was used instead of integrated values. Note that when the solar altitude is low in morning and evening, the airmass is large and the clearness index decreases even if there are no clouds. To suppress this effect, we performed the analysis from 9:00 to 15:00. Consequently, in the analysis with the clearness index, the analyzed duration in dataset reduced to 2,125 h from 4,252 h with the GHI and the ASIs.

[Figure 3](#) shows an example of determining the number of cloud layers along with sky images. The solar irradiation, the clearness index, and the airmass are also shown. The airmass was modeled by treating the atmosphere around the Earth as a spherical shell. With the presence of clouds, the solar irradiation and the clearness index varied. Around 14:30, the clearness index exceeded unity, which was due to a cloud enhancement event (CEE) [\[22–26\]](#). As discussed above, the airmass rapidly grew in morning and evening when the solar altitude was low. For these durations, the optical path length for sunlight in the atmosphere increased and lowered the clearness index even if it was a clear day.

[Figure 4](#) shows the flowchart to make the dataset explained in this section. [Figures 5, 7–13](#) are plotted with the dataset.

3 Statistical analysis of cloud layers, solar irradiation, and generated PV power

3.1 Result of analysis through the year

[Figure 5a](#) shows the number of hours with one-hour increments for different number of cloud layers observed for months from June 2021 to May 2022. In [Figure 5](#),

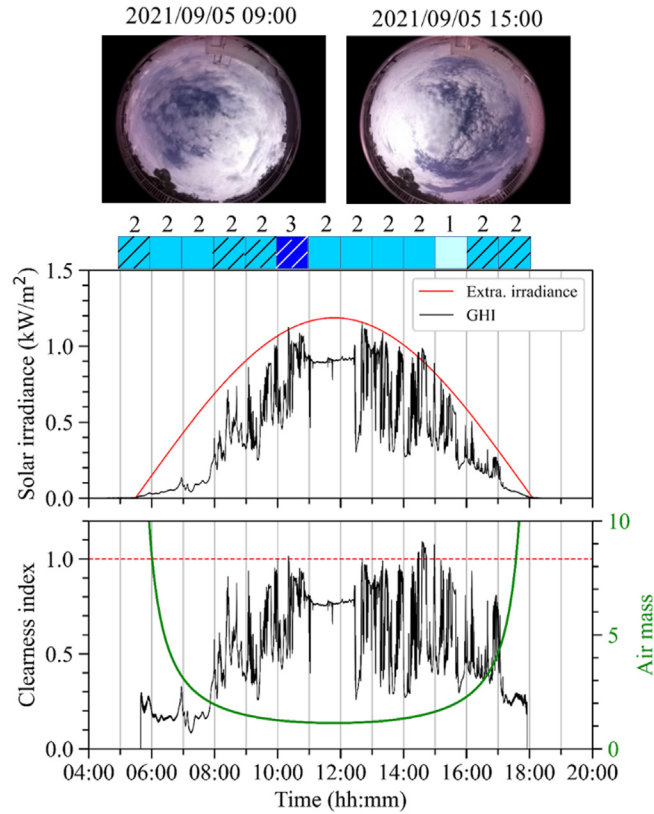


Fig. 3. Temporal distribution of solar irradiation on a horizontal surface, extra-terrestrial solar irradiance on a horizontal surface, clearness index, and airmass on 2021/09/05. The number of cloud layers determined by sky images is also shown. The clearness index exceeded unity around 14:30 due to a cloud enhancement event. When the extra-terrestrial solar irradiance was $<50 \text{ W/m}^2$, the clearness index was set to zero.

