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1 **Change in Wind Renewable Energy Potential under Stratospheric Aerosol Injections**

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7

8 **Key Points:**

- 9
- 10 • Stratospheric Aerosol Injections have been proposed as a method to temporarily counteract the warming from greenhouse gases.
 - 11 • Stratospheric Aerosol Injections do not compensate the atmospheric circulation changes from climate change but create new dynamics.
 - 12 • Total global wind energy potential is negligibly reduced under Stratospheric Aerosol Injections but regional trends can be large.
- 13
- 14
- 15

16 **Abstract**

17 Wind renewable energy (WRE) is an essential component of the global sustainable energy
18 portfolio. Recently, there has been increasing discussion on the potential supplementation of this
19 conventional mitigation portfolio with Solar Radiation Modification (SRM). However, the impact
20 of SRM on conventional mitigation measures has received limited attention to date. In this study,
21 we explore one part of this impact, the potential effect of one type of SRM, Stratospheric Aerosol
22 Injections (SAI), on WRE. Using hourly output from the Earth System Model CNRM-ESM2-1,
23 we compare WRE potential under a medium emission scenario (SSP245) and a high emission
24 scenario (SSP585) with an SRM scenario that has SSP585 baseline conditions and uses SAI to
25 cool to approximately SSP245 global warming levels. Our results suggest that SAI may affect
26 surface wind resources by modifying large-scale circulation patterns, such as a significant
27 poleward jet-shift in the Southern Hemisphere. The modeled total global WRE potential is
28 negligibly reduced under SAI compared to the SSP-scenarios. However, regional trends in wind
29 potential are highly variable, with large increases and decreases frequently reaching up to 16 %
30 across the globe with SAI. This study provides valuable insights into the potential downstream
31 effects of SRM on climatic elements, such as wind patterns, and offers perspectives on its
32 implications for our mitigation efforts.

33 **1 Introduction**

34 Wind renewable energy (WRE) is a key component of the transition to a low-carbon energy
35 system (IPCC, 2018; Clarke et al., 2022; Riahi et al., 2022). Modeling assessments estimate that
36 in Paris Agreement compatible scenarios, such as the C1 and C2 scenarios from the recent IPCC
37 Assessment Report (Riahi et al., 2022), a significant portion of energy would come from wind
38 with projected production ranging from 4,760 to 50,960 TWh/yr by 2050 depending on the
39 scenario and model (Byers et al., 2022). However, present policies are taking us closer to a global
40 mean surface temperature increase of 2.5-2.9°C than the Paris compatible 1.5°C (CAT, 2023),
41 whilst current warming already leads to numerous climate change related damages (Ripple et al.,
42 2023). Hence, a growing number of people are investigating a group of technologies, termed Solar
43 Radiation Modification (SRM), as a potential addition to conventional mitigation, to rapidly
44 manage climate change risks. SRM does not resolve the global warming problem as it does not
45 eliminate greenhouse gases (GHGs), but is proposed to temporarily mask some of the impacts with

46 the logic of providing more time to sufficiently roll out mitigation measures and halt or reverse the
47 rise of atmospheric GHG concentration (Horton, 2015; MacCracken, 2009; Royal Society, 2011;
48 Schäfer et al., 2014). It works by modifying the balance of incoming and outgoing radiation in the
49 Earth system, which, if done on a significant scale, can exert a global cooling effect to counteract
50 warming due to greenhouse gases. SRM is perceived controversially by experts and laypeople
51 alike (Müller-Hansen et al., 2023) due, in part, to the large social and ecological risks and
52 unknowns involved in intentionally manipulating the complex Earth system.

53 Various proposals have been put forward to alter the radiative equilibrium, with the
54 injection of aerosols into the stratosphere (SAI) receiving the most attention thus far. An SAI
55 intervention aiming at global impact entails the continuous placement of aerosols at low latitudes
56 in the lower stratosphere (Dai et al., 2018; Kravitz et al., 2019a; Tilmes et al., 2017; Tilmes et al.,
57 2018b), where the Brewer-Dobson circulation slowly transports them towards the poles. The
58 aerosols reflect the incoming short-wave radiation allowing less radiative energy to reach the
59 surface. While this process leads to cooling at the surface, evidenced by large volcanic eruptions,
60 not all radiation is reflected by the aerosols. Instead, some of the radiative energy is absorbed by
61 the particles, leading to localized heating of the stratosphere, which can affect global circulation
62 patterns (Baldwin & Dunkerton, 2001; DallaSanta et al., 2019; Stenchikov et al., 2002; Graft et
63 al., 1993). For example, several studies on the impact of stratospheric aerosols from volcanic
64 eruptions have found a poleward jet shift (Barnes et al., 2016; Polvani & Kushner, 2002; Simpson
65 et al., 2009). This has been attributed to two general mechanisms, surface cooling and stratospheric
66 warming (DallaSanta et al., 2019). The surface cooling from the stratospheric aerosols decreases
67 the tropospheric meridional temperature gradient (Stenchikov et al., 2002; Graf, 1992), which
68 reduces midlatitude baroclinity, driving a strengthening of the stratospheric vortex, which leads to
69 a poleward shift of the jet (Baldwin & Dunkerton, 2001). The second and primary mechanism,
70 however, is the observed warming of the stratosphere in the tropics due to the aerosol's absorption
71 of the radiative energy. This enhances the stratospheric meridional temperature gradient leading
72 to a strengthened stratospheric vortex that shifts the jet poleward (DallaSanta et al., 2019).
73 Modeling studies on SAI impacts have also found large-scale circulation changes. Liu et al. (2023)
74 studied the East Asian Winter Monsoon under SAI and found that aerosol injections reverse the
75 weakening of the monsoon that occurs in SSP585. In Africa, however, SAI can lead to weaker
76 monsoon winds (Da-Allada et al., 2020; Robock et al., 2008) and a slight southward shift of the

77 ITCZ (Cheng et al., 2019). It should be emphasized that the outcomes of these studies are likely
78 strongly reliant on the selected injection design and the underlying model (Kravitz et al., 2016,
79 2019b; Lee et al., 2020; MacMartin & Kravitz, 2019).

80 Wind power generation relies significantly on local and regional wind patterns and even
81 minor fluctuations in wind velocity can have a meaningful impact on the energy output (Veers et
82 al., 2019). This is because the energy in the wind follows the cube of the wind speed. While to our
83 knowledge no research has been conducted on WRE potential under SRM, several studies have
84 looked at the impact of climate change on wind potential. They found significant alterations in
85 wind velocity and its temporal distribution as a result of global warming (Solaun & Cerdá, 2019).
86 One of the main mechanisms behind large-scale circulation changes from anthropogenic warming
87 is the reduced equator-to-pole temperature gradient at the surface as a result from polar
88 amplification, which is expected to alter tropical circulation (Ma et al., 2012), such as the Hadley
89 cell, monsoon circulations and tropical cyclone frequency, as well as the behavior of midlatitude
90 jet streams and storm tracks (Martinez & Iglesias, 2024; Pryor et al., 2020; Shaw et al., 2016).
91 However, wind resources can be further impacted by ocean circulation and surface roughness
92 changes from land cover modifications (Jung & Schindler, 2022; Vautard et al., 2010; Zeng et al.,
93 2019). Additionally, local wind resources exhibit high variability on sub-hourly and multi-decadal
94 scales (Jung et al., 2018). Due to the difficulty to accurately represent all drivers and the resulting
95 temporal and spatial variations of wind patterns in Global Circulation Models, it is not entirely
96 certain whether climate change will result in a decrease or increase in wind speeds at the global
97 scale (Pryor et al., 2020). Most studies find highly diverse regional trends with large increases and
98 decreases in wind speed and wind energy potential all over the globe (Gernaat et al., 2021; Jung
99 & Schindler, 2022; Pryor et al., 2020; Solaun & Cerdá, 2019). As a result, on a global scale,
100 changes in total wind energy density (Martinez & Iglesias, 2024) and wind energy potential
101 (Gernaat et al., 2021) are small and may be slightly negative.

102 Given that WRE already plays an important role in the prevailing mitigation strategy, and
103 that mitigation is an important aspect of ensuring the temporary use of SRM, it is important to
104 understand whether SRM complements or conflicts with this existing method of energy generation
105 and mitigation. Only through an understanding of the full spectrum of consequences from SAI can
106 responsible decision-making be enabled. Here, we analyze the interplay between WRE and SAI

107 by calculating and comparing on- and offshore wind potential when SAI is used versus when
108 mitigation has brought the climate to approximately the same GMST (SSP245). Additionally, we
109 compare the SAI-modified climate with the fossil-fuel heavy emission baseline of the scenario
110 without SAI (SSP585).

