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What determines future changes in photovoltaic potential over East Asia?

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ABSTRACT

Heavily industrialized East Asia, with its high greenhouse gas emissions, must inevitably increase renewable energy production to achieve the goals of the Paris Agreement. Photovoltaics (PV), a widely utilized renewable energy source, is directly affected by the weather and climate. This study conducted the first analysis of current and future PV potential (PVpot) changes over East Asia using the ERA5 reanalysis and multiple high-resolution regional climate model simulations. The recent PVpot over East Asia did not exhibit any notable changes, but the future PVpot of the multi-model ensemble is predicted to decrease by −4.3% (winter) to −1.5% (summer) on average with excellent inter-model agreements. Results demonstrated that the widespread increase in near-surface air temperature causes the overall PVpot decrease (around −2.0%) over East Asia across all seasons. Interestingly, surface down-welling shortwave radiation increases in summer, offsetting temperature-induced PVpot decreases (by about 0.7%) while it declines in winter and spring, intensifying the warming-driven PVpot decrease (by approximately −1.4% to −2.3%). Further, the changes in the number of rainy days are associated with the changing patterns of surface down-welling shortwave radiation, indicating the importance of reliable projections of precipitation. Wind speed exerts a negligible effect on the future PVpot change.

1. Introduction

Greenhouse gases (GHGs) are the major driver of global warming, and most of the GHG emissions into the atmosphere since industrialization has been due to fossil fuel use [1]. Conventional energy sources, such as fossil fuels, remain dominant in global power generation [2]. Global efforts are being made to reduce fossil fuel use and shift to utilizing renewable energy for power generation. According to the United Nations Sustainable Development Goals (SDGs), which were launched in 2015 for achievement by 2030, the acceleration of decarbonization and the climate-resilient transition are directly related to the sustainable development of human society [3]. The power generation from renewable energy sources such as photovoltaics (PV) plays a significant role in SDG implementation. As the price and power unit cost of PV systems continues to decline, it is expected that the solar energy market share of future power generation will grow [4,5].

East Asia is a highly industrialized region with elevated GHGs emissions from extensive fossil fuel use. To achieve the Paris Agreement's primary goal of restricting global warming below 2 °C above pre-industrial levels, and to implement measures to limit the temperature increase to 1.5 °C above pre-industrial levels [6], an increase in the production of renewable energy such as PV power is required in this region. Therefore, East Asia is expected to drive the PV power generation wave as a solar energy leader with a market share of over 50% by 2050 [5]. The PV power generation is directly affected by weather and climate [4,5,7]. Recent studies for Europe and Africa indicated that surface down-welling shortwave radiation (RSDS) directly affects the PV power generation, and near-surface air temperature (TAS) and wind speed (SFCWIND) affect

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Table 1
Configurations of RCMs used in this study.

Configuration\Model	HadGEM3-RA	SNURCM	CCLM
GCMs	HadGEM2-AO and MPI-ESM-LR	HadGEM2-AO and MPI-ESM-LR	HadGEM2-AO and MPI-ESM-LR
Number of grid points (latitude × longitude)	251 × 396	260 × 405	251 × 396
Vertical levels	63 eta	σ-24	Hybrid-40
Dynamic framework	Non-hydrostatic	Non-hydrostatic	Non-hydrostatic
Convection scheme	Revised mass flux	Kain-Fritch II	Tiedtke
Microphysics	Single moment bulk	Reisner II	Extended DM
Radiation	General 2-stream radiation [26,27]	NCAR CCM2 package [28,29]	Ritter and Geleyn [30]
Land surface model	Joint UK Land Environment Simulator (JULES)	NCAR CLM3	TERRA ML
References	Davis et al. [31]	Cha and Lee [32]	Rockel et al. [33]

solar panel efficiency [7–9]. However, studies for East Asia have been very limited. To develop an efficient and reliable future solar energy production policy, detailed investigations into the present and future changes in the climate variables affecting solar energy production and the PV power potential (PVpot) are required.

Many research institutes have developed regional climate models (RCMs) by applying a dynamical downscaling process to resolve the limitation of global climate model (GCM) simulation due to their low spatial resolution [10–19]. The Coordinated Regional Climate Downscaling Experiment (CORDEX) project, covering 14 regional domains, was established by the World Climate Research Programme (WCRP) to provide downscaled quality-controlled climate information at the regional scale [10]. The CORDEX–East Asia project team has produced phase II climate change scenarios using multiple RCMs forced by various GCMs, which exhibit a higher spatial resolution (25-km) than those of phase I (50-km). This current study investigated the present PVpot distribution over East Asia using the ERA5 reanalysis datasets and

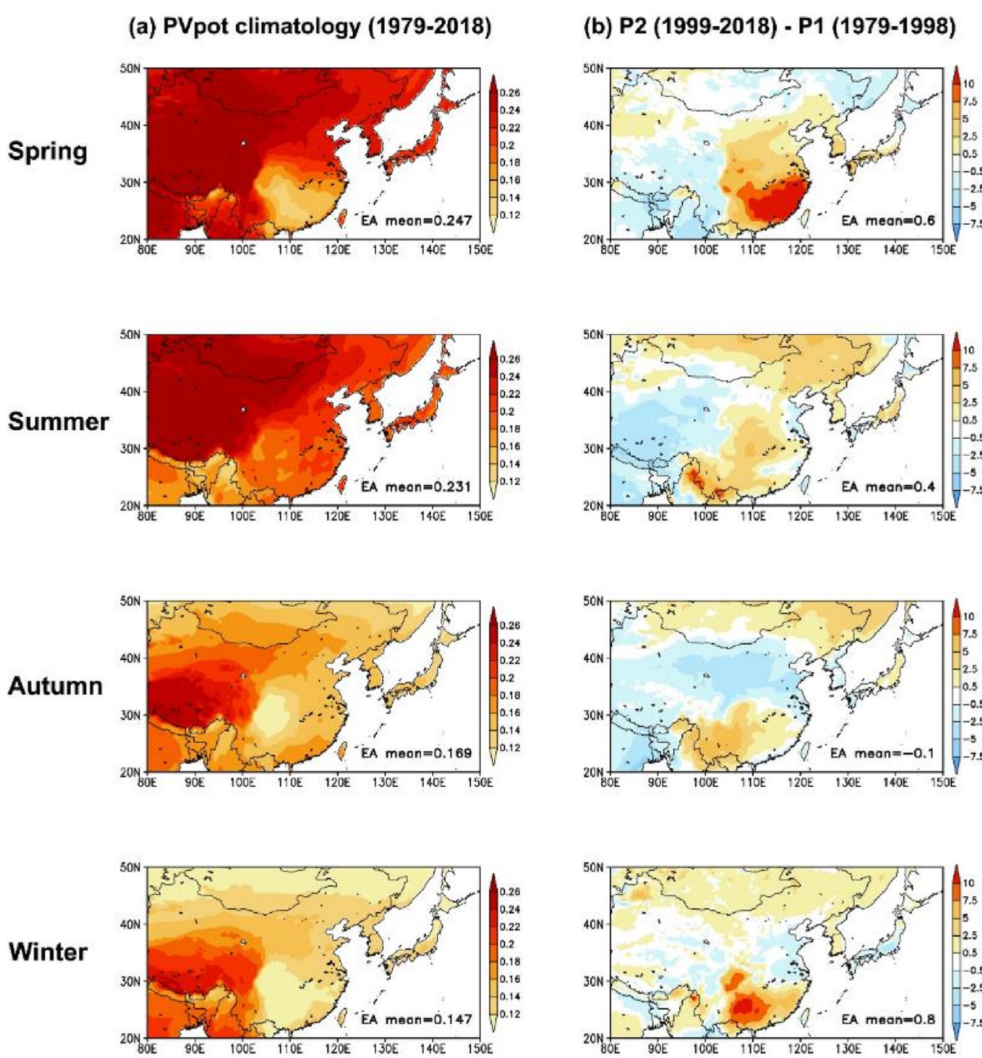

Fig. 1. Spatial distributions of (a) observed seasonal mean for the PVpot (W m^{-2}) and (b) the difference (%) between the second half (1999–2018) and the first half (1979–1998) of the recent 40 yr (1979–2018) over East Asia. Area mean values are given in the bottom right corners.

estimated its future change and associated climate variables at the end of the 21st century using multiple RCMs forced by two GCMs (HadGEM2-AO and MPI-ESM-LR) participating in the CORDEX-East Asia phase II project.