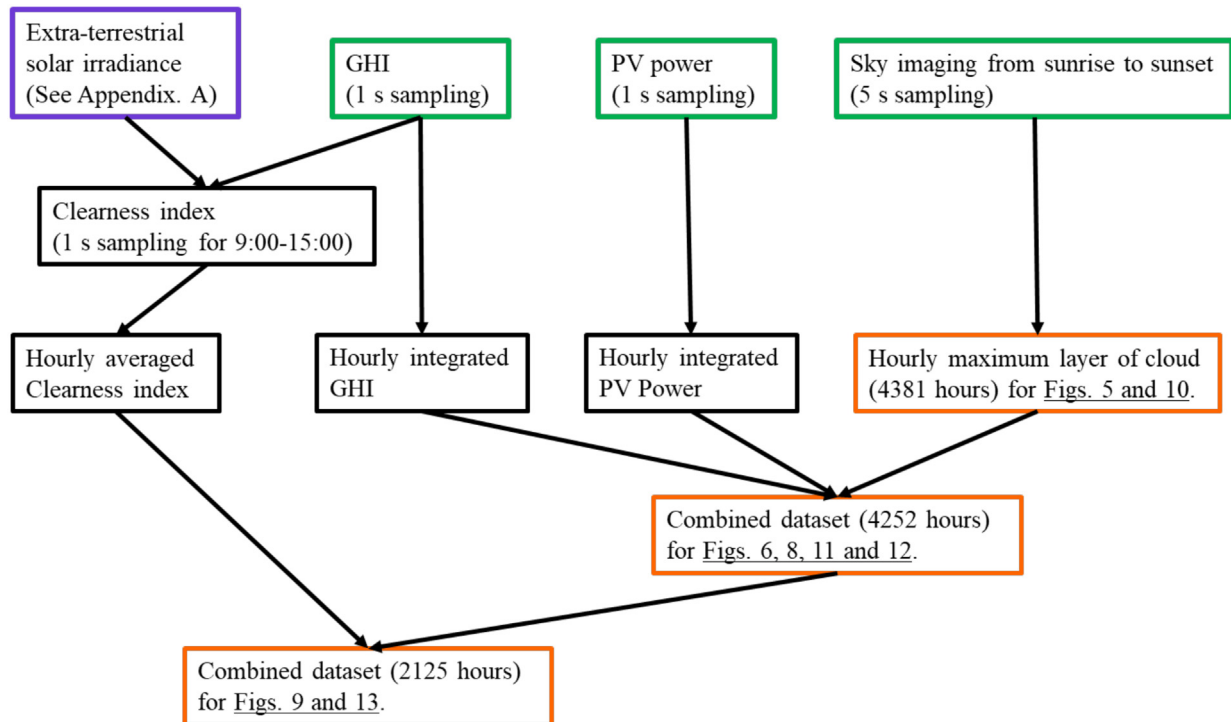


Fig. 4. Flowchart to make the dataset described in Section 2.

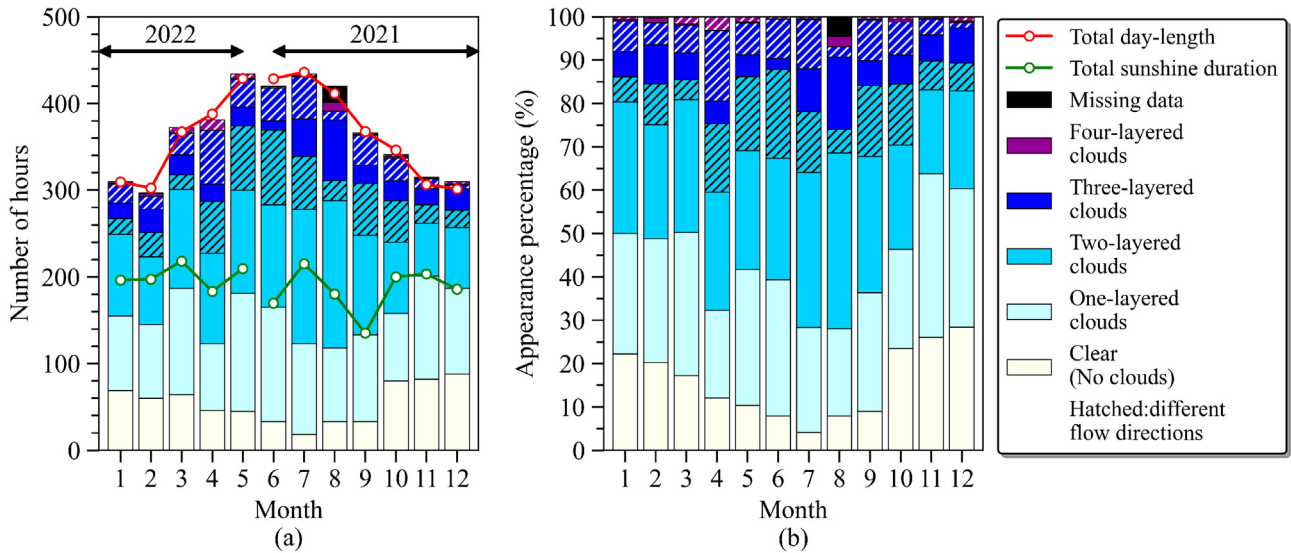


Fig. 5. (a) Monthly data for the number of hours with no clouds and one-, two-, three-, and four-layered clouds during daytime; (b) Monthly data for the appearance percentage of absence of clouds and one-, two-, three-, and four-layered clouds during daytime

Table 1. Annual data for the number of hours and the appearance percentage of absence of clouds and one-, two-, three-, and four-layered clouds during daytime (2021/6 – 2022/5).

	Number of hours	Appearance percentage (%)
Four-layered clouds (different flow directions)	38	<1
Four-layered clouds	22	<1
Three-layered clouds (different flow directions)	327	7
Three-layered clouds	322	7
Two-layered clouds (different flow directions)	516	12
Two-layered clouds	1280	29
One-layered clouds	1225	28
Clear (No clouds)	651	15
Total	4381	100

“Missing data” refers to the duration when the ASIs were not available due to maintenance, and therefore, no analysis was performed. Total day-length is the sum of hours from sunrise to sunset for each month, which was highest for July and lowest for February. The longest day in Japan (the summer solstice) is around 21 June, and the shortest day (the winter solstice) is around 21 December. However, because the number of days in a month is not all the same, the months with the highest and lowest total day-lengths did not match with the months of summer and winter solstices. Figure 5b shows the appearance percentage of different number of cloud layers over the months. The presence of multilayered clouds with at least two layers

was highest in July (72%) and lowest in December (40%), which is consistent with the months that have the high and low average temperatures, as shown in Figure 1. As previously discussed, the atmosphere is unstable in July with high temperatures, favoring multilayered cloud formation. There is also a month where three cloud movements with different directions were observed for ~30%. As a different view of Figure 5, annual data for the number of hours and the appearance percentage are also shown in Table 1.