111 **2 Model Experiments and Methods**

112 2.1 Data and Simulations

113 This study is based on three experiments: a fossil-fuel intensive, high-emission scenario
114 called SSP585 (O'Neill et al., 2016), a moderately ambitiously mitigated scenario, SSP245
115 (O'Neill et al., 2016), and a stratospheric aerosol injection (SAI) simulation that cools down from
116 an SSP585 baseline to SSP245. The SAI experiment originates from the GeoMIP6 protocol
117 (Kravitz et al., 2015) and is referred to therein as G6sulfur. We run these experiments from 2015
118 to 2100 in a 6-member ensemble with perturbed initial conditions on the CNRM-ESM-2.1 Earth
119 system model (Séférian et al., 2019). Ensemble means are displayed except if defined otherwise.
120 As a proxy for SAI we use prescribed aerosol optical depth derived from the GeoMIP G4SSA
121 experiment (Tilmes et al., 2015) which scales up to 0.35 in the last decade of the simulation. The
122 variables related to the directional winds u and v at 150m altitude are produced at hourly resolution
123 on a $1^\circ \times 1^\circ$ grid. During the postprocessing we bilinearly regrid the climate model output to match
124 the land use and land cover data (described in 2.2.3 Politico-economic dimension) which is on a
125 $0.1^\circ \times 0.1^\circ$ grid. For the zonal winds we create two altitudinal categories: upper and surface. Upper
126 refers to a pressure level of 200-400hPa, roughly corresponding to the upper troposphere, and
127 surface, referring to a pressure level of 850-1050hPa, representing the air close to the Earth's
128 surface.

129 2.2 Wind Potential Calculation

130 In the same manner as Baur et al. (2023), we use the term “potential” to refer to an enhanced
131 version of the traditional definition of the “technical potential”. The technical potential is the
132 theoretical potential, here the surface wind resource, constrained by geographical and technical
133 restrictions. In this study, we distinguish between three dimensions that are involved in the wind
134 energy potential calculation: the technical dimension that establishes the technical restrictions to

135 the theoretical potential, the physical dimension, which is related to the energy extractable from
 136 surface wind speed, and the politico-economic one, which is related to the suitability of the grid
 137 cell i for wind turbine placement. We calculate the wind potential in a similar fashion to Gernaat
 138 et al. (2021) as:

$$139 \quad TP_{i,loc} = Politicoeconomic_i \times Technical_{loc} \times Physical_{i,loc} \times gridcell_i \left[\frac{MWh}{yr} \right] \quad (1)$$

140 All parameters, their values, units and sources are given in Table S1. The subscript loc indicates
 141 whether it is an on- or offshore wind farm. The resulting electricity generation potential is
 142 expressed in various time slices, such as 10-year seasonal mean changes, weekly sums and yearly
 143 sums, calculated from the hourly wind speed input. Seasons refer to the four periods December,
 144 January, February (DJF), March, April, May (MAM), June, July, August (JJA) and September,
 145 October, November (SON). We calculate the Low Energy Week (LEW) metric as introduced by
 146 Baur et al. (2023).

147 2.2.1 Technical Dimension

148 This part of the calculation reduces the physical potential by accounting for the
 149 unavailability of the turbines due to maintenance, the wind farm array inefficiencies and the
 150 density of wind turbine placement. We use technical indicators from on- and offshore exemplary
 151 real-world wind turbines. To avoid projecting technological developments into the future we
 152 choose turbines which are either already or about to be in serial production but are at the
 153 forefront of current wind turbine development. We justify this choice with the argument that the
 154 average wind turbines of the future will be the most powerful wind turbines of today. Table 1
 155 lists their characteristics:

156 **Table 1.** Exemplary on- and offshore wind turbine specifications. Data from Vestas (2023a),
 157 (2023b).

	Vestas V162-6.2 (onshore)	Vestas V236-15 (offshore)
Rated power (P_r)	6.2 MW	15 MW
Cut-in windspeed (v_{ci})	3.0 m/s	3.0 m/s
Cut-out windspeed (v_{co})	25 m/s	30 m/s

Rotor diameter (d_{Rotor})	162 m	236 m
Serial production	2021	2024

158

159 The technical dimension consists of η_a , the annual availability of the turbine due to maintenance,
 160 η_{ar} , the wind farm array efficiency, and D_{loc} , the turbine density, and is a simple multiplication
 161 of these terms:

$$162 \quad \text{Technical}_{loc} = \eta_a \times \eta_{ar} \times D_{loc} \left[\frac{\text{turbines}}{\text{km}^2} \right] \quad (2)$$

163 D is the average installed turbine density in the grid cell and is calculated as:

$$164 \quad D_{loc} = \frac{1}{(\text{spacing} \times d_{Rotor,loc})^2} \left[\frac{\text{turbines}}{\text{km}^2} \right] \quad (3)$$

165 We assume that turbine spacing is equal in prevailing and perpendicular wind direction.
 166 For the turbines set out in Table 1, this gives a $D_{onshore}$ of 1.56 turbines/km² and a
 167 $D_{offshore}$ of 0.51 turbines/km². Translated into the more commonly used metric power
 168 density, this implies 9.68 MW/km² onshore and 7.65 MW/km² offshore.

169 2.2.2 Physical Dimension

170 The physical dimension represents the power produced by a wind turbine $p(v)$, which is
 171 described by the wind turbine power curve (Carrillo et al., 2013; Saint-Drenan et al., 2020; Fig S1)
 172 and calculated as:

$$173 \quad p(v)_i = \begin{cases} 0 & v < v_{ci} \text{ or } v > v_{co} \\ q(v) & v_{ci} \leq v < v_r \\ P_r & v_r \leq v \leq v_{co} \end{cases} \quad (4)$$

174 The power curve depends on the instantaneous wind speed v and the characteristics of the wind
 175 turbine (Table 1) and distinguishes between four different operation regimes (Fig S1): I, the area
 176 of wind speeds (v) that are smaller than the cut-in wind speed (v_{ci}), and therefore too low to
 177 produce any energy, II, the area of non-linear relationship between wind speed and power output
 178 ($q(v)$), III, the area of maximum power output, i.e. rated power (P_r), and IV, the area after the cut-

179 out threshold, where wind speed is too high ($v > v_{co}$) and turbines shut down to protect themselves
 180 from damage (Saint-Drenan et al., 2020; Wood & Wollenberg, 1996).

181 Power production in area II follows the parametric wind turbine power curve described in Saint-
 182 Drenan et al. (2020) and is calculated as:

$$183 \quad q(v_i) = 0.5 \times \rho \times \varepsilon_{loc} \times v^3 \times pc \left[\frac{\text{MWh}}{\text{turbine}} \right] \quad (5)$$

184 With ρ being the air density, which is kept constant, ε the area swept by the rotor blades calculated
 185 from the rotor blade diameters (Table 1), v instantaneous wind speed and pc the power coefficient,
 186 a measure for aerodynamic-mechanical-electrical performance of the turbines (Veers et al., 2019).
 187 For simplicity, in our study, the power coefficient is held constant, however, as demonstrated in
 188 Saint-Drenan et al. (2020), it is ultimately dependent on and varies with the wind's velocity. The
 189 power coefficient parameterization leads to a slight overestimation in power output from higher
 190 wind speeds and underestimation of output from lower wind speeds in the $q(v_i)$ -part of our
 191 calculation.

