Solar dimming or brightening in the upper reaches of the Yangtze River Basin under 1.5 °C and 2 °C global warming targets?

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Abstract. Solar radiation, as the primary energy source of the Earth, influences the climate conditions and changes of our planet. Whether solar dimming or brightening would occur in the future under 1.5 °C and 2 °C global warming background was an important question. In this study, climate data under four Representative Concentration Pathway (RCP) scenarios were used to calculate and analyse temporal and spatial changes of solar radiation in the upper reaches of the Yangtze River Basin for the future period 2020-2099. Results showed that surface solar radiation would increase under RCP2.6 and RCP4.5, while it would decrease under RCP6.0 and RCP8.5. Especially, dramatic solar dimming would occur in all years in the future under RCP8.5, which indicated that the fluctuations of the amount of solar energy in the future were related to the emission scenarios. Spatially, under global warming 1.5 °C, solar brightening would occur mainly in the central regions and become weaker with the higher emission scenarios. However, under global warming 2 °C, solar dimming would occur mainly in the upper Jinsha River Basin and the lower reaches of the Jialing River Basin and become stronger with the higher emission scenarios. Relative to the other three RCP, obvious and dramatic solar dimming would occur under RCP8.5 in the total area.

1. Introduction

The United Nations Framework Convention on Climate Change 21st Conference of the Parties in 2015 published the Paris Agreement, which approved by about 200 countries and established the 1.5 °C and 2 °C global warming targets [1]. This goal required more focus on the impact evaluation under different climate scenarios in the future, and called for more assessments of climate change impact under the 1.5 °C and 2.0 °C warming scenarios [2].

Solar radiation, as the primary energy source of the Earth, influences the climate conditions and changes of our planet. The solar energy is an important component of the surface energy balance, which governs a lot of surface climatic and hydrologic processes [3]. During the latest 60 years, a large number of studies found that the surface solar radiation amount undergoes significant and decadal variations, such as from dimming to brightening in many regions of the world [4], always dimming in India, and from dimming to leveling off in China [5].

The Yangtze River is the third largest river in the world and the first largest river in China. In recent years, industrial development and expansion of urbanization had led to serious air pollution in
the Yangtze River Basin. High concentrations of air pollutants can affect spectral composition and the content of surface solar radiation [6]. Moreover, the study of the evolution of surface solar radiation in the Yangtze River Basin is unique because of its diverse climate and complex topography [7]. Former studies showed that global solar radiation over the Yangtze River basin decreased since 1960, but the decreasing trend did not persist into the 1990s which coincided with global dimming and brightening [8]. Moreover, a number of researchers [9-10] have examined the possible tendencies of climate and river discharge during future periods in the Yangtze River Basin at global warming of 1.5 °C and 2 °C. However, it remains an open question whether the surface solar radiation would be decreasing or increasing, in other words, solar dimming or brightening would occur in the future under 1.5 °C and 2 °C global warming targets.

In this study, to estimate the future variation of solar radiation, the Inter-Sectoral Impact Model Inter-comparison Project was used to present an analysis of temporal and spatial changes of solar radiation in the upper reaches of the Yangtze River Basin for the 1.5 °C and 2 °C global warming targets.

2. Data and methods

2.1. Study area
The upper reaches of the Yangtze River Basin are located in the west highland geographical region of China. This study focuses on the areas about 860000 km² controlled by the Cuntan station, which is the inflow site of the Three Gorges Reservoir. A subtropical monsoon is prevalent, with the annual average precipitation about 1018 mm and temperature about 12.3°C.

2.2. Data
Climate projections (annual average daily maximum/minimum air temperature) from four General Circulation models (GCM) (GFDL-ESM2M, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M respectively) and under four Representative Concentration Pathway (RCP) scenarios (2.6, 4.5, 6.0 and 8.5 respectively) are used in the study to calculate the amount of solar radiation for the reference period (1986-2005) and the future period (2020-2099). The GCM data had been downscaled to 0.5° resolution grid and bias-corrected to ensure long-term statistical agreement with the Water and Global Change data (http://www.eu-watch.org/data_availability) [11].

