

Climate model forecasts of surface-level solar spectrum variation: effects on photovoltaics and crop photosynthesis

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Abstract

Accumulation of greenhouse gases and aerosols in the atmosphere alter the spectrum of sunlight that reaches the Earth's surface. The change in spectrum affects the output of photovoltaics and crop photosynthesis. To forecast the global impacts, atmospheric parameters from five climate models in the Coupled Model Intercomparison Project (CMIP) were input to the radiative transfer model SMARTS to generate representative spectra over six decades (2018-2082). Geographic and temporal variation was then forecast for the spectral responses of one-, two- and three-junction photovoltaic cells, and three crop plants: corn, wheat, and rice. Results for photovoltaics show baseline global outputs lower than for the standard spectrum, particularly for solar cells with more than one junction. In the decades ahead, photovoltaic output declines due to increased water vapor absorption, but crop photosynthesis is largely unaffected. For both photovoltaics and crop photosynthesis, forecast long-term decreases in atmospheric aerosols lead to net production increases over most of the globe.

Introduction

Humanity converts sunlight into usable energy directly, via solar (and wind) power, and indirectly, via photosynthesis of crop plants. The efficiency of this conversion, in photovoltaics and crop photosynthesis, is altered by changes in sunlight spectrum resulting from atmospheric shifts induced by climate change. As sunlight passes through the Earth's atmosphere to the surface, the spectrum is altered by absorption and scattering by gas molecules and aerosols. As greenhouse gases accumulate, radiative forcing increases, resulting in further modification of atmospheric gases and aerosol levels. The ongoing change in the spectrum of radiation reaching the Earth's surface will vary with geographic location and over time. To model the changing spectrum, atmospheric parameters from five climate models from the Coupled Model Intercomparison Project were input to the radiative transfer model SMARTS to forecast solar spectrum variation over six decades (2018-2082). The resulting geographic and temporal variation of photovoltaic and photosynthetic output was forecast using the spectral responses of one-, two- and three-junction photovoltaic cells, and three crop plants: corn, wheat, and rice.

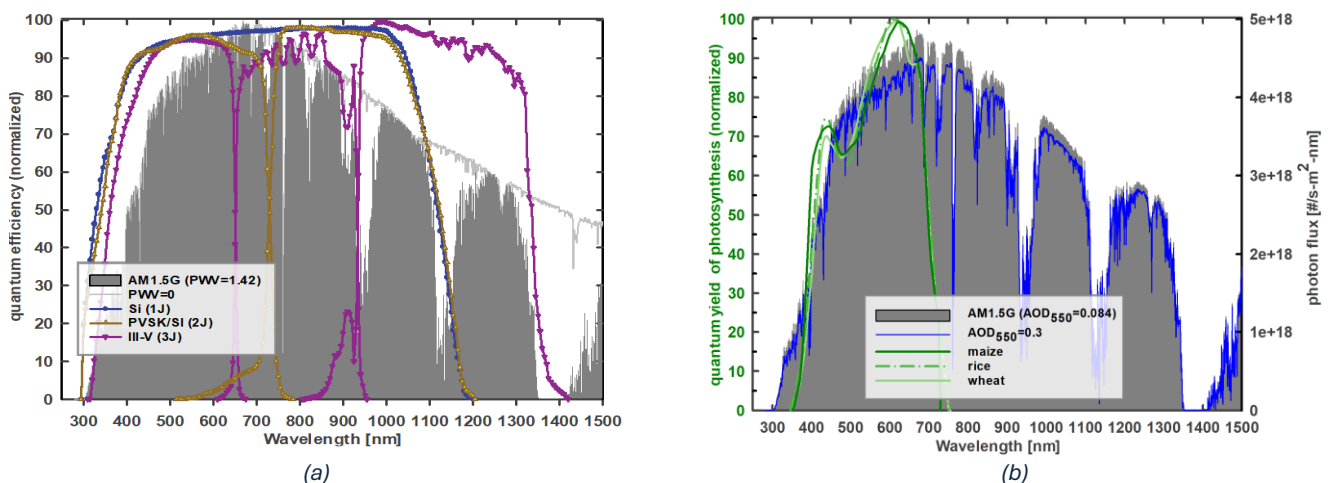


Figure 1. (a) Quantum efficiencies of a single-junction (1J) silicon (Si), tandem (2J) perovskite-silicon (PVS/K/SI) and three-junction (3J) III-V multijunction cells¹²⁻¹⁴. The standard terrestrial solar spectrum (AM1.5G) is shown against a spectrum for which the precipitable water (PWW) has been changed from 1.42 to 0.00 [g/cm²].

(b) Spectra of quantum yield of photosynthesis for maize, wheat, and rice¹⁵ shown against the standard terrestrial solar spectrum (AM1.5G) and a spectrum for which the aerosol optical depth at 550 nm (AOD₅₅₀) has been changed from 0.084 to 0.3.

The atmosphere both reflects and absorbs incoming solar radiation. Molecular scattering by oxygen and nitrogen gives us our blue skies and the diffuse component of solar irradiance at the surface. Proportional to the inverse fourth power of the wavelength¹, molecular scattering depends on the density of the air column that the sun's

rays pass through. The value may be derived from surface atmospheric pressure, which rises with temperature. Suspended aerosols (particle and liquid) both scatter and absorb radiation. Prehistoric drivers of increased aerosol levels include forest fires, windborne desert dust and ocean salt, and volcanism. Since the Industrial Revolution, combustion of fossil fuels has been contributing various additional man-made aerosols, including sulfates, nitrates, and carbon.

The roles of water vapor and carbon dioxide in absorbing radiation and thereby altering the climate (radiative forcing) have been recognized since Eunice Foote's groundbreaking demonstrations in 1856². As climate change accelerates, the radiation trapped by greenhouse gases initiates numerous feedback loops that are altering the composition of the atmosphere that does the trapping³. The increase in global mean temperature⁴ means persistently more water vapor in the atmosphere, due to elevated ocean and air temperatures that, respectively, increase evaporation rates and the atmosphere's ability to retain the evaporated water.

The future trend for aerosol levels in the atmosphere is harder to predict. The burning of fossil fuels produces a range of aerosols, including small particles of sulfates and carbon, which can persist in the upper atmosphere until they form the nucleation site for water droplets and precipitation. A global transition towards cleaner fuels would decrease these levels. Local differences in aerosol levels will arise from increases and decreases in regional wind speeds that are occurring as the planet warms and patterns shift⁵. The distribution of aerosol levels from both natural and manmade sources will therefore remain heterogeneous across the planet⁶. Temperature changes from the scattering and absorption of sunlight by these localized aerosols lead to fluctuations in rates of evaporation, cloud formation, and precipitation, as well as a host of other feedbacks that alter both regional and global weather patterns³.