Figure 6 shows a histogram for the hourly integrated GHI relative to the number of cloud layers. As shown in Figure 6a, the number of hours was higher when the integrated GHI was low. From Figure 6b, we observe that ~40% of clouds that appeared in the sky were multilayered when the integrated GHI was high (0.8–1.0 kWh/m²). Furthermore, when the integrated GHI was low, the proportion of multilayered cloud was basically high. The similar trend was observed on the sunshine duration. Figure 7 shows the relationship between the average number of cloud layers for each day and the sunshine duration. There is a slight negative correlation between the average number of layers and the sunshine duration, which is consistent with an intuitive interpretation that a higher number of cloud layers results in increased sunlight blocking.

Figure 8 shows a histogram of the hourly integrated PV power relative to the number of cloud layers. Figure 8a shows a peak at the middle of the histogram, 3.0–3.5 kWh, unlike Figure 7a. This difference in distribution is probably due to the strong dependence of the amount of the generated PV power on solar irradiation over an inclined surface [27]. In fact, when we construct a similar histogram using solar irradiation on an inclined surface of PV cells, the distribution is close to that shown in Figure 8a. It is also noted that there is a difference in the relative proportions of multilayered clouds between data of the integrated GHI

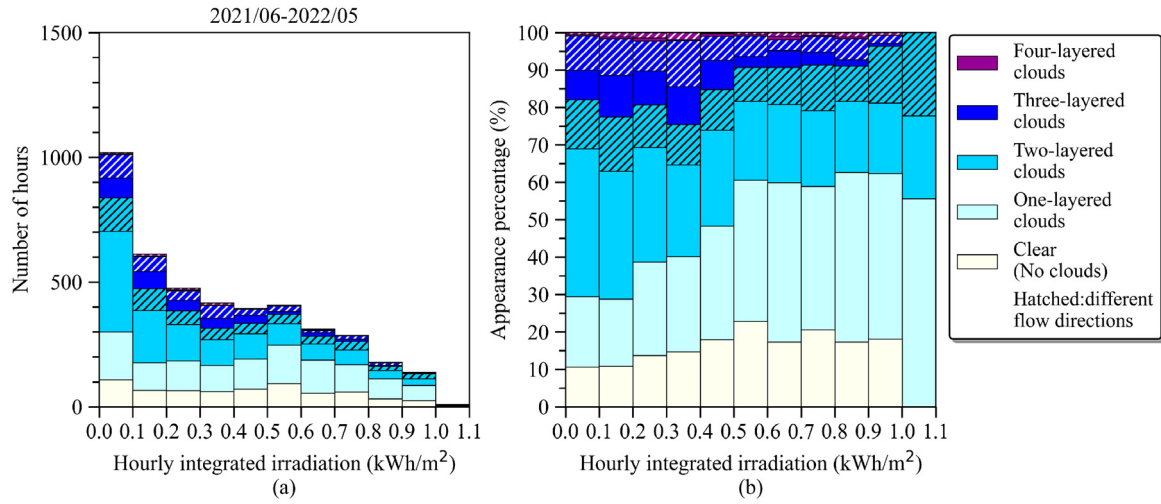


Fig. 6. Histogram of hourly integrated GHI (2021/6-2022/5) relative to: (a) number of hours and (b) appearance percentage.

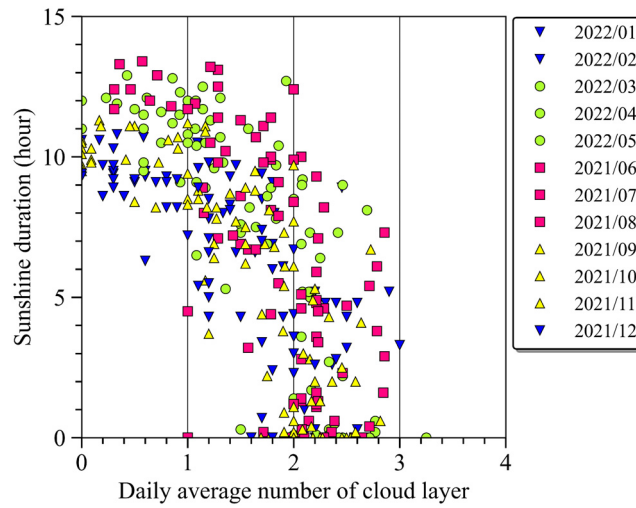


Fig. 7. Daily average number of cloud layers and sunshine duration (2021/6-2022/5). Spring, summer, fall, and winter seasons are color-coded.

