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An Assessment of the Influences of Clouds on the Solar Photovoltaic Potential over China

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Abstract: Clouds are important modulators of the solar radiation reaching the earth's surface. However, the impacts of cloud properties other than cloud cover are seldom mentioned. By combining the satellite-retrieved cloud properties, the latest radiative transfer model, and an advanced PVLIB-python software for solar photovoltaic (PV) estimation, the impacts of different types of clouds on the maximum available solar PV potential (measured with the plane-of-array-irradiance, POAI) are quantified. The impacts of ice and liquid water clouds are found to be the highest on Tibetan Plateau over western China in spring, and central and southern China in winter, respectively. The reduction of POAI by liquid water clouds is almost twice of that by ice clouds except for spring. It is found that the POAI can be reduced by 27–34% by all clouds (ice + liquid water clouds) in different seasons. The sensitivities of the solar PV potential to the changes in cloud properties including the cloud fraction, cloud top pressure, cloud effective radius, and cloud water path are also analyzed. Three kinds of settings of PV panel tilting, namely fixed tilt, one-axis tracking, and two-axis tracking, are considered. It is found that the cloud properties are essential to estimate the solar PV potentials, especially for the cloud fraction. The attenuation of solar radiation by clouds are growingly larger as the solar plane tilting settings get more complicated. The outlook of solar PV potential is quite variable as the changes in cloud properties are highly uncertain in the future climate scenarios.

Keywords: solar photovoltaic; cloud properties; cloud impacts



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1. Introduction

Solar energy has become one of the most popular renewable energy sources as it is vast and inexhaustible. However, when the solar radiation is transmitted through the atmosphere, several atmospheric components such as clouds, aerosols, water vapor, carbon dioxide, and ozone attenuate the shortwave radiation by scattering and absorbing processes [1–3]. Among all the atmospheric factors, clouds are found to be one of the largest contributors to the reduction of the solar radiation reaching the surface. However, specifically, how the surface solar radiation (SSR) is affected by the cloud types and cloud properties remain unsolved.

Previous studies have recognized that clouds are important modulators of the SSR. Hatzianastassiou et al. [4] found that the increasing trend of the global SSR from 1990 to 2000 can be largely explained by the decrease of low cloud amount. The sunshine duration and the total cloud cover over the Iberian Peninsula were found to be strongly negatively correlated [5]. Stjern et al. [6] stressed the importance of clouds which contribute to the increase/decrease of SSR, leading to global brightening/dimming. Xia [7] pointed out that it is the trend of changes in low-level cloud cover instead of that of the total cloud cover which contributes to the sunshine duration trend in southern China. The study by Bonkaney et al. [8] revealed the different impacts of cloud cover and dust on the photovoltaic (PV) module in Niamey, with the former factor being immediate and the later factor being persistent and accumulative. Li et al. [9] used satellite-derived surface

irradiance and a PV performance model to find out comparable impacts of aerosols and clouds on the PV potential over northern and eastern China. Hill et al. [10] calculated the effects of 12 cloud types on the regional radiation budget over southern West Africa by combining multi-satellite retrievals and radiative transfer modeling. Yang et al. [11] found that the ‘dimming’ and ‘brightening’ over China over the past 60 years are closely related to the cloud ‘shrinking’ and ‘optical thinning’, and the subsequent recovery. Dumka et al. [12] pointed out the much larger impacts of clouds than aerosols on the solar energy potential over the central Gangetic Himalayan region. Based on multi-source data and radiative transfer model, Wang et al. [13] explored the potential driving factors on the SSR trends over China during 2005–2018. They also pointed out that the different changes in high-, middle-, and low-level clouds contribute differently to the SSR trend in southern China. Yang et al. [14] identified the dramatic differences in the solar PV potentials over southern China and northern India, and attributed the reasons to the different cloud and aerosol types as well as their properties between the two regions.

From the above analysis, it is found that although clouds exert remarkable influences on the surface solar irradiance, the studies that quantify the influences of clouds and their properties are rare. Furthermore, the relative importance of different cloud types and cloud properties on the solar PV potential is still not clear. This is partially due to the lack of reliable knowledge about the distributions of various cloud types and their properties. This study aims at quantifying the reductions of surface solar PV potential by different cloud types and their sensitivities to the related cloud properties. This paper is organized as follows. Section 2 introduces the data sets, method, and the model used in this study. The results are presented in Section 3. Section 4 discusses and summarizes the conclusions.

2. Materials and Methods

2.1. Data

The cloud phase and cloud property retrieval products (“MYD06_L2”) from the AQUA MODIS (Moderate resolution Imaging Spectroradiometer) level-2 Collection 6 data set [15], including the cloud effective radius (CER), cloud optical depth (COD), and cloud water path (CWP) at 1 km resolution [16], and the cloud top pressure (CTP) and cloud fraction (CF) at 5 km resolution [17–19], are used. The cloud phase is separated by the MODIS cloud phase product (“Cloud_Phase_Optical_Properties” for the 1 km resolution variables and “Cloud_Phase_Infrared” from 8.5 μm and 11 μm bands for the 5 km resolution variables [20]. Note the MODIS cloud phase products only distinguish ice and liquid water clouds, while the other clouds that could not be classified as the ice or liquid water clouds are classified as uncertain clouds (including the mixed-phase clouds and others). Kahn et al. [21] found that the ice optical properties (CER and COT) from MODIS and AIRS (Atmospheric Infrared Sounder) are highly consistent for single-layer, homogeneous clouds. Compared with the surface observation, the MODIS COD are overestimated when liquid water clouds are optically thin, while the CER from the sky radiometer and MODIS are generally poorly correlated [22]. Huo et al. [23] and Yang et al. [24] reported that the MODIS cloud top height is generally underestimated for about 1 km lower than that retrieved by the ground-based cloud radar over Beijing and SACOL site in China, respectively. In general, the performance of the MODIS cloud property retrievals is dependent on various factors including but not limited to the surface state, cloud thickness, cloud overlap, observation/zenith angle, etc. Given that there are some uncertainties, the MODIS cloud property data set is still a high-quality data set which provides comprehensive cloud properties on the global scale. We follow the same methodology described in Yi et al. [25,26] to process the level-2 data variables for ice and liquid water clouds into daily and monthly level-3 products at $0.5^\circ \times 0.5^\circ$ spatial resolution for one year (2012).

