BILINGUAL PUBLISHING GROUP

Journal of Atmospheric Science Research

https://journals.bilpubgroup.com/index.php/jasr

ARTICLE

Analysis of the Climatic Impacts of SO_2 Injection into the Stratosphere on Precipitation Indices in the Sahel

Tji Souleymane Coulibaly [1,2*], *Cheick Diarra* [1], *Souleymane Sanogo* [1], *Issiaka Traore* [1]

[1] *Laboratory of Optics, Spectroscopy and Science of Atmosphere (LOSSA), Faculty of Science and Technology (FST), University of Science, Techniques and Technology of Bamako (USTT-B), Bamako P.O. Box E 423, Mali*

[2] *Department of Education Sciences, University Pedagogical Institute (IPU), Bamako 233, Mali*

ABSTRACT

Stratospheric Aerosol Injection (SAI) emerges as a geoengineering strategy to mitigate global warming by reflecting sunlight back into space. However, this approach raises significant concerns, particularly regarding its impact on rainfall characteristics in the Sahel. This study investigates the effects of injecting sulfur dioxide (SO_2) into the stratosphere using the IPSL-CM5A-LR climate model, under two forcing scenarios: RCP4.5 (Representative Concentration Pathway of 4.5 W m^{-2}) and a combination of RCP4.5 with geoengineering forcing (G3). The analysis focuses on future climate conditions in the Sahel, based on 30-year averages over two distinct periods: 2020–2050 and 2050–2080. The results highlight notable differences between the "with injection" and "without injection" scenarios. The number of consecutive wet days (CWD) increases with SO_2 injection, indicating prolonged rainfall periods. Annual total precipitation on wet days (PRCPTOT) exhibits a slight upward trend with SO_2 injection, potentially mitigating drought effects. Conversely, maximum daily precipitation (Rx1day) and five-day precipitation (Rx5day) are slightly higher in the absence of injection, suggesting a reduction in extreme precipitation intensity when SO_2 is introduced. The Simple Daily Intensity Index (SDII) shows moderate variations between scenarios, with a slight decrease observed under SO_2 injection. These findings indicate that SO_2 injection could help stabilize precipitation regimes and reduce climate extremes in the Sahel. However, further research is crucial to gaining a deeper understanding of the long-term implications of this method and optimizing its application.

Keywords: Stratospheric Aerosol Injection; Geoengineering; Sulfur Dioxide; Climate Model; Sahel; Precipitation Indices

*CORRESPONDING AUTHOR:

Tji Souleymane Coulibaly, Laboratory of Optics, Spectroscopy and Science of Atmosphere (LOSSA), Faculty of Science and Technology (FST), University of Science, Techniques and Technology of Bamako (USTT-B), Bamako P.O. Box E 423, Mali; Department of Education Sciences, University Pedagogical Institute (IPU), Bamako 233, Mali; Email: ctjisouleymane@gmail.com

ARTICLE INFO

Received: 20 December 2024 | Revised: 2 January 2025 | Accepted: 5 January 2025 | Published Online: 17 January 2025

DOI: https://doi.org/10.30564/jasr.v8i1.8603

CITATION

Coulibaly, T.S., Diarra, C., Sanogo, S., et al., 2025. Analysis of the Climatic Impacts of SO_2 Injection into the Stratosphere on Precipitation Indices in the Sahel. Journal of Atmospheric Science Research. 8(1): 27–40. DOI: https://doi.org/10.30564/jasr.v8i1.8603