2. Data and methods

2.1. Observational data and models

In this study, the latitude–longitude box spanning of 80 °E–150 °E and 20 °N–50 °N as the East Asia domain was selected, which includes China, the Korean peninsula, Japan, and parts of Mongolia and Russia. The major variables for the reference data and the RCMs were monthly RSDS, TAS, and SFCWIND, which were used to calculate the PVpot for the present and future periods. Additionally, 3-hourly precipitation and RSDS datasets from the *Historical* and Representative Concentration Pathway (RCP) 8.5 experiments were used to investigate the influence of precipitation on the daytime RSDS changes over East Asia. The variables and PVpot were evaluated seasonally: spring (March-April-May), summer (June-July-August), autumn (September-October-November), and winter (December-January-February).

The European Centre for Medium-Range Weather Forecasts reanalysis 5 (ERA5) datasets with a horizontal resolution of 0.25° × 0.25° were used as the reference data to evaluate model performance for the present conditions (1979–2018). The ERA5 datasets have been improved in many configurations (e.g., higher spatial and temporal resolutions, improved representation of tropical cyclones and enhanced global balance of precipitation and evaporation) compared to the ERA-Interim datasets [20].

Multiple RCMs with 25-km horizontal resolution forced by two GCMs participating in the CORDEX-East Asia phase II project were used to estimate the future PVpot change over East Asia. The climate information of two GCMs involved in the Climate Model Intercomparison Project phase 5 (CMIP5) experiment was applied to both the *Historical* and *RCP8.5* experiments for three non-hydrostatic RCMs (HadGEM3-RA, SNURCM, and CCLM) as large-scale forcings. Compared with other CMIP5 GCMs, HadGEM2-AO and MPI-ESM-LR exhibited a relatively good performance for capturing the observed global and East Asian climate [21–24]. The model configurations of six RCM simulations with different physical schemes are presented in Table 1.

The spectral nudging technique [25] was implemented in SNURCM and CCLM as an alternative method for boundary condition. The *Historical* experiment was used to evaluate the RCM performance for 1981–2005 and the *RCP8.5* experiment, a high-

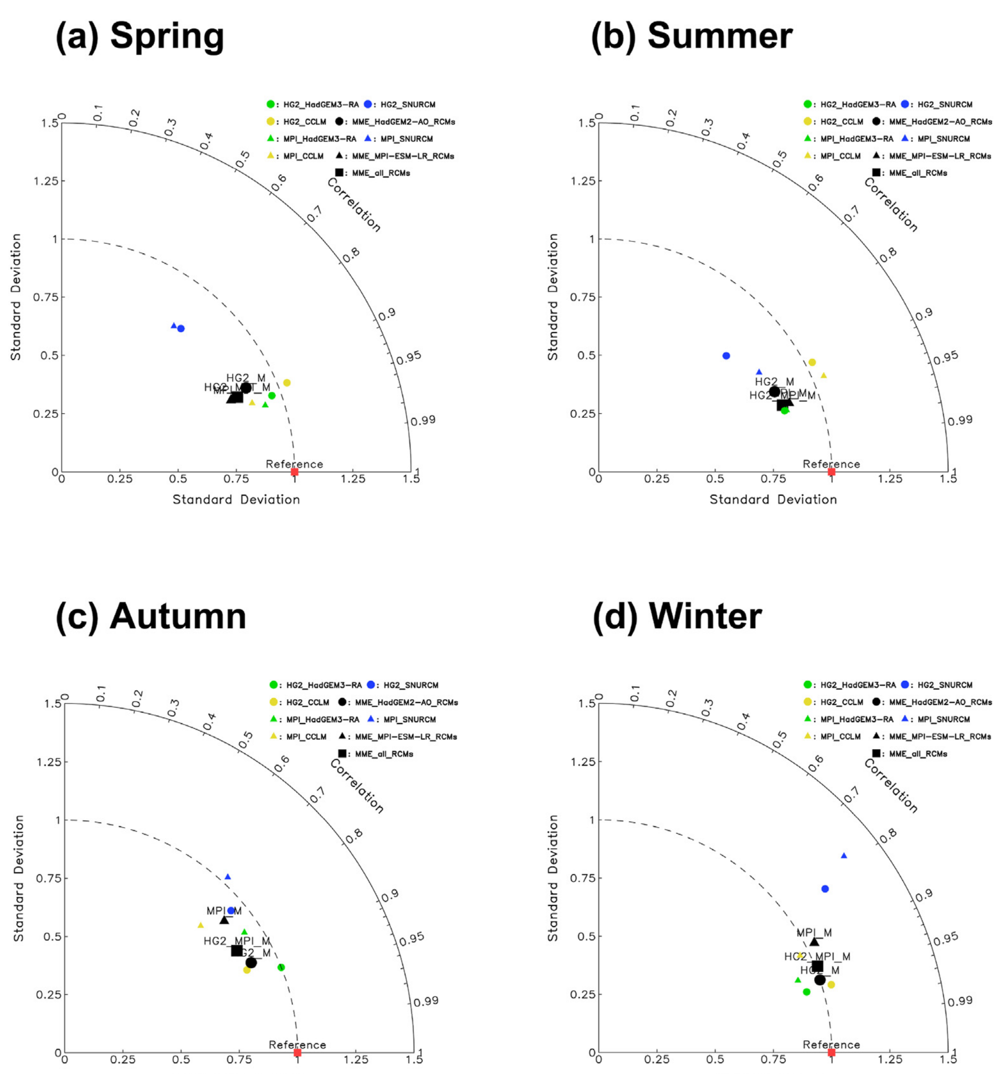

Fig. 2. Taylor diagrams of seasonal PVpot for RCMs and MMEs of the *Historical* experiment over East Asia.

emissions scenario referred to as the *business as usual* (BAU), was used to assess future changes in the PVpot and related climate variables for 2070–2099. A multi-model ensemble (MME) that averaged the six RCM simulations with equal weighting to reduce the inter-RCM uncertainties arising from different model configurations was constructed. For comparison with the ERA5 results, all RCM outputs were interpolated into a 0.25° × 0.25° grid by the bilinear interpolation method before the analysis.

2.2. Analysis methods

The future prediction of the PVpot was expressed as a percentage (%) change (i.e., the differences between the *RCP8.5* and *Historical* experiments) relative to the climatology of the *Historical* experiment. The estimation of PVpot and the contributions of TAS and SFCWIND to PVpot changes were calculated following the method by Jerez et al. [7]. Here, the PVpot is an indicator of PV cell performance, which exhibits a dimensionless magnitude. Thus, the PV power production was estimated by multiplying the PVpot by the nominal installed watts of the PV power capacity. The PVpot is expressed as follows;

$$PV_{pot}(t) = P_R(t)\frac{RSDS(t)}{RSDS_{STC}} \tag{1}$$

where STC indicates the standard test conditions by the International Electrotechnical Commission (IEC) 61215 standard [34] and $RSDS_{STC}$ is defined as 1,000 W m^{-2} P_R is the performance ratio and is calculated as follows;

$$P_R(t) = 1 + \gamma[T_{cell}(t) - T_{STC}] \tag{2}$$

where T_{STC} and γ are defined as 25 °C and −0.005 °C^{-1}, respectively, for the monocrystalline silicon solar cell panels. T_{cell} is the PV cell temperature and estimated using three variables as follows;

$$T_{cell}(t) = c_1 + c_2TAS(t) + c_3RSDS(t) + c_4SFCWIND(t) \tag{3}$$

where $c_1 = 4.3\,°C$, $c_2 = 0.943$, $c_3 = 0.028°C\,m^2\,W^{-1}$, and $c_4 = -1.528\,°C\,s\,m^{-1}$ [7,35,36].