192 Due to the high variability of wind, a temporal resolution of 1 hour and a spatial resolution
 193 of $1^\circ \times 1^\circ$ may not adequately represent all prevailing wind speeds in the area during the specified
 194 time period. To account for the requirement of instantaneous wind velocity in the wind power
 195 curve calculation and the low spatial resolution of the input data, we represent wind speed through
 196 a probability density function. Weibull distributions have frequently been used to represent the
 197 spread in wind speed over a time period at a given location (e.g. Aukitino et al., 2017; Mohammadi
 198 et al., 2016; Shi et al., 2021; Shu et al., 2015) and as a means of downscaling to represent the
 199 spread of wind over a larger area (Alizadeh et al., 2020; Chang et al., 2015; Tye et al., 2014; Zhou
 200 & Smith, 2013). The temporal resolution of the underlying wind data can range from 10 min (Eskin
 201 et al., 2008), to hourly (Chang et al., 2015; Li et al., 2020; Mohammadi et al., 2016; Burton et al.,
 202 2001), 6-hourly (Elsner, 2019), to daily (Shu & Jesson, 2021) and longer. Cradden et al. (2014)
 203 and Pryor et al. (2020) have highlighted the importance of a high temporal resolution of at least 1
 204 hour for WRE analyses. Although hourly and daily average wind speeds have been shown to lead
 205 to similar power output results from a turbine over a long time period, hourly input data is much
 206 better at representing the peaks and lows during the day and can give a more precise result for
 207 shorter time periods (Shin et al., 2018; Veronesi & Grassi, 2015; Justus et al., 1978). In this study,

208 the Weibull distribution is used to represent sub-grid spatial and temporal variation in wind. We
 209 use a constant shape-parameter for all regions across the globe. This is a frequently applied
 210 simplification (Dvorak et al., 2010; Elsner, 2019; Eureka et al., 2017; Shu et al., 2015; Sohoni et
 211 al., 2016; Valencia Ochoa et al., 2019; Arendt et al., 2013) related to the width of the distribution
 212 and therefore the gustiness of the wind regimes (Eureka et al., 2017) that is most commonly used
 213 in larger scale analyses. Studies have demonstrated variation of the shape parameter across regions
 214 (Zhou & Smith, 2013), especially for oceanic winds (Shi et al., 2021; Perrin et al., 2006). However,
 215 apart from coastal areas, oceanic regions are excluded from this analysis and using the Rayleigh-
 216 form of the Weibull distribution, which sets the shape parameter β to 2 and implies moderately
 217 gusty winds across all areas (Eureka et al., 2017), drastically reduces the computational effort. The
 218 scale parameter, α , is calculated according to Lysen (1983) as follows:

$$219 \quad \alpha = ws_i \times (0.568 + 0.433 \times 0.5)^{\frac{1}{\beta}} \quad (6)$$

220 with ws_i being the hourly wind speed from our model output calculated as the square root of the
 221 sum of the squares of the east- and northward wind components u and v . We calculate $p(v)$ for all
 222 1000 samples in the Weibull distribution for each 1 m/s wind speed bin from 0-50 m/s.
 223 The 2-parameter Weibull distribution representing the range of wind speeds prevalent in the 1-
 224 hour mean 1° grid cell model output is calculated as:

$$225 \quad f(T) = \frac{\beta}{\alpha} \times \left(\frac{T}{\alpha}\right)^{\beta-1} \times e^{-\left(\frac{T}{\alpha}\right)^\beta} \quad (7)$$

226 For computational feasibility we fit a curve between the 1-hour mean wind speed and the power
 227 output, i.e., $p(v)$, that takes into account the Weibull spread of wind speed and the turbine power
 228 curve:

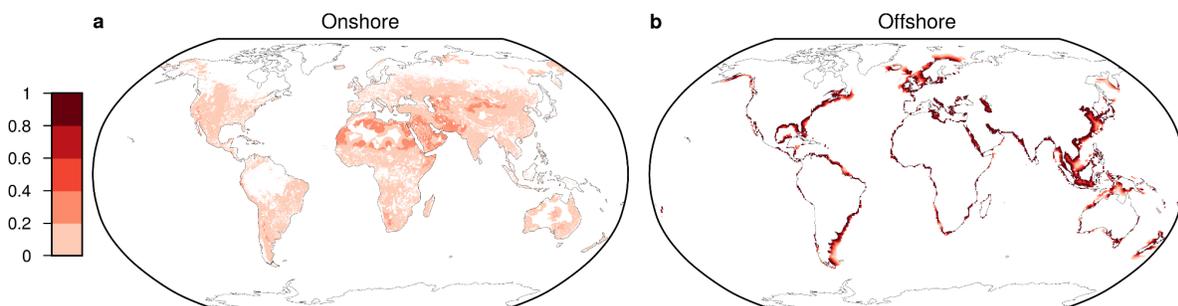
$$229 \quad Physical_{i,loc} = p(ws_i)_{loc} = a_{loc} \times \left(1 - e^{-\frac{ws_i^2}{b_{loc}}}\right) \times \left(1 - e^{-\frac{ws_i^2}{c_{loc}}}\right) \times e^{-\frac{ws_i}{d_{loc}}} \left[\frac{MWh}{turbine}\right] \quad (8)$$

230 Please consult Table S1 in the SI for the values of the parameters a_{loc} , b_{loc} , c_{loc} and d_{loc} . To
 231 assess how much energy is lost due to a change in the distribution of hourly wind speeds we
 232 additionally calculate the wind potential without the cut-out wind speed limit (no-cut-out). Instead,
 233 power output at $v > v_{co}$ is kept at P_r . By subtracting the yearly cumulative “standard”-turbine-

234 power-curve power output with the output from these no-cut-out calculations, we can estimate the
 235 amount of TWh that is gained or lost in a year due to a change in fast winds. Figure S2 shows the
 236 fitted power curve of an onshore and offshore grid cell in the normal setting and in the no-cut-out-
 237 setting.

238 2.2.3 Politico-Economic Dimension

239 The incorporation of a politico-economic dimension is a long-standing approach for wind
 240 potential calculations (e.g. Elliott & Schwartz, 1993; Archer & Jacobson, 2005; Bosch et al., 2017;
 241 Hoogwijk, 2004; Zhou et al., 2012) and is related to the suitability of each grid cell to harbor wind
 242 turbines. Various parameters have been taken into account in the past. Here, we consider surface
 243 properties and land use competition for our onshore wind farms as done in Baur et al. (2023).
 244 Figure 1 displays the convolutions of the single area restrictions for on- and offshore wind farms
 245 which are used in the wind potential calculation ($Politicoeconomic_i$). The single area restrictions
 246 and their weights are displayed in Figure S3 and S4. We exclude all areas marked as protected
 247 with any status as characterized by the United Nations Environment Programme (IUCN, 2023) as
 248 possible wind power installation sites and weigh areas according to the prevalent land-use and
 249 distance to highly populated centers as an indicator for the future existence of transmission lines
 250 and demand. Highly populated areas are excluded since wind turbines are rarely situated in close
 251 proximity to, or on top of, buildings. For offshore we add additional constraints, such as the
 252 bathymetry over 1000m, exclusion of grid cells outside the Exclusive Economic Zone (EEZ)
 253 (Flanders Marine Institute, 2019) and consideration of only those grid cells that are at least 95%
 254 sea-ice free in every season of the year.



255
 256 **Figure 1.** Convolution of area restrictions for a) onshore and b) offshore.

257 Land-use cover and population density data were obtained from the IMAGE3.0-LPJ model
 258 (Doelman et al., 2018; Stehfest et al., 2014) with a spatial resolution of $0.1^\circ \times 0.1^\circ$. The model

259 differentiates between 20 different land use and land cover categories. We weigh each type
260 according to the fraction of a grid cell that could be covered by wind farms, in line with Baur et
261 al. (2023), but with different fractions assigned (see Table S2 for land use categories and assigned
262 suitability fractions). The rationale behind the suitability fraction is that only part of a grid cell is
263 available for wind farms as they could potentially conflict with other land uses such as cities,
264 agricultural production or ecosystem services from forests. A suitability fraction of 15% denotes
265 that 15% of the grid cell is able to accommodate a wind farm. The spacing between the turbines
266 of several hundred meters enables a certain level of coexistence between wind farms and
267 predominant land uses. This explains the assignment of higher fractions for, for example,
268 agricultural areas in this study than in Baur et al. (2023), which looked at solar farms.

269 We use the same approach as Baur et al. (2023) to weigh the proximity to highly populated areas.
270 The population data from the IMAGE3.0 LPJ model consists of 5-year intervals and is aggregated
271 to 10-year means for our analysis (Doelman et al., 2018; Stehfest et al., 2014). Using a sigmoidal
272 function, we impose that the weight diminishes proportionally as the distance to densely populated
273 cells grows, ultimately tapering to zero at approximately 500 km. Unlike Baur et al. (2023), we
274 exclude highly populated areas, which we define as cells where population density is larger than
275 1000 inhabitants/km².