1. Introduction

The injection of sulphur dioxide (SO_2) into the stratosphere has been proposed as a geoengineering strategy to counteract the effects of anthropogenic climate change by reflecting sunlight back into space [1,2]. This technique, known as solar radiation management (SRM), aims to reduce global warming by enhancing the Earth's albedo, which could offset the rise in global temperatures caused by increasing concentrations of greenhouse gases [3,4]. By increasing the reflectivity of the Earth's atmosphere, SO_2 injection could potentially lead to a global cooling effect. However, the regional impacts of this intervention, particularly on precipitation patterns in vulnerable regions such as the Sahel, are still poorly understood and raise significant concerns [5,6]. The Sahel, a semi-arid region in West Africa, is highly dependent on rainfall for its agricultural and socio-economic activities, making it particularly sensitive to changes in precipitation [7]. In recent decades, the Sahel has experienced increased climate variability, including both prolonged droughts and unexpected rainfall events, which have exacerbated food and water insecurity [8]. Therefore, understanding the effects of geoengineering interventions like SO_2 injection on rainfall patterns is crucial for assessing their potential to either mitigate or exacerbate climate-related challenges in this region. Several studies have investigated the broader effects of SO_2 injection on the Earth's climate using sophisticated climate models that incorporate stratospheric chemistry and aerosol microphysics [9,10]. These studies have shown that the spatial distribution, altitude, and timing of SO_2 injections are critical factors influencing the formation and distribution of sulphate aerosols, which in turn impact the Earth's radiative balance and climate system [11,12]. However, the specific regional impacts of SO_2 injection, especially in the context of African climate systems, remain understudied. Notably, it has been suggested that unilateral injection in the northern hemisphere could lead to significant drought conditions in the Sahel, while injections in the southern hemisphere might result in enhanced precipitation [9,13]. This study aims to fill this gap by exploring the effects of SO_2 injection on precipitation indices in the Sahel, a region that has been identified as especially vulnerable to climate variability and change [14]. The indices examined include the Simple Precipitation Intensity Index (SDII), the Maximum Length of Wet Spell (CWD), Annual Total Precipitation in Wet Days (PRCPTOT), Maximum Daily Precipitation (Rx1day), and Maximum 5-Day Precipitation (Rx5day). These indices offer a comprehensive view of precipitation patterns, from the intensity of daily rainfall to the frequency of extreme wet spells, which are essential for understanding the implications of geoengineering on regional water resources and agriculture [8,15]. The primary objective of this study is to assess whether SO_2 injection into the stratosphere influences rainfall patterns in the Sahel under different climate scenarios. The study compares future projections for the periods 2020–2050 and 2050–2080, integrating both standard climate models (RCP4.5) and a geoengineering scenario that combines RCP4.5 with SO_2 injection (G3). This comparison will provide insights into the potential mitigation or exacerbation of regional climate extremes as a result of geoengineering interventions. The main contribution of this manuscript lies in its focus on regional climate impacts in the Sahel, an area that is often overlooked in global climate studies. By analyzing the changes in precipitation indices under various SO_2 injection scenarios, this study aims to contribute to a better understanding of how geoengineering strategies could be tailored to suit the specific needs of vulnerable regions. Furthermore, the research contributes to the ongoing debate on the feasibility and ethics of geoengineering, providing crucial information for policymakers considering such interventions in the future [2,6]. In this article, Section 2 provides a detailed description of the datasets used in this study, along with the methodologies employed to assess climate variations. Section 3 presents the results, which include seasonal variations in temperature and precipitation for the different periods and scenarios. These results will be analyzed to identify trends and significant changes, with a particular focus on the implications for the Sahel region. Finally, Section 4 summarizes the conclusions drawn from the analysis and provides recommendations for future research and the potential application of geoengineering strategies in the region.

2. Materials and Methods

2.1. Study Area

West Africa contains the Sahel, a geographical area of great importance. This landmass, which crosses many nations in the area, is distinguished by a gradual change from the immense Saharan deserts in the north to the more verdant savannah zones in the south. The Sudanese savannah borders the area to the south, while the Sahara borders it to the north. The Sahel region, which includes nations like Senegal, Mauritania, Mali, Burkina Faso, Chad, and Sudan, spans a huge territory from the Atlantic Ocean in the west to the Red Sea in the east. There are many different types of landscapes, weather, and civilizations in this area. The northern Sahelian deserts are dry and sandy, with little flora, whereas the southern Sahelian regions are more productive and conducive to cultivation. Rainfall, which is scarce and erratic, is crucial to these productive regions. The vegetation in the southern Sahel changes to savannahs, which sustain agricultural activity and give cattle pasture area. With rainfall patterns heavily impacted by regional and global climatic phenomena, such as El Niño and La Niña occurrences, as well as changes in the location of the Intertropical Convergence Zone (ITCZ), the region is especially susceptible to climate fluctuation. **Figure 1** below illustrates the geographic extent of the Sahel, highlighting the transition zones between the desert to the north and the savannahs to the south. It provides a clear visual representation of the region's varying landscapes and geographical boundaries, essential for understanding its climate and environmental dynamics. This variation in terrain is a critical factor influencing the agricultural potential and socio-economic development of the region, which is heavily dependent on its climate and water resources.

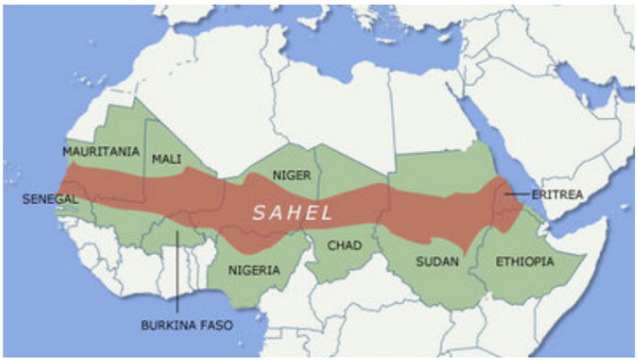

Figure 1. Map of the Sahelian Zone (Highlighted in Brown), Defined Based on Ecological Criteria Such as Climate and Vegetation Patterns. The Green-Shaded Countries Represent the Broader Sahel Region.