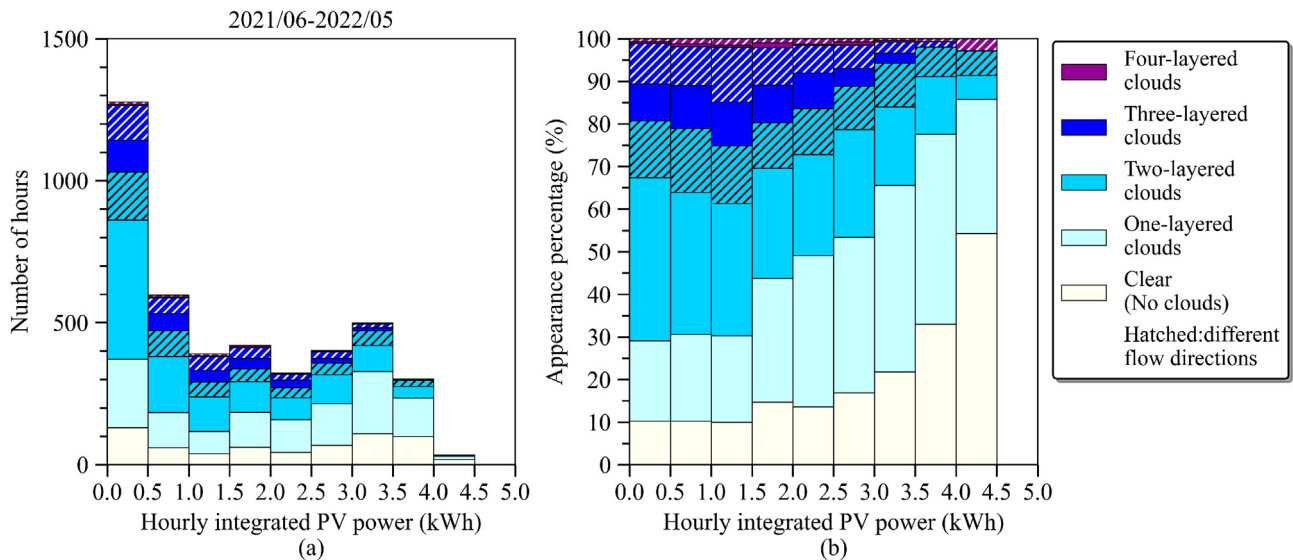


Fig. 8. Histogram of hourly integrated photovoltaic (PV) power (2021/6-2022/5) relative to: (a) number of hours and (b) appearance percentage.

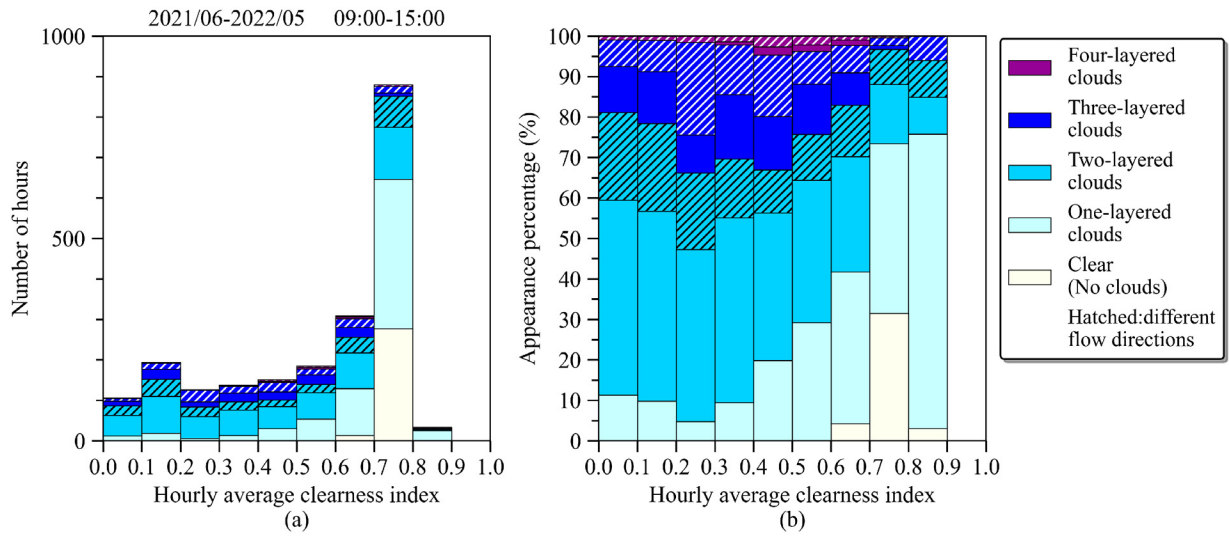


Fig. 9. Histogram of hourly average clearness index (2021/6-2022/5) relative to: (a) number of hours and (b) appearance percentage.