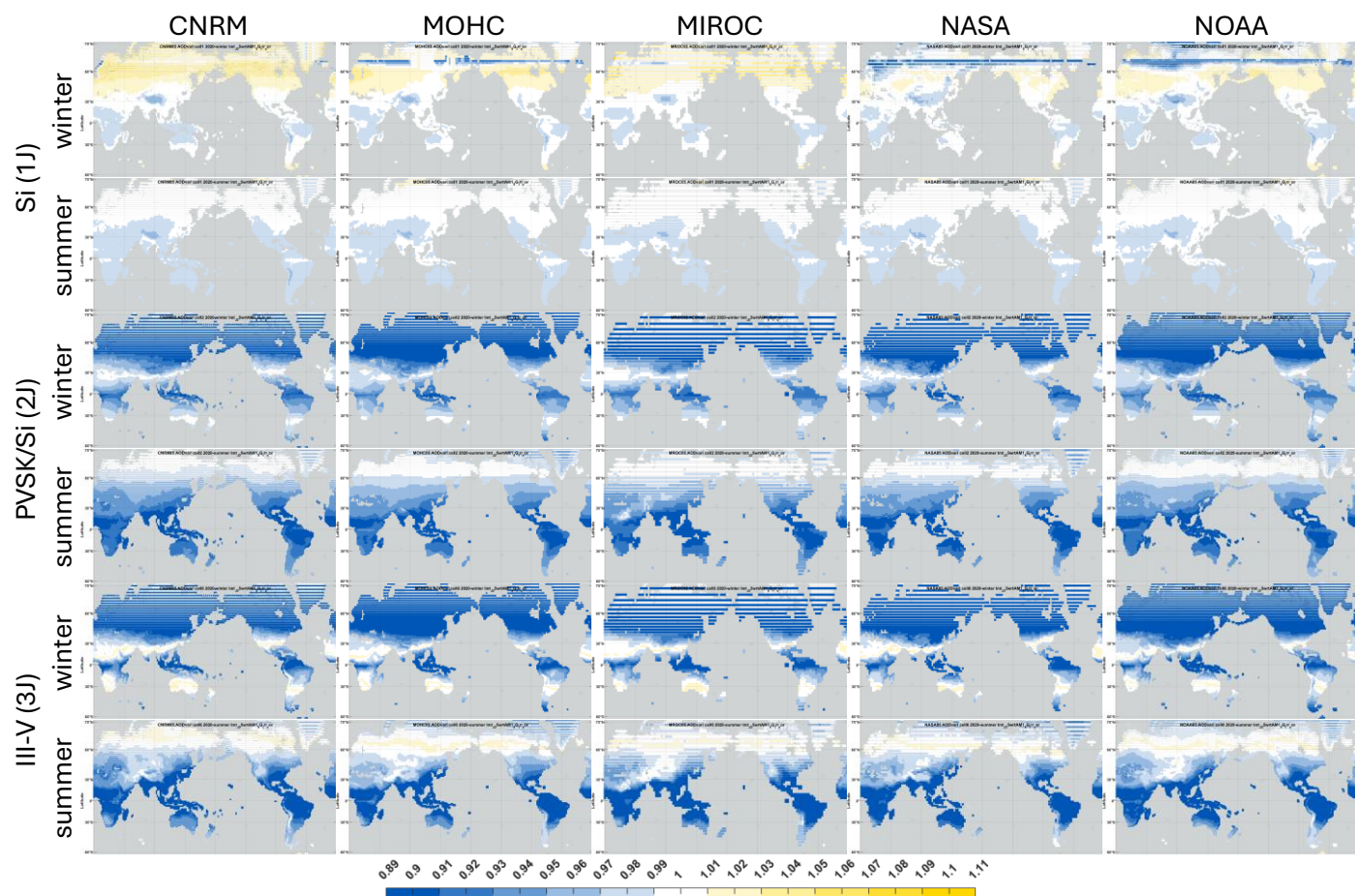


Figure 2. Predicted 2020 solar cell short-circuit current relative to that under the standard spectrum (AM1.5G) at 25°C (scenario: SSP585). Currents are normalized to 1000 W/m² irradiance. “Summer”/ “winter” corresponds to months 6-8/12-2 in the northern hemisphere and 12-2/6-8 in the southern hemisphere.

Efforts to measure and model these trends, and their interactions, span more than a century⁷. Foote's experiments in the mid-1800s largely resolved the mystery that had surrounded evidence of temperature oscillations found in the geological record⁸. Decades later, climate modeling had its beginnings in weather modeling, which first incorporated atmospheric circulation (1955) and then coupled it with oceanic circulations in the 1960s⁹. The Coupled Model Intercomparison Project (CMIP) was established in 1995 to improve model

accuracy and provide a knowledge base to inform international action to mitigate climate change. The sixth iteration (CMIP6¹⁰) began in 2013 and comprises 23 models which provide the underlying data for the multi-decade forecasts in reports by the Intergovernmental Panel on Climate Change (IPCC)¹¹. Various future scenarios (Shared Socioeconomic Pathways, SSPs) are evaluated based on the expected level of radiative forcing from additional solar radiation being retained in the atmosphere, land, and water. The scenarios are numbered sequentially by the expected radiative forcing by 2100: scenario 1 assumes aggressive carbon reduction and low radiative forcing of 1.9 W/m² (SSP119); with continued expansion of fossil-fuel combustion, scenario 5 expects forcing to reach 8.5 W/m² by 2100 (SSP585). An intermediate condition considered here is scenario 2: 4.5 W/m² (SSP245).

The effects of climate change on photovoltaics due to alterations in temperature, broadband irradiance, and cloud cover, have been studied previously^{16–34}. To isolate the impact of spectrum variation, results here are taken at 25° C and normalized to the broadband irradiances. Clear sky conditions are assumed.

The rate of photosynthesis is a primary factor in crop yield³⁵. Changes in the available spectrum affect leaf morphology and the resulting rate of photosynthesis³⁶. Attention to the spectrum of light is a key condition for productive growth under artificial lights, for example^{37,38}. Slowing of the rate of photosynthesis due to deficits in the solar spectrum can further reduce outdoor crop yields by extending the time to harvest and thereby increasing the risk of exposure of the crop to droughts, floods, and pests.

The CMIP6 models used to predict sunlight spectrum at the surface produce over a thousand parameters for changes to the geosphere. The parameters of interest here are those used by the radiative transfer model SMARTS to generate representative solar spectra at the Earth's surface³⁹. The SMARTS model is widely used in photovoltaics for its ability to calculate the spectra incident on tilted surfaces, and to define reference spectra⁴⁰. Parameters used for generating spectra in SMARTS are: aerosol optical depth at 550 nm (AOD, Figure 5), carbon dioxide, relative humidity, ozone, precipitable water (Figure 3), surface pressure (Figure 11), surface air temperature, and surface maximum temperature. These inputs to SMARTS were drawn from five of the available CMIP6 models: ESM2-1 (National Centre for Meteorological Research, "CNRM"), UKESM1-0-LL (Met Office Hadley Center, "MOHC"), ES2L (Japan Agency for Marine-Earth Science and Technology, Centre for Climate System Research / National Institute for Environmental Studies "MIROC"), GISS-E2-1-G (National Aeronautics and Space Administration, "NASA"), and GFDL-ESM4 (National Oceanic and Atmospheric Administration, "NOAA"). Data was sampled at monthly intervals.

For forecasting solar cell performance, the spectra generated by SMARTS combined with the quantum efficiency (Figure 1a) of the solar cell gives the predicted short-circuit current^{41–44}. The quantum efficiency was drawn from cells with the current-best laboratory efficiency^{12–14}. An analogous process was used for crop plants, using the relative spectra of quantum yield of photosynthesis¹⁵ (Figure 1b). Crop growth is not necessarily limited by the available sunlight, but the quantum yield of photosynthesis provides a prediction of the crop growth rates that result when water, nutrient, and temperature conditions are sufficient to give growth that becomes limited by the available sunlight.

2020 baseline: comparison with the PV standard spectrum

Using 2020 as a baseline year, the geographic distribution of photovoltaic output can be compared against that under the standard reference spectrum (AM1.5G). Results for the three solar cell designs are shown in Figure 1. With the exception of silicon solar cells in the northern hemisphere in winter, the modeled spectra indicate lower output than under the standard spectrum. Lower performance of silicon in the southern hemisphere, and the generally lower performance for 2- and 3-junction designs, is consistent with measured results⁴⁴. While solar technologies are evaluated using ranges for temperature and broadband irradiance, use of a single standard for spectrum remains commonplace. As with temperature and broadband irradiance, evaluation under more than the one spectrum condition would better inform design optimization and reduce forecast errors^{41,44}. To put the magnitudes in Figure 1 into perspective, widespread use of photovoltaics as an energy source means that even single-digit percent changes translate to large global impacts. Approximately 760 GW of PV was operating worldwide in 2020⁴⁵, so (assuming 1500 kWh of generation per kW of capacity) a 1% increase/decrease equates to 11 TWh of generation gained/lost, equivalent to the annual electricity consumption of Lithuania⁴⁶.

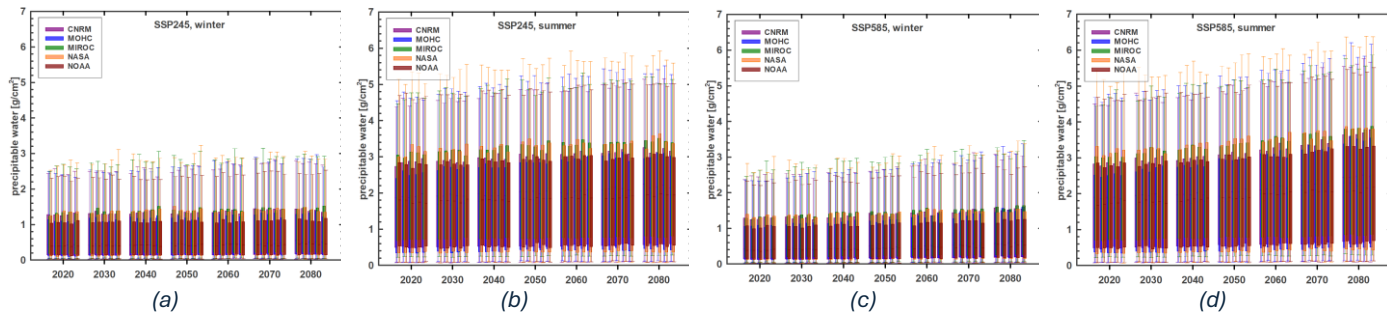


Figure 3. Precipitable water under SSP245 winter (a) & summer (b) and SSP585 winter (c) & summer (d). Winter/summer correspond to months 12-2/6-8 in the northern hemisphere and 6-8/12-2 in the southern hemisphere. Bars are for the 25th to 75th percentiles; whiskers show the 5th to 95th percentiles.