Note: Area defined based on an ecological criterion.

Source: Potts et al. (2013) [34].

2.2. Data Description

As part of this study, precipitation data are collected from two different scenarios to evaluate the impact of sulfur dioxide (SO_2) injection on precipitation patterns in the Sahel region. These data are analyzed for two distinct periods: 2020–2050 and 2050–2080. The two scenarios are studied as follows:

- Scenario I_G3 (With SO_2 Injection): This scenario involves the injection of sulfur dioxide (SO_2) into the stratosphere as a geoengineering technique aimed at reflecting a portion of the sun's radiation back into space, thereby cooling the Earth's surface [16]. Precipitation data are collected from 2020 to 2050. This period allows the assessment of the combined effect of SO_2 injection and the expected rise in greenhouse gas emissions on precipitation patterns in the region.
- Scenario NO I_RCP4.5 (Without SO_2 Injection) [17]. This scenario represents a climate trajectory under the RCP4.5 scenario, which assumes moderate greenhouse gas emissions and no geoengineering intervention [2]. Precipitation data are also collected for the same periods, 2020–2050 and 2050–2080, providing a baseline for comparison with the geoengineering scenario. This scenario allows us to understand the changes in precipitation patterns in the absence of SO_2 injection, driven solely by greenhouse gas emissions under a relatively mod-

erate climate policy pathway [18].

2.3. Description of the Simulations

The IPSL-CM5A-LR simulation model is used for this investigation in order to concentrate on understanding the particular effects of SO_2 injection. Prior to performing a comparison study with other models, our main goal is to fully examine these implications using a single, well-documented model. Since almost all models show that SO_2 injection lowers the temperature, this method guarantees a thorough understanding of the mechanisms at work. We systematically analyse the results under different conditions using IPSL-CM5A-LR, which provides full scenario coverage, including historical climatology, RCP4.5, and G3. In order to replicate the Earth system, the IPSL-CM5A-LR model, a lower-resolution (1.9° × 3.75°) variant of the IPSL-CM5, combines atmospheric, terrestrial, oceanic, and glacial components [19]. Notably, the Geoengineering Model Intercomparison Project (GeoMIP) is established in order to gain a better understanding of how climate models agree and propagate in relation to the global climate response. To maintain the radiative flux of the atmosphere at 2020 levels, consistent with the RCP4.5 scenario, the G3 experiment, in conjunction with RCP4.5 forcing, starts in 2020 with a progressive rise in the amount of sulphate aerosol (SO_2) injected into the stratosphere. From 2020 until 2069, 5 teragrams (Tg) of SO_2 above the equator will be injected annually into the lower stratosphere (16–25 km height) as part of the G3 experiment, which is based on the RCP4.5 scenario [20]. To quantify the climatic rebound impact, the simulation is then run for a further 20 years with regular RCP4.5 forcing after the Solar Aerosol Injection (SAI) is stopped. Variations in greenhouse gases and aerosols are included in the RCP4.5 simulation (without SO_2 injection) such that, in comparison to the pre-industrial period, the net radiative forcing in the year 2100 approaches 4.5 watts per square meter (W m^{-2}) [21]. The RCP4.5 data are still available through the Earth System Grid Federation and are a component of phase 5 of the Coupled Model Intercomparison Project (CMIP) [22]. We add 5 Tg of SO_2 to our scenario of choice. Notably, the CMIP5 phase 5 multi-model averages across the West African area closely match the IPSL-CM5A-LR historical simulations of temperature and precipitation [23,24].

2.4. Methods

To determine the impacts of SO_2 injection on precipitation indices such as PRCPTOT, Rx1day, Rx5day, SDII, and CWD, this study adopts an approach based on climate modeling and statistical analysis. The methods implemented in this study are detailed below.

2.4.1. Climate Modeling

Climate modeling serves as the primary tool for assessing the effects of SO_2 injection on precipitation indices. The IPSL-CM5A-LR climate model, developed by the Institut Pierre-Simon Laplace [25], simulates interactions between the atmosphere, ocean, land surface, and cryosphere. The IPSL-CM5A-LR model is a general circulation model with low spatial resolution (1.9° × 3.75°) that covers different components of the climate system. The simulations cover the historical period and future projections from 2020 to 2050. The analyzed scenarios include the historical scenario, based on past greenhouse gas concentrations, RCP4.5 without SO_2 injection, which accounts for greenhouse gas increases with a radiative forcing of 4.5 W m^{-2} in 2100 [23], and RCP4.5 with SO_2 injection, which introduces an annual injection of 5 Tg of SO_2 into the stratosphere (16–25 km altitude) from 2020 to 2069, following the Geoengineering Model Intercomparison Project (GeoMIP) G3 experiment [20]. Daily precipitation and precipitation indices derived from model outputs are analyzed.

