

# Historical and future climate changes impact global solar photovoltaic power potential: Role of key meteorological variables



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## ABSTRACT

Renewable energy, especially solar power, is vital for mitigating global warming, while climate change also impacts solar photovoltaic potential (PVpot). This study analyzes historical (1985–2014) and future (2015–2100) climate effects on PVpot, and quantifies contributions from changed radiation, temperature, and wind speed. Historically, global PVpot increased by 0.42 %, with notable rises in eastern China (+7.1 %) and southern Europe (+3.5 %). By the end of the century, increased radiation-induced PVpot (+1.27 %) offsets temperature-induced PVpot loss (−0.54 %) under SSP1-2.6, yielding a net PVpot increase (+0.74 %). Under SSP2-4.5, the temperature-induced PVpot decline (−1.50 %) drives the final PVpot reduction (−1.15 %). Under SSP3-7.0 and SSP5-8.5, combined radiation-induced (−1.94 % and −1.99 %) and temperature-induced PVpot changes (−2.67 % and −3.41 %) result in significant PVpot declines (−4.57 % and −5.31 %). Regional analysis reveals that eastern China (+0.7% to +8.6 %), southern Europe (+0.3 % to +2.5 %), and Northwest South America (+0.6 % to +2.1 %) retain positive changes in future PVpot across all climate scenarios, which may be due to reduced aerosols and cloud cover, suggesting these areas can remain suitable for photovoltaic installations despite climate changes. In contrast, temperature-driven PVpot declines over the Qinghai–Tibet Plateau (−9.1 % to −4.3 %) and northern Africa (−9.3 % to −4.9 %) under future high-emission scenarios indicate that these historically advantageous regions will become less suitable for solar energy deployment. The findings underscore that climate changes driven by sustainable development pathways will generate more PVpot in the future for better global warming mitigation.

### 摘要

可再生能源，特别是太阳能发电对于减缓全球变暖至关重要，但气候变化会影响太阳能光伏潜力 (PVpot)。本研究分析了历史 (1985–2014年) 和未来 (2015–2100年) 气候对PVpot的影响，量化了辐射、温度和风速的贡献。从历史上看，全球PVpot增加了0.42%，其中中国东部 (+7.1%) 和南欧 (+3.5%) 的增长显著。到本世纪末，在SSP1-2.6下，辐射引起的PVpot增加 (+1.27%) 抵消了温度引起的PVpot损失 (−0.54%)，从而PVpot增加 (+0.74%)。在SSP2-4.5下，温度引起的PVpot下降 (−1.50%) 导致最终PVpot减少 (−1.15%)。在SSP3-7.0和SSP5-8.5中，辐射引起的 (−1.94%和−1.99%) 和温度引起的PVpot变化 (−2.67%和−3.41%) 共同导致PVpot显著下降 (−4.57%和−5.31%)。区域分析表明，中国东部 (+0.7%~+8.6%)，南欧 (+0.3%~+2.5%) 和南美洲西北部 (+0.6%~+2.1%) 在所有气候情景下的PVpot都保持正变化，这可能是由于气溶胶和云量减少，这表明尽管未来气候变化，这些地区仍然适合安装光伏设备。相比之下，在高排放情景下，青藏高原 (−9.1%~−4.3%) 和北非 (−9.3%~−4.9%) 的光伏发电量因温度升高而下降，这些历史上有利的地区将不再适合部署太阳能。本研究结果强调，可持续发展道路推动的气候变化将在未来产生更多的光伏发电量，从而更好地减缓全球变暖。

## 1. Introduction

Climate warming has become an urgent global problem that needs to be addressed seriously. The COP29 report indicates that the global mean temperature in 2024 reached a new record level, temporarily exceeding the critical 1.5 °C threshold. This highlights the accelerating impacts of climate warming, including frequent extreme weather events, rising

sea levels, and ecosystem degradation (IPCC, 2018; King and Harrington, 2018; UNFCCC, 2015).

In response to the climate change crisis, reducing greenhouse gas emissions has become a priority for countries worldwide, among which the rapid development of renewable energy is regarded as a key solution (Gaetan et al., 2024). In recent years, the application of green energy such as solar energy has grown significantly. By the time of net-zero

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emissions, renewable energy can account for about 60 % of global primary energy, with solar energy being a key contributor (DeAngelo et al., 2021). As Creutzig et al. (2017) pointed out, photovoltaic (PV) power generation will provide 30 %–50 % of electricity in the future. Solar energy can play a key role in future energy production, with renewable energy needs being met by using only 0.5 %–1 % of the world's land surface, as long as deployment strategies effectively take into account the location-specific climate change impacts (Saxena et al., 2023). Therefore, solar PV energy is fundamental for decarbonizing the global economy and supporting the renewable energy transitions that are needed to combat climate change.