The ERA-interim atmospheric reanalysis data set [27] is used to provide vertical atmospheric profiles of pressure, temperature, moisture, and trace gases which are needed for radiative transfer calculations. The default profiles with 37 vertical pressure levels are

interpolated to 101 levels ranging from 1000 hPa to 1 hPa to increase the vertical resolution for radiative transfer simulations.

The Clouds and the Earth's Radiant Energy System (CERES) SYN1deg (Synoptic) Edition 4A data set [28,29] that provides the solar irradiances at the surface are provided for comparison against simulation results. This product includes the direct and diffused components of the surface shortwave (SW) radiant fluxes at the spatial resolution of $1^\circ \times 1^\circ$ under four conditions with or without clouds and aerosols. For this study, we used the all-sky-no-aerosol (including clouds without aerosols) and the pristine (no aerosols and no clouds) conditions because our simulations do not consider the impacts of aerosols.

2.2. Models

The rapid radiative transfer model for general circulation model applications (RRTMG) [30] has been widely used in various studies and have been proven to be relatively fast and accurate. The RRTMG SW has 14 bands and is based on a two-stream approximation for multiple scattering [31]. The Monte-Carlo-independent column approximation [32,33] has been implemented in RRTMG to improve the representation of subgrid cloud overlap conditions. In addition, the cloud optical property parameterization schemes in the RRTMG model has been updated with the MODIS collection 6 cloud particle models [26]. Our previous studies show that such an update is critical to accurately simulating the cloud radiative effects.

The PVLIB-python (version 0.7.2) is a numerical modeling system to estimate the solar photovoltaic generation based on the inputs of direct and diffused surface solar radiation and the atmospheric condition [34,35]. The PVLIB-python package is capable of modeling the impacts of different settings of solar panel adjusting scheme, such as the FIX setting in which the angle between the solar panel and the ground surface (tilting angle), as well as the azimuthal angle is fixed at the optimal values and could not be changed; the one-axis tracking (OAT) setting in which the azimuthal angle of solar panel can be adjusted to track the east–west movement of the sun; and the two-axis tracking (TAT) setting in which both the azimuthal angle and the tilting angle can be adjusted to track the position of the sun at all times.

2.3. Methodology and Experiment Design

In this study, we combine the ERA-interim atmospheric profile and the MODIS cloud property products and implement the RRTMG model to generate the direct and diffused components of the surface downward solar irradiances. The simulation processes are simplified as follows to avoid the influence from the other factors. The monthly averages of the gridded ice and liquid water cloud properties (including the CF, CER, CTP, COD, and CWP) in 2012 are used. In the RRTMG simulations, the cloud layer is set to occupy the atmospheric layer that is directly underneath the cloud top which is determined by the CTP. In the all cloud case (both ice and liquid water clouds exist), the higher ice and lower liquid water cloud layers are assumed to be random-maximum overlapped. The solar zenith angle is set as the daily averaged solar zenith angle [36] on the fifteenth day of the corresponding month at each grid cell. The surface is assumed to be lambertian, and the surface albedo is derived from the ERA-Interim reanalysis. As the focus of this study is on the impacts of clouds, no aerosols are considered here. Thus, the radiative transfer calculations are carried out under pristine (no-cloud-no-aerosol), cloudy-no-aerosol (ice cloudy-no-aerosol and liquid water cloudy-no-aerosol), and all-sky-no-aerosol conditions, respectively. The radiative effect of clouds (CRE) is defined as the difference in the irradiances between the conditions with and without the presence of clouds. This study mainly considers two cloud types, namely ice cloud (IC) and liquid water cloud (LWC), as were identified in the MODIS cloud retrieval algorithm. The contributions of individual cloud types can be conveniently separated and quantified as follows.

The PVLIB-python software is applied to estimate the solar photovoltaic potentials (denoted as the plain-of-array irradiance, POAI in the unit of $\text{kWh m}^{-2}\text{d}^{-1}$) by taking the

RRTMG simulated irradiances as inputs. The POAI is the incident solar irradiance on the PV panel which depends on several conditions [9,14]. We express the reductions in the solar photovoltaic potential by clouds in terms of cloud impacts written as ΔPOAI , thus

$$\Delta\text{POAI} = \text{POAI}_{\text{pristine}} - \text{POAI}_{\text{cloudy}}, \quad (1)$$

where $\text{POAI}_{\text{cloudy}}$ refers to the POAI under cloudy-no-aerosol condition and $\text{POAI}_{\text{pristine}}$ refers to the POAI under pristine (no-cloud-no-aerosol) condition. In this way, we could derive the ice cloud impact (ICI), liquid water cloud impact (LWCI), as well as all cloud impact (ACI) on the POAI.

One set of experiments is designed to recognize the sensitivities of different cloud impacts on POAI to the PV panel tilting setting, which are the fixed tilting (FIX), one-axis tracking (OAT), and two-axis tracking (TAT). Here, the FIX experiment is also referred to as the control (CTL) case. Note the tilting angle in the FIX setting is configured to be equal to the latitude of the desired position in degrees in this study.

Another set of experiments is designed to examine how the cloud impacts on POAI will change in response to future climate change when clouds are expected to occur less frequent (CF decreases by 10%), indicate higher cloud tops (CTP decreases by 10%), have smaller particle size (CER decreases by 10%), and become thicker (CWP increases by 10%) [37–39]. Note the CWP is calculated from the COD and the CER in the MODIS satellite retrieval algorithm [15], the changes in the CWP have the same effect as the changes in the COD when the CER is fixed. As there is no consensus on how the cloud properties could vary in the future climate, the 10% variations in the CF, CTP, CER, and CWP is only regarded as a simple emulation of the future changes.