2.4.2. Analysis of Precipitation Indices

To quantify the impacts of SO_2 injection on precipitation regimes, several standard indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI) are analyzed [26].

PRCPTOT (Annual Total Precipitation in Wet Days) is calculated by summing the daily precipitation for all wet days (RR ≥ 1 mm) over a year, providing a global measure of total precipitation accumulation.

Rx1day (Maximum 1-Day Precipitation Amount) quantifies the maximum precipitation recorded in a single day during the year and serves as a key indicator for extreme rainfall events.

Rx5day (Maximum 5-Day Precipitation Amount) measures the maximum accumulated precipitation over a five-day consecutive period, allowing for an assessment of prolonged heavy rainfall events.

CWD (Consecutive Wet Days) determines the longest sequence of consecutive wet days (RR ≥ 1 mm), serving as an indicator of wet spell duration.

SDII (Simple Daily Intensity Index) calculates the average precipitation intensity on rainy days (RR ≥ 1 mm) by dividing PRCPTOT by the total number of wet days. Each index is calculated based on daily data from the IPSL-CM5A-LR model simulations for the different considered scenarios.

2.4.3. Scenario Comparison

The final stage of the analysis consists of a comparison between the different scenarios to assess the impact of SO_2 injection. Long-term trends in precipitation indices are estimated using linear regression, with statistical analysis determining the significance of observed trends. Differences between index distributions under RCP4.5 without and with SO_2 injection are analyzed using statistical tests such as the Mann-Whitney test and the Kolmogorov-Smirnov test to determine the significance of changes [27]. Graphical visualization includes time series representations to observe annual variations, as well as histograms and box plots to compare distributions. This approach enables the determination of whether SO_2 injection leads to significant modifications in precipitation indices and helps to understand its implications for the Sahelian climate.

3. Results

3.1. Evaluating the Impact of SO_2 Injection on Precipitation Indices: A Comparative Analysis

3.1.1. Evaluating the Impact of SO_2 Injection on Total Precipitation (PRCPTOT)

Figure 2 presents the annual evolution of total precipitation (PRCPTOT) from 2020 to 2080 under two climate scenarios: with and without the injection of sulfur dioxide (SO_2) into the stratosphere. During the first period (2020–2050), both scenarios exhibit a generally stable to slightly increasing trend, but precipitation levels are consistently higher in the scenario with SO_2 injection. The annual average reaches approximately 320 mm with injection, compared to about 300 mm without, suggesting a moderating effect of SO_2 on interannual variability. In the second period (2050–2080), the difference between the two scenarios becomes more pronounced: the scenario without