TAS and SFCWIND-induced changes in PVpot change are estimated as follows;

$$\Delta TAS\ induced\ PV_{pot}(t) = \left(\frac{\alpha_3 RSDS(t).\Delta TAS}{PV_{pot_{Historical}}mean}\right).100 \tag{4}$$

$$\Delta SFCWIND\ induced\ PV_{pot}(t) = \left(\frac{\alpha_4 RSDS(t).\Delta SFCWIND}{PV_{pot_{Historical}}mean}\right).100 \tag{5}$$

where $\alpha_3 = -4.715 \times 10^{-6}$ and $\alpha_4 = 7.64 \times 10^{-6}$. These are expressed in percentage. The RSDS contribution to PVpot change was obtained by subtracting the TAS and SFCWIND-induced PVpot from PVpot change.

The performance of multiple RCMs for estimating PVpot was investigated using the Taylor diagram, which evaluates models in terms of spatial patterns. To explore the influence of precipitation on the future change in PVpot, the inter-RCM correlation between the future change in the number of rainy days (precipitation >0.1 mm d^{-1}) and the future change in RSDS was examined.

3. Results

3.1. Observed mean for the PVpot and RCM performances over East Asia

The spatial distribution of the observed seasonal mean for the PVpot and its recent change using the ERA5 dataset was examined (Fig. 1). The seasonal PVpot mean over East Asia for 1979–2018 was

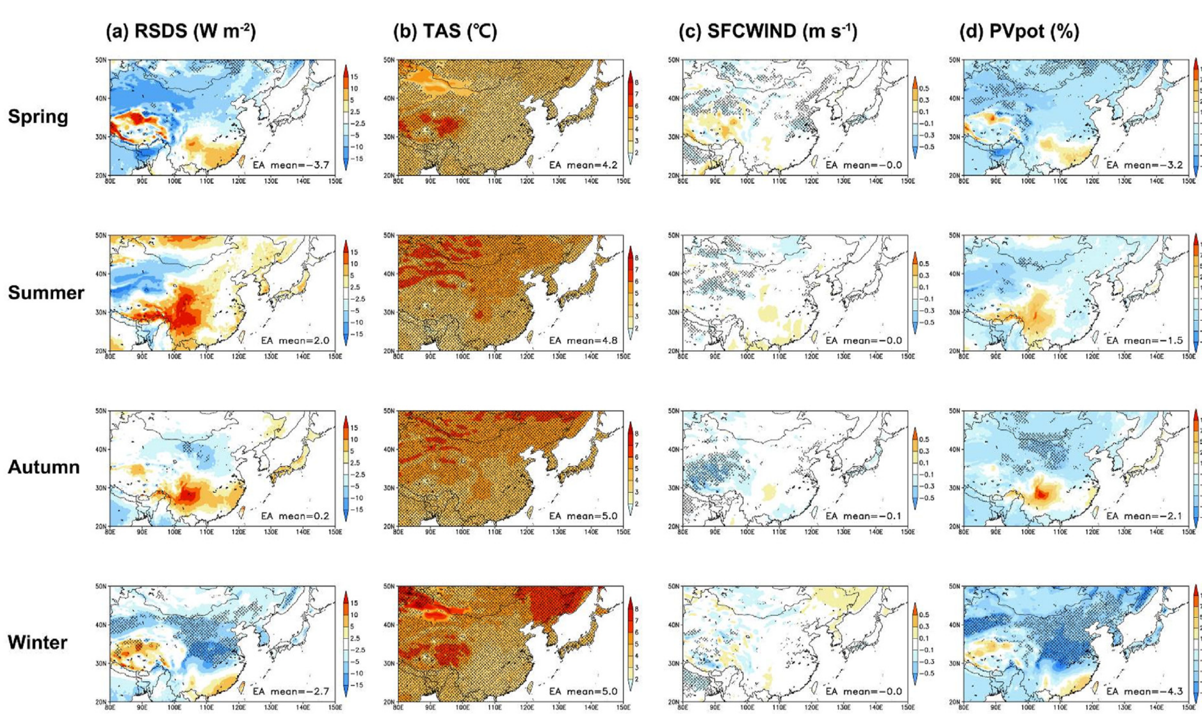

Fig. 3. Spatial distributions of seasonal future (2070–2099) changes of (a) RSDS (W m^{-2}), (b) TAS (°C), (c) SFCWIND (m s^{-1}), and (d) PVpot (%) over East Asia. Note that the hatched areas represent grids with good inter-RCM agreements, which are the same sign for four or more of the six RCM simulations. Numbers in the bottom right corners indicate area mean values.

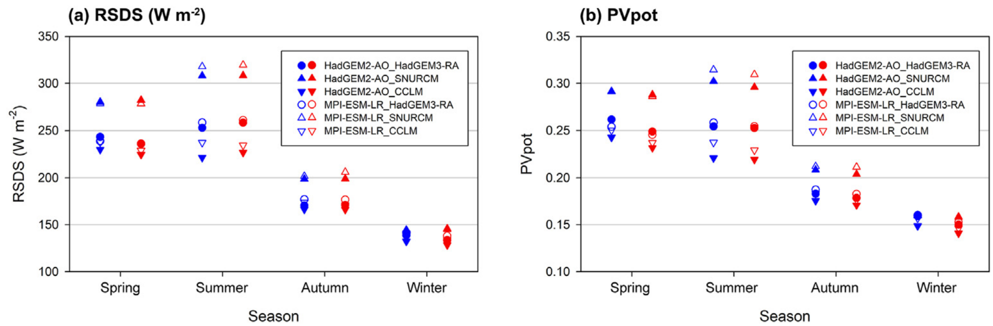

Fig. 4. Seasonal means of the East Asian-averaged (80 °E–150 °E and 20 °N–50 °N) (a) RSDS and (b) PVpot from individual RCMs for the Historical (blue) and RCP8.5 (red) experiments.

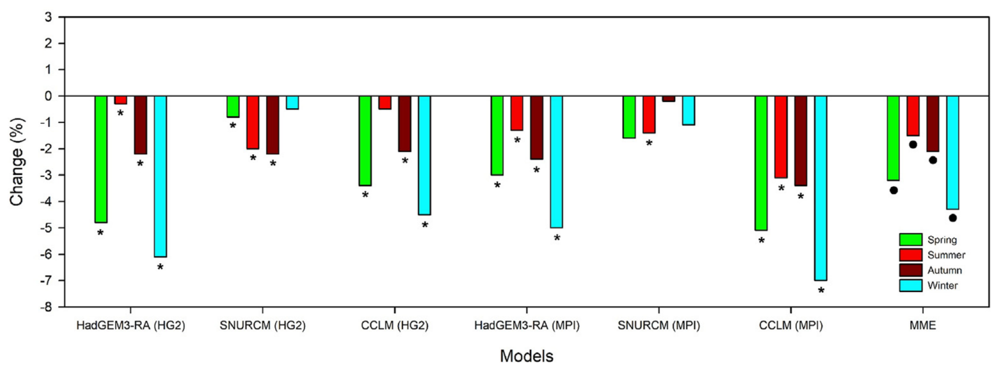

Fig. 5. Seasonal future (2070–2099) changes (%) in the East Asian-averaged (80 °E–150 °E and 20 °N–50 °N) PVpot from individual RCMs and MME. Asterisks from individual RCMs denote seasonal changes exceeding 95% confidence level of the *t*-test and dots from MME represent seasonal changes with the same sign for four or more of the six RCMs.