3. Results

In this section, the distributions of the IC and LWC properties are presented for the various seasons in Section 3.1. A rough comparison of the surface downward SW fluxes and the cloud radiative effects between CERES data and the RRTMG simulation is given in Section 3.2. The ICI, LWCI, ACI on the POAI are quantified, respectively, in Section 3.3. The sensitivity experiments which depict the influences of changes in cloud properties and the effects of PV panel tilting settings are shown in Sections 3.4 and 3.5, respectively.

3.1. The Physical and Optical Properties of Ice and Liquid Water Clouds

3.1.1. Ice Clouds

The physical and optical properties (CF, CTP, CER, and COD) of ice clouds for the four seasons (spring: March–April–May, MAM; summer: June–July–August, JJA; autumn: September–October–November, SON; winter: December–January–February, DJF) are shown in Figure 1. Overall, the ice cloud properties exhibit strong but different seasonal variations in different regions. The ice CF (Figure 1a–d) is generally higher in spring and summer and lower in autumn and winter, and is generally higher to the north of 30°N than that to the south of 30°N except for summer. The ice clouds over southern China mostly have higher cloud tops than the northern China especially for summer (Figure 1e–h) partially due to the stronger and more frequent convections in southern China. Northeastern China has the lowest cloud tops ranging from 400–500 hPa in winter. Note larger CTP corresponds to lower cloud top height, and vice versa. The ice CER also shows strong north–south contrast with the northern ones being twice as large as the southern ones (Figure 1i–l). The ice COD is different from the other cloud properties in that central and southern China frequently have higher COD than the other regions, especially for boreal spring and winter (Figure 1m–p).

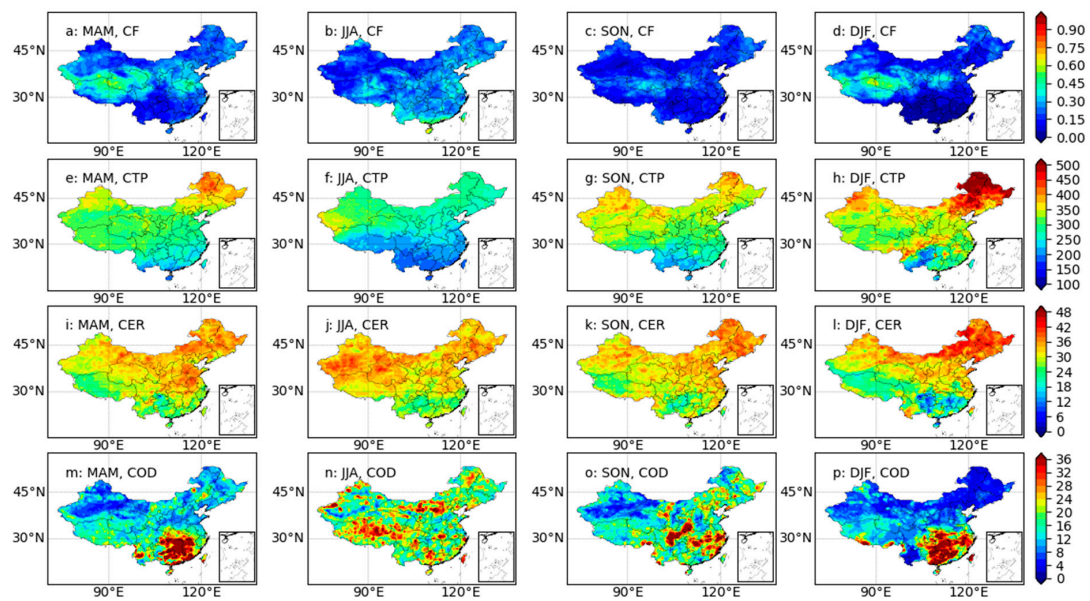


Figure 1. The seasonal averaged physical and optical properties of ice clouds over China: (a–d) cloud fraction (CF); (e–h) cloud top pressure (CTP, unit: hPa); (i–l) cloud effective radius (CER, unit: μm); (m–p) cloud optical depth (COD). The columns from left to right denotes the cases in boreal spring (March–April–May, MAM), summer (June–July–August, JJA), autumn (September–October–November, SON), and winter (December–January–February, DJF), respectively.

3.1.2. Liquid Water Clouds

The physical and optical properties of liquid water clouds for the four seasons are shown in Figure 2. Contrary to the ice clouds, the liquid water clouds occur more frequently in the central and southern China with the largest CF occurring in winter (Figure 2a–d). The CTP distribution shows a pattern of west–east contrast with the eastern part constantly having CTP larger than 700 hPa, while the CTPs in the western parts are lower than 450 hPa (Figure 2e–h). This is due to the large differences in topography between the west and east in China. Similarly, the liquid water cloud CERs are apparently larger in western China than eastern China (Figure 2i–l). In the winter, northern and northeastern China also show large CER of more than 20 μm . The liquid water COD is similar to the ice COD counterpart in terms of the spatial pattern in the four seasons with the highest COD occurring in southern China except for summer (Figure 2m–p). The features of the cloud properties are similar as the results found in previous studies [37,38].