PV power generation is primarily driven by surface downwelling shortwave radiation. Air temperature and wind speed can also affect the efficiency of solar panels (Jerez et al., 2015). As ambient temperature rises, solar panel efficiency typically decreases, while wind speed can cool the panels to increase efficiency (Peters and Buonassisi, 2019; Kazem and Chaichan, 2016; Dubey et al., 2013). Therefore, climate change potentially affects both PV power production and the operational stability of solar panel arrays. The actual PV power output is determined by multiplying the PV potential (PVpot) by the nominal installed capacity. Calculating changes in PVpot across different climate scenarios can provide a standardized evaluation method, enabling more accurate comparisons of meteorological impacts on PV power generation. This approach also supports the development of adaptation and optimization strategies tailored to diverse regions. Given the context of global warming and the large-scale deployment of PV power generation, it is crucial to investigate how historical and future climate warming affect PV energy yield.

Many previous studies focusing on the regional scale have assessed both long-term and short-term changes in future PV availability (Arregocés et al., 2024; Poddar et al., 2021), but their conclusions often remain inconsistent due to differences in methodology, assumptions, and scope. For the global scale, some previous studies have relied on Representative Concentration Pathway (RCP) scenarios (Saxena et al., 2023; Feron et al., 2020). Since the RCPs were finalized for use in the IPCC's Fifth Assessment Report, the development of the more complex Shared Socioeconomic Pathways (SSPs) has been a much longer and more intricate process. Additionally, some studies have used specific calculation methods to evaluate PV performance under particular conditions (e.g., Lei et al., 2023), while different regions may require more tailored methods for accurate assessment, owing to their different local factors such as climate, geography, and infrastructure.

Meanwhile, previous research has often neglected to thoroughly compare the impacts of various climate scenarios (i.e., SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5), predominantly focusing on a limited selection of scenarios of interest while overlooking intermediate and more nuanced pathways (Arregocés et al., 2024; Lei et al., 2023; Feron et al., 2020; Jerez et al., 2015). Given the wide array of potential future conditions, a more comprehensive analysis of the historical and projected extent of global solar PV power generation is crucial. This includes identifying the key factors that influence these changes across diverse climate scenarios. Such an approach can provide valuable insights into the geographical distribution of solar PVpot and inform investment strategies for future PV capacity development.

In order to assess the historical and future impacts of climate changes on solar PVpot, historical data from ERA5 (1985–2014) and predicted future simulations from CMIP6 under various SSP scenarios (2015–2100) are analyzed. To minimize uncertainties resulting from different calculation methods of PVpot, the multi-algorithm ensemble mean is finally analyzed, including evaluating the changes in PVpot driven by variations in meteorological factors. This study aims to comprehensively quantify the variations in global solar PVpot and their meteorological influencing factors under complex climate conditions. Section 2 introduces the data and methods. Section 3 explores the historical and future impacts of climate change on solar PVpot. Finally, Section 4 provides conclusions.

## 2. Data and methods

### 2.1. Historical and future meteorological variables

We analyze the impacts of historical and future climate change on solar PVpot and further quantify the contribution of each changed meteorological variable. The historical meteorological variables during 1985–2014 are adopted from the ERA5 reanalysis dataset (<https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5>). The future meteorological variables during different periods (2015–2044, denoted as early-century; 2045–2074, denoted as mid-century; and 2071–2100, denoted as late-century) are obtained from the future projections of the Scenario Model Intercomparison Project (ScenarioMIP) in CMIP6 (<https://esgf-node.llnl.gov/search/cmip6/>) with five different SSP scenarios (i.e., SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5). We downloaded simulations from 15 global climate models as shown in Table S1, and a nearest-neighbor interpolation method was applied to resample the simulated variables to the specified horizontal resolution of  $0.25^\circ \times 0.25^\circ$ .

### 2.2. Calculation method of solar PVpot

The solar PV power production depends on its PVpot, which means that PVpot multiplied by the nominal installed watts of the PV power capacity is the actual PV power output. In other words, PVpot is a dimensionless value that describes the performance of a solar cell relative to its nominal power capacity under the real environmental conditions.