For solar cells with more than one junction, series connection of the sub-cells means that the output current is limited by whichever junction is producing the least. The resulting increase in spectrum sensitivity makes the use of a single spectrum less predictive of operating efficiency and insufficient for comparing cells with different spectrum sensitivities^{41,42,44}. If a cell with more than one junction is tuned so that its sub-cell currents match under the standard spectrum, peak performance is obtained: performance will fall off under the range of other spectrum conditions found in operation. This is evident in Figure 1 for the two-junction (2J) perovskite-silicon and the three-junction (3J) III-V multijunction cells, for which the predicted output is often more than 5% lower than for silicon in tropical latitudes, in summer (or outside tropical latitudes, in winter).

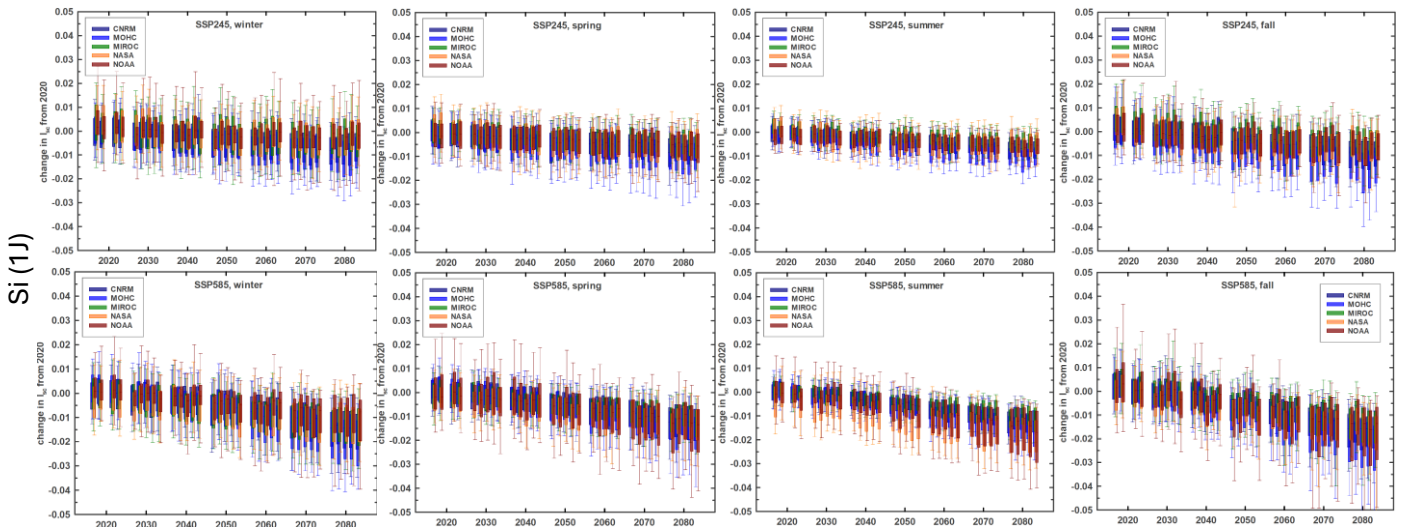


Figure 4. With aerosols held at 2020 levels, the decadal projections of the change in seasonal short-circuit current of silicon (Si) solar cells from 2020 values. Data is normalized by the relative irradiances.

Decadal forecasts: effect of water vapor

The ability of solar PV to slow destabilization of the climate will itself be altered as changes take effect. Increases in global surface temperatures increase evaporation and the precipitable water content in the column of atmosphere above the surface⁴⁷. The decrease in stability that results from thermal energy accumulating in the atmospheric system is expected to lead to both changes in magnitude, and larger fluctuations. Absorption of radiation by water vapor occurs at wavelengths both within and beyond the absorption bands of solar cells, so the proportional impact on their outputs differs from what might be found from analysis of the broadband solar irradiance. For example, the number of photons in the standard spectrum (250-4000 nm, precipitable water=1.42 g/cm²), is about 22% lower than that of a spectrum in a perfectly dry atmosphere (precipitable water=0 g/cm²), Figure 1(a). The relative decrease within the absorption range of silicon solar cells (300-1200 nm) is less: about 10%. Precipitable water vapor increases with temperature, so the forecast downward trends in cell current over time shown in Figure 4 are expected from this component of anthropogenic climate change⁴⁸. Similar decreases in current due (primarily) to increases in water vapor are seen with 2-junction and 3-junction cells (supplemental materials, Figure 14).

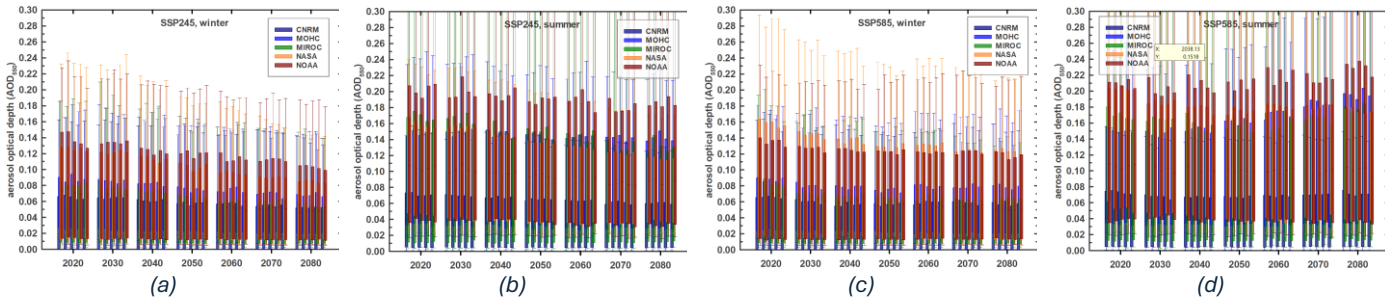


Figure 5. Aerosol optical depth at 550 nm (AOD_{550}) under SSP245 winter (a) & summer (b) and SSP585 winter (c) & summer (d). Winter/summer correspond to months 12-2/6-8 in the northern hemisphere and 6-8/12-2 in the southern hemisphere.

Decadal forecasts: water vapor and aerosols

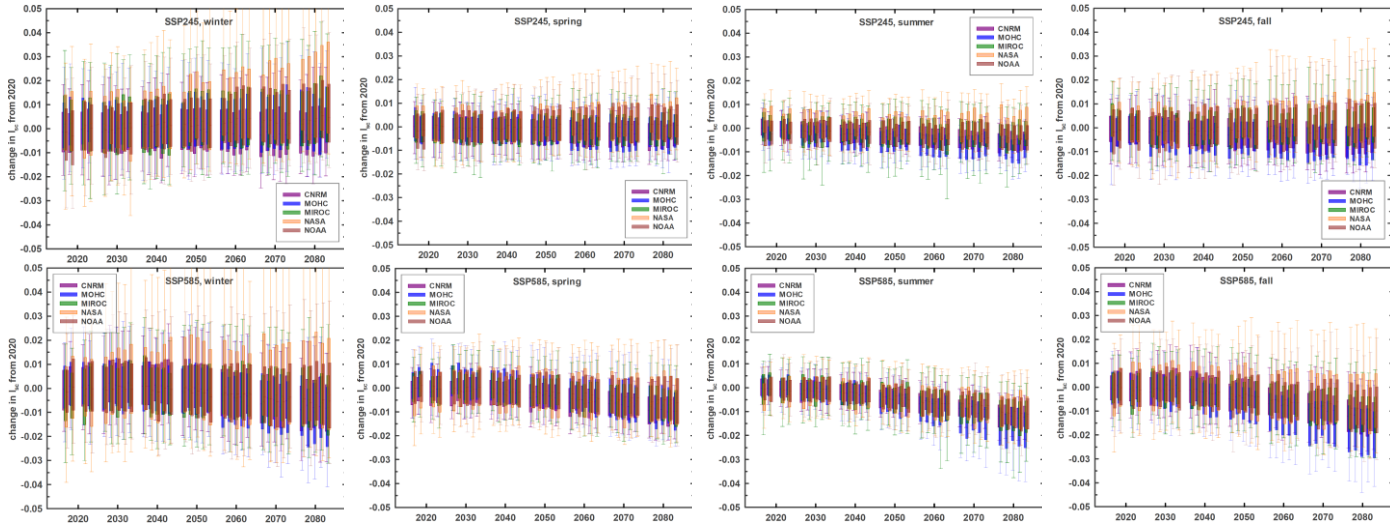
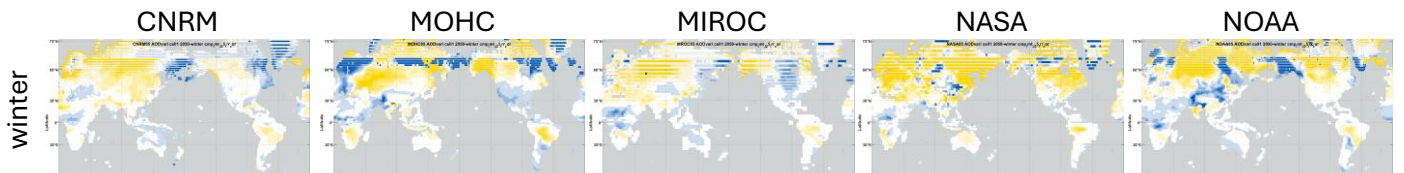