largest in spring and smallest in winter. Across seasons, the highlands in western China exhibited the largest PVpot mean, while southern China displayed the smallest. The seasonal and regional PVpot distributions were similar to the RSDS distribution, indicating that the PVpot is primarily determined by the RSDS (Fig. S1). This result coincides with previous studies conducted using observational data and various climate models [7–9,37]. The difference between the second half (1999–2018) and the first half (1979–1998) of the last 40 yr (1979–2018) was examined as a percentage change to analyze the observed recent changes in PVpot seasonal mean over East Asia. The area-averaged recent PVpot seasonal mean over East Asia did not demonstrate any notable changes; the changes were within ±5% in most areas. However, the PVpot displayed a large increase exceeding +10% in southern China in the spring and winter. This result is consistent with the distribution of the recent changes in the observed seasonal mean RSDS over East Asia (Fig. S2).

RCM performances were evaluated prior to investigating the predictions of future changes in the PVpot over East Asia using multiple RCMs. The Taylor diagram was used, which intuitively displays model errors at a given distance from the reference point, to evaluate the PVpot spatial patterns for each *Historical* experiment over East Asia (Fig. 2). In the Taylor diagram, a reference point (red dot) indicates a perfect model which has the same spatial variability (standard deviation) as the observations and the spatial correlation coefficient of 1.0. The distance from each model point to a reference point represents the centered root mean square error of each model in the considered spatial climatology pattern [38]. In all seasons, most RCM PVpots had a correlation over 0.9 with observations and a standard deviation ratio ranging from 0.8 to 1.1. However, the SNURCM forced by HadGEM2-AO and MPI-ESM-LR had lower correlations with the observations than experienced by other RCMs, indicating poorer performances in simulating PVpot spatial patterns. Furthermore, the East Asian averaged PVpot absolute biases of the SNURCM forced by HadGEM2-AO and MPI-ESM-LR were larger than the other models across most seasons (Fig. S3). This may be due to differences in physical processes (e.g., radiation, cloud microphysics, cumulus convection and land surface) simulated by RCMs. Still, the RSDS has the most significant effect on the PVpot, thus the difference in the radiation scheme of each RCM seems to be the leading cause. The radiation schemes of all RCMs applied in this study were developed in the early- and mid-1990s. Nevertheless, the HadGEM3-RA and CCLM RCMs were applied with an improved version of the original radiation scheme. For example, the HadGEM3-RA improved cloud treatment [39–41], and the CCLM has introduced a new treatment of the optical properties of ice particles [42]. However, the SNURCM has a limitation that the original NCAR CCM2 (National Center for Atmospheric Research Community Climate Model 2) radiative package was applied as it was. Consequently, the RSDS of the SNURCM forced by HadGEM2-AO and MPI-ESM-LR had significantly larger absolute biases than other models across all seasons, which led to poorer performances in simulating PVpot (Fig. S4). Nevertheless, the MMEs (black circles and triangles) of the RCMs forced by HadGEM2-AO and MPI-ESM-LR tended to exhibit a relatively high correlation and a similar standard deviation to the observed. Therefore, the results indicate that MMEs can be used to assess future PVpot changes over East Asia.

3.2. Future change of RCM MMEs for the PVpot over East Asia

Based on the *RCP8.5* scenario, the future changes of RCM MMEs

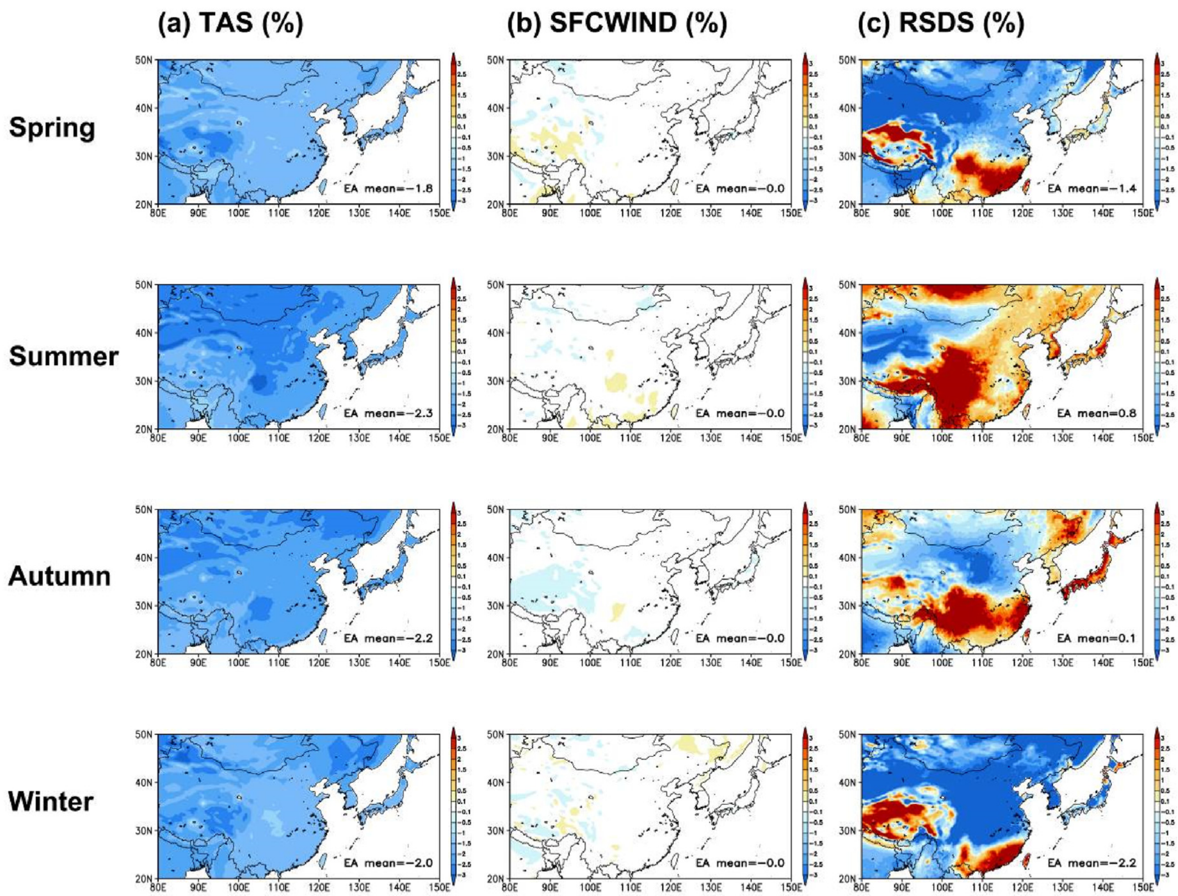

Fig. 6. Spatial distributions of effects of (a) TAS (%), (b) SFCWIND (%), and (c) RSDS (%) on seasonal future changes of the PVpot over East Asia (Eq. (4) and (5)). Area mean values are given in the bottom right corners.