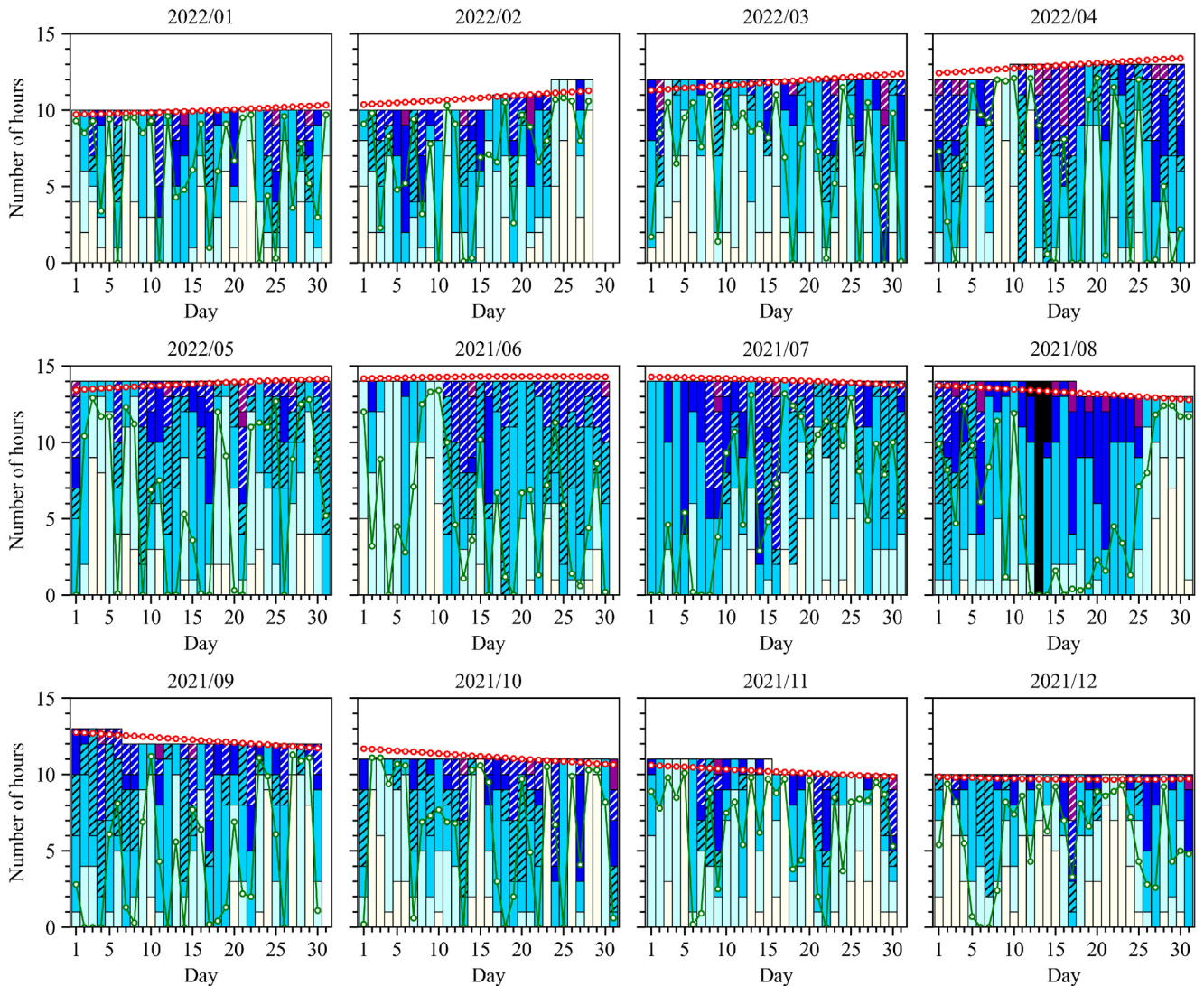


Fig. 10. Daily data for number of hours with no clouds and one-, two-, three-, and four-layered clouds during daytime for each month. The red markers and the green markers means the day-length and the sunshine duration.