Figure 6. Decadal projections of the change in seasonal short-circuit current of single-junction (1J) silicon solar cells relative to 2020 values. Data is for latitudes below $\pm 60^\circ$ (inclusive) and is normalized by the relative irradiance.

Whereas the effect of water vapor on spectral irradiance is confined to the water absorption bands (Figure 1a), the absorption and scattering from aerosols is more broadband; it depends on the size (for soot and dust) and (for molecular scattering) the chemical composition of the particles. The wavelength dependence is therefore more spread out across the spectrum of interest for solar cells and crops (Figure 1b). Aerosol levels in the atmosphere (quantified as aerosol optical depth, AOD) are both rising and falling due to human activity and climate change feedbacks, so are more difficult to forecast. A patchwork approach to decarbonization globally will give rise to fluctuations in aerosol levels locally and over time. Potential attempts at atmospheric geoengineering would add to the uncertainty⁴⁹. While the transition from coal to natural gas to zero-carbon sources reduces the aerosols emitted per unit of energy, this may prove to be more than offset by growth in total energy demand worldwide. As climate zones shift, large-scale wildfires (in forests and peat bogs) may further accelerate as permafrost thaws⁵⁰, as some of today's forest areas will no longer receive sufficient moisture to support them⁵¹. Conversely, decreases in aerosols are expected from climate-change-driven reductions in wind speeds⁵. The wide variation in model forecasts for aerosol optical depth at 550 nm (Figure 5) reflects this uncertainty.

The forecast for solar cell short circuit currents with aerosol variation included is shown in Figure 6. Where a decrease in aerosols is predicted, "solar brightening" occurs and the downward trends seen in Figure 4 are reduced or, in some instances, reversed. Spectrum-driven decreases in PV output will thus be largely avoided in cases where substantial decreases in aerosols are obtained.



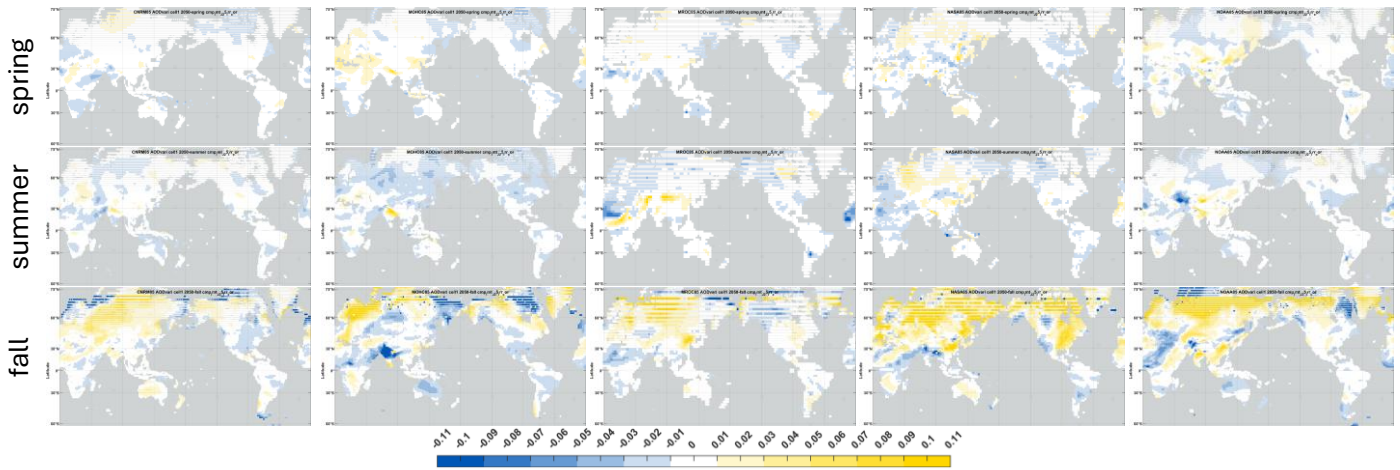


Figure 7. Silicon (1J) short-circuit current in 2050, relative to 2020 (SSP585). (The step change seen at high latitudes in winter is due to a decline in the number of monthly values averaged (from three to two), when the sun is below the horizon for the remaining month.)

Effect on crop photosynthesis

For plants, analogous to the quantum efficiency of solar cells is the spectrum of quantum yield of photosynthesis¹⁵. Integrating across the “action spectrum” (the range of wavelengths that drive photosynthesis reactions) gives the quantum yield, a measure of the efficiency at which photon energy is absorbed and converted to chemical energy via fixation of carbon. Figure 1(b) shows normalized spectra of quantum yields for three commercial crops¹⁵. The absorption of plant pigments such as chlorophylls and carotenoids cuts off beyond ~700 nm, so is largely unaffected by the variations in atmospheric water vapor which affect solar PV.

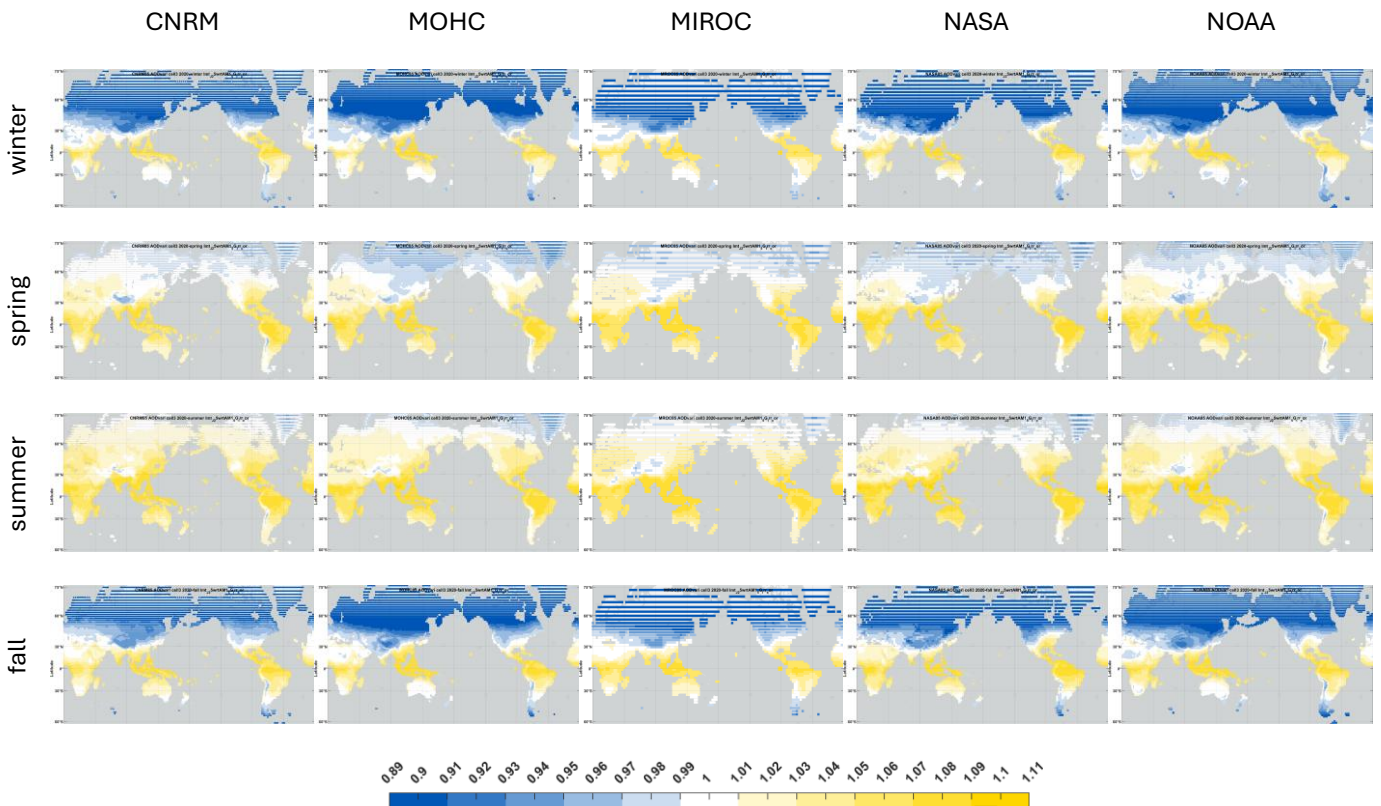


Figure 8. Predicted 2020 quantum yield of photosynthesis for maize, relative to that under the standard spectrum (AM1.5G), for scenario SSP585. Data is normalized to 1000 W/m² irradiance. “Winter”/“spring”/“summer”/“fall” correspond to months 12-2/3-5/6-8/9-11 in the northern hemisphere and 6-8/9-11/12-2/3-5 in the southern hemisphere.