According to previous studies (Jerez et al., 2015), PVpot can be calculated as follows:

$$\text{PVpot}(t) = P_r(t) \times \frac{R(t)}{R_{\text{STC}}}, \quad (1)$$

where  $R(t)$  represents surface downward shortwave radiation (SWDOWN) at time  $t$ ;  $R_{\text{STC}}$  is a constant value ( $R_{\text{STC}} = 1000 \text{ W m}^{-2}$ ), which refers to the surface downwelling shortwave radiation on a PV panel under standard test conditions; and  $P_r(t)$  is the performance ratio, indicating the temperature influence on the PV power efficiency.  $P_r(t)$  can be calculated as follows:

$$P_r(t) = 1 + \gamma \times (T_{\text{cell}}(t) - T_{\text{STC}}), \quad (2)$$

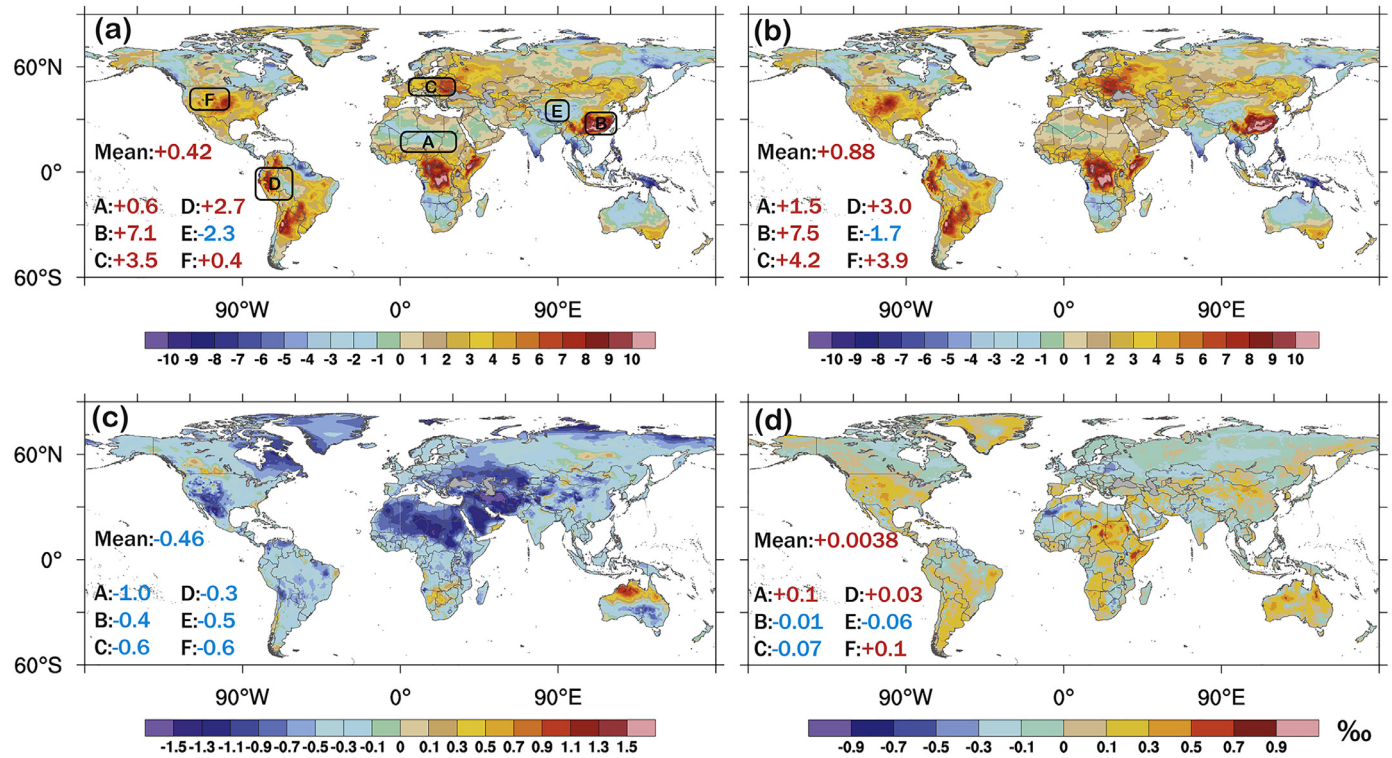
where  $T_{\text{STC}}$  represents the temperature standard test condition ( $T_{\text{STC}} = 25^\circ \text{C}$ ), and  $\gamma$  is taken here as  $-0.005^\circ \text{C}^{-1}$ , considering the conversion rate of typical monocrystalline silicon solar panels.  $T_{\text{cell}}(t)$  represents the temperature of the solar cell. Solar cell performance declines as the temperature rises, primarily due to elevated carrier concentrations, intensifying internal carrier recombination rates. PV modules' electrical efficiency and power output do not always exhibit a linear dependence on operating temperature (Dubey et al., 2013; Peters and Buonassisi, 2019). As the efficiency of solar cells varies depending on the temperature sensitivities of different PV modules, three commonly used formulas of  $T_{\text{cell}}(t)$  (Eqs. (S1–S3)) are selected for the ensemble mean to reflect the more general result (Table S2).