276

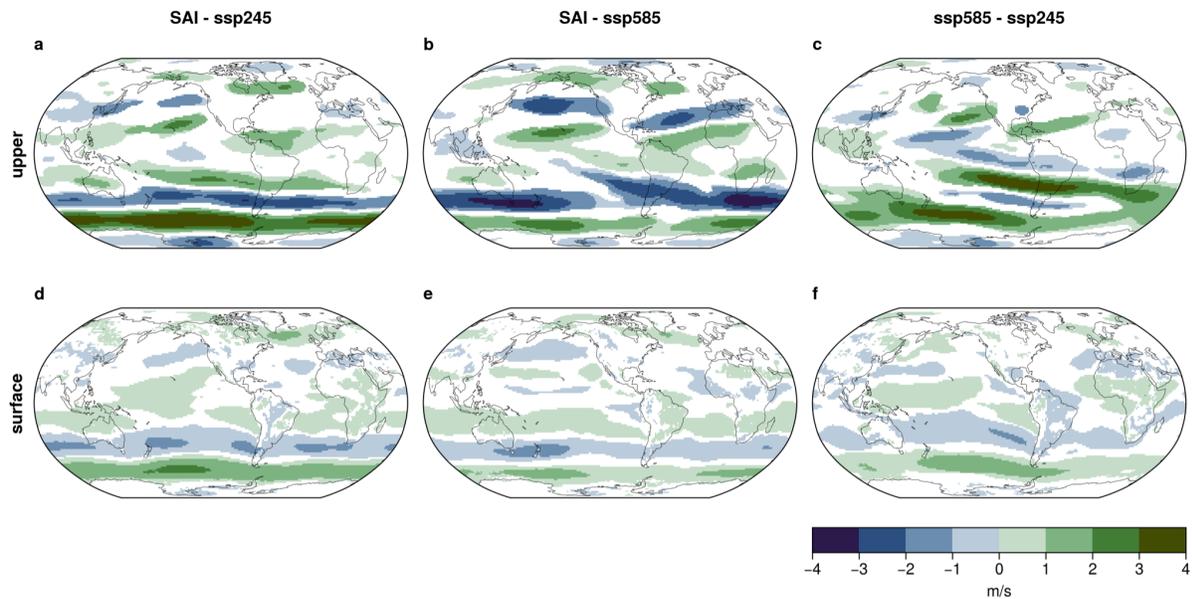
277 We present results that are calculated using equal weights across all scenarios and time intervals.
278 Therefore, the data underlying population, sea ice and land use are related to the 2090-2099 time
279 frame of SSP245 but are used as a basis for all three scenarios.

280 **3 Results**

281 3.1 Large-scale Circulation Response to SAI

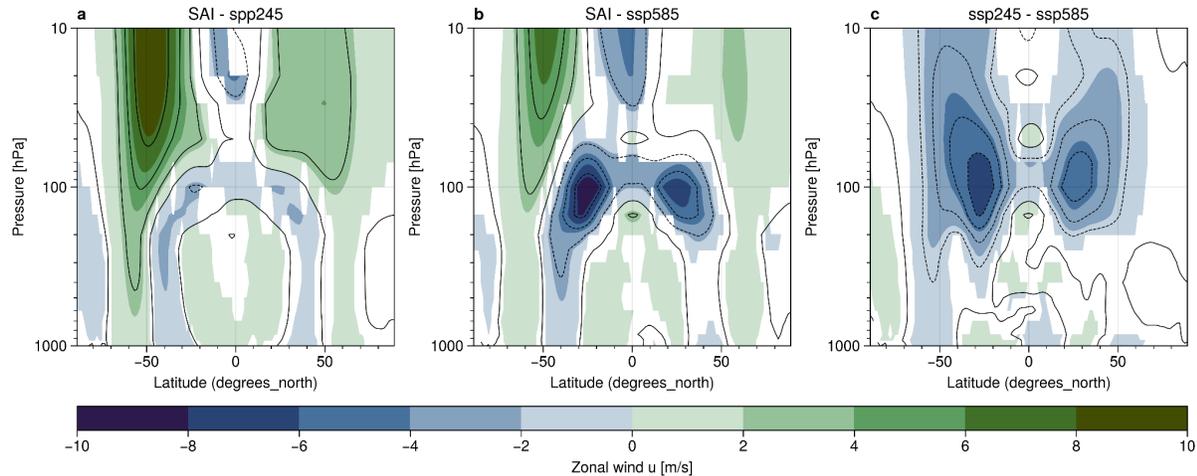
282 Our simulations indicate substantial alterations in 10-year mean zonal wind from the
283 present (2015-2024) to the end of the century (2090-2099) (Fig S5). While the patterns of change
284 show some similarities for SAI, SSP585 and SSP245, the magnitude of the circulation differences
285 from present to future varies considerably and is especially pronounced for SAI and SSP585 (Fig
286 S5). When comparing the future conditions of the scenarios with each other, substantial differences
287 become apparent (Fig 2). Regardless of altitude or scenario-comparison, the largest differences are
288 registered in the Southern Hemisphere (SH): Here, the westerlies' shift towards the pole is more

289 pronounced under SAI compared to the SSP-scenarios and, comparing the SSP-scenarios, there is
 290 a more intense strengthening of the westerlies and poleward shift of the SH jet for SSP585
 291 compared to SSP245 at the end of the century. The signal is strongest in the upper troposphere for
 292 all scenario-comparisons with differences in zonal wind speed of up to 4 m/s (Figure 2 a-c). While
 293 the sign of difference between SAI and the SSPs stays consistent across most seasons, the intensity
 294 varies (Fig S6, S7).



295
 296 **Figure 2.** Difference in 2090-99 mean zonal winds between a,d) SAI and SSP245, b,e) SAI and
 297 SSP585 and c,f) SSP245 and SSP585 at a-c) the upper troposphere and d-f) the surface.

298 In the NH, the changes are less latitudinally and, over the Atlantic Ocean, altitudinally consistent.
 299 While both upper tropospheric and surface winds show a pronounced equatorward shift of the
 300 midlatitude westerlies over the Pacific under SAI compared to the SSPs, the upper troposphere
 301 over the Atlantic entails a strengthened equatorward shift of the subtropical jet that does not
 302 propagate as much to the surface as for the SH (Fig 2, 3, S5). The decrease in midlatitude wind
 303 speed under SAI moves towards the equator as it propagates to the surface when comparing to
 304 SSP245, while shifting slightly poleward when comparing to SSP585 (Fig 3 a,b). The largest
 305 circulation changes occur in the upper troposphere and stratosphere (Fig 2, 3).

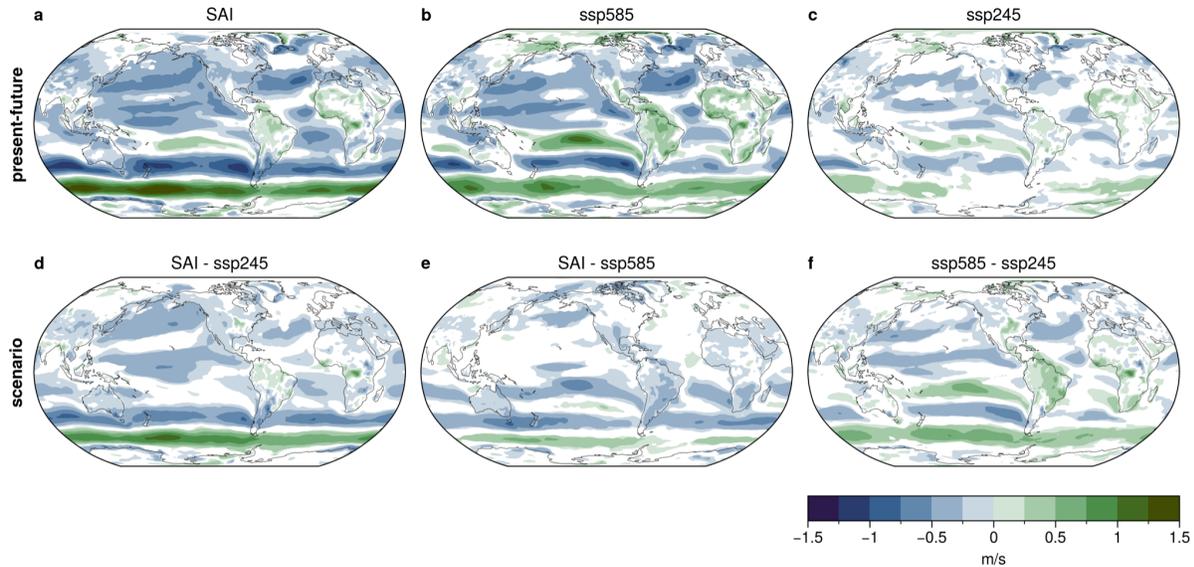


306

307 **Figure 3.** Difference in 2090-99 average zonal mean winds between a) SAI and SSP45, b) SAI
 308 and SSP585 and c) SSP245 and SSP585.