Borrowing the concept of a standard spectrum from PV allows for comparison of the effect of spectrum variation on the rate of photosynthesis globally (Figure 8). For the baseline year of 2020, the global spectra are more favorable worldwide in the spring and summer, and year-round in the southern hemisphere. Given that corn, rice, and wheat are estimated to provide 60% of the food calories consumed globally, a 1% gain/loss in crop yields from this spectrum variation would correspond to the annual calorie intake of Canada. After normalizing to the broadband irradiance, the quantum yield for maize remains ~5-10% higher for much of the southern hemisphere in the spring and summer (the peak growing seasons).

The change in quantum yield of photosynthesis for maize in 2050, relative to 2020, is shown in Figure 9. The results for wheat and rice are substantially similar; their results are included in the Supplemental Materials (Figure 19 & Figure 20). Aerosol levels are projected to mostly decrease in fall and winter (Figure 5), leading to increases in the quantum yield of photosynthesis over much of the globe during these seasons. For the peak growing seasons of spring and summer, changes are more modest.

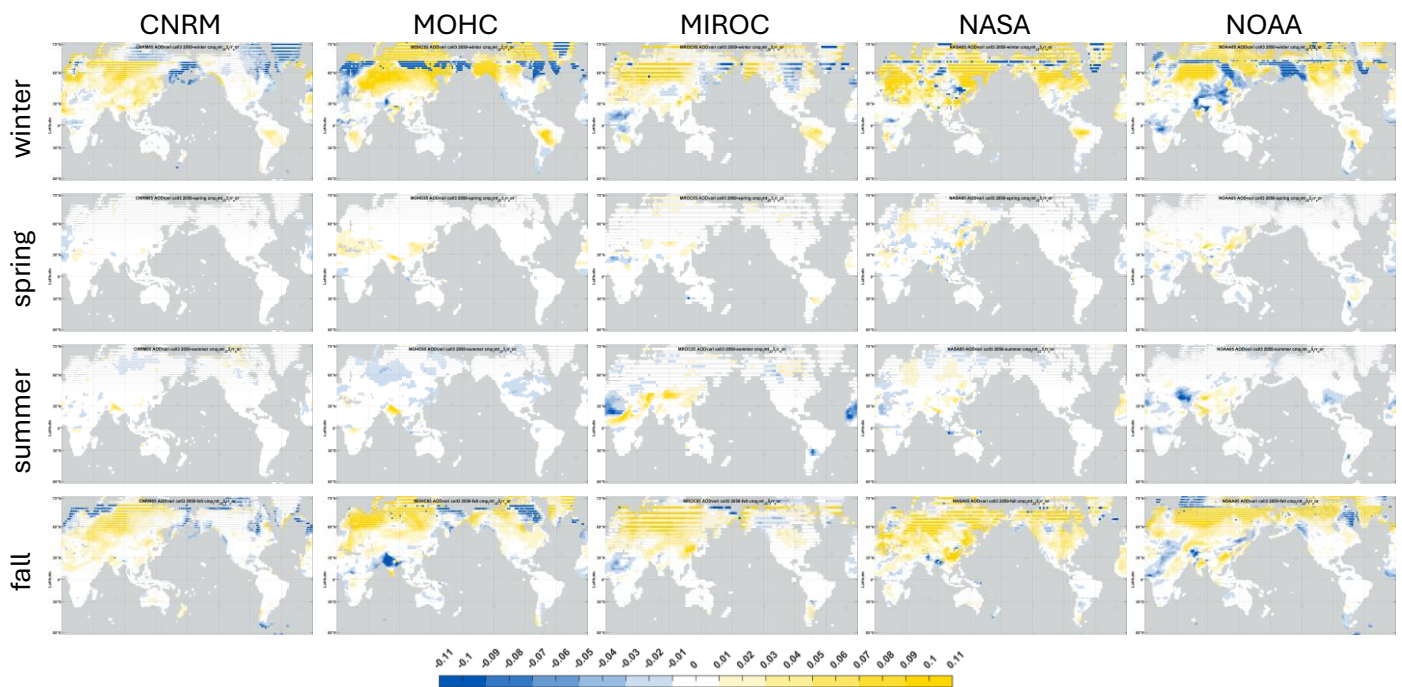


Figure 9. Maize quantum yield of photosynthesis in 2050, relative to 2020, scenario SSP585. (The step change seen at high latitudes in winter is due to a reduction in the number of values averaged (from three to two), when the sun falls below the horizon.)

Conclusion

CMIP climate models provide a forecast of for the impact of spectrum variation on photovoltaic and crop production. In the decades ahead, changes in the levels of greenhouse gases and aerosols in the atmosphere will shift the sunlight spectrum that reaches the surface, thereby altering solar PV and crop production. Global warming leads to levels atmospheric water vapor that will be larger and more erratic, resulting in decreases - as well as higher variability - in PV performance worldwide. The spectrum used in photosynthesis in corn, wheat, and rice lies largely outside the water absorption bands, so is relatively unaffected by changes in atmospheric water vapor. The projected global decreases in aerosols will benefit both crops and photovoltaics, contingent on long-term declines in fossil fuel combustion and wildfires.

Supplemental Materials

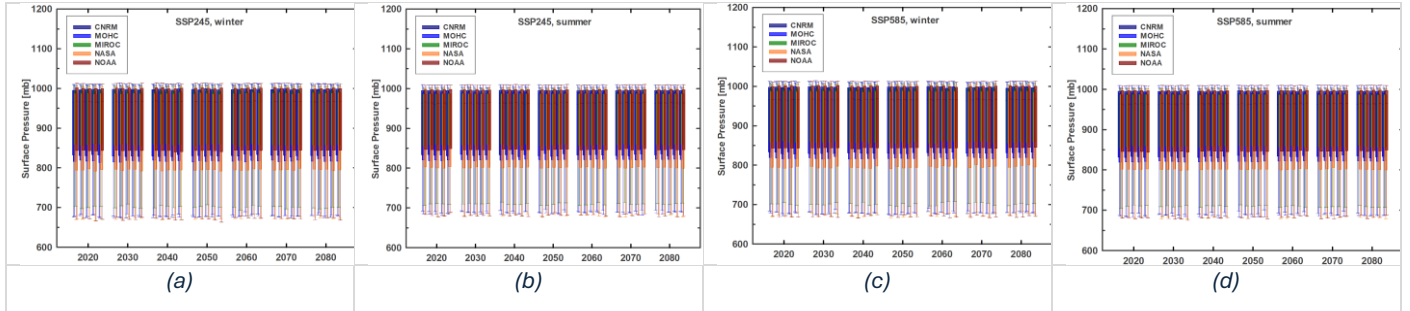


Figure 10. Figure 11. Surface atmospheric pressure under SSP245 winter (a) & summer (b) and SSP585 winter (c) & summer (d). Winter/summer correspond to months 12-2/6-8 in the northern hemisphere and 6-8/12-2 in the southern hemisphere.