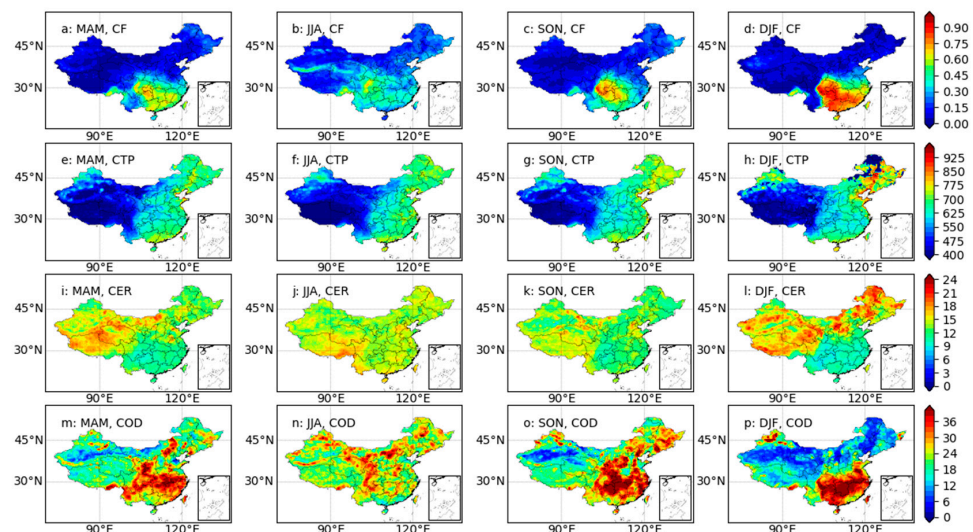


Figure 2. The same as Figure 1, but for the liquid water clouds.

3.2. The Comparison between CERES Data and the Control Simulation

We first set up the control simulation case which is calculated by using the RRTMG SW RTM with ERA-interim reanalysis atmospheric profiles and the MODIS cloud properties as inputs. Note aerosols are not included in the calculation. Thus, the suitable counterpart for comparison purpose is the CERES SYN1deg data set under all-sky-no-aerosol condition. The surface downward shortwave radiative fluxes and the surface cloud radiative effects (which is defined as the difference in SW downward radiative fluxes between pristine and all-sky-no-aerosol conditions) are displayed in Figure 3. It is found that the surface SW downward fluxes in the control simulation (Figure 3e–h) are larger than those in the CERES SYN1deg data set (Figure 3a–d) by 8.3–10.5%, while the surface cloud radiative effects in the control simulation (Figure 3m–p) are lower than the counterparts in CERES data set (Figure 3i–l) by 14.5–21.2%. These differences could be due to a couple of reasons such as the differences in the sampling sizes in time and space, the biases in cloud property retrieval, the biases in RTM calculations, the other unconsidered missing cloud types, etc. Thus, we do not intend for a rigorous comparison but instead for a qualitative examination of the simulation results. In this sense, the performance of the control case simulation is reasonable when compared to the CERES products in terms of the spatial distribution and seasonal variation of the surface fluxes and cloud radiative effects.

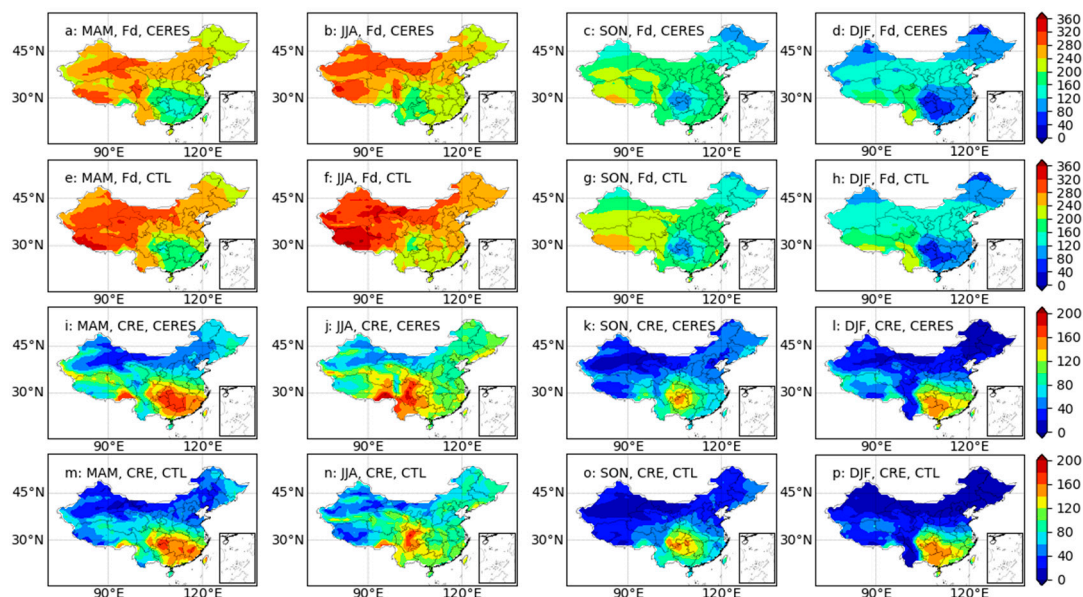


Figure 3. The comparison of the downward shortwave radiative fluxes (Fd) and the cloud radiative effects (CRE) at the surface between the CERES SYN1deg data and the control (CTL) simulation (unit: W m^{-2}). (a–d) the downward shortwave radiative fluxes from the CERES SYN1deg data set; (e–h) the downward shortwave radiative fluxes from the control simulation; (i–l) the cloud radiative effects from the CERES SYN1deg data set; (m–p) the cloud radiative effects from the control simulation. The columns from left to right denotes the cases in boreal spring (MAM), summer (JJA), autumn (SON), and winter (DJF), respectively.