### 2.3. Calculation method of meteorology-driven PVpot changes

In order to quantify the contribution of each changed meteorological variable (i.e., surface SWDOWN, 2-m temperature, and 10-m wind speed) to PVpot changes, the equation of meteorology-driven PVpot change can be expressed as follows by combining Eqs. (1) and (2), and one calculation method of the temperature of the solar cell ( $T_{\text{cell}}$ ) as listed in Table S2. Here, we take Eqs. (1), (2), and (S1) as an example:

$$\Delta \text{PVpot} = \Delta R(i_1 + i_2 \Delta R + 2i_3 R + i_4 T + i_5 W) + i_6 R \cdot \Delta T + i_7 R \cdot \Delta W + i_8 \Delta R \cdot \Delta T + i_9 \Delta R \cdot \Delta W, \quad (3)$$

where  $i_1 = 1.1035 \times 10^{-3} \text{ m}^2 \text{ W}^{-1}$ ,  $i_2 = -1.4 \times 10^{-7} \text{ m}^4 \text{ W}^{-2}$ ,  $i_3 = -4.715 \times 10^{-6} \text{ m}^2 \text{ W}^{-1} \text{ }^\circ\text{C}^{-1}$ , and  $i_4 = 7.64 \times 10^{-6} \text{ m s W}^{-1}$ .  $R$ ,  $T$ , and  $W$  are the surface SWDOWN, 2-m temperature, and 10-m wind



**Fig. 1.** (a) Historical changes in PVpot from 1985–1999 to 2000–2014, and the contributions of (b) changed surface SWDOWN flux, (c) changed 2-m temperature, and (d) changed 10-m wind speed to the changed PVpot. The global land mean and the averages of six analyzed areas are listed in the lower left of each panel. The regions A, B, C, D, E, and F represent northern Africa, eastern China, southern Europe, Northwest South America, the Qinghai–Tibet Plateau, and the western United States, respectively.

speed, respectively.  $\Delta R$ ,  $\Delta T$ , and  $\Delta W$  represent the changed radiation, changed temperature, and changed wind speed, respectively. Therefore, the changed PVpot induced by the changes only in surface SWDOWN flux (2-m temperature, 10-m wind speed) can be obtained by taking  $\Delta T = \Delta W = 0$  ( $\Delta R = \Delta W = 0$ ,  $\Delta R = \Delta T = 0$ ).

Additionally, the *t*-test has been adopted to reduce uncertainties among CMIP6 models. Changes are considered significant only if more than half of the CMIP6 models pass the *t*-test ( $p < 0.05$ ). If none of the models meets the significance threshold ( $p \geq 0.05$ ), the values for that region are treated as negligible and excluded from the final calculation. For the mean values of the six analyzed regions, we also use the *t*-test to assess their significance (significant ( $p < 0.05$ ) and robust ( $p < 0.01$ )). For the time trend analysis, the Mann–Kendall test is applied to detect significance.

### 3. Results and discussion

#### 3.1. Historical changes in solar PVpot

The global land mean solar PVpot and its trend from 1985 to 2014 are first assessed. Six key regions representing different geographic and socioeconomic conditions are also selected for detailed analysis, including northern Africa (7°–18°N, 0°–35°E), eastern China (24°–34°N, 105°–120°E), southern Europe (43°–50°N, 5°–30°E), Northwest South America (0°–20°S, 60°–80°W), the Qinghai–Tibet Plateau (28°–40°N, 84°–95°E), and the western United States (35°–47°N, 100°–120°W).

The historical global land mean PVpot is 17.06 % during 1985–2014, with high values in northern Africa (26.1 %), the Qinghai–Tibet Plateau (26.5 %), and western United States (21.9 %), and low values predominantly in southern Europe (15.2 %) and eastern China (15.7 %) (Fig. S1(a)). This distribution aligns with previous research (Dubey et al., 2013), which identified plateaus and deserts as optimal for PV installation. However, according to the 30-year trend of PVpot (Fig. S1(b)), we

find contrasting changes over these regions, e.g., significant increases (decreases) in PVpot are calculated over Southeast China (Qinghai–Tibet Plateau) with a value of +0.37 %/10 yr (−0.11 %/10 yr), where the 30-year averaged PVpot is very small (large), indicating inconsistent reference information for PV installation by results from the time mean and the time trend of PVpot.