for the RSDS, TAS, SFCWIND, and PVpot over East Asia during the late 21st century were estimated for each season (Fig. 3). The hatched areas represent grids with good inter-RCM agreements, which are the same sign for four or more of the six RCM simulations. The future RSDS averaged over East Asia is predicted to change from -3.7 W m^{-2} (spring) to 2.0 W m^{-2} (summer) compared to the present. However, the future RSDS simulations reveal the insufficient inter-RCM agreements from multiple RCMs in most grids except for central and eastern China in winter (Fig. S5). In both experiments, the SNURCM simulated significantly larger RSDS than other RCMs. This widened the spread between multiple models, leading to large uncertainties in simulating RSDS and PVpot (Fig. 4). Furthermore, these large uncertainties of RSDS simulations may be related to the insufficient inter-RCM agreements in future precipitation simulations from multiple RCMs (e.g., Park and Min [13]). Southern China is projected to have an overall increase in the future RSDS although large inter-RCM difference across all seasons (Fig. S5). The future TAS predictions indicate increasing patterns everywhere with an excellent inter-RCM agreement in most grids across all seasons. The future TAS change averaged over East Asia at the end of the 21st century is expected to increase by 4 °C–5 °C compared to that of the present. The future SFCWIND does not display any significant changes throughout East Asia. In all seasons, the spatial patterns of future PVpot change over East Asia are similar to those of future RSDS change and inter-RCM agreements. Among the seasons, the area with sufficient inter-RCM agreements for future PVpot simulations is widest in winter. These regions, centered on central and eastern China, are expected to decrease by over -10.0% with sufficient inter-RCM agreement. The future PVpot will increase over certain regions, such as southern China in spring and winter, and southwestern China in summer and autumn. However, these regions have insufficient inter-RCM agreements across all seasons.

To quantitatively investigate the future PVpot changes, the East Asian-averaged PVpot for individual RCMs was analyzed (Fig. 5). Asterisks from individual RCMs denote seasonal changes exceeding 95% confidence level of the *t*-test, and dots from MME represent seasonal changes with the same sign for four or more of the six RCMs. The East Asian-averaged future PVpot simulations of MME are predicted to decrease with a range from -4.3% (winter) to -1.5% (summer) compared to the present with excellent inter-RCM agreements. For all RCM simulations, the future PVpot predictions at the end of the 21st century are lower across seasons, which have a statistically significant level in most seasonal RCMs, than those of the present. Across seasons, the future PVpot of the CCLM forced by the MPI-ESM-LR has the largest decrease at the statistically significant level. For all models and MME, except the SNURCM forced by the HadGEM2-AO and MPI-ESM-LR GCMs, the magnitude of the future PVpot decrease is dependent on season, in the order of winter (largest), spring, autumn, and summer (smallest). However, unlike these seasonal trends for future PVpot changes, the decreased magnitude of the SNURCM forced by the HadGEM2-AO (MPI-ESM-LR) GCM is expected to have the largest PVpot change in autumn (spring) and the smallest in winter (autumn).

As mentioned in Section 1, the RSDS directly affects the PV

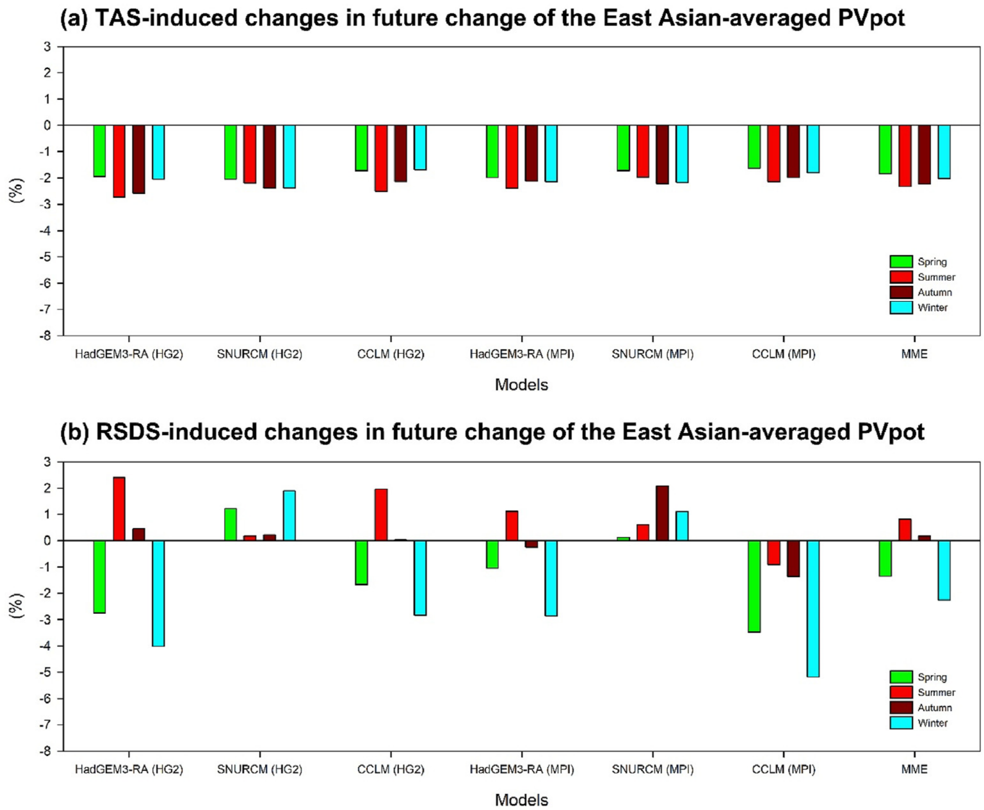

Fig. 7. Seasonal (a) TAS and (b) RSDS-induced changes (%) in the future change of the East Asian-averaged (80 °E–150 °E and 20 °N–50 °N) PVpot from individual RCMs and MME.

power generation, and the TAS and SFCWIND influence the efficiency of the solar panel [7]. Therefore, this study examined the roles of TAS, SFCWIND, and RSDS in future PVpot changes over East Asia from Eqs. (4) and (5) (Fig. 6). The future TAS increase is expected to induce a negative effect on future PVpot changes across all regions and seasons. This means that the poorer solar panels efficiency in future warming scenarios will lead to a reduction in the positive change or the intensification of a negative change of the future PVpot, which coincides with previous studies results [7,37,43–45]. In summer and autumn, the future RSDS averaged over East Asia increases slightly compared to that of the present, while predictions of the future PVpot averaged over East Asia for these seasons decrease overall (Fig. 3a and d). Therefore, it appears that the negative effect of the TAS increase may play a significant role in decreasing the future PVpot in summer and autumn. Over southwestern China, where the future RSDS increase is estimated to be the greatest, the projected future RSDS increase in summer is larger than in autumn, while the projected future PVpot increase is the opposite (Fig. 3a and d). This may be because the future TAS increases during the summer, which is the hottest of the seasons, are expected to be slightly larger than those in autumn over southwestern China (Fig. 3b); therefore, future TAS change in summer induces a larger negative effect (less than −3.0%) on future PVpot change than in autumn (Fig. 6a). The effect of SFCWIND changes on the future PVpot appears to be negligible (Fig. 6b) because its change is particularly small (Fig. 3c). Seasonal spatial distributions of the RSDS contribution to PVpot change (Fig. 6c) are similar to those of future PVpot changes illustrated in Fig. 3d.

We also examined the effects of future TAS increase and future RSDS change on the East Asian-averaged (80 °E–150 °E and 20 °N–50 °N) PVpot changes for individual RCMs and MME (Fig. 7). In all models and MME, the effects of TAS increase on PVpot changes are all negative, and the differences between models and between seasons are very small. Therefore, these results indicate that TAS increase played a major role in the negative change of the PVpot (Fig. 7a). In contrast, the future PVpot differences between models and between seasons appear to be dependent on future RSDS changes (Fig. 7b). In MME, the RSDS increase in summer compensates for TAS-induced PVpot decrease by approximately 0.7% on future PVpot change. In contrast, RSDS decreases in winter and spring, intensifying the warming-driven PVpot decrease (by about −1.4% to −2.3%).