3.3. The Impacts of Different Cloud Types on the POAI

In this sub-section, the influences of different types of clouds (namely IC and LWC) as well as all clouds (IC + LWC) on the POAI in the four seasons are derived by running another two separate cases specifying only ice clouds and only liquid water clouds in addition to the control simulation. Thus, the reductions of the surface POAI by IC/LWC is calculated as the differences between the POAI in the pristine case and that in the IC/LWC only case. Figure 4 depicts the distribution of POAI under all-cloud-no-aerosol condition and the impacts of ice, liquid water, and all clouds in the four seasons. The northern part of China typically has higher POAI than the southern China (Figure 4a–d). It is also interesting

to find that the POAI in western China is much higher in spring and autumn, while the POAI in southern China is higher in spring and summer. Similar features can be found in Li et al. [9] and Yang et al. [14], although aerosols are not considered in our case, which indicates the important influences of clouds. Overall, the averaged POAI under all-cloud condition over China in the four seasons are 6.44 (spring), 5.85 (summer), 6.13 (autumn), and 5.6 (winter) $\text{kWh m}^{-2}\text{d}^{-1}$, respectively.

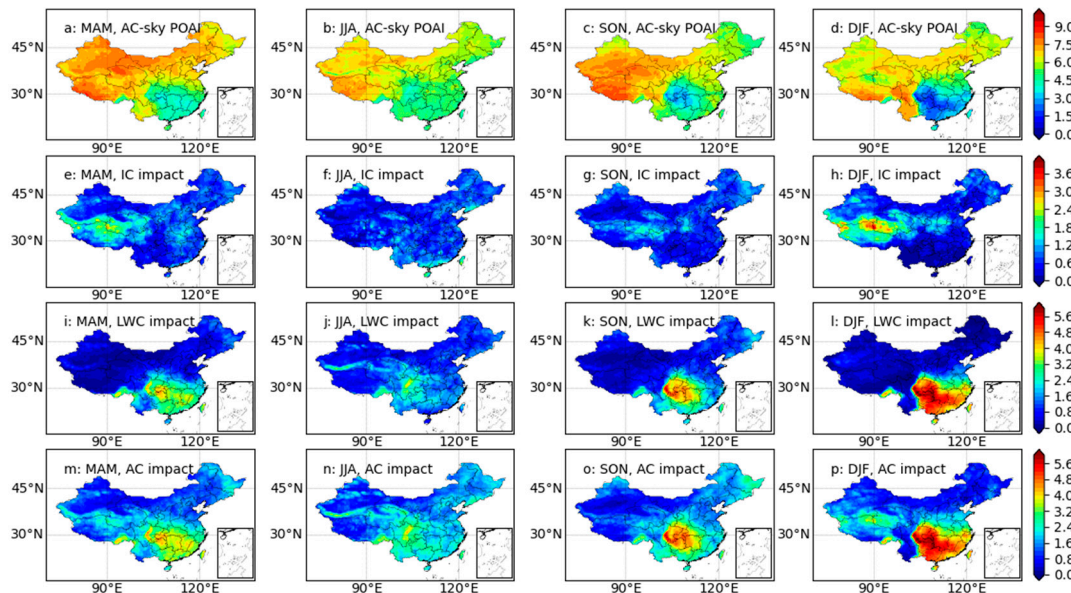


Figure 4. The seasonal distributions of POAI under all-cloud condition (a–d) and the reductions of POAI by ice clouds (IC, e–h), liquid water clouds (LWC, i–l), and all clouds (AC, m–p). Unit: $\text{kWh m}^{-2}\text{d}^{-1}$. The columns from left to right denotes the cases in boreal spring (MAM), summer (JJA), autumn (SON), and winter (DJF), respectively.

The reductions of POAI by ice clouds (which is the ICI) are mostly low over the low altitude regions locating at the eastern and southern parts of China, and are much stronger over the Tibetan Plateau (Figure 4e–h). This is partially because the ice CF over the Tibetan Plateau are higher than elsewhere in China (see Figure 1a–d). Although the ice COD is high in spring and winter in southern China, the POAI is not significantly affected by ice clouds due to the low occurrence frequency. Overall, the ice clouds contribute to the highest reduction of POAI of $0.82 \text{ kWh m}^{-2}\text{d}^{-1}$ (12.8% of the all-cloud sky POAI) in spring and a lowest reduction of POAI of $0.63 \text{ kWh m}^{-2}\text{d}^{-1}$ (10.3% of the all-cloud sky POAI) in autumn in China. However, on regional scale, the ICI can be up to 50% of the surface POAI on the Tibetan Plateau.

The POAI reduction by liquid water clouds (which is the LWCI) corresponds well with the liquid water CF and the strongest influence is found around southern China with the national average of $1.23 \text{ kWh m}^{-2}\text{d}^{-1}$ (22% of the all-cloud sky POAI) in winter (Figure 4i–l). In the other seasons, the POAI reduction due to liquid water clouds also surpasses $1 \text{ kWh m}^{-2}\text{d}^{-1}$ and increases sequentially from spring to winter (ranging from 16.2–22% of the all-cloud sky POAI). This feature also corresponds well with the results by Yang et al. [14] in that the POAI over southern China is constantly attenuated by middle- and low-level clouds. The changes in the cloud impacts are likely related to the large-scale weather systems that take effect in different seasons, such as the Asian summer monsoon. Comparing the ICI and LWCI, we could find that the LWCI is almost always twice as large as the ICI in every season except for spring.

The effect of all clouds on the POAI is mostly a combination of the ICI and LWCI except for some regions where the IC and LWC overlapped (Figure 4m–p). However, as the LWCI is apparently stronger than the ICI in southern China, while the reverse is true

over the northwest and the Tibetan Plateau, we could find that the relative importance of ice and liquid water clouds are different region by region.