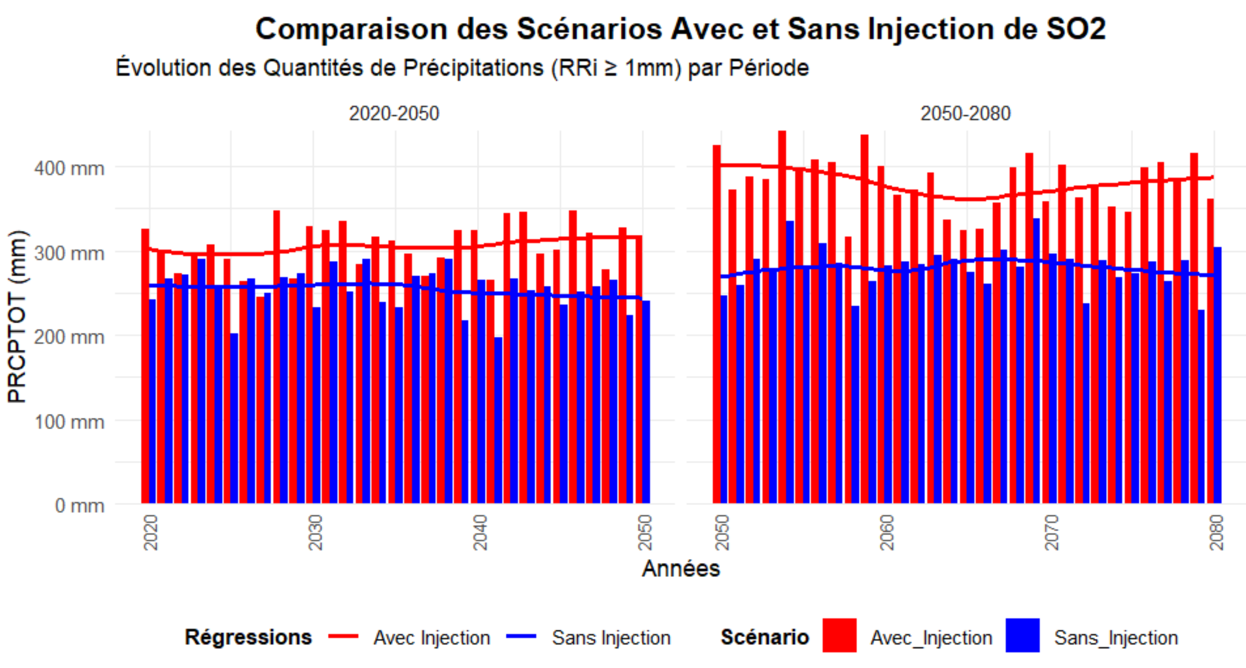

Figure 2. Trends in PRCPTOT Indices From 2020 to 2050: Comparison with and Without SO_2 Injection.

injection shows a significant decline in precipitation, with a clearly negative trend dropping to around 260 mm by the end of the period. In contrast, the scenario with injection maintains relatively stable levels, fluctuating around 310 mm, with a nearly flat regression slope. This stability indicates that SO_2 injection may play a mitigating role against long-term precipitation decline, helping to preserve rainfall amounts over time. Therefore, the overall effect of SO_2 injection is not necessarily an increase in precipitation, but rather a stabilization of the rainfall regime in the face of decreasing trends expected in the absence of such intervention.

3.1.2. Assessing the Influence of SO_2 Injection on Maximum 1-Day Precipitation (Rx1day)

The effect of SO_2 injection on severe precipitation episodes demonstrates how the maximum 1-day precipitation (Rx1day) is influenced. As illustrated in **Figure 3,** during the 2020–2050 timeframe, the SO_2 injection scenario records an average Rx1day of nearly 120 mm, whereas the injection-free scenario shows an Rx1day of roughly 100 mm. This 20 mm difference suggests that daily maximum precipitation occurrences are more intense due to SO_2 injection. In the subsequent 2050–2080 decade, the average Rx1day in the injection scenario remains higher, at approximately 125 mm, compared to 105 mm in the without injection scenario. This consistent variation across both time periods underscores how SO_2 injection increases the frequency or severity of intense precipitation episodes. Furthermore, regression trends (**Figure 3**) show a more stable Rx1day pattern in the scenario with SO_2 injection, while the scenario without injection exhibits greater variability and a slight downward trend. This suggests that SO_2 injection plays a role in moderating extreme weather events by maintaining higher levels of maximum daily precipitation.

3.1.3. Impact of SO_2 Injection on Maximum 5-Day Precipitation (Rx5day)

Figure 4 shows the maximum 5-day consecutive precipitation (Rx5day) from 2020 to 2050 and 2050 to 2080. The impact of SO_2 injection on prolonged severe precipitation occurrences is demonstrated by the examination of maximum 5-day precipitation totals (Rx5day). The average Rx5day for the 2020–2050 timeframe with SO_2 injection is around 550 mm, whereas the average Rx5day for the scenario without injection is about 500 mm, suggesting a 50 mm discrepancy. This suggests that SO_2 injection enhances the intensity of prolonged heavy rainfall events. During the