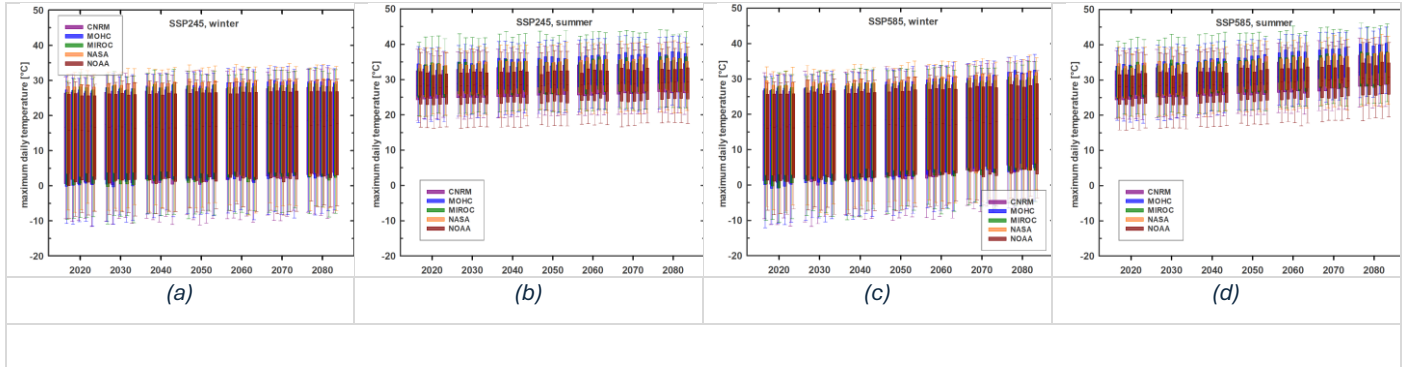


Figure 12. Figure 13. Maximum daily temperature under SSP245 winter (a) & summer (b) and SSP585 winter (c) & summer (d), for latitudes up to and including $\pm 60^\circ$. Winter/summer correspond to months 12-2/6-8 in the northern hemisphere and 6-8/12-2 in the southern hemisphere.

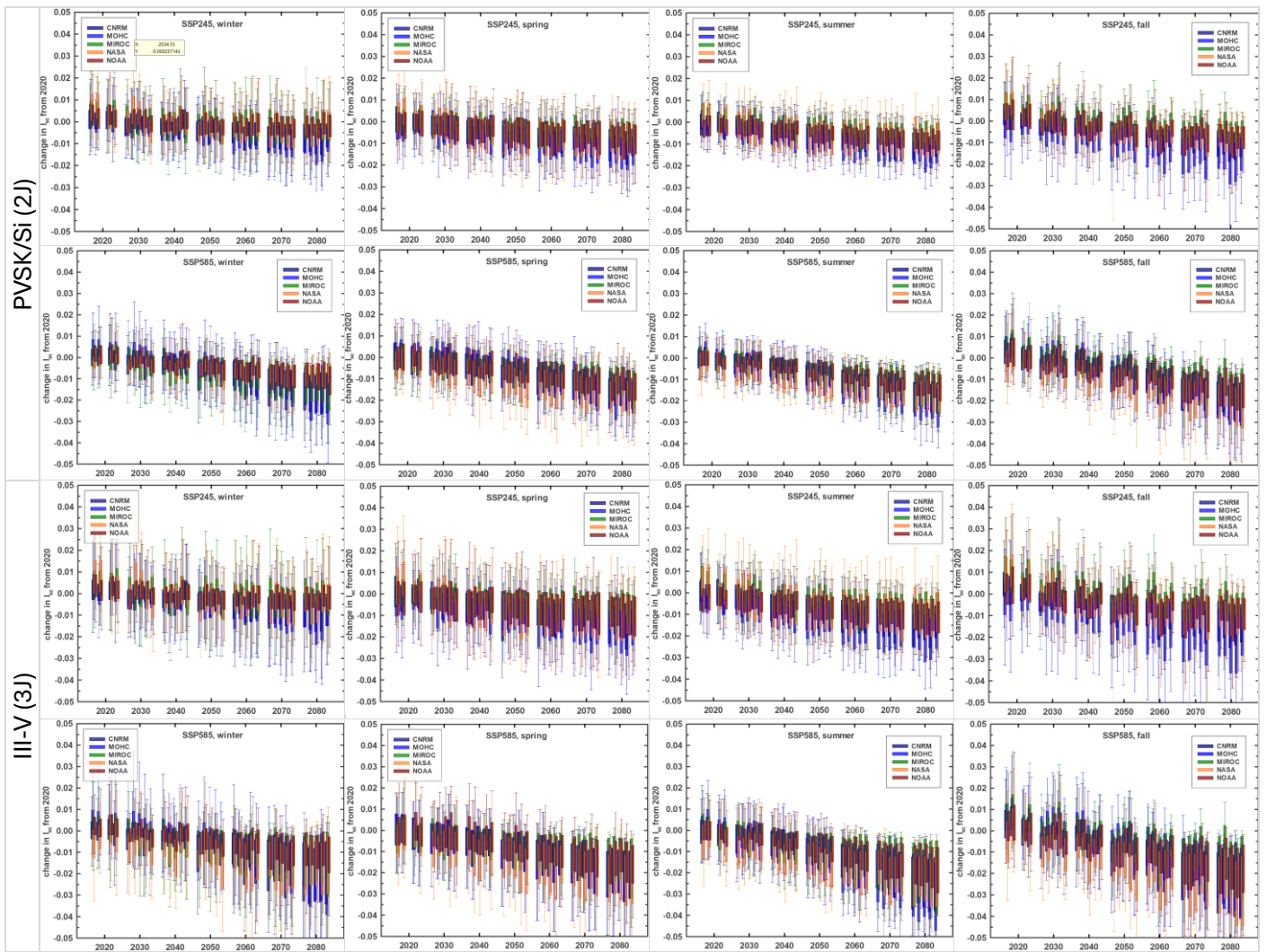


Figure 14. Decadal projections of the change in seasonal short-circuit current of tandem (2J) perovskite-silicon (PVSK/Si) and three-junction (3J) III-V multijunction (III-V) solar cells relative to 2020 values: aerosol optical depth is held constant at 2020 values. Data is normalized by the relative irradiances.

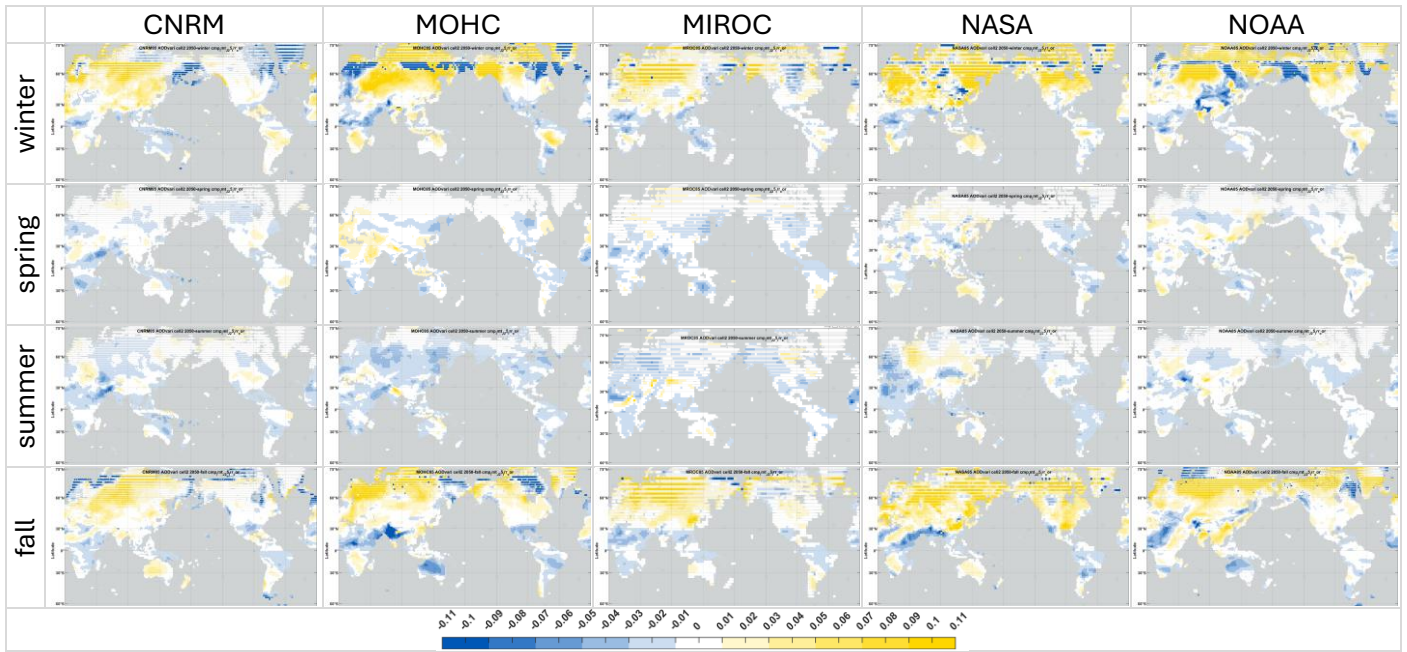


Figure 15. PVSK/Si (2J) short-circuit current in 2050, relative to 2020 (SSP585). (The step change seen at high latitudes in winter is due to a reduction in the number of values averaged (from three to two), when the sun falls below the horizon.)