3.4. Sensitivities of the Cloud Impacts on POAI to Various Cloud Properties

Under the future climate scenarios, the physical and optical properties of clouds are expected to change accordingly. According to the latest IPCC 6th assessment report [39], the clouds are anticipated to occur less frequently but grow to a higher altitude. The high-latitude clouds are believed to increasingly turn into more numerous but small liquid water cloud droplets from large ice crystals. Thus, we design a couple of sensitivity experiments to explore the interesting question of how the impacts of clouds on the POAI will vary in response to the possible cloud property changes in the future. These sensitivity experiments include: (1) a 10% decrease in the CF; (2) a 10% decrease in the CTP; (3) a 10% decrease in the CER; (4) a 10% increase in the CWP of the IC, LWC, and all clouds. The results of the sensitivity experiment are shown in Figure 5 and the averaged values are outlined in Table 1. The annual averaged impacts of ice, liquid water, and all clouds on the POAI from the control case are displayed in Figure 5a–c, respectively. The impact of liquid water clouds is about 1.6 times larger than that of the ice clouds, while they affect different areas of China as is discussed in the last sub-section. Since there are some overlaps between ice and liquid water clouds, the all-cloud impact is not a simple summation of those of the ice and liquid water clouds.

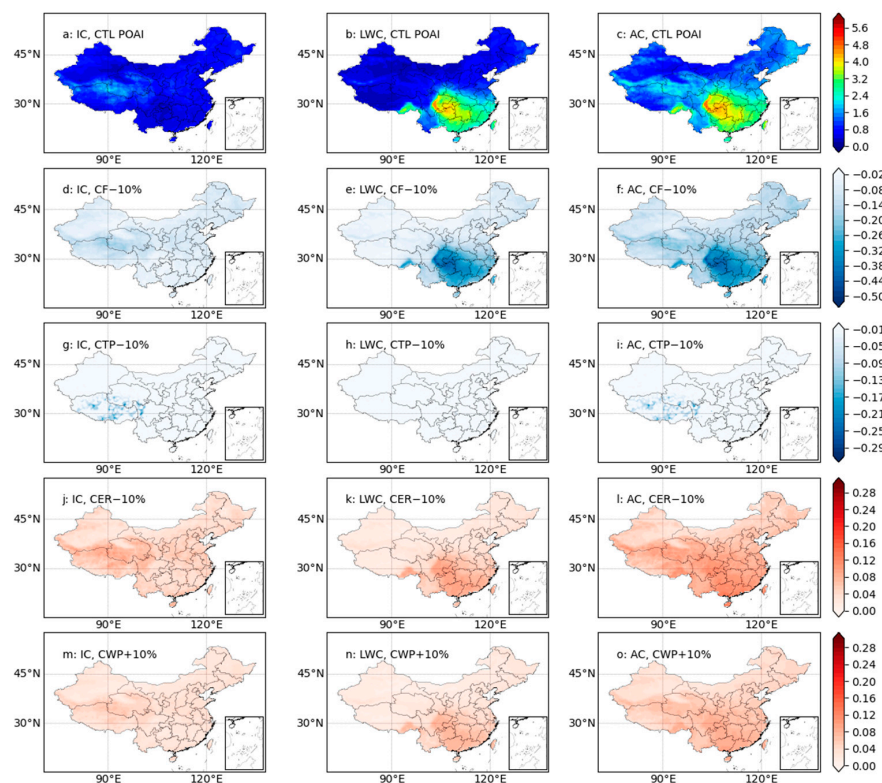


Figure 5. The annual averaged reductions of POAI (a–c) by ice (left column), liquid water (middle column), and all clouds (right column). Unit: $\text{kWh m}^{-2}\text{d}^{-1}$. The panels (d–o) show the differences in POAI reduction in various experimental cases and the control case (the former minus the later): (d–f) the case with cloud fraction decreased by 10%; (g–i) the case with cloud top pressure decreased by 10%; (j–l) the case with cloud effective radius decreased by 10%; (m–o) the case with cloud water path increased by 10%.

Table 1. Sensitivities of averaged POAI to the variations of cloud properties (unit: kWh m^{−2}d^{−1}). The numbers in the parentheses indicate the relative changes in POAI to that of the control case in percentage.

Experiments		CTL	(CF − 10%) − CTL	(CTP − 10%) − CTL	(CER − 10%) − CTL	(CWP + 10%) − CTL
FIX	IC	0.72	−0.08 (−11%)	−0.01(0%)	0.04 (5.6%)	0.03 (4.2%)
	WC	1.16	−0.12 (−10.3%)	0.0 (0%)	0.03 (2.6%)	0.03 (2.6%)
	AC	1.78	−0.17 (−9.5%)	−0.01 (0%)	0.07 (3.9%)	0.05 (2.8%)

With the 10% decrease in the CF, less clouds are attenuating the solar radiation reaching the surface. It can be seen that the decreases in the cloud impacts on the POAI are almost proportional to the reductions in the CF, which is also about 10% for ice, liquid water, or all-cloud cases (see Table 1 and Figure 5d–f). However, the same 10% decrease in the CF results in much stronger reduction of the LWCI than the ICI. It is important to also note that the reductions of LWCI and ICI are not temporally and spatially uniform.

From Figure 5g–i and Table 1, we find that the minor changes in the CTP (which determines the location of the cloud layer in this study) do not induce remarkable changes in the POAI. Only a portion of ice clouds over the Tibetan Plateau are affected by the lifted cloud layer and result in lower impacts on the POAI.

It is interesting to observe that the cloud impacts on the POAI both increase for the ice and liquid water cloud cases at the same magnitude when the CER decreases. This indicates that the ICI are more effectively affected by the effective particle size than the LWCI. As the ice clouds are expected to transform into liquid water clouds in a warmer climate as depicted in the IPCC AR6, the influences of CER decrease on the POAI could be reduced.

For the case with 10% increase in the CWP, the results also show an increase in the ICI and LWCI which is similar in magnitude and distribution pattern as the CER case. It should be noted that although we derived the impacts of cloud properties by perturbing one variable at a time, the real process could be much more complicated involving multivariable changes at the same time. Further studies are still needed to explore this problem.