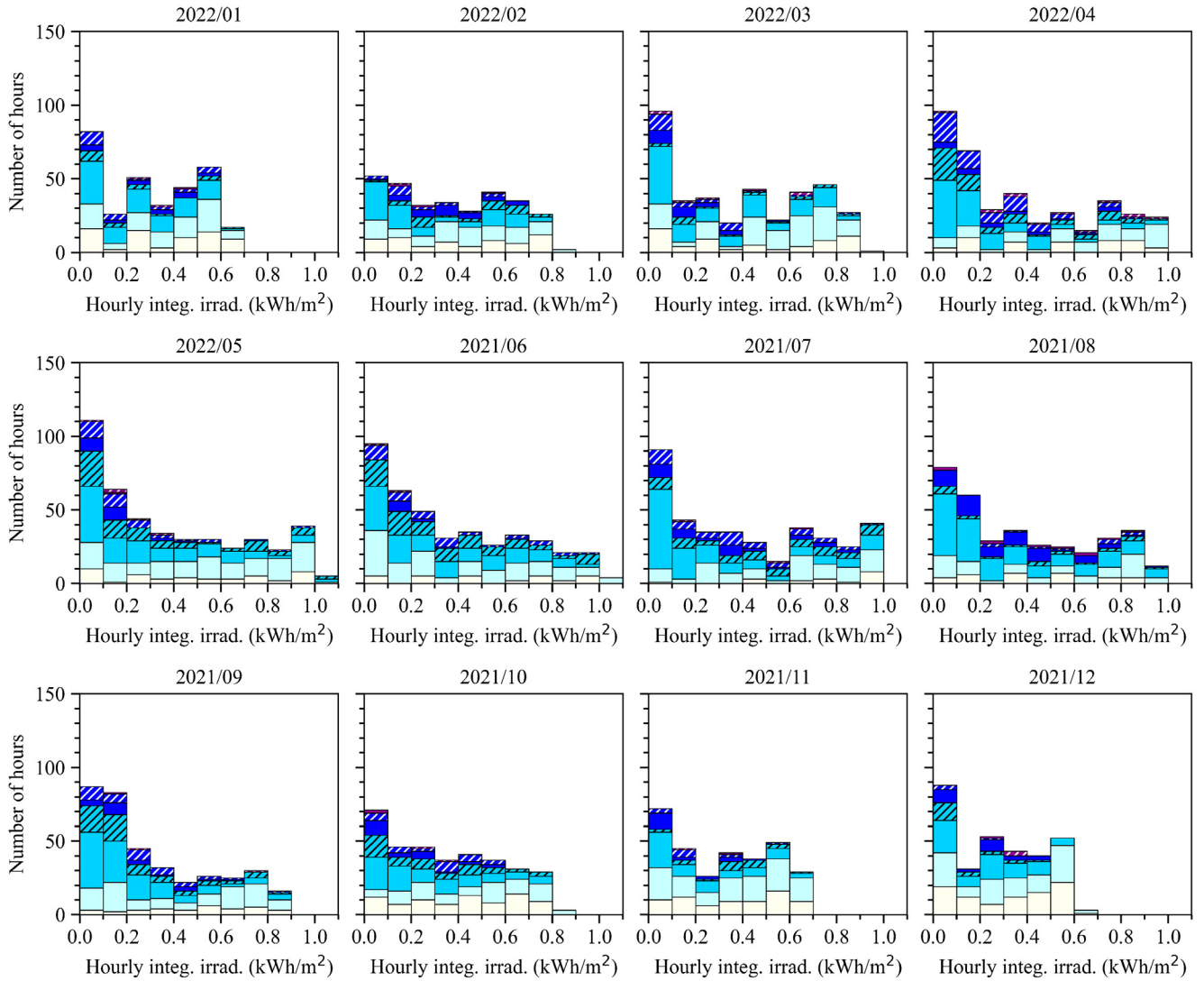


Fig. 11. Histogram of hourly integrated GHI for each month. “Hourly integ. irradi.” is an abbreviation for “Hourly integrated irradiation.”.

of Figure 7b and data of the integrated PV power of Figure 8b. This may be due to, in winter, the solar irradiation on an inclined surface is higher compared with the GHI and the proportion of multilayered clouds is lower as shown in Figure 5b.

Figure 9 shows a histogram of the hourly average clearness index. The number of hours was high for the clearness index range of 0.7–0.8, where multilayered clouds were also observed with a high number of hours. Because the clearness index is usually 0.7–0.8 on clear days in Toyohashi city, it can be said that the average clearness index is high even if there are multilayered clouds. Results of the average clearness index in the range 0.8–0.9 may come from an increase in solar irradiation due to CEE [22–26]. In addition, the peak in the range 0.1–0.2 is observed and is consistent with a bimodal distribution of the clearness index shown in [28], which discusses the relation with clouds. Figure 9b shows the proportion of multilayered clouds, it also shows that a decrease in

clearness index results in an increase in the number of cloud layers.

As shown in Figures 6, 8, and 9, as the integrated GHI, the integrated PV power, and the average clearness index increased, the proportion of clouds with a high number of layers decreased. On the other hand, even if the above-mentioned quantities are high, multilayered clouds were also observed with a certain proportion, which indicates that the effect of multilayered clouds cannot be neglected in forecasting.

3.2 Results of analysis in each month

In the previous subsection, the data obtained for an entire year (Figs. 5, 6, 8, and 9) was discussed. In this subsection, monthly data is presented and discussed. Note that, because the sum of day-lengths differs monthly, the total number of hours for each month also differs. Figure 10 shows the data for the number of cloud layers for each day