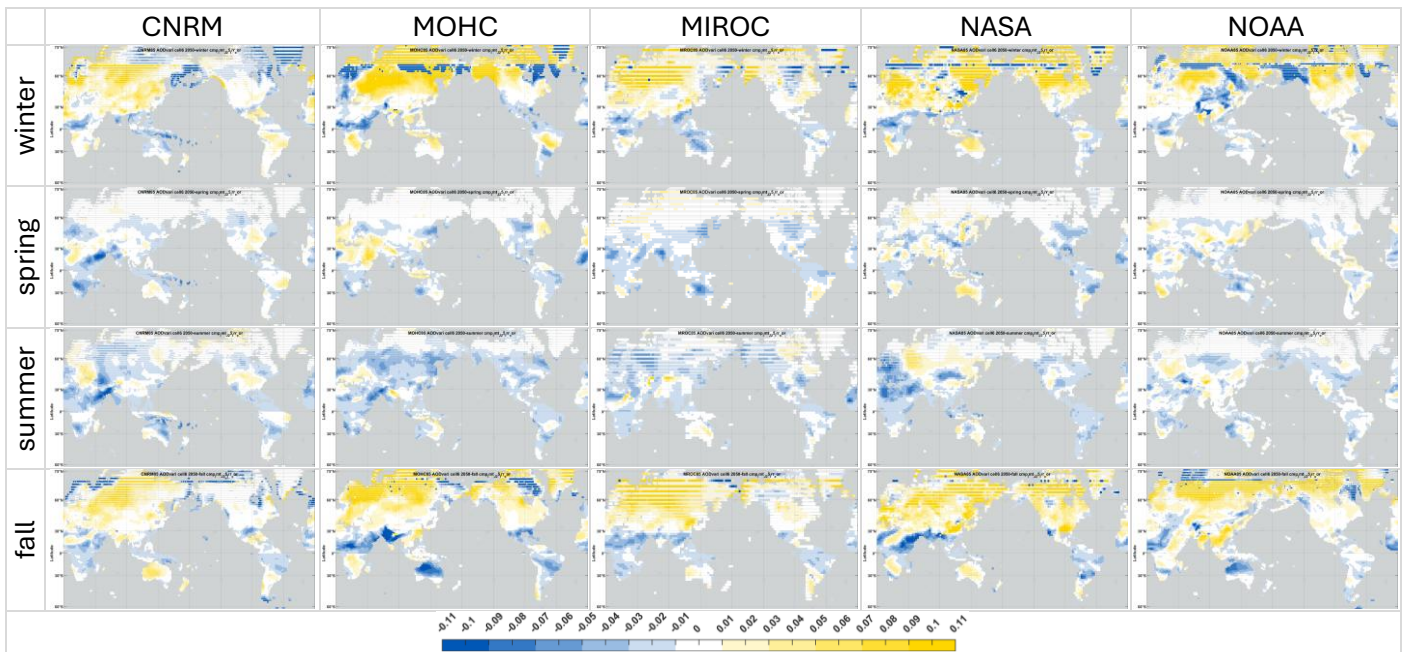


Figure 16. III-V (3J) short-circuit current in 2050, relative to 2020 (SSP585). (The step change seen at high latitudes in winter is due to a reduction in the number of values averaged (from three to two), when the sun falls below the horizon.)

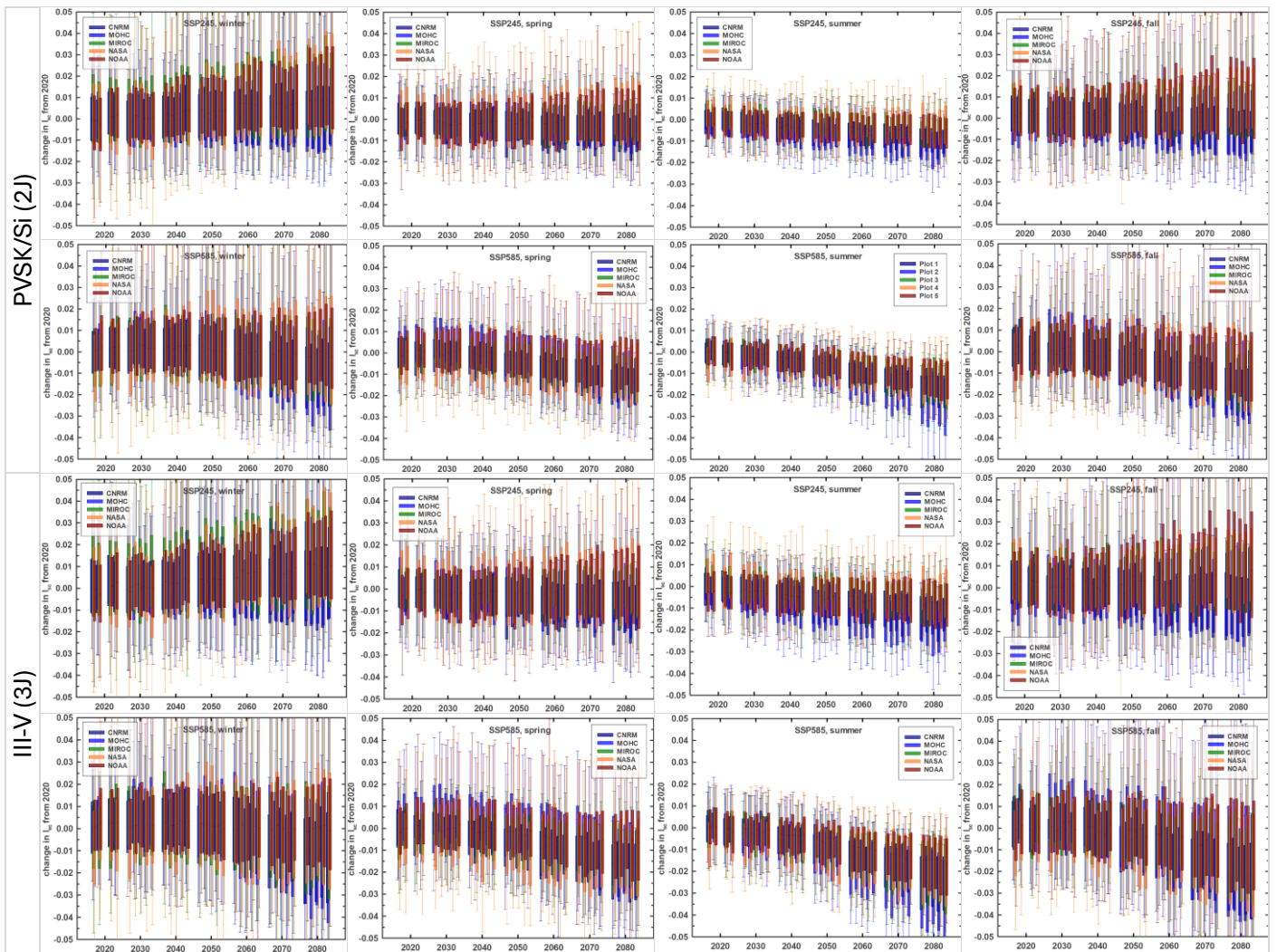


Figure 17. Decadal projections of the change in seasonal short-circuit current of perovskite/silicon (2J) and III-V (3J) solar cells relative to 2020 values. Data is normalized by the relative irradiance.