309 Variation in large-scale circulation has been attributed to temperature changes in the stratosphere
 310 and resulting increases or decreases in the temperature gradients at the surface and/or the upper
 311 troposphere (Baldwin & Dunkerton, 2001; Charlesworth et al., 2023; DallaSanta et al., 2019;
 312 Simpson et al., 2019; Stenchikov et al., 2002; Graf, 1992). In our simulations we see a large
 313 temperature shift of up to 14K under SAI compared to the SSP-scenarios in the tropical
 314 stratosphere (Figure S8). The largest increase is at around 80hPa. As expected, temperatures at the
 315 surface are lower under SAI than SSP585, especially in the tropics, which is a common
 316 phenomenon observed in SRM simulations. Due to the augmented CO₂ concentration, which
 317 increases the rate that the stratosphere radiates heat to space, the stratosphere is colder under
 318 SSP585 than SSP245 (Figure S8c).

319 Long-term average wind speed is substantially lower in the NH under SAI compared to the present
 320 (Fig 4a) and compared to the SSPs (Fig 4d,e). A trend fairly consistent throughout the scenarios
 321 but most noticeable in SSP585 is the increase in wind speed in tropical land regions compared to
 322 the present, especially in Brazil and on the African continent. Most other land regions experience
 323 reductions in wind speed (Fig 4a-c).



324

325 **Figure 4.** 150m wind speed comparing present (2015-2024) and future (2090-2099) states under
 326 a) SAI, b) SSP585 and c) SSP245 and comparing future states of scenarios d) SAI and SSP245, e)
 327 SAI and SSP585 and f) SSP585 and SSP245.

328

3.2 SAI effect on onshore and offshore wind potential

329

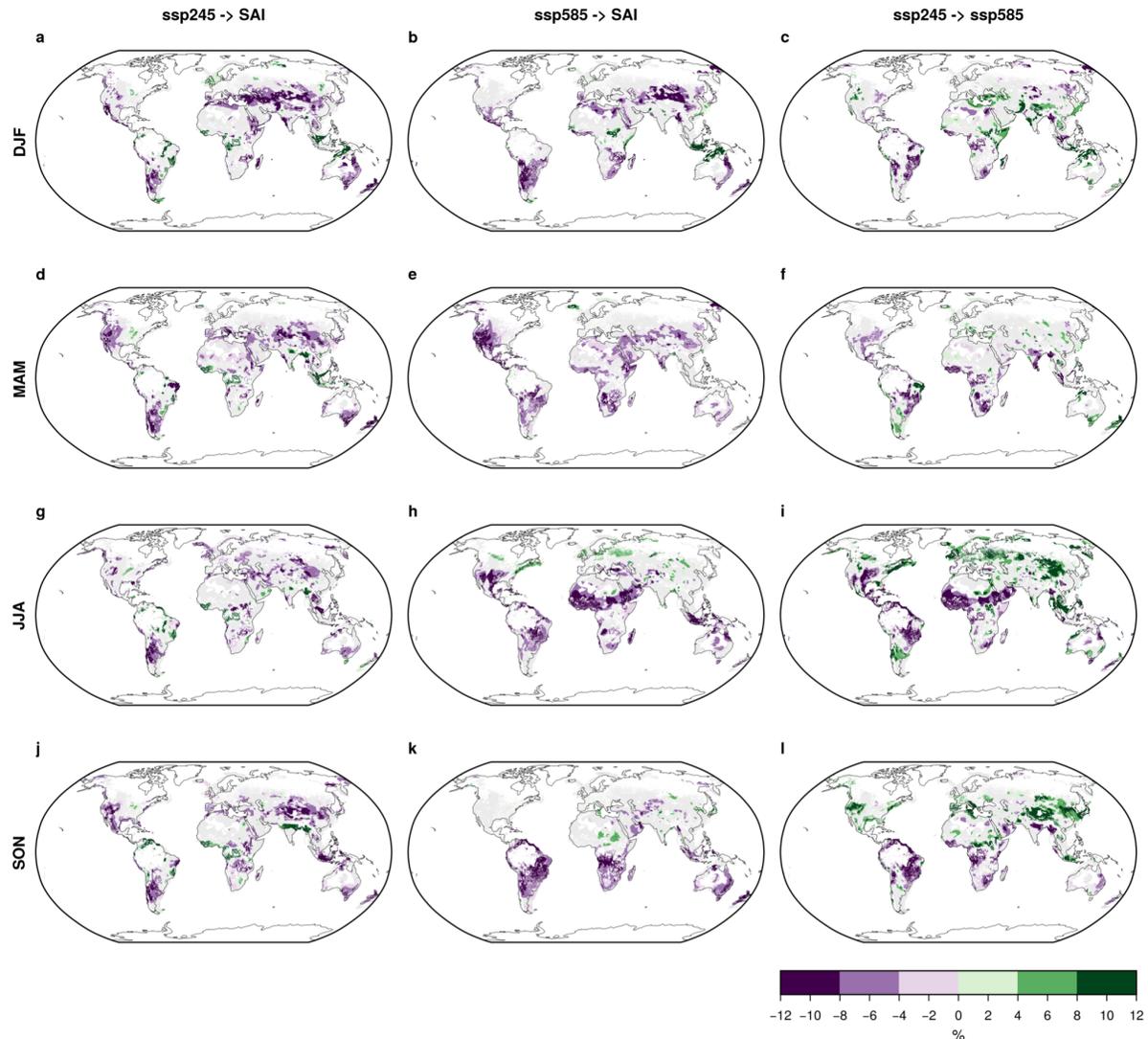
Results in this part are presented with respect to three different areas of interest: long-term
 330 relative seasonal changes, changes in extended low-energy periods (LEW) and the effect of
 331 changes in high hourly wind speed on annual energy production.

332

Figure 5 displays the relative difference in 2090-99 seasonal wind potential between the SSP-
 333 scenarios and SAI (see Figure S9 for 10-year mean present to future comparisons for each
 334 scenario). The sign of change is relatively consistent, although varying in strength, through the
 335 different seasons for SSP245 -> SAI, except for the South East Asian and Northern European
 336 region, where DJF and MAM show a large increase in wind potential, while JJA and SON show a
 337 decrease (Fig 5a,d,g,j). The same seasonal pattern is visible for SSP585 -> SAI in South East Asia,
 338 but not in Europe. In general, the seasons appear to agree less on the sign of the relative change
 339 between SSP585 and SAI than for SSP245 and SAI. For example, apart from Europe and South
 340 East Asia, also Central Africa and Central Asia show different trends depending on the season
 341 when comparing SSP585 with SAI (Fig 5b,e,h,k). While there is not one single region that stands
 342 out with especially large differences compared to others, the most pronounced differences in
 343 SSP585 to SAI of around 16% are the large decrease in JJA in the southern Sahara (Fig 5h), the
 344 decrease in northern China in DJF (Fig 5b), the decrease in South America through all seasons but
 345 especially in Brazil in SON (Fig 5k) and Argentina, Bolivia and Paraguay in DJF (Fig 5b) and the

346 increase in South East Asia and the Chad and Sudan area in the south-east of the Sahara desert in
347 DJF (Fig 5b). For SSP245 to SAI, Central Asia sees a significant decrease through all seasons but
348 especially in DJF (Fig 5a). DJF furthermore indicates a large increase for southern South East
349 Asia, northern offshore Australia and Central and South-East Brazil (Fig 5a). In MAM, East Brazil
350 shows a big decreasing signal (Fig 5d). The SON months see a large increase in potential under
351 SAI for Myanmar and Central/North India (Fig 5j). While the regional differences are diverse and
352 large, globally, relative differences are small. SAI potential is only 2.2 % lower onshore and 1.3
353 % lower offshore than for SSP245 and 3.0 % lower onshore and 0.9 % lower offshore than for
354 SSP585. Between the SSP-scenarios the total global relative difference ends up being 0 % since
355 onshore potential is increased under SSP585 compared to SSP245 by 0.6 % but onshore potential
356 decreased by 0.6 %.