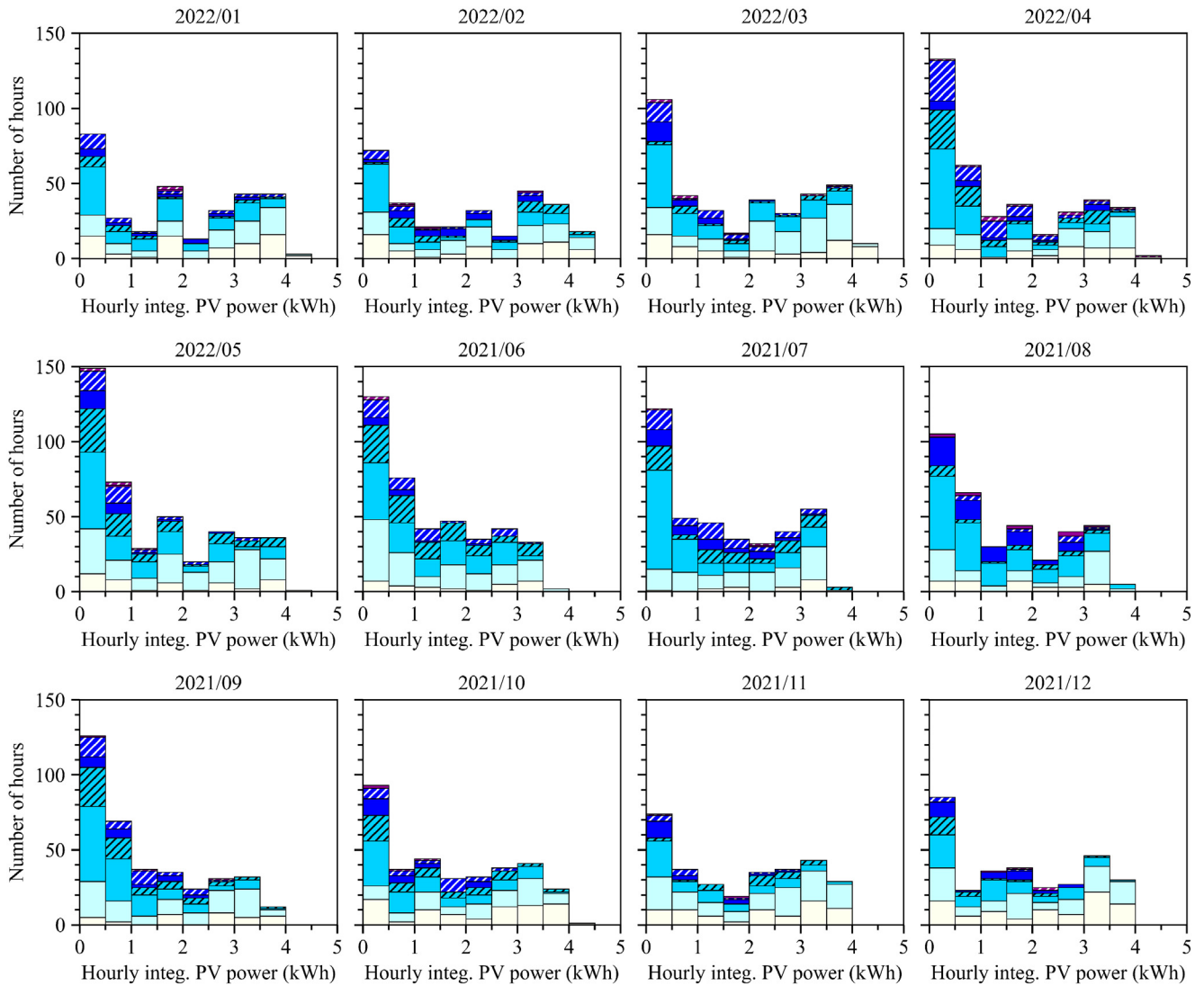


Fig. 12. Histogram of hourly integrated PV power for each month.

of the month along with the sunshine duration. Days with a higher number of cloud layers tend to have a shorter sunshine duration, which is consistent with the results presented in Figure 7. Figure 11 shows a histogram of the hourly integrated GHI relative to the number of cloud layers. In May and June having high solar altitudes, the hourly integrated GHI can be $1.0\text{--}1.2\text{ kWh/m}^2$. In contrast, in January and December having low solar altitudes, the maximum of the hourly integrated GHI was low. For all months, multilayered clouds were observed even when the GHI was high. Figure 12 shows a histogram of the hourly integrated PV power relative to the number of cloud layers. There was a large generated power even in the winter as well as the summer, unlike that observed in Figure 11. As discussed in the previous subsection, in the winter, the solar irradiation on a horizontal surface becomes low while the solar irradiation on an inclined surface of PV cells becomes high resulting in the high integrated PV power. Figure 13 shows a histogram of the hourly average clearness index relative to the number of cloud layers. For all months, there

was a peak in the range $0.7\text{--}0.8$. The multilayered clouds were also observed even when the clearness index was high.

4 Discussion and conclusions

In this study, for the first time, we analyzed the effect of multilayered clouds on the GHI, the generated PV power, and the clearness index with ground-based measurement. The results for an entire year, as well as for each month, show that multilayered clouds were observed even when the GHI, the generated PV power, and the clearness index were high, indicating considerable effect by multilayered clouds on the abovementioned quantities. This suggests that the effect of multilayered clouds must be considered in forecasting of the solar irradiation and the generated PV power. As explained in Section 1, the one of the purposes of this study are to decide whether the multilayered clouds have to be considered in forecasting of solar irradiation. In the whole observation duration, the percentage with