To investigate the impacts of historical climate change on PVpot and further quantify the contribution of each changed meteorological variable, we divide the period into two phases (1985–1999 and 2000–2014) according to the temporal variation in PVpot during 1985–2014 (Fig. S2). Our findings indicate that historical climate change promoted an increase in PVpot across most regions, such as eastern China (+7.1 %), southern Europe (+3.5 %), and Northwest South America (+2.7 %), while the Qinghai–Tibet Plateau shows a decrease (−2.3 %) (Fig. 1(a)). Comparing the contributions of changed meteorological variables (Fig. 1(b–d)), radiation changes dominate PVpot gains (+0.88 %). The rising air temperature inhibits the decrease in PVpot, especially over northern Africa (−1.0 %). The impact of historical wind speed changes on PVpot is minor (+0.0038 %). Overall, despite the 30-year averaged PVpot being very high over northern Africa and the Qinghai–Tibet Plateau, the rising air temperature (Fig. S3(b)) mitigates the increase in PVpot during 1985–2014. Conversely, eastern China and southern Europe, where the PVpot is relatively low, exhibit substantial increases in PVpot driven by the rising radiation (Fig. S3(a)). By comparing the contribution of each meteorological element to the PVpot and the absolute time trend of meteorological elements (Fig. S4), the changes in PVpot are similar to the changes in radiation (Fig. S4(a)), but there is inconsistency between the temperature changes (Fig. S4(b)) and the changes in the temperature-induced PVpot (Fig. 1(c)); the areas with the largest temperature increases are not necessarily the areas where the temperature-induced PVpot decreases most significantly.

### 3.2. Projected future changes in solar PVpot

In addition to assessing the impact of historical climate change on PVpot, it is essential to estimate how PVpot will evolve under future climate scenarios, to facilitate better comparative analyses and future planning. This section quantitatively examines the future changes in PVpot under multiple climate scenarios (i.e., SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) during mid-century (2045–2074) and late-century (2071–2100) periods compared with the early-century (2015–2045) period.

#### 3.2.1. Change in PVpot under future climate scenarios

By the end of the century, the declines in PVpot under SSP3-7.0 (−4.57 ‰) and SSP5-8.5 (−5.31 ‰) are nearly doubled comparing with that during the mid-century (−2.67 ‰ and −2.68 ‰) (Fig. 2). More PVpot is obtained under SSP1-1.9 and SSP1-2.6, with the changes increased from +1.08 ‰ to +1.86 ‰ and +0.26 ‰ to +0.74 ‰, respectively, underscoring how climate change under a low-emissions scenario will generate more PVpot in the future.

For the changes in PVpot in the six analyzed regions, eastern China (+0.7 ‰ to +8.6 ‰), southern Europe (+0.3 ‰ to +2.5 ‰) and Northwest South America (+0.6 ‰ to +2.1 ‰) remain positive in the future across all climate scenarios (Fig. 2), not only during the mid-century but also during the late-century period, suggesting these areas remain suitable for PV installations despite climate changes in the future. However, the positive changes in future PVpot over northern Africa and the Qinghai–Tibet Plateau can only be found under SSP1-1.9 and SSP1-2.6, and the negative changes are significant under SSP3-7.0 and SSP5-8.5, with values of −9.3 ‰ to −4.9 ‰ for northern Africa and −9.1 ‰ to −4.3 ‰ for the Qinghai–Tibet Plateau.

#### 3.2.2. Impact of driving meteorological factors

Fig. 3 highlights the influence of changes in SWDOWN on future PVpot. Under high-emission scenarios (SSP3-7.0 and SSP5-8.5), reductions in SWDOWN (Fig. S5) are the primary driver of declining PVpot. Especially, by the end of the century under SSP5-8.5, eastern China shows a radiation increase of  $10.4 \text{ W m}^{-2}$ , which will contribute a 10.4 ‰ rise in PVpot (Fig. 3(j)), while northern Africa will experience a radiation drop of  $4.9 \text{ W m}^{-2}$ , resulting in a 4.5 ‰ PVpot reduction. Severe emission scenarios lead to radiation declines in regions such as the Sahara Desert, Qinghai–Tibet Plateau, and the western United States, which subsequently reduce PVpot, while eastern China shows the opposite. These results underscore the significant influence of changed radiation on future PVpot.

Temperature changes are also a critical factor affecting PVpot (Fig. S6). Future temperature increases consistently reduce PVpot, with more severe impacts under higher emission scenarios. Only during the late-century period under SSP1-1.9 does the decreased temperature over high-latitude regions (Fig. S7(b)) cause a slight increase in PVpot (+0.016 ‰, Fig. S6(b)), while all other scenarios show significant temperature-induced PVpot declines (−0.2 ‰ to −3.41 ‰). Notably, regions experiencing the greatest temperature increases are located at high latitudes around 60°–90°N (Fig. S7), whereas temperature-induced declines in PVpot are predominantly concentrated near the equator. This discrepancy indicates that the relationship between temperature rise and PVpot reduction is not linear but influenced by regional climatic differences. Among the analyzed regions, northern Africa and the Qinghai–Tibet Plateau are most vulnerable to temperature-induced PVpot declines, highlighting their sensitivity to temperature variations.