357



358

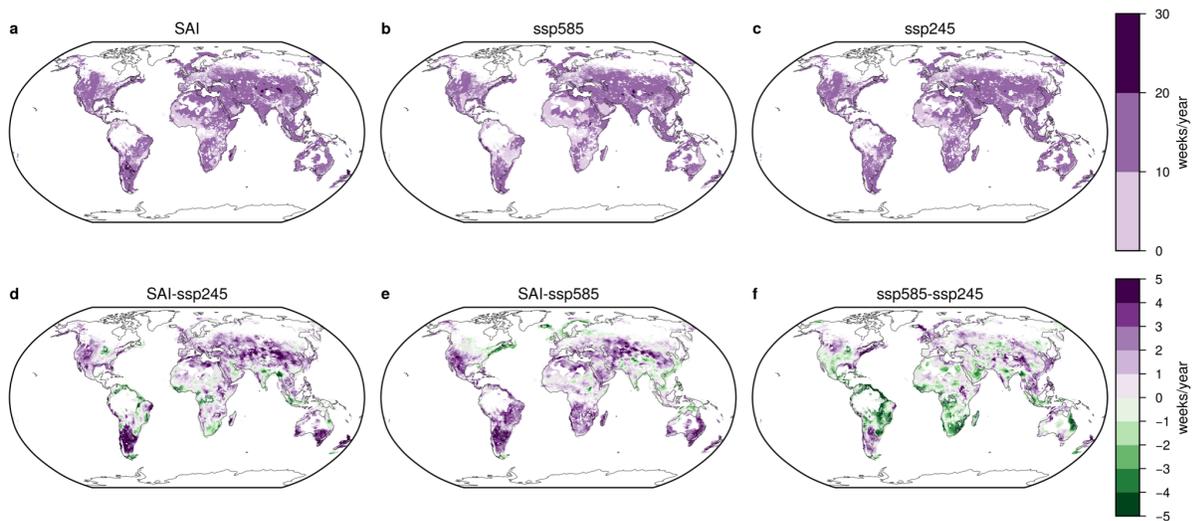
359 **Figure 5.** Relative differences in seasonal 2090-2099 wind potential for a,d,g,j) SSP245 to SAI,
 360 b,e,h,k) for SSP585 to SAI and c,f,i,l) for SSP245 to SSP585 in the seasons a-c) December, January,
 361 February (DJF), d-f) March, April, Mai (MAM), g-i) June, July, August (JJA) and j-l) September,
 362 October, November (SON). Colored areas are statistically significant $p < 0.05$, gray areas are
 363 considered suitable for wind production but show no significant change. $x \rightarrow y$ denotes $(y - x)/x$.

364

365 The LEW metric assesses which regions experience prolonged periods of particularly low energy
 366 production. Figure 6 displays the number of weeks per year in SAI, SSP585 and SSP245 that have
 367 a wind energy output below the current (2015-2024) 20th seasonal percentile. Areas with up to 10
 368 weeks per year imply that they stay unchanged in terms of low energy weeks or have less than in
 369 the present. Apart from some small areas in central South America and central China, globally,
 370 most areas see a slight increase in LEWs regardless of the scenario. West Africa, parts of the

371 Arabian Peninsula and south-east Brazil see no change or a decrease in LEWs in all scenarios.
 372 However, when comparing the scenarios with each other and refining the color-coding, substantial
 373 differences become apparent (Fig 6d-f). SAI leads to an increase of more than 6 additional LEWs
 374 per year compared to SSP245 or SSP585 in large parts of southern South America, south-east
 375 Australia, Central Asia and the Middle East. At the same time, many regions see less LEWs with
 376 SAI than with the SSP-scenarios. For example, compared to SSP245, the Great Plains in the US,
 377 several areas in Brazil, South Africa, West Africa, parts of the Arabian Peninsula, Myanmar and
 378 India and north-east Australia seem to benefit from SAI in terms of LEW count. Compared to
 379 SSP585, SAI appears to be especially advantageous in the north-east of North-America, northern
 380 Europe, the Arafura and Timor Sea between Australia and Indonesia/Timor and some regions in
 381 central China.

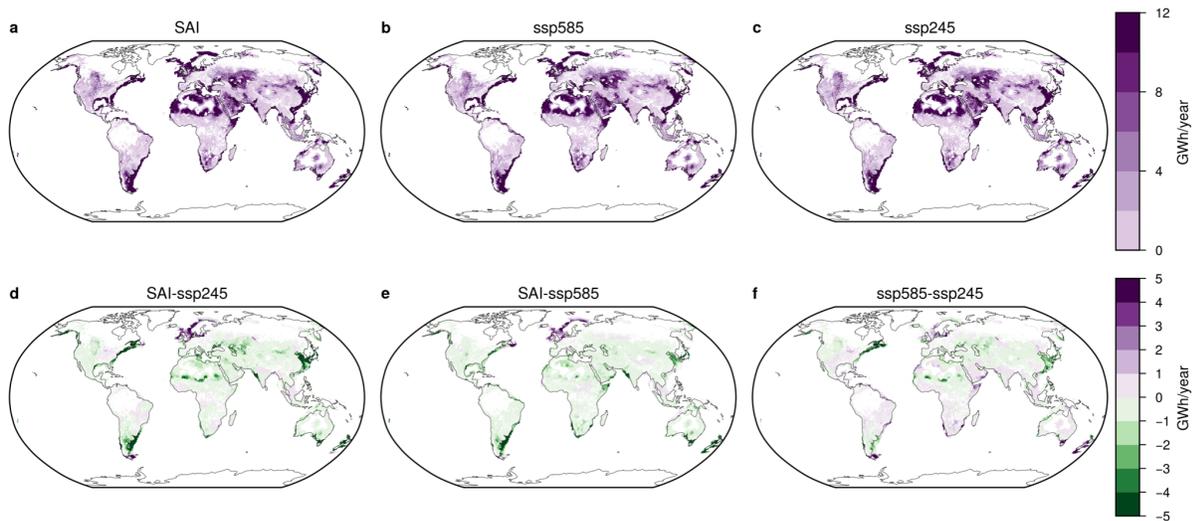
382 With some exceptions, such as north-east Australia, South Africa, northern Russia, offshore north-
 383 east North America and offshore Indonesia, the sign and magnitude of change stays consistent
 384 with the LEWs and the 10-year averages for SAI compared to SSP245 (Fig 6d, S10a). Similar for
 385 SAI versus SSP585, where exceptions are in the offshore area of north-east North-America,
 386 Mexico and southern US, offshore Borneo, Myanmar and South America, especially Argentina
 387 (Fig 6e, S10b).



388
 389 **Figure 6.** Low Energy Week (LEW) metric for a) SAI, b) SSP585 and c) SSP245. The LEW is
 390 calculated between the present (2015-2019) and the future (2095-2099). See Baur et al. (2023) for
 391 the LEW equation. d-f) are the differences between a-c).

392

393 To evaluate how much of the changes in wind potential are caused by changes in fast wind speed,
 394 we measure the annual power loss resulting from winds exceeding the cut-out threshold. Figure 7
 395 shows which areas are mostly affected by energy losses due to fast winds in GWh per year per
 396 grid cell. Unsurprisingly, offshore areas are mostly affected by losses due to fast winds since wind
 397 is generally significantly slower over land areas (Fig 7a-c) and we applied lower suitability
 398 restrictions on offshore than onshore grid cells. Nevertheless, there are several onshore areas that
 399 see substantial reductions, such as the Great Plains in the US, the Southern parts of the Sahara,
 400 Central Asia and Russia. The differences between the scenarios are displayed in Figure 7d-f.
 401 Offshore northern Europe, the tip of Argentina and eastern Canada are the only regions that have
 402 substantially higher losses due to fast winds under SAI than the SSP-scenarios. SAI makes winds
 403 offshore of China, eastern USA, New Zealand and south-east South America and, onshore, the
 404 Sahara more accessible to energy generation. The total global energy loss due to fast winds is
 405 lowest for SAI with 8.5 PWh/yr (2.6 %) and identical for SSP245 and SSP585 with 8.9 PWh/yr
 406 (2.7 %).



407

408 **Figure 7.** Difference between normal power curve setting and “no-cut-out” power curve setting
 409 for a) SAI, b) SSP245 and c) SSP585. Differences in energy lost due to fast winds between a) SAI
 410 and SSP245, b) SAI and SSP585 and c) SSP585 and SSP245.

411 4 Discussion

412 In this study, we examined the interplay between Stratospheric Aerosol Injections (SAI)
 413 and renewable wind energy potential. We found large changes in wind potential under SAI
 414 compared to a medium emission (SSP245) or high emission (SSP585) climate state depending on

415 the season and region (Fig 5, 6). The change in potential under SAI is especially regionally highly
416 diverse with magnitudes frequently reaching 16 %. These large regional differences average out
417 to a total global potential that is slightly smaller than for SSP245 or SSP585.