Climate change resulting from an increase in GHGs in the atmosphere can affect atmospheric water vapor content and precipitation, influencing the PVpot in many regions worldwide [4]. To examine the relationship between precipitation and PVpot over East Asia, the inter-RCM correlation between the future change in the number of rainy days with precipitation of >0.1 mm d^{-1} and the future PVpot change was calculated on each grid (Fig. 8). Here, we calculated the number of rainy days using 3-hourly precipitation datasets during daytime when the RSDS is positive to exclude the nighttime precipitation. Fig. 8a shows the overall decrease in the number of rainy days over East Asia across seasons. In spring, autumn, and winter, the number of rainy days is predicted to decrease in southern China, the Korean peninsula, and Japan, and to increase in the inland arid regions of northern China and Mongolia. In summer, the number of rainy days is expected to increase in eastern China and the Korean peninsula. This may be related to the future enhancement of the quasi-stationary front (i.e., East Asian summer monsoon rain band), which significantly affects these regions in summer [13,18,19,32,46–49]. The relationship between the future change in the number of rainy days and the future PVpot change over East Asia is expected to have a widespread negative correlation across all seasons (Fig. 8b). Area mean correlation

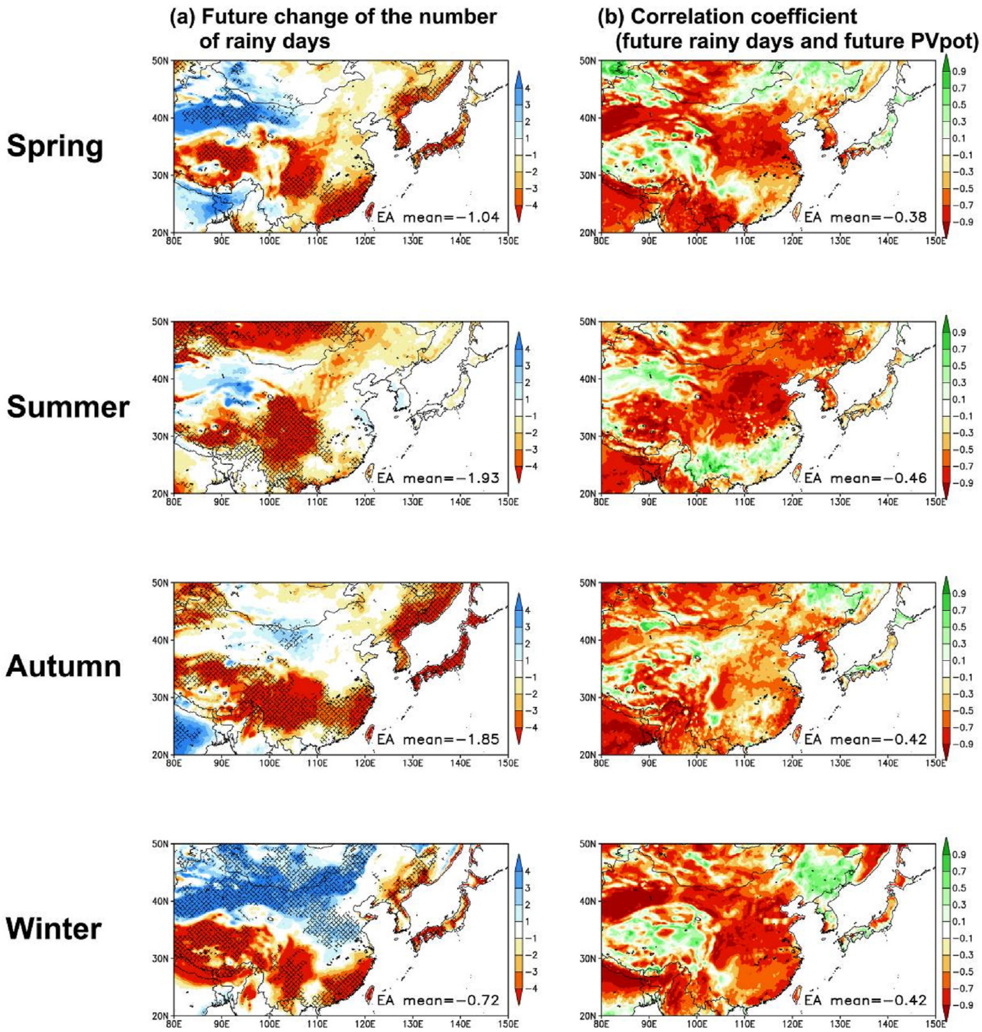

Fig. 8. Spatial distributions of (a) seasonal future change for the number of days with precipitation of >0.1 mm d^{-1} and (b) the inter-RCM correlation coefficients between the future change of the number of days with precipitation of >0.1 mm d^{-1} and the future PVpot change. Note that the hatched areas represent grids with good inter-RCM agreements, which are the same sign for four or more of the six RCM simulations in (a). In (b), correlation coefficients are calculated on each grid using six individual RCM's future change of the number of rainy days and six individual RCM's future PVpot change. Area mean correlation coefficients are given in the bottom right corners.

coefficients over East Asia appear from −0.46 (summer) to −0.38 (spring). In particular, the negative correlation is predicted to be high in central China during spring, summer, and winter. These results indicate that the increase (decrease) in the number of future rainy days negatively (positively) affects future PVpot changes through decreasing (increasing) RSDS. The inter-RCM correlation between the future change in the number of rainy days and the future RSDS change is very similar to that of the PVpot (Fig. S6).

4. Conclusions and discussion

Using the ERA5 datasets and the results of multiple RCM simulations participating in the CORDEX-East Asia phase II, this study investigated a first analysis of the present distribution and future change in the PVpot over East Asia. The PVpot tended to be most affected by the RSDS, supporting previous findings. The recent change in observed PVpot demonstrated the largest increase in southern China region. The overall PVpot over East Asia is expected to decrease in the future, whereas it is predicted to increase over the southern China region. The future TAS will negatively affect future PVpot changes, while the effect of future SFCWIND will be negligible. The TAS increase played a significant role in the negative projection of the PVpot, but the future PVpot differences between models and between seasons were found to be due to future RSDS changes. The effects of TAS and SFCWIND on the future PVpot change in East Asia were very similar to the results of Jerez et al. [7], a European region study. Regarding the relationship between precipitation and PVpot over East Asia, an increase (decrease) in the number of future rainy days leads to a negative (positive) effect on the future PVpot change. Particularly, central China in spring, autumn, and winter is projected to have a high negative correlation. These results can greatly help in developing policies for efficient and reliable future solar energy production.

The future RSDS simulations are predicted to have large uncertainties from multiple RCMs. These may be related to large uncertainties of future precipitation simulations. Consequently, these also lead to considerable uncertainty in future PVpot simulations. Therefore, for more reliable future PVpot simulations using RCMs, precipitation simulation should be improved. The TAS increase plays a major role in the transition to decreasing the future PVpot over East Asia. If global warming accelerates under the BAU scenario condition, the efficiency of solar panels in the future will inevitably decrease. To overcome this, efforts are required to reduce the drop-off in the performance of solar panels under higher ambient temperature, or to reduce the dependence of PV cell performance on ambient temperature as described by Jerez et al. [7]. Further, although the price is higher than the monocrystalline silicon solar cell panels, the use of thin-film solar panels, etc., which have a lower negative effect on the increase in ambient temperature [50], could be a solution. A recent study by Gutiérrez et al. [51] argued that aerosol forcing evolution should be reflected in the future PVpot changes using RCMs. However, because aerosol datasets were not produced in multiple RCMs of the CORDEX-East Asia phase II, this study, which only considers the evolution of carbon dioxide forcing, has a limitation.