Compared to radiation- and temperature-induced PVpot changes, variations in future wind speed have a relatively minor impact on PVpot (−0.019 ‰ to +0.037 ‰) (Fig. S9). Except under the SSP2-4.5 scenario, all other scenarios show that increased (decreased) wind speed (Fig. S8) will lead to a rise (decline) in PVpot, and the change in PVpot caused by wind speed change is more obvious at the end of this century.

### 3.3. Discussion

The above results highlight the impacts of climate change on PVpot. The changes under SSP1-2.6 are most similar to the patterns of historical change. By maintaining conditions similar to those projected under SSP1-1.9 and SSP1-2.6, we can anticipate a continuous increase in global PVpot.

Regional analysis reveals a significant increase in PVpot in eastern China, where a remarkable rise in PVpot (+0.7 ‰~+8.6 ‰) is exhibited across all climate scenarios, driven primarily by increased SWDOWN. This increase is likely linked to regional reductions in aerosol concentrations and cloud cover dynamics (Zhang et al., 2022; Hong et al., 2020), which enhance solar radiation availability.

In contrast, regions such as the Qinghai–Tibet Plateau and northern Africa exhibit significant declines in PVpot under high-emission scenarios (SSP3-7.0 and SSP5-8.5), with reductions ranging from −9.3 ‰ to −4.3 ‰. These declines can primarily be attributed to reductions in SWDOWN and the adverse effects of rising temperatures. The Qinghai–Tibet Plateau, despite its high elevation and historically favorable conditions for solar energy, faces similar challenges due to increased cloud cover and temperature (Yang et al., 2022; Dumka et al., 2021). These regional disparities underscore the importance of understanding the underlying climatic mechanisms driving PVpot changes, particularly in areas vulnerable to the adverse effects of climate change.

Additionally, there are also uncertainties with limited meteorological factors. In this study, we focused on three key meteorological variables—radiation, temperature, and wind speed—as they are directly incorporated into the PVpot formula. However, other factors such as cloud cover and relative humidity may also influence PVpot (Yang et al., 2022; Neher et al., 2019). Therefore, future studies should further refine the analysis by incorporating these factors to achieve more comprehensive results.

## 4. Conclusions

The historical analysis carried out in this study shows a global mean PVpot of 17.06 ‰, with high values over the Qinghai–Tibet Plateau (26.5 ‰), northern Africa (26.1 ‰), and western United States (21.9 ‰), and low values predominantly over eastern China (15.7 ‰) and southern Europe (15.2 ‰). The 30-year trend of PVpot reveals contrasting changes over these hotspot regions, with significant increases of 0.37 ‰/10 yr (0.17 ‰/10 yr) over eastern China (southern Europe) and significant decreases of 0.11 ‰/10 yr (0.026 ‰/10 yr) over the Qinghai–Tibet Plateau (northern Africa). The rising air temperatures mitigate the increase in PVpot over northern Africa and the Qinghai–Tibet Plateau, while rising radiation dominates the substantially increased PVpot over eastern China and southern Europe. All these results indicate that climate changes have been affecting strategies for PV installation.

Future projections show significant declines in the global land mean PVpot under the extreme climate scenarios of SSP3-7.0 (−2.67 ‰) and SSP5-8.5 (−2.68 ‰) during the mid-century compared with that during the early-century period, and the decline nearly doubles by the end of the century (−4.57 ‰ for SSP3-7.0 and −5.31 ‰ for SSP5-8.5). Meanwhile, more PVpot is obtained under the low-emissions scenario of SSP1-1.9 (SSP1-2.6), with the changes increased from +1.08 ‰ (+0.26 ‰) during the mid-century to +1.86 ‰ (+0.74 ‰) by the end of the century.

Hotspot regions like northern Africa and the Qinghai–Tibet Plateau will be vulnerable to future climate changes due to increased cloud cover and temperature, and the negative changes in PVpot are significant under SSP3-7.0 and SSP5-8.5. In contrast, regions such as eastern China (+0.7 ‰ to +8.6 ‰), southern Europe (+0.3 ‰ to +2.5 ‰), and Northwest South America (+0.6 ‰ to +2.1 ‰) retain positive changes in future PVpot across all climate scenarios because of reductions in aerosol concentrations and cloud cover dynamics, suggesting these ar-