418 Wind energy potential is highly dependent on wind resources and long-term changes therein are
419 mainly due to large-scale atmospheric circulation (Jung & Schindler, 2022). Previous analyses on
420 stratospheric aerosols and atmospheric circulation have found impacts on global and regional
421 circulation patterns, in particular a poleward shift of the jet (Barnes et al., 2016; McCusker et al.,
422 2014; Polvani & Kushner, 2002; Simpson et al., 2009, 2019). In our analysis, we also found
423 significant differences in zonal wind between SAI and the SSP-scenarios, as well as under the
424 SSP-scenarios themselves (Fig 2, 3). The largest disparities exist within the Southern Hemisphere
425 (SH) westerlies, which show a poleward shift under SAI compared to the SSP-scenarios, leading
426 to both an increase and a decrease in the zonal mean wind of up to 4 m/s (Figure 2, 3). Our results
427 are in agreement with those of Simpson et al. (2019), who studied alterations in large-scale
428 circulation patterns using an SAI-setup known as GLENS. GLENS uses SAI to stay at 2020
429 conditions under an SSP585 baseline (Tilmes et al., 2018a). Simpson et al. (2019) conducted
430 separate isolated forcing experiments to analyze how shifts in zonal wind patterns are driven by
431 the stratospheric temperature change from SAI in GLENS. The authors note westerly stratospheric
432 anomalies in the extra-tropics of similar magnitude and pattern as those identified in our study,
433 and attribute the dominant role driving this change in the SH to the heating of the tropical lower
434 stratosphere, an effect likewise observed in our experiments (Figure S8). Studies on stratospheric
435 aerosols from volcanic eruptions and circulation anomalies have made the same observation
436 (Barnes et al., 2016; DallaSanta et al., 2019; Karpechko et al., 2010; McGraw et al., 2016; Graft
437 et al., 1993; Kirchner et al., 1999) and attribution to stratospheric heating (Barnes et al., 2016;
438 DallaSanta et al., 2019; Polvani & Kushner, 2002; Simpson et al., 2009). However, not all volcanic
439 modeling results lead to the same conclusion: In the Northern Hemisphere (NH), Ramachandran
440 et al. (2000) and Marshall et al. (2009) find an equatorward shift in response to the volcanic forcing
441 instead and in the SH Robock et al. (2007) and Roscoe & Haigh (2007) found no or a slight
442 equatorward shift. Simpson et al. (2019) and McCusker et al. (2015) observe, and our study
443 confirms, that the SH shows a much stronger signal, and that not all the changes in the NH are
444 attributable to the stratospheric heating, such as, for example, in the North Pacific or the Atlantic
445 during JJA (Simpson et al., 2019).

446 Tang et al. (2023) noted a total global reduction in onshore wind speed as a side effect of SAI
447 using the same underlying scenarios as this study, but a different model and a lower temporal
448 resolution. They see similar spatial patterns and magnitudes of change in surface wind speed as
449 we do (Fig 51-k in Tang et al., 2023), especially over land (Fig 4e), and results from regional
450 analyses also broadly overlap with our findings (Da-Allada et al., 2020; Mousavi et al., 2023).
451 However, Xie et al. (2022) used a 6-model ensemble to identify the impacts of SAI on the Atlantic
452 Meridional Overturning Circulation and report changes in global wind speed patterns as a result
453 of SAI that are different from ours. The divergence in results may be partially explained by the
454 difference in scenario comparisons but it nevertheless suggests that the impacts of SAI on wind
455 are not well understood to date. The scenario-comparisons in Figure 4 and 5 suggest that SAI does
456 not compensate for changes from global warming but modifies wind resources in a novel way.

457 While no studies exist to date that evaluate wind energy potential changes under SRM,
458 studies looking at changes in WRE potential due to climate change have found regionally highly
459 diverse trends (e.g. Gernaat et al., 2021; Solaun & Cerdá, 2019; Tobin et al., 2015). We generally
460 see similar developments for the SSP245 and SSP585 comparison as other studies that look at
461 wind potential under climate change. Remarkable similarities exist on the South American (De
462 Jong et al., 2019; Gernaat et al., 2021; Pereira De Lucena et al., 2010; Pereira et al., 2013) and
463 African continent (Gernaat et al., 2021; Sawadogo et al., 2021) and Europe (Carvalho et al., 2017;
464 Davy et al., 2018; Gernaat et al., 2021; Tobin et al., 2015, 2018).

465 Gernaat et al. (2021) note a relative global reduction in offshore wind potential of 2.1 % from
466 historical (1970-2000) values to the end of the century under an RCP6.0 pathway and a reduction
467 in onshore potential by 4.1 %. This is much higher than what we see for SSP245 versus SSP585,
468 which has a global mean reduction in onshore wind potential of 0.6 % and an increase in offshore
469 potential of 0.6 %. Our analyses are not directly comparable due to differences in underlying data
470 and methodology and because our pathways result in a greater level of warming at the point of
471 comparison. However, the absolute temperature difference between SSP245 and SSP585 and
472 Gernaat et al.'s historical and end-of-century value is of similar range. Despite the much smaller
473 relative global change in potential with climate change compared to Gernaat et al.'s study, we
474 calculate a total global potential that is broadly comparable with the results from Gernaat et al. and
475 other studies that provide wind technical potential in energy units (Table 2; Archer & Jacobson,
476 2005; Bosch et al., 2017; Chu & Hawkes, 2020; Eureka et al., 2017; Gernaat et al., 2021; Hoogwijk,

477 2004; de Vries et al., 2007; Lu et al., 2009; Krewitt et al., 2009). Discrepancies are possible due to
 478 differences in the underlying models, unlike methodological approaches in calculating the
 479 potential, such as dissimilar assumptions regarding land suitability and the characteristics of the
 480 wind turbines, as well as the temporal resolution of the wind data. Contrary to those studies, our
 481 offshore potential is much greater than onshore, and energy losses offshore are also much higher
 482 than onshore (Figure 7). This is due to the stronger suitability constraints we apply on land grid
 483 cells and, as demonstrated by Martinez & Iglesias (2024) and Tian et al. (2019), the generally
 484 higher energy density offshore.

485 **Table 2.** Comparison of total global on- and offshore wind potential with previous studies. Our
 486 results: SSP245 in 2090-2099 based on yearly sums of hourly output. NA means not available.

	Onshore [PWh/yr]	Offshore [PWh/yr]	Area	Year
Our results	217	399	global	2090-2099
Hoogwijk, 2004	96	NA	global	2000
de Vries et al., 2007	34	NA	global	2000 / 2050
Krewitt et al., 2009	105	16	global	2050
Eurek et al., 2017	560	315	global	NA
Chu & Hawkes, 2020	211	216	global	NA
Bosch et al., 2017	587	330	global	NA
Lu et al., 2009	690	157	global	2000
Archer & Jacobson, 2005	630	NA	global	2000
Gernaat et al., 2021	149	114	global	2070-2100

487
 488 The LEW metric assesses whether an area encounters notably low weekly energy production
 489 variations, tackling the intermittency apprehension of RE. Extended durations of considerably low
 490 production, as measured by the LEW metric, may be more significant than a minor decline from
 491 high production days to medium production days, as indicated by long-term average data. Several
 492 areas all over the globe see up to 6 additional or 6 fewer LEWs per year on average under SAI
 493 than the SSP-scenarios (Figure 6). The regional sign and magnitude of change mostly overlaps
 494 with that from the 10-year average changes (Figure S10). Baur et al. (2023) computed the LEW
 495 metric for Photovoltaic potential under SAI and found much larger increases in the order of up to

496 12 additional LEWs per year under SAI compared to SSP245 and less agreement on the sign and
497 magnitude of change between long-term average and LEW difference. While their change in
498 LEWs is much higher than what we see for wind, their relative decrease in long-term averages is
499 much lower. This means that in those weeks where energy production is low for wind RE, it is
500 particularly low, pulling the long-term average to higher numbers. Whereas for Photovoltaic
501 potential, the LEWs are frequent but not as unproductive. Since long periods of calm winds or
502 cloudy conditions can be problematic for energy systems that rely on wind or solar RE, it is
503 relevant to look at whether regions with high general wind potential and high LEW increase
504 correlate with regions of high solar potential and high solar LEW increase or trends in other types
505 of intermittent renewable energies.