3.5. The Sensitivities of Cloud Impacts to the Solar PV Panel Tilting Settings

The PV panel array which is configured as tilted and fixed (FIX case) for maximum solar irradiance is used in the above analysis as the control case. There are some other configurations that are also implemented, such as the one-axis tracking (OAT) and two-axis tracking (TAT). The OAT setting means the PV panel array has a fixed tilting angle but is capable to rotate around a horizontal axis to track the movement of the sun from east to west during a day. The TAT setting means the PV panel can be adjusted around two axes to keep it pointed normal to the sun for maximum incident irradiance. It is important to know how the impacts of clouds on the POAI can be affected by the PV panel settings. Figure 6 shows the seasonal averaged cloud impacts on the POAI from two additional sensitivity experiments that apply the OAT and TAT settings. Table 2 summarizes the averages of cloud impacts on POAI using the OAT and TAT settings in China. In comparison with the control experiment where the FIX setting is applied (Figure 4), the OAT experiment shows quite similar results of POAI reductions by ice, liquid water, and all clouds. In fact, the cloud impacts on the POAI for the OAT case is slightly lower than those for the control (FIX) case in spring and summer, while the situation reverses in autumn and winter. Overall, the differences in the all-cloud sky POAI and the cloud impacts between the FIX and OAT cases are minor.

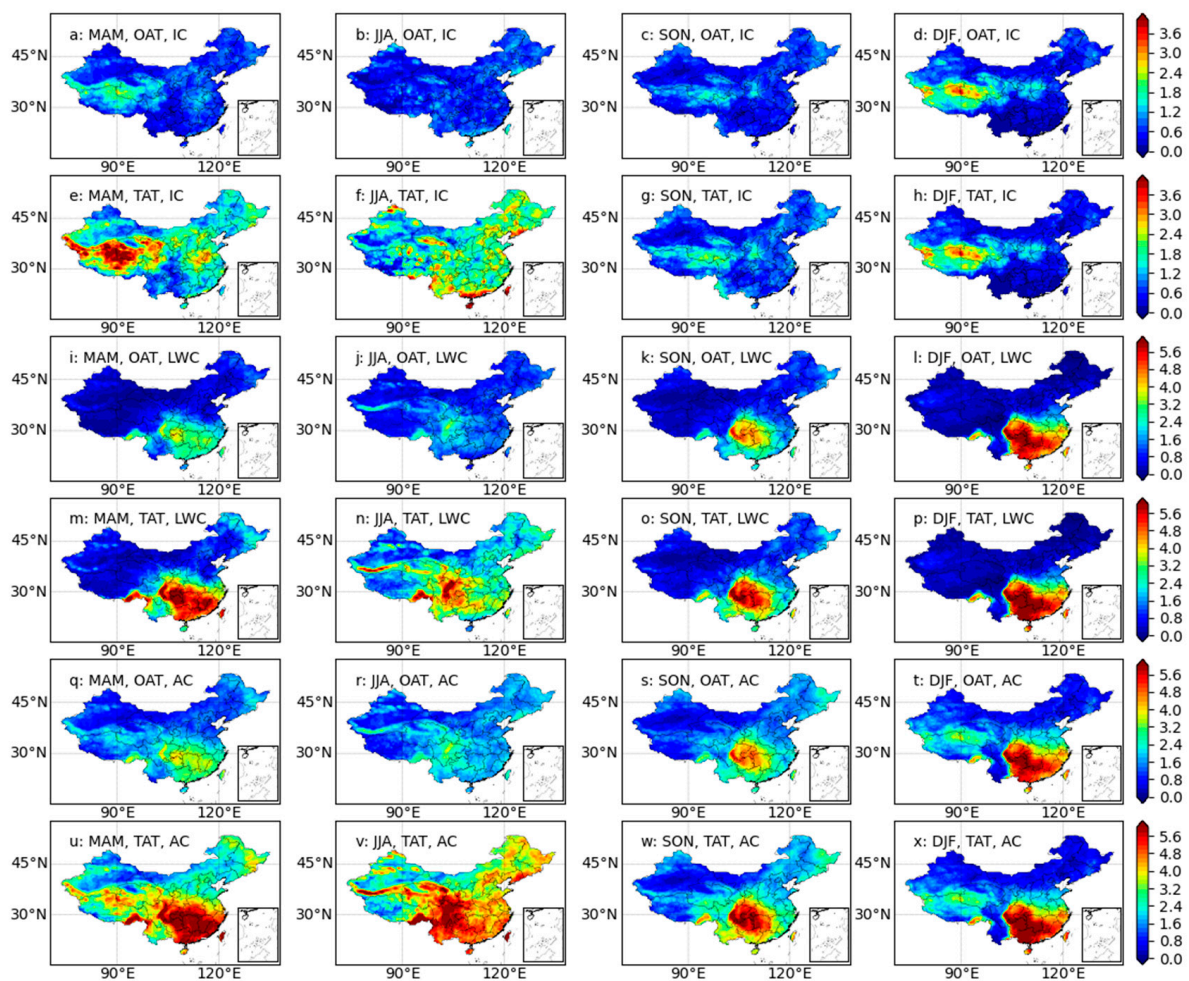


Figure 6. The seasonal averaged reductions of POAI by ice, liquid water, and total clouds under one-axis-tracking (OAT) and two-axis-tracking (TAT) experiments (unit: $\text{kWh m}^{-2}\text{d}^{-1}$). (a–d) the POAI reduction by ice clouds with OAT; (e–h) the POAI reduction by ice clouds with TAT; (i–l) the POAI reduction by liquid water clouds with OAT; (m–p) the POAI reduction by liquid water clouds with TAT; (q–t) the POAI reduction by all clouds with OAT; (u–x) the POAI reduction by all clouds with TAT. The columns from left to right denotes the cases in boreal spring (MAM), summer (JJA), autumn (SON), and winter (DJF), respectively.

Table 2. Sensitivities of regional averaged POAI to the PV panel axis settings (unit: $\text{kWh m}^{-2}\text{d}^{-1}$). The numbers in the parentheses indicate the cloud-induced POAI reductions relative to the all-cloud sky POAI in percentage.