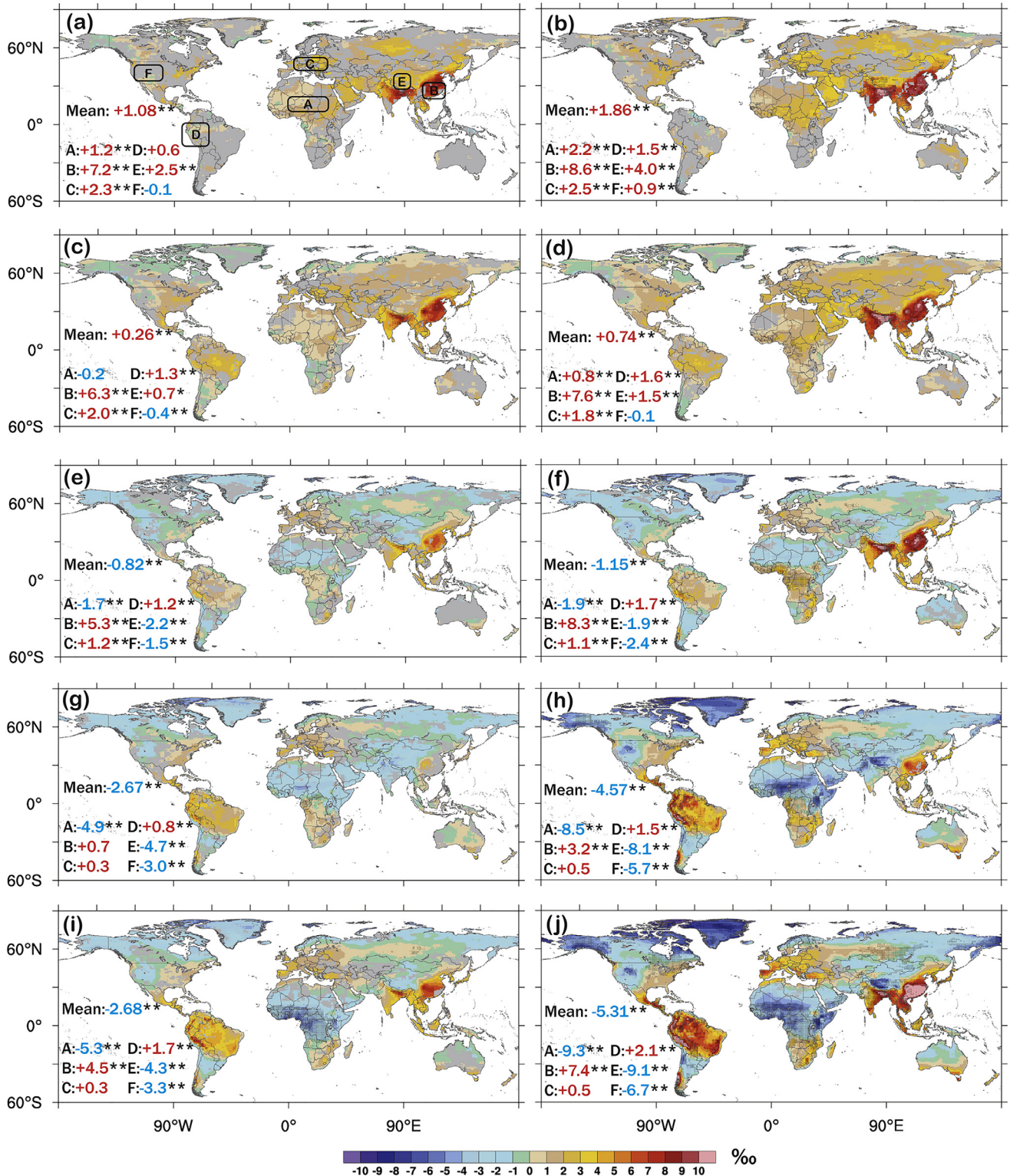
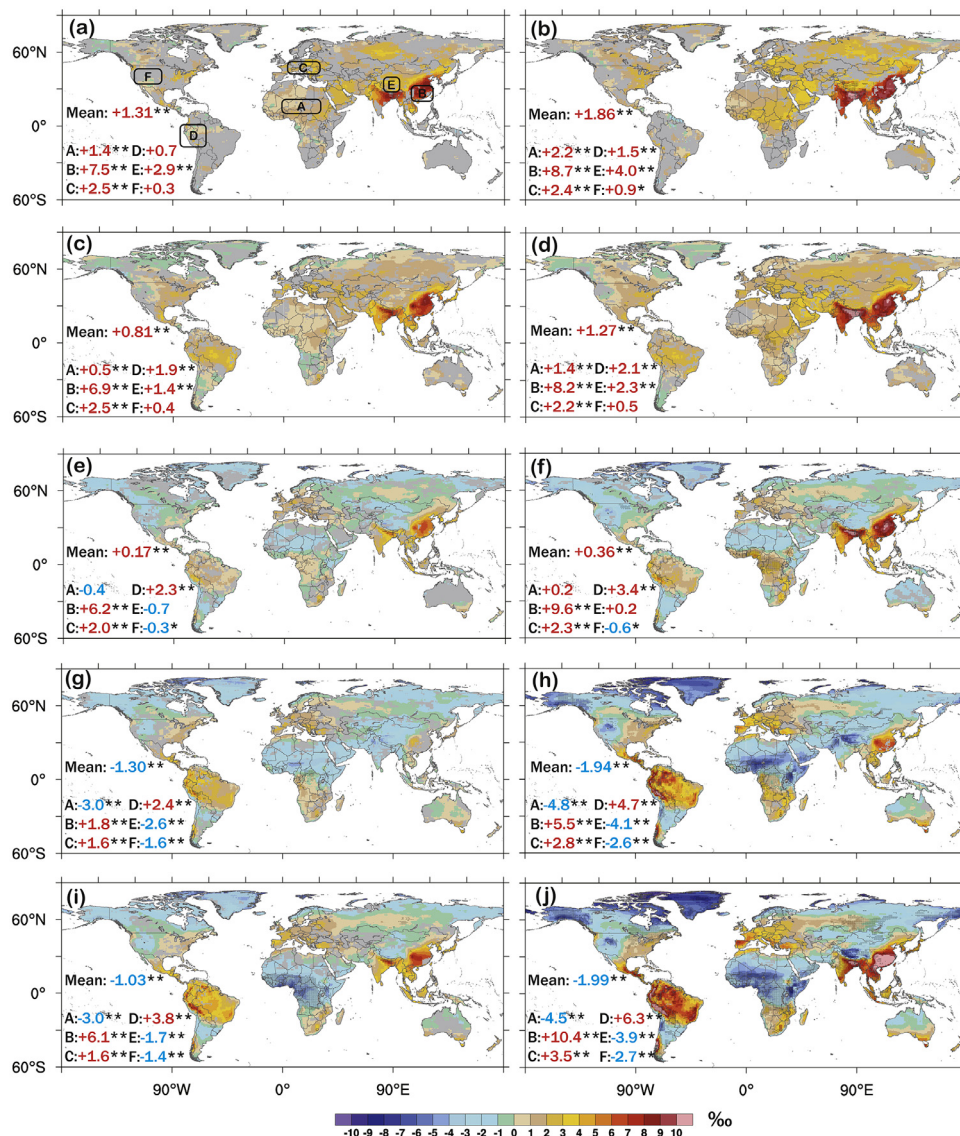