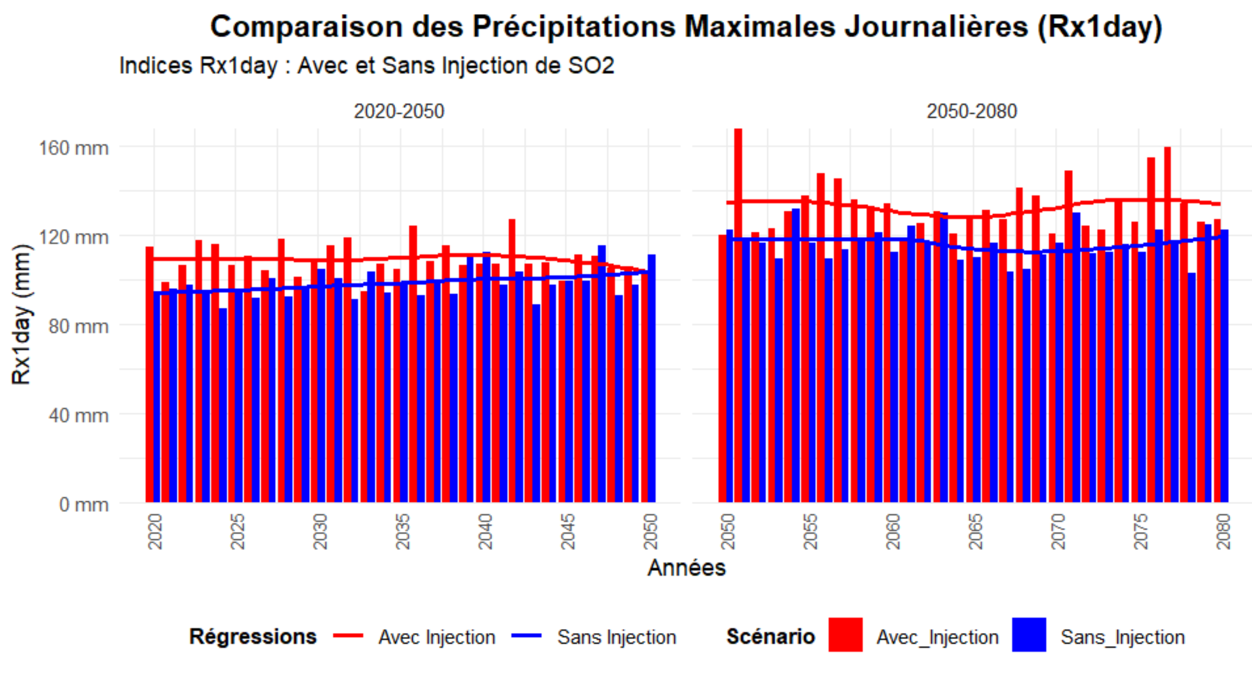

Figure 3. Trends in Rx1day Indices From (2020 to 2050 and 2050 to 2080): Comparison with and Without SO_2 Injection.

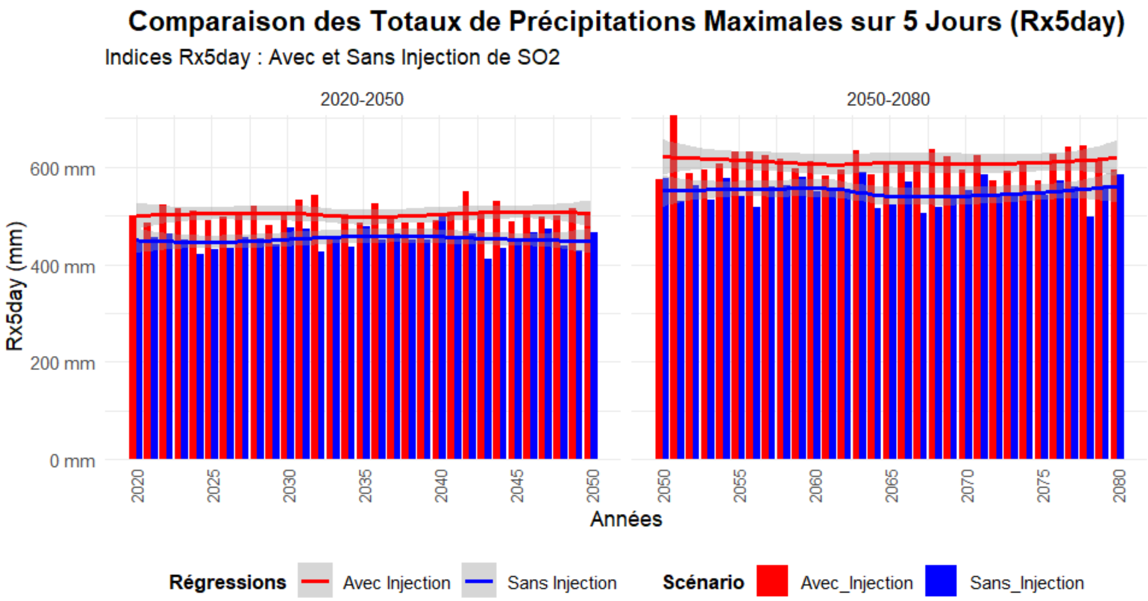

Figure 4. Trends in Rx5day indices from (2020 to 2050 and 2050 to 2080): Comparison with and without SO_2 injection.

period 2050–2080, the scenario with injection maintains higher Rx5day values, averaging around 560 mm, while the scenario without injection records about 520 mm. This sustained difference across both periods highlights the role of SO_2 injection in increasing the magnitude of extreme precipitation over a 5-day period. The regression lines show a relatively stable trend in the scenario with SO_2 injection, while the scenario without injection exhibits more fluctuations and a slight decreasing trend. This suggests that SO_2 injection helps stabilize the occurrence and severity of heavy precipitation over long timeframes.