2.3. Methods
Solar radiation is estimated from air temperature based on Hargreaves & Samani [12] equation.

\[ \frac{R_s}{R_A} = a(\frac{T_m - T_m}{b})^{0.5} + b \]  

where \( R_s \) and \( R_A \) mean the surface and extraterrestrial solar radiation (MJ m\(^{-2}\) day\(^{-1}\)). \( T_m \) and \( T_m \) mean the daily maximum and minimum air temperatures (°C). \( R_A \), as the function of the latitude and day number of the year, is calculated presenting in Allen [13]. \( a \) and \( b \) are empirical coefficients (\( a=0.18 \) and \( b=-0.13 \) in this study).

3. Results and discussions
The reference period 1986-2005 was selected in this study, which was consistent with many other studies and showed 0.61 °C warmer than the period of 1850-1900 (preindustrial levels) [14-15]. Then 0.89 °C and 1.39 °C warmer than 1986-2005 could correspond to the 1.5 °C and 2 °C warming targets, compared to the preindustrial levels [10]. Global mean surface temperature with respect to the reference period was calculated from combinations of four GCMs and RCPs in this study. Results showed that global warming of 1.5 °C was likely to occur during the period 2020-2039 under the RCP 2.6, RCP 4.5, RCP 6.0, and global warming of 2 °C was likely to occur during the period 2040-2059 under the RCP4.5, RCP6.0 but 2020-2039 under the RCP 8.5. Especially, under RCP 2.6 warming did not reach 2 °C until 2099, whereas under RCP 8.5 warming had reached 1.5 °C threshold as early as 2010s.
3.1. Temporal variations of solar radiation

Relative changes in annual solar radiation for the future time horizon 2020-2099 in the upper Yangtze under the four RCPs were presented relative to the calculated solar radiation for the reference period (Figure 1). Results showed that high variability occurs between the different climate change scenarios.

Under RCP2.6, 62 years showed an increasing trend for the annual solar radiation in the period of 2020-2099, relative to the period of 1986-2005, but only 18 years showed a decreasing trend in the study area (Figure 1a). Especially, the range of simulation results from the average of four GCMs was -1.35% (in 2027) ~ 2.92% (in 2065). It should be noted that the average relative change of the results forced by all the 80 years was 0.71%, which indicated that annual solar radiation tended to slightly increase under RCP2.6. Moreover, the average relative change for the period of 2020-2039 (representing global warming 1.5 °C) was 0.27%, which indicated that slight solar brightening would occur under global warming 1.5 °C of RCP2.6.

Under RCP4.5, 55 years showed an increasing trend for the annual solar radiation and only 25 years showed a decreasing trend in the period of 2020-2099, relative to the reference period in the study area (Figure 1b). In these 80 years, the 2078 Year had the largest positive variation (2.51%), while the 2033 Year had the largest negative variation (-1.75%). Moreover, the average relative change of the results forced by all the 80 years was 0.40%, which was a little lower than that under RCP2.6 and also indicated that annual solar radiation tended to slightly increase under RCP4.5. The average relative change for the period of 2020-2039 (representing global warming 1.5 °C) and 2040-2059 (representing global warming 2 °C) were 0.23% and 0.37% respectively, which indicated that slight solar brightening would occur when global warming 1.5 °C and 2 °C under RCP4.5.

Under RCP6.0, 50 years showed a decreasing trend for the annual solar radiation in the period of 2020-2099 relative to the reference period, but only 30 years showed an increasing trend in the study area (Figure 1c). Especially, the range of simulation results from the average of four GCMs was -2.18% (in 2036) ~ 2.27% (in 2070). The average relative change of the results for all the 80 years was -0.26%, which indicated that annual solar radiation tended to slightly decrease under RCP6.0. Moreover, the average relative change for the period of 2020-2039 (representing global warming 1.5 °C) and 2040-2059 (representing global warming 2 °C) were -0.24% and -0.54% respectively, which indicated that slight solar dimming would occur under global warming 1.5 °C and 2 °C of RCP6.0.
Under RCP8.5, all 80 years showed an evidently decreasing trend for the period of 2020-2099 relative to the reference period in the study area (Figure 1d). The range of simulation results from the average of four GCMs was -6.51% to -9.99%, which was much lower than that from other three RCPs. Moreover, the average relative change of the results forced by all the 80 years was -8.68%, which was also much lower than that under the other three RCPs and indicated that annual solar radiation tended to dramatically decrease under RCP8.5. The average relative change for the period of 2020-2039 (representing global warming 2 °C) were -8.91%, which indicated that evident solar dimming would occur when global warming 2 °C under RCP8.5.