Fig. 2. Future changes in PVpot under the scenarios of (a, b) SSP1-1.9, (c, d) SSP1-2.6, (e, f) SSP2-4.5, (g, h) SSP3-7.0, and (i, j) SSP5-8.5 during the mid-century (2045–2074, left column) and late-century (2071–2100, right column) periods compared with during the early-century period (2015–2030). Dotted regions are defined as those where at least half of selected models agree on the sign of the changes as significant ( $p < 0.05$ ), while missing regions (in gray) are considered negligible, indicating that no model shows significant changes. The global land means and the averages of six analyzed areas are listed in the lower left of each panel. A single asterisk (\*) indicates the average change in this area is statistically significant ( $p < 0.05$ ), while double asterisks (\*\*) indicate a robust ( $p < 0.01$ ) value. The regions A, B, C, D, E, and F represent northern Africa, eastern China, southern Europe, Northwest South America, the Qinghai–Tibet Plateau, and the western United States, respectively.



**Fig. 3.** Changed solar photovoltaic power potential induced by the changes only in surface downward short-wave radiation flux during the mid-century (2045–2074, left column) and the late-century (2071–2100, right column) compared with that during the early-century (2015–2030) under scenarios of (a–b) SSP1-1.9, (c–d) SSP1-2.6, (e–f) SSP2-4.5, (g–h) SSP3-7.0, and (i–j) SSP5-8.5. Dotted regions are defined as those where at least half of selected models agree on the sign of the changes as significant ( $p < 0.05$ ), while missing regions (in grey) are considered negligible, indicating that no models show significant changes. The global land means and the averages of six analyzed areas are listed in the lower left bottom of each panel. A single asterisk (\*) indicates the average change in this area is statistically significant ( $p < 0.05$ ), while double asterisks (\*\*) indicate a robust ( $p < 0.01$ ) value. The regions A, B, C, D, E, and F represent Northern Africa, Eastern China, Southern Europe, Northwest South America, Qinghai-Tibet Plateau, and the Western United States, respectively.

eas may remain suitable for PV installations despite climate changes in future.

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## Supplementary materials

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