3.1.4. Comparative Study of SO_2 Injection Effects on Consecutive Wet Days (CWD)

Figure 5 compares the evolution of consecutive wet days (CWD) for the periods 2020–2050 and 2050–2080 under two scenarios: with and without SO_2 injection. The results highlight a noticeable reduction in CWD when SO_2 is injected into the stratosphere. During the first pe-

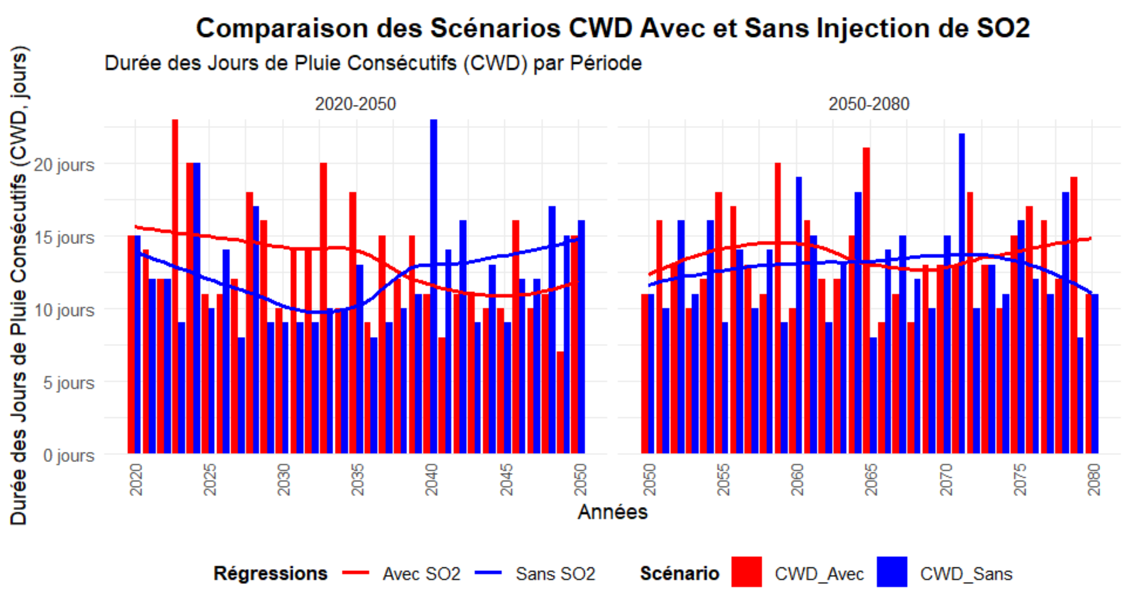

Figure 5. CWD Index Trends From (2020 to 2050 and 2050 to 2080): Comparison with and Without SO_2 Injection.

riod (2020–2050), the average duration of consecutive wet days is approximately 12 days in the scenario without SO_2, whereas it drops to 10 days in the injection scenario, representing a 16.7% reduction. This trend persists in the second period (2050–2080), where the average CWD is about 13 days without SO_2 injection and 11 days with SO_2, indicating a further 15.4% decrease. The regression analysis shows an overall downward trend in CWD for both scenarios, but the decline is more pronounced in the SO_2 injection scenario. This suggests that stratospheric aerosol injection affects the persistence of wet periods, likely due to the cooling effect induced by SO_2, which may suppress convective activity. The reduction in consecutive wet days could have significant implications for regional hydrological cycles, potentially decreasing the risk of prolonged flooding events while also affecting soil moisture and groundwater recharge. These findings indicate that SO_2 injection not only modifies precipitation intensity but also alters its temporal distribution, which could have important consequences for water resource management in climate-sensitive regions.

3.1.5. Analysis of SO_2 Injection Influence on Simple Daily Intensity Index (SDII)

Figure 6 presents the comparison of the Simple Daily Intensity Index (SDII) for the periods 2020–2050 and 2050–2080, under both scenarios: with and without SO_2 injection. SDII measures the average intensity of precipitation on wet days (in mm per day), providing insights into the typical strength of rainfall events.

Contrary to expectations that SO_2 injection might suppress rainfall intensity due to reduced convective activity, the results indicate a slightly higher SDII in the injection scenario.

From 2020 to 2050, the SDII averages around 9 mm per day with SO_2 injection, compared to 8.5 mm per day without, suggesting an increase of approximately 5.9%. Similarly, during 2050–2080, SDII values are about 8.9 mm per day with SO_2, versus 8.4 mm per day without, marking a further 6% increase.