506 Wind turbine energy output does not scale linearly with wind speed. Rather, they have a
507 delicate range of wind speeds in which they can produce electricity, described by the wind turbine
508 power curve. Hence, lower (higher) wind speeds do not necessarily imply lower (higher) wind
509 potential. Nevertheless, in our analysis, with the same time periods considered, the maps of
510 differences in wind potential (Figure S9) correlate well (correlation coefficient 0.68 for SAI; 0.70
511 for the SSP-scenarios) with the maps of differences in wind speed (Figure 4). However, while total
512 global potential is smaller under SAI than in the SSP-scenarios, SAI reduces the amount of energy
513 that is lost due to fast winds that are not harvested by wind turbines (Fig 7). The observed decrease
514 in WRE potential under SAI can therefore not be attributed to alterations in fast wind patterns and
515 the current quest for wind turbines with ever-higher cut-out thresholds might take up a lower
516 priority in an SAI-modified world. The total amount of energy lost due to fast winds for all three
517 scenarios in our results is likely to be smaller than real-world applications would suggest, partly
518 due to the Weibull distribution we apply to power output to represent variations in wind speed
519 over time and space. This distribution results in power outputs for 1-hour average wind speeds that
520 are above the cut-out wind speed (Fig S2), because even if the average wind speed is above the
521 cut-out threshold, some samples of the Weibull distribution of that average wind speed may be
522 below the cut-out and therefore produce electricity. In reality, however, the wind turbines are not
523 instantly turned on and off for wind gusts above or below the cut-out threshold. This means that
524 we could be overestimating the energy gained and underestimating the energy lost from fast winds.
525 However, the wind turbine power curve represents the power output of a single turbine, and our
526 positively-skewed normal distribution of power output may a better representation of the output

527 from an entire grid cell, as other studies have shown (Bosch et al., 2017; Pryor & Barthelmie,
528 2010).

529 Wind varies greatly in space and time (Cradden et al., 2014; Lee et al., 2018; Yan et al., 2020) and
530 our hourly input data, which represents entire 1° grid cells, is not able to fully reflect that. We
531 regridded our wind data using a bilinear method to match the spatial resolution of the land use data
532 rather than conducting a costly statistical downscaling. As an approximation of the different wind
533 speeds in space and time we applied a Weibull distribution. A constant Weibull shape parameter
534 was used across the globe to ensure computational practicality. However, this approach may lead
535 to under- or overestimation of wind power output in certain regions (Zhou & Smith, 2013).
536 Selecting a constant shape parameter in the Weibull distribution is a simplification because it
537 ultimately relies on the regional wind system and terrain. Nevertheless, any errors that may be
538 produced from this simplification will affect all three scenarios equally and will be largely negated
539 when comparing the scenarios. Our study focuses on the impact of SAI on wind renewable energy
540 potential, specifically differences in predicted future states rather than precise and accurate
541 regional representations of wind potential.

542 The study's findings are specific to a single SAI experimental set-up (continuous injection
543 of sulfate aerosols) and model that may have a larger SAI signal than is currently considered in a
544 hypothetical deployment scenario but allows us a larger signal-to-noise ratio. Since no other
545 modeling groups have performed SAI experiments with hourly wind output, the study's robustness
546 is constrained by these limitations. However, several studies looking at surface wind speed changes
547 under SAI have found similar patterns to us (Da-Allada et al., 2020; Mousavi et al., 2023; Tang et
548 al., 2023). To increase the robustness of the results, more model intercomparison studies such as
549 Xie et al.'s 2022 study will need to be performed, as well as different SAI experiment designs.

550 Not all regions have signal-to-noise ratios that are above 1 (Fig S9) or show statistically significant
551 differences between scenarios (Fig 5, S10), which is a common occurrence for sensitive variables
552 such as wind. Despite the ongoing debate surrounding the consistency of Global Circulation
553 Models with observations and their ability to simulate long-term trends (Pryor & Barthelmie, 2010;
554 Pryor et al., 2020; Tian et al., 2019; Sheperd, 2014), particularly in coastal areas (Soares et al.,
555 2017; Solaun & Cerdá, 2019), they are presently the most reliable source for global wind
556 projections with SAI.

557 Our offshore energy assessment may further incur inaccuracies as a result of overestimating
558 suitable areas by ignoring common shipping lanes and their unsuitability for wind farms. It is likely
559 that for energy generation purposes unsuitable areas such as ports and frequently used
560 transportation routes are located in proximity to areas that we consider particularly suitable, that
561 is, areas close to population centers.

562 This study looks at the large-scale changes in the dynamics of the circulation system. While these
563 have an important influence on local wind conditions, wind speeds in the lower levels of the
564 atmospheric boundary layer, i.e., those accessible to wind turbines, are highly susceptible to
565 turbulence from small-scale features such as buildings, trees and valleys (Veers et al., 2019). These
566 microscale processes are not resolved in our global analysis. An SSP245-world would likely have
567 substantial differences in terms of land cover and population distribution compared to an SSP585-
568 or an SAI-world. As these things are hard to predict and would complicate the comparison between
569 scenarios, we chose equal area weighting for all scenarios.

570 Future research should not only consider other types of renewable energy sources such as
571 biofuels and hydropower but look at the effects of SAI on renewable energy sources in conjunction.
572 This would allow to identify regions where not just one RE technology, but potentially several,
573 may experience a change in their productivity with SAI. Additionally, it is relevant to consider not
574 only resource changes due to SRM but also demand changes. One could imagine a modified
575 demand for heating and cooling under SRM, for example. Studies looking at other types of SRM,
576 such as Marine Cloud Brightening, would offer a more complete picture on SRM and renewable
577 energy. At the same time, improvements in the representation of SRM and the response of
578 atmospheric circulation to a change in forcing in the Earth System Models would substantially
579 increase accuracy of the results. Since stratospheric heating has been found to play an important
580 role in changing large-scale circulation (Simpson et al., 2019; Charlesworth et al., 2023, Baldwin
581 & Dunkerton, 2001; Graft et al., 1993; Stenchikov et al. 2002; DallaSanta et al., 2019), narrowing
582 down the uncertainty related to the radiative properties of stratospheric aerosols could improve the
583 understanding of the impacts of SAI on wind RE. And lastly, since SAI seems to significantly
584 affect the spatial distribution of wind resources, regional scale analyses are an essential addition
585 in better understanding wind potential under SAI.

586

587 **5 Conclusion**

588 Wind renewable energy is considered a critical component in the efforts to reduce
589 greenhouse gas emissions and transition to a more sustainable energy system. Studying the
590 interplay between SAI and wind energy is important to understand whether mitigation and SAI
591 could work together to address climate change. Here, we examined the alterations in wind patterns
592 and RE resources under SAI using the CNRM-ESM2-1.

593 We find that SAI, while counterbalancing the temperature increase of climate change, does not
594 seem to counterbalance the effects of climate change on wind RE. Instead, our model simulations
595 suggest that SAI may create new atmospheric circulation features (Fig 2-4). The overall long-term
596 impact on WRE resources appears to be highly location-specific, with large increases and
597 reductions in potential under SAI compared to SSP245 or SSP585 of 16 % (Fig 5, S10). However,
598 the long-term total global change in potential is negligible. Furthermore, we find that SAI increases
599 the number of weeks of considerably low production per year in most places around the world (Fig
600 6) compared to the SSP-scenarios and to the present, although to a much lesser degree than for
601 solar RE (Baur et al., 2023). We note that the reduction in long-term potential and the increase in
602 low energy weeks is not due to an increase of wind speed under SAI (Fig 7).

603 This paper contributes to the ongoing discourse on climate intervention strategies and their
604 implications for mitigation. While this study entails a high temporal resolution and a fairly high
605 number of ensemble members, future studies could rely on higher spatial resolution models and a
606 larger range of emission scenarios with SAI to test and improve accuracy of the current
607 assumptions. Climate projections are still faced with the challenge of understanding the effect of
608 global warming on atmospheric circulation change and pattern formation (Shepherd, 2014).
609 Improvements in these fundamental understandings might help in attributing the changes from the
610 combined effects of global warming and SAI on wind allowing for a better investigation of the
611 impacts of SAI on WRE potential. We suggest that further research is necessary to assess the wider
612 impacts of SAI on renewable energies to enable more responsible and informed decision-making
613 on climate intervention.

614

615

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620 Future), 821003 (4C, Climate-Carbon Interactions in the Coming Century) and 101003687
621 (PROVIDE).

622

623 **Conflict of Interest**

624 The authors declare no conflict of interest.

625

626 **Open Research**

627 **Availability Statement**

628 The code is available at https://github.com/susannebaur/SRM_wind_RE.git. Upon final
629 publication the code will be made publicly available with a DOI under zenodo.

630 Underlying data is output from the CNRM-ESM2-1 Earth System Model. Due to the large size of
631 the raw data (>1.5TB) it is available upon request from the authors until a sufficiently large storage
632 repository has been found. The post-processed model output will be made available upon final
633 publication with a DOI on zenodo. Land use and land cover as well as population density
634 projections are from the IMAGE3.0-LPJ model (Doelman et al., 2018; Stehfest et al., 2014). Land
635 and ocean protected areas are from the International Union for Conservation of Nature (IUCN,
636 2023). The Exclusive Economic Zone (EEZ) is from the Flanders Marine Institute (2019),
637 bathymetry and sea-ice information is output from the CNRM-ESM2-1 simulations. Figures were
638 created using the matplotlib library and the matplotlib wrapper proplot.

639

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