Overall, surface solar radiation would increase under RCP2.6 and 4.5, while it would decrease under RCP6.0 and 8.5 in the upper reaches of the Yangtze River Basin. Especially, dramatic solar dimming would occur in almost all years in the future under RCP8.5. This indicated that the fluctuations of the amount of solar radiation in the future were related to the different RCPs which meant the different radiative forcing and industrial CO₂ emissions. In a high-emission scenario, the amount of solar energy would show relatively decreasing tendency, whereas in a low-emission scenario, the corresponding solar energy would show relatively increasing tendency. Similarly, the tendency of the temperature and precipitation for the future periods was consistent with the different pathways [16]. However, the solar radiation tendency in this study was inconsistent with the results from previous study [17] in the Northeast Asia region, which concluded that solar radiation would decrease in the future for all the RCPs, except for the RCP 2.6.

3.2. Spatial variations of solar radiation
The spatial pattern of relative changes of solar radiation for the period of 2020-2039 under RCP2.6, which represented that the annual average temperature increased 1.5 °C compared with the reference period in the upper Yangtze was shown in Figure 2. The relative changes of solar radiation for 2020-2039 had a median of 0.34% with a range from -2.27% to 2.50%. The areas which showed relatively decreased trends in solar radiation accounted for 35% of the study area, mainly observed in the upper reaches of Jinsha River Basin and the lower reaches of the Jialing River Basin, whereas the areas showing increasing trends accounted for 65% of the study area, predominantly located in the central regions, especially in the Sichuan Basin and the lower reaches of the Jinsha River Basin.

Figure 2. Spatial distribution of relative changes of solar radiation for the period of 2020-2039 (representing global warming 1.5 °C) under RCP2.6 compared with the reference period of 1986-2005 in the upper Yangtze.

The spatial distribution of relative changes of solar radiation for the period of 2020-2039 and 2040-2059 under RCP4.5 (corresponding to global warming 1.5 °C and 2 °C respectively) compared with the reference period in the upper Yangtze was shown in Figure 3. The relative changes of solar radiation for 2020-2039 had a median of 0.28% with a range from -2.51% to 2.25% (Figure 3a), while the relative changes of solar radiation for 2040-2059 had a median of 0.55% with a range from -2.78%
to 4.25% (Figure 3b). There was not dramatic difference in the spatial patterns of solar radiation change for the period of 2040-2059 and 2020-2039. The areas where relatively decreased trends occurred in solar radiation accounted for about 45% of the whole study area, mainly located in the upper Jinsha River Basin and the Jialing River Basin, whereas the areas where relatively increased trends occurred accounted for 55%, mainly observed in the central low latitude regions, especially in the Sichuan Basin and the lower reaches of the Jinsha River Basin. However, the ranges showing not only relative decreasing but also relative increasing in 2020-2039 showed evidently wider than that in 2040-2059. For example, the areas accounting for about 20% showed more than 0.5% negative change of solar radiation in 2020-2039 but more than 1% negative change in 2040-2059. Similarly, the areas accounting for about 25% showed more than 1% positive change of solar radiation in 2020-2039 but more than 2% positive change in 2040-2059.

Figure 3. Spatial distribution of relative changes of solar radiation for the period of 2020-2039 and 2040-2059 under RCP4.5 (representing global warming 1.5 °C and 2 °C respectively) relative to the reference period of 1986-2005 in the upper Yangtze.

Figure 4. Spatial distribution of relative changes of solar radiation for the period of 2020-2039 and 2040-2059 under RCP6.0 (representing global warming 1.5 °C and 2 °C respectively) relative to the reference period of 1986-2005 in the upper Yangtze.