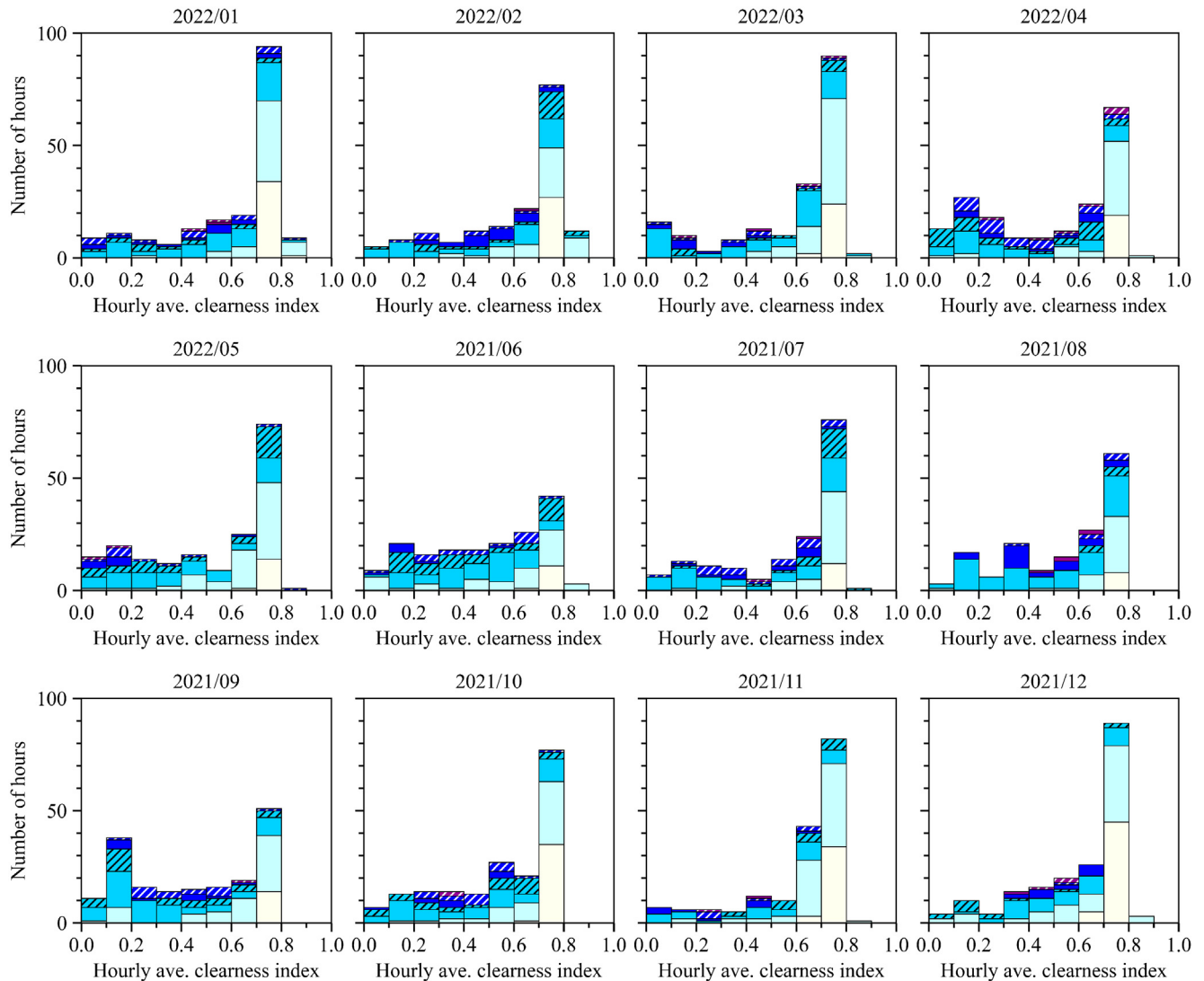


Fig. 13. Histogram of hourly average clearness index in every month. “Hourly ave. clearness index” is the abbreviation of “Hourly averaged clearness index.”.

the number of hours where the number of the cloud layers is smaller than three is 98%. Thus, we recommend considering up to clouds with three layers in forecasting.

Here, the results in this study are compared with that of previous studies. Some results from satellite images are shown in [20], where the number of the cloud layers was evaluated through four years across the globe. According to Figure 1 of the study [20], the one-layered cloud is observed with the similar appearance frequency around Toyohashi city during DJF (December-January-February), MAM (March-April-May), JJA (June-July-August), and SON (September-October-November). On the other hand, as shown in Figure 2 of the study [20], the two-layered cloud are more observed during MAM and JJA. These are corresponding to the observation seen in Figure 5b the

appearance percentage of two-layered cloud are high from April to September.

In the future statistical study, we need to distinguish the type of clouds because the scattered amount of solar irradiation in clouds depends not only on the number of cloud layers but also on the type of clouds [16]. Further, not only the reduction in the mean solar irradiation but instant fluctuation of the solar irradiation also has effect on the PV power generation system [4], and this must be investigated.

Abbreviation

ASI	All sky imager
AMeDAS	Automated meteorological data acquisition system

CEE	Cloud enhancement event
DJF	December-January-February
GHI	Global horizontal irradiation
JJA	June-July-August
MAM	March-April-May
NWP	Numerical weather prediction
PV	Photovoltaic
SON	September-October-November

Conflict of interest

The author declare that they have no conflict of interest.

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Author contribution statement

Takahiro Bando: Conceptualization, Supervision, Writing – review & editing, Funding acquisition, Statistical analysis. Tsubasa Ito: Statistical analysis. Hayate Wakisaka: Statistical analysis. Yuki Miyahara: Data curation, Statistical analysis. Takeshi Aizawa: Data curation. Toru Harigai: Discussion on the analysis. Hirofumi Takikawa: Conceptualization, Discussion on the analysis, Supervision. Motohisa Hiratsuka: Providing measurement system. Shiro Maki: Providing measurement system.

Appendix A: Evaluation of the clearness index

The clearness index K_0 is written as.

$$K = H/H_0.$$

Here, H is the solar irradiation on a horizontal surface and H_0 is the extra-terrestrial solar irradiance on a horizontal surface. H_0 can be written as.

$$H_0 = G_0 E_0 \sin \alpha.$$

G_0 is the solar constant (1.367 kW/m^2). E_0 is the eccentricity correction factor of the Earth's orbit, derived from equation (10) of reference [29]. α is the solar altitude and is written as

$$\sin \alpha = \sin \phi \sin \delta + \cos \phi \cos \delta \cosh$$

ϕ is the latitude, δ is the Sun's declination, and h is the hour angle. The declination δ is derived with the Spencer's formula, equation (2) of reference [29]. In the calculation of h , we considered the difference in longitude between Akashi City, Hyogo Prefecture (135° longitude), where Japanese Standard Time is set, and the longitude for Toyohashi City, Aichi

Prefecture (137.4° longitude). We also considered the equation of time evaluated with equation (18) of reference [30].

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