Experiments		Spring	Summer	Autumn	Winter
OAT	IC	0.76 (12.4%)	0.59 (10.6%)	0.62 (10.5%)	0.77 (14%)
	WC	0.97 (15.8%)	1.07 (19.1%)	1.18 (19.9%)	1.29 (23.5%)
	AC	1.65 (26.8%)	1.54 (27.4%)	1.71 (28.8%)	1.99 (36.2%)
TAT	IC	1.67 (18.4%)	1.66 (17.9%)	0.81 (11.6%)	0.76 (14.6%)
	WC	1.78 (19.6%)	2.36 (25.4%)	1.53 (22%)	1.35 (26%)
	AC	3.26 (35.8%)	3.68 (39.6%)	2.21 (31.8%)	2.04 (39.2%)

For the TAT experiment, it is found that the impacts of clouds on the POAI apparently increase, and the ice cloud impacts grow faster than the liquid water cloud. It is also interesting to note that the changes of cloud impacts are more significant in spring and summer (about $1 \text{ kWh m}^{-2}\text{d}^{-1}$ for the IC and about $0.81\text{--}1.3 \text{ kWh m}^{-2}\text{d}^{-1}$ for the LWC) than those in autumn and winter (lower than $0.35 \text{ kWh m}^{-2}\text{d}^{-1}$), thereby changing the

seasons when the cloud impacts maximize. As a result, although the surface POAI could be increased under the TAT panel setting, the cloud impacts have doubled (more than 30% of the all-cloud sky POAI). It is worthwhile to study further that whether the relatively costly TAT PV panel array should be considered to universally applied in real circumstances.

4. Discussion and Conclusions

In this study, we focus on assessing the influences of clouds and cloud properties on the solar photovoltaic potential over China. Although clouds have long been recognized as the major component in the atmosphere to affect the solar radiation reaching the surface, the studies on how the cloud properties influence the solar photovoltaic potential are rare and limited partially due to the lack of appropriate data and methods for this purpose.

One year (2012) of level-2 cloud properties (including CER, COD, CWP, CTP, and CF) for ice and liquid water clouds from the MODIS collection 6 cloud retrieval products are processed following the method described in Yi et al. [16] to generate a $0.5^\circ \times 0.5^\circ$ degree grid data set for modeling experiments. The ERA-interim reanalysis data is used to provide the atmospheric vertical profile conditions. The RRTMG SW model (version 5) with updated MODIS collection 6 ice cloud radiative property parameterization scheme is used to provide accurate surface downward (direct and diffused) radiative fluxes under pristine, IC-no-aerosol, LWC-no-aerosol, and all-cloud-no-aerosol conditions. These fluxes are subsequently input to the PVLIB-python module to estimate the POAIs under different conditions, respectively. The absolute values of the cloud and cloud property impacts on the POAI can be estimated by taking the difference of POAI under pristine and cloudy-no-aerosol conditions. Note although only one year of cloud property data is used, it is deemed sufficient to represent the seasonal characteristic of cloud property conditions in China. It is observed that the physical and optical properties of the ice and liquid water clouds display distinct features in different areas of China, which indicates the different roles of clouds in specific regions.

The calculated surface downward SW radiative fluxes under all-cloud-no-aerosol condition as well as the cloud radiative effects are inter-compared with the counterparts from CERES SYN1deg data set. Although there exist several differences between our calculation and the CERES results including but not limited to the radiative transfer model, the vertical profiles of cloud layers, the atmospheric condition, etc., the two results are similar in magnitude and in the spatial distributions. This adds to our confidence that our approach mostly provides reasonable results for further analysis.

The impacts of different types of clouds on the POAI is first separated. The impacts of ice clouds are found to be low in the eastern and southern China, while they are much higher over the Tibetan Plateau, where the averaged values range from 0.63 to 0.82 kWh m⁻²d⁻¹ over China. This is closely related to the distributions of the ice CF and the other cloud properties. For certain region like the Tibetan Plateau, the ice cloud impact on the POAI can be more than half of the surface total POAI. The averaged impacts of liquid water clouds in every season over China are all higher than 1 kWh m⁻²d⁻¹ and is highest in winter (1.23 kWh m⁻²d⁻¹). However, the relative importance of ice and liquid water clouds varies depending on the time and location of interests. Overall, the ice cloud impacts range from 10–13% while the liquid water cloud impacts are 16–22% of the all-cloud sky POAI for various seasons. All clouds (IC + LWC) contribute to reduce the POAI by more than 27% with the largest reduction occurring in winter (34%).

We examine the sensitivities of the cloud impacts on the POAI to the cloud physical and optical properties by applying a 10% variation on the CF, CTP, CER, and CWP. In comparison with the control case where the cloud properties are not perturbed, it is interesting to find that the reductions of CF and CTP both contribute to reduce the cloud impacts with the former being almost proportional to the CF changes (also about 10%) and the latter being only effective to ice clouds. Conversely, the reduction of CER and the increase of CWP both acts to strengthen the cloud impacts at the similar magnitudes for ice and liquid water clouds.

Another sets of sensitivity experiments are carried out by applying the OAT and TAT PV panel tilting settings in the PVLIB-python system. It is found that the OAT panel setting is not expected to significantly increase the cloud impacts. However, the TAT panel setting will remarkably strengthen the cloud impacts especially in spring and summer. More in-depth investigations on the balancing between cost and performance are needed to answer the question of whether it is worthwhile to promote the OAT and TAT PV panels to replace the FIX tilting configuration.

This study presents unprecedented results concerning the impacts of ice and liquid water clouds on the surface solar PV potential. The sensitivities of the cloud impacts to the possible changes in the cloud physical and optical properties in the future are also investigated. Our findings are potentially useful for the location planning of new PV power plants as the cloud impact is a crucial factor, which amounts to 27–34% of the total POAI.

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