The following research is required as follow-up studies on the future change in renewable energy over East Asia due to climate change. (1) Several large-scale solar power plants are located in western China. We will conduct detailed investigations of future PVpot by sub-regions, focusing on the regions where major solar power plants (e.g., Huanghe Hydropower Hainan Solar Park, Tengger Desert Solar Park, Longyangxia Dam Solar Park, etc.) are located. (2) The frequency and intensity of future heat waves over East Asia are expected to increase [12,13]. When a heat wave occurs in densely populated East Asia, the demand for electricity for cooling explodes. The PV will be used as the major power generation source in the future, but the PV power generation is expected to decrease due to the increase in the frequency and intensity of heat waves. This may cause problems for future power management. Therefore, the research on the effect of extreme temperature on the future PVpot needs to be investigated. (3) The research on the impact of natural climate variability, e.g., Arctic Oscillation (AO), El Niño–Southern Oscillation (ENSO), and Indian Ocean Dipole (IOD), which has a considerable influence on the climate in this region, on the renewable energy production potential should be continuously conducted. (4) The RSDS dominates future PVpot changes, but the effect of the TAS cannot be ignored. This study has a limitation in applying only a single scenario of the *RCP8.5*, the BAU scenario, to predict future PVpot change over East Asia. Therefore, a comparative study of future PVpot predictions according to various future warming scenarios (i.e., other RCP or shared socio-economic pathways) should be conducted.

Data availability

The data that support the findings of this study are available upon reasonable request from the authors.

CRediT authorship contribution statement

Changyong Park: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Seok-Woo Shin:** Software, Investigation, Data curation, Writing – review & editing. **Gayoung Kim:** Investigation, Data curation, Writing – review & editing. **Dong-Hyun Cha:** Conceptualization, Supervision, Funding acquisition, Writing – original draft, Writing – review & editing. **Seung-Ki Min:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Donghyun Lee:** Data curation, Writing – review & editing. **Young-Hwa Byun:** Data curation, Writing – review & editing. **Jin-Uk Kim:** Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

[1] IPCC, Climate change 2013: the physical science basis, in: T.F. Stocker, et al. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2013.
[2] R.L. Arantegui, A. Jäger-Waldau, Photovoltaics and wind status in the European union after the Paris agreement, Renew. Sustain. Energy Rev. 81 (2) (2018) 2460–2471, https://doi.org/10.1016/j.rser.2017.06.052.
[3] UN, The Sustainable Development Goals Report 2020, United Nations Publications, New York, 2020.
[4] D. Arvizu, et al., Direct solar energy, in: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, Cambridge and New York, 2011.
[5] IRENA, Future of Solar Photovoltaic: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects, International Renewable Energy Agency, Abu Dhabi, 2019.
[6] IPCC, *Global warming of 1.5 °C*, An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in: The Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, 2018 (In Press).
[7] S. Jerez, et al., The impact of climate change on photovoltaic power generation in Europe, Nat. Commun. 6 (2015) 10014, https://doi.org/10.1038/ncomms10014.
[8] J.C. Pérez, A. González, J. P Díaz, F.J. Expósito, J. Felipe, Climate change impact on future photovoltaic resource potential in an orographically complex archipelago, the Canary Islands, Renew. Energy 133 (2019) 749–759, https://doi.org/10.1016/j.renene.2018.10.077.
[9] A. Bichet, B. Hingray, G. Evin, A. Diedhiou, C.M.F. Kebe, S. Anquetin, Potential impact of climate change on solar resource in Africa for photovoltaic energy: analyses from CORDEX-AFRICA climate experiments, Environ. Res. Lett. 14 (2019) 124039, https://doi.org/10.1088/1748-9326/ab500a.
[10] F. Giorgi, C. Jones, G.R. Asrar, Addressing climate information needs at the regional level: the CORDEX framework, WMO Bull 58 (2009) 175–183.
[11] D.H. Cha, D.K. Lee, C.S. Jin, G. Kim, Y. Choi, M.S. Suh, J.B. Ahn, S.Y. Hong, S.K. Min, S.C. Park, H.S. Kang, Future changes in summer precipitation in regional climate simulations over the Korean peninsula forced by multi-RCP scenarios of HadGEM2-AO, Asia, Pac. J. Atmos. Sci. 52 (2016) 139–149, https://doi.org/10.1007/s13143-016-0015-y.
[12] G. Kim, D.H. Cha, C. Park, G. Lee, C.S. Jin, D.K. Lee, M.S. Suh, J.B. Ahn, S.K. Min, S.Y. Hong, H.S. Kang, Future changes in extreme precipitation indices over Korea, Int. J. Climatol. 38 (2018) e862–e874, https://doi.org/10.1002/joc.5414.
[13] C. Park, S.K. Min, Multi-RCM near-term projections of summer climate extremes over East Asia, 2019, Clim. Dynam. 52 (2019) 4937–4952, https://doi.org/10.1007/s00382-018-4425-7.
[14] D.K. Lee, D.H. Cha, Regional climate modeling for Asia, Geosci. Lett. 7 (2020) 13, https://doi.org/10.1186/s40562-020-00162-8.
[15] M. Lee, D.H. Cha, M.S. Suh, E.C. Chang, J.B. Ahn, S.K. Min, Y.H. Byun, Comparison of tropical cyclone activities over the western North Pacific in CORDEX-East Asia phase I and II experiments, J. Clim. 33 (2020), https://doi.org/10.1175/JCLI-D-19-1014.1.
[16] G. Kim, D.H. Cha, G. Lee, C. Park, C.S. Jin, D.K. Lee, M.S. Suh, J.B. Ahn, S.K. Min, J. Kim, Projection of future precipitation change over South Korea by regional climate models and bias correction methods, Theor. Appl. Climatol. 141 (2020) 1415–1429, https://doi.org/10.1007/s00704-020-03282-5.
[17] G. Kim, D.H. Cha, G. Lee, C. Park, C.S. Jin, D.K. Lee, M.S. Suh, S.G. Oh, S.Y. Hong, J.B. Ahn, S.K. Min, H.S. Kang, Evaluation and projection of regional climate over East Asia in CORDEX-East Asia phase I experiment, Asia, Pac. J. Atmos. Sci. 57 (2021) 119–134, https://doi.org/10.1007/s13143-020-00180-8.
[18] C. Park, D.H. Cha, G. Kim, G. Lee, D.K. Lee, M.S. Suh, S.Y. Hong, J.B. Ahn, S.K. Min, Evaluation of summer precipitation over Far East Asia and South Korea simulated by multiple regional climate models, Int. J. Climatol. 40 (2020) 2270–2284, https://doi.org/10.1002/joc.6331.
[19] C. Park, G. Lee, G. Kim, D.H. Cha, Future changes in precipitation for identified sub-regions in East Asia using bias-corrected multi-RCMs, Int. J. Climatol. 41 (2021) 1889–1904, https://doi.org/10.1002/joc.6936.
[20] H. Hersbach, et al., Global reanalysis: goodbye ERA-Interim, hello ERA5, ECMWF Newsletter 159 (2019), https://doi.org/10.21957/vf291hehd7.
[21] G.M. Martin, N. Bellouin, W.J. Collins, The HadGEM2 family of met office