The spatial distribution of relative changes of solar radiation for the period of 2020-2039 and 2040-2059 under RCP6.0 (corresponding to global warming 1.5 °C and 2 °C respectively) compared with the reference period in the upper Yangtze was shown in Figure 4. The relative changes of solar radiation for 2020-2039 had a median of -0.24% with a range from -2.45% to 0.61% (Figure 4a), while the relative changes of solar radiation for 2040-2059 had a median of -0.54% with a range from -2.78% to 0.92% (Figure 4b). There was dramatic difference in the spatial patterns of solar radiation change for the period of 2040-2059 and 2020-2039. The area showing a relative decreasing solar
radiation in 2040-2059 (accounting for >85%) had a wider distribution than that in 2020-2039 (accounting for about 50%). The areas showing relative increasing trends in solar radiation contents were predominantly located in the central regions and the upper reaches of the Jialing River Basin in 2020-2039, whereas almost all of the areas showed decreasing trends in 2040-2059, especially in the upper reaches of the Jinsha River Basin and the lower reaches of the Jialing River Basin. This indicated that under RCP6.0, solar dimming would inevitably occur in almost areas of the upper Yangtze River when global warming 2 °C, comparing that in about half areas when global warming 1.5 °C.

The spatial distribution of relative changes of solar radiation for the period of 2020-2039 under RCP8.5 (corresponding to global warming 2 °C) compared with the reference period in the upper Yangtze was shown in Figure 5. The relative changes of solar radiation for 2020-2039 had a median of -8.95% with a range from -11.37% to 6.78%. The areas showing less dramatically decreasing trends in solar radiation (> -9%) accounted for about 60% of the study area and were predominantly located in the central regions, especially in the lower reaches of the Jinsha River Basin, whereas the areas showing more dramatically decreasing trends (< -9%) accounted for 40% of the study area and were mainly observed in the upper Jinsha River Basin and the middle and lower reaches of the Jialing River Basin. This indicated that under RCP8.5, solar dimming would inevitably occur in all areas of the upper Yangtze River when global warming 2 °C.

![Figure 5](image.png)

*Figure 5. Spatial distribution of relative changes of solar radiation for the period of 2020-2039 under RCP8.5 (global warming 2 °C) relative to the reference period of 1986-2005 in the upper Yangtze.*

Therefore, under global warming 1.5 °C, solar brightening would occur mainly in the central regions and become weaker with the higher emission scenarios. However, under global warming 2 °C, solar dimming would occur mainly in the upper Jinsha River Basin and the lower reaches of the Jialing River Basin and become stronger with the higher emission scenarios. Relative to the other three RCPs, the spatial distribution of relative change of solar radiation under RCP8.5 showed obviously dramatic negative values in the total area, which was consistent with the average change trend for the long period in the upper Yangtze (Figure 1).

Recent studies suggested that the variations of solar radiation may not relate to changes in the light intensity of the sun, but originate from the obvious alterations of the atmosphere transparency, which depended on the change in the amount of aerosols, clouds, and radiative active gases [4]. It was obvious that the variations of solar radiation played the most important role in climate change. Moreover, solar dimming/brightening may have counteracted/added to global greenhouse warming [18]. It could be required in the further research to establish and quantify the relationship between the solar dimming/brightening and global warming.
4. Conclusions
Assessment of the impacts of the future climate change on solar energy is important for energy managing and planning of the catchment. However, it was an open question that whether solar dimming or brightening would occur in the future under 1.5 °C and 2 °C warming targets. This study presented the quantitative effects of global warming of 1.5 °C and 2 °C on solar radiation in the upper reach of Yangtze River, using average of four GCMs under four RCPs. The primary conclusions were as follows.

(1) Solar brightening would occur under RCP2.6 and RCP4.5, while solar dimming would occur under RCP6.0 and RCP8.5. The fluctuations of the amount of solar energy in the future were related to the emission scenarios.

(2) Under global warming 1.5 °C of RCP2.6, RCP4.5 and RCP6.0, solar brightening would occur mainly in the central regions and become weaker with the higher emission scenarios. However, under global warming 2 °C of RCP4.5, RCP6.0 and RCP8.5, solar dimming would occur mainly in the upper Jinsha River Basin and the lower reaches of the Jialing River Basin and become stronger with the higher emission scenarios.

(3) Different from the other three RCPs, dramatic solar dimming would occur in every year of 2020-2099 under RCP8.5. Especially, solar dimming would inevitably occur in all areas of the upper Yangtze River when global warming 2 °C under RCP8.5.

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