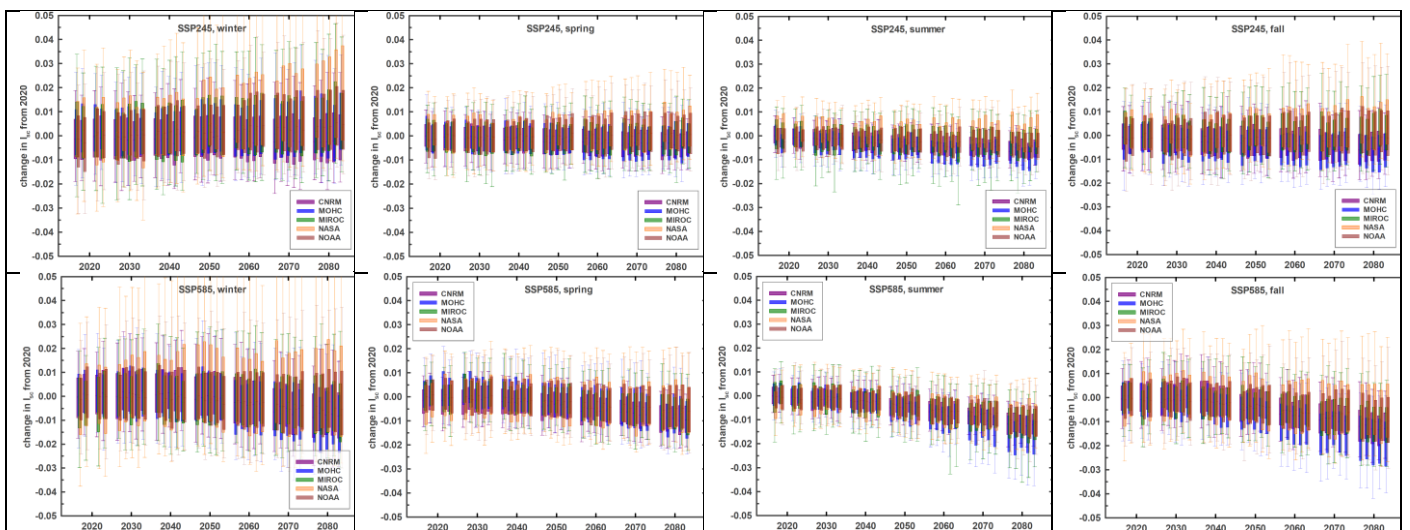
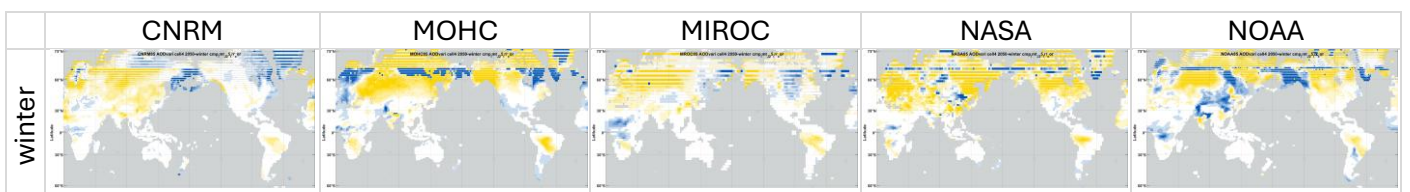


Figure 18. Decadal projections of the change in seasonal short-circuit current of single-junction (1J) silicon solar cells relative to 2020 values, but without normalization of irradiance. Data is for latitudes below $\pm 60^\circ$ (inclusive).



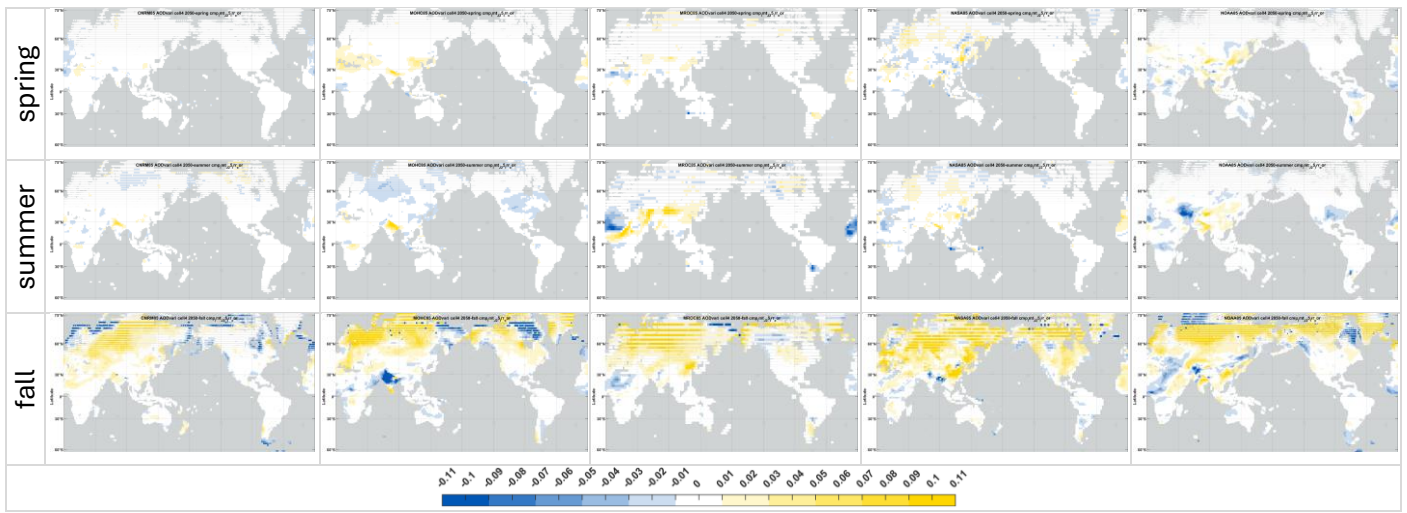


Figure 19. Wheat quantum yield of photosynthesis in 2050, relative to 2020, scenario SSP585. (The step change seen at high latitudes in winter is due to a reduction in the number of values averaged (from three to two), when the sun falls below the horizon.)

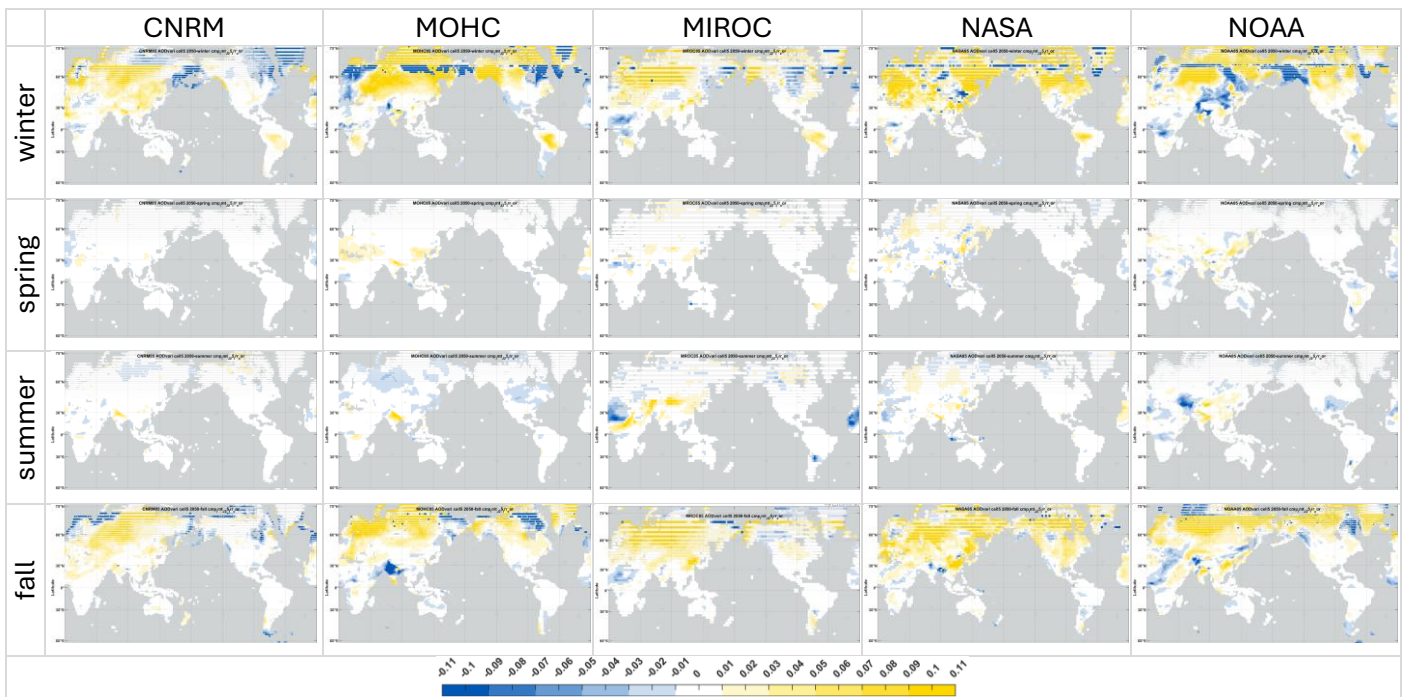


Figure 20. Rice quantum yield of photosynthesis in 2050, relative to 2020, scenario SSP585. (The step change seen at high latitudes in winter is due to a reduction in the number of values averaged (from three to two), when the sun falls below the horizon.)

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