Unified model climate configurations, Geosci. Model. Dev. 4 (2011) 723–757, https://doi.org/10.5194/gmd-4-723-2011.
[22] H.J. Baek, et al., Climate change in the 21st century simulated by HadGEM2-AO under representative concentration pathways, Asia Pac, J. Atmos. Sci. 49 (2013) 603–618, https://doi.org/10.1007/s13143-013-0053-7.
[23] K.R. Sperber, H. Annamalai, I.S. Kang, A. Kitoh, A. Moise, A. Turner, B. Wang, T. Zhou, The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century, Clim. Dynam. 41 (2013) 2711–2744, https://doi.org/10.1007/s00382-012-1607-6.
[24] Y. Guo, J. Cao, H. Li, J. Wang, Y. Ding, Simulation of the interface between the Indian summer monsoon and The East asian summer monsoon: intercomparison between MPI-ESM and ECHAM5/MPI-OM, Adv. Atmos. Sci. 33 (2016) 294–308, https://doi.org/10.1007/s00376-015-5073-z.
[25] H. von Storch, H. Langenberg, F. Feser, A spectral nudging technique for dynamical downscaling purposes, Mon. Weather Rev. 128 (2000) 3664–3673.
[26] J.M. Edwards, A. Slingo, Studies with a flexible new radiation code. I: choosing a configuration for a large-scale model, Q. J. R. Meteorol. Soc. 122 (1996) 689–719, https://doi.org/10.1002/qj.49712253107.
[27] S. Cusack, J.M. Edwards, M.J. Crowther, Investigating k distribution methods for parameterizing gaseous absorption in the Hadley Centre Climate Model, J. Geophys. Res. 104 (1999) 2051–2057, https://doi.org/10.1029/1998JD200063.
[28] B.P. Briegleb, Delta-Eddington approximation for solar radiation in the NCAR community climate model, J. Geophys. Res. 97 (1992) 7603–7612, https://doi.org/10.1029/92JD00291.
[29] J.J. Hack, B.A. Boville, B.P. Briegleb, J.T. Kiehl, D.L. Williamson, Description of the NCAR Community Climate Model (CCM2) (No. NCAR/TN-382+STR), University Corporation for Atmospheric Research, 1993, https://doi.org/10.5065/D6QZ27XV.
[30] B. Ritter, J.F. Geleyn, A comprehensive radiation scheme for numerical weather prediction models with potential applications in climate simulations, Mon. Weather Rev. 120 (1992) 303–325.
[31] T. Davies, M.J.P. Cullen, A.J. Malcolm, M.H. Mawson, A. Staniforth, A.A. White, N. Wood, A new dynamical core for the met office's global and regional modeling of the atmosphere, Q. J. R. Meteorol. Soc. 131 (2005) 1759–1782, https://doi.org/10.1256/qj.04.101.
[32] D.H. Cha, D.K. Lee, Reduction of systematic errors in regional climate simulations of the summer monsoon over East Asia and the western North Pacific by applying the spectral nudging technique, J. Geophys. Res. 114 (2009) D14108, https://doi.org/10.1029/2008JD011176.
[33] B. Rockel, A. Will, A. Hense, The regional climate model COSMO-CLM(CCLM), Meteorol. Z. 17 (2008) 347–348, https://doi.org/10.1127/0941-2948/2008/0309.
[34] I.E.C. IEC, 61215 Second *Edition:* Crystalline Silicon Terrestrial Photovoltaic (PV) Modules- Design Qualification and Type Approval, International Electrotechnical Commission, Geneva, 2005.
[35] G. TamizhMani, L. Ji, Y. Tang, L. Petacci, C. Osterwald, Photovoltaic module thermal/wind performance: long-term monitoring and model development for energy rating, in: NCPV and Solar Program Review Meeting 2003, 2003, pp. 936–939.
[36] S. Jerez, F. Thais, I. Tobin, M. Wild, A. Colette, P. Yiou, E. Vautard, The CLIMIX model: a tool to create and evaluate spatially-resolved scenarios of photovoltaic and wind power development, Renew. Sustain. Energy Rev. 42 (2015) 1–15, https://doi.org/10.1016/j.rser.2014.09.041.
[37] J.A. Crook, L.A. Jones, P.M. Forster, R. Crook, Climate change impacts on future photovoltaic and concentrated solar power energy output, Energy Environ. Sci. 9 (2011) 3101–3109, https://doi.org/10.1039/C1EE01495A.
[38] K.E. Taylor, Summarizing multiple aspects of model performance in a single diagram, J. Geophys. Res. 106 (2001) 7183–7192, https://doi.org/10.1029/2000JD900719.
[39] R. Pincus, H.W. Barker, J. J Morcrette, A fast, flexible, approximate technique for computing radiative transfer in inhomogeneous cloud fields, J. Geophys. Res. 108 (2003) 4376, https://doi.org/10.1029/2002JD003322.
[40] P. Räisänen, H.W. Barker, H. W, M.F. Khairoutdinov, J. Li, D.A. Randall, Stochastic generation of subgrid-scale cloudy columns for large-scale models, Q. J. R. Meteorol. Soc. 130 (2004) 2047–2067, https://doi.org/10.1256/qj.03.99.
[41] J.M. Edwards, J.C. Thelen, W.J. Ingram, The Radiation Code. Unified Model Documentation Paper No. 23, 2013 (Exeter: Met Office).
[42] U. Schättler, G. Doms, C. Schraf, A Description of the Nonhydrostatic Regional COSMO-Model Part VII User's Guide, 2013, https://doi.org/10.5676/DWD_pub/nwv/cosmo-doc_5.00_VII. Offenbach: Deutscher Wetterdienst).
[43] R. Pašičko, R.Č. Branković, Z. Šimić, Assessment of climate change impacts on energy generation from renewable sources in Croatia, Renew. Energy 46 (2012) 224–231, https://doi.org/10.1016/j.renene.2012.03.029.
[44] I.S. Panagea, I.K. Tsanis, A.G. Koutroulis, M.G. Grillakis, Climate change impact on photovoltaic energy output: the case of Greece, Adv. Meteorol. (2014) 264506, https://doi.org/10.1155/2014/264506.
[45] M. Wild, D. Folini, F. Henschel, N. Fischer, B. Müller, Projections of long-term changes in solar radiation based on CMIP5 climate models and their influence on energy yields of photovoltaic systems, Sol. Energy 116 (2015) 12–24, https://doi.org/10.1016/j.solener.2015.03.039.
[46] B. Wang, LinHo, Rainy season of the Asian-Pacific summer monsoon, J. Clim. 15 (2002) 386–398.
[47] B. Wang, Z. Wu, J. Li, J. Liu, C.P. Chang, Y. Ding, G. Wu, How to measure the strength of the East Asian summer monsoon, J. Clim. 21 (2008) 4449–4463, https://doi.org/10.1175/2008JCLI2183.1.
[48] S.K. Min, et al., Changes in weather and climate extremes over Korea and possible causes: a review, Asia, Pac. J. Atmos. Sci. 51 (2015) 103–121, https://doi.org/10.1007/s13143-015-0066-5.
[49] D. Lee, S.K. Min, J. Jin, J.W. Lee, D.H. Cha, M.S. Suh, J.B. Ahn, S.Y. Hong, H.S. Kang, M. Joh, Thermodynamic and dynamic contributions to future changes in summer precipitation over Northeast Asia and Korea: a multi-RCM study, Clim. Dynam. 49 (2017) 4121–4139, https://doi.org/10.1007/s00382-017-3566-4.
[50] A. Patt, S. Pfenninger, J. Lilliestam, Vulnerability of solar energy infrastructure and output to climate change, Clim. Change 121 (2013) 93–102, https://doi.org/10.1007/s10584-013-0887-0.
[51] C. Gutiérrez, S. Somot, P. Nabat, M. Mallet, L. Corre, E. van Meijgaard, O. Perpiñán, M.Á. Gaertner, Future evolution of surface solar radiation and photovoltaic potential in Europe: investigating the role of aerosols, Environ. Res. Lett. 15 (2020), 034035, https://doi.org/10.1088/1748-9326/ab6666.

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Corrigendum to “What determines future changes in photovoltaic potential over East Asia?” [Renew. Energy 185 (2022) 338–347]

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