The regression lines in **Figure 6** show relatively stable trends over time, but a consistent positive offset in the scenario with SO_2 injection. These findings suggest that stratospheric aerosol injection may slightly enhance the intensity of precipitation on wet days, aligning with the observed increase in extreme precipitation indices (e.g., Rx1day and Rx5day).

This outcome may reflect changes in cloud microphysics or atmospheric dynamics resulting from aerosol-cloud interactions. While a modest intensification of precipitation could increase the risk of flooding events in the Sahel, it might also support improved soil moisture and crop water availability during wet periods. Thus, the net impact remains complex and highlights the necessity for

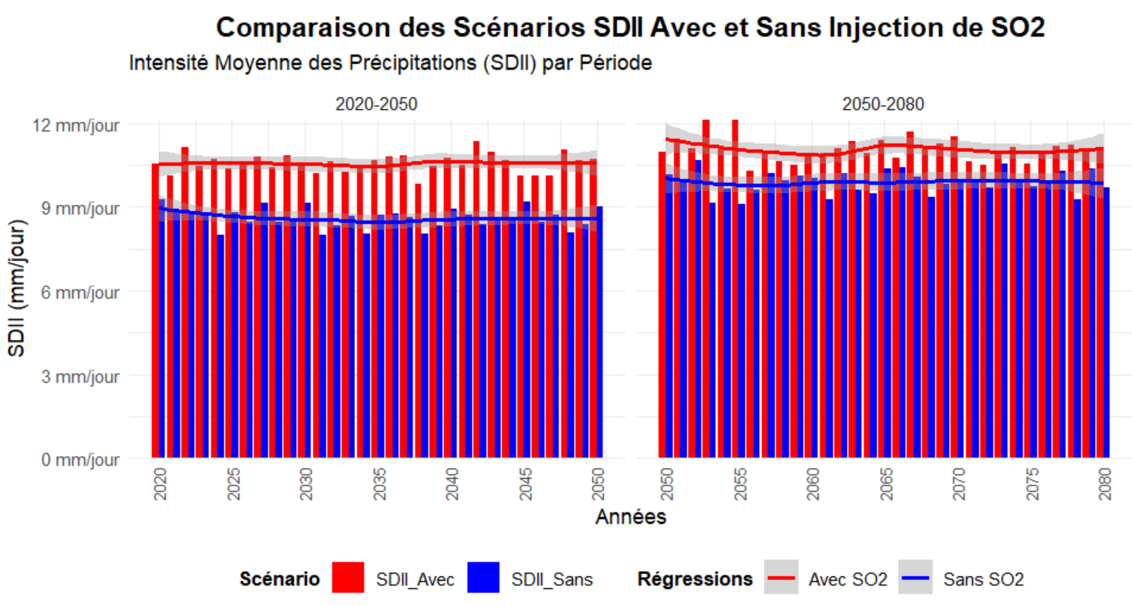

Figure 6. Trends in SDII Indices From 2020 to 2050: Comparison with and Without SO_2 Injection.

careful, regional-scale assessment of geoengineering effects.

4. Implication of Projected Change in the Sahel

The Sahel, an area that is extremely vulnerable to climatic fluctuations, will be significantly impacted by the anticipated changes in precipitation patterns brought on by SO_2 injection. The 2020–2050 period research indicates that SO_2 injection may moderate precipitation indices, resulting in fewer consecutive dry days and more consecutive wet days. This change suggests that droughts, a persistent problem for the Sahelian ecology and agricultural practices, may be less frequent. By increasing overall moisture availability, SO_2 injection may help mitigate the consequences of protracted droughts, as seen by the modest increase in total yearly precipitation seen in the injection scenario. Additionally, a possible reduction in flood hazards and related soil erosion is implied by the decline in severe precipitation occurrences, as demonstrated by decreases in maximum daily (Rx1day) and five-day (Rx5day) precipitation. These results are consistent with other studies [28,29], which also show that stratospheric aerosol injection stabilizes regional precipitation regimes. Although these findings demonstrate the possible advantages of SO_2 injection, more investigation is required to fully comprehend the extent of its impact on weather extremes and hydrological cycles. These patterns continue during the 2050–2080 timeframe, confirming the long-term efficacy of SO_2 injection in influencing Sahelian precipitation patterns. By lowering extended drought occurrences, the intervention may help maintain agricultural viability, as seen by the ongoing decline in consecutive dry days. In a similar vein, the stability of wet periods suggests that although the overall amount of rainfall may not vary significantly, the distribution of precipitation becomes more predictable, decreasing the possibility of unpredictable rainfall patterns that can quickly cause both droughts and floods. Further evidence that extreme weather events may become less severe, reducing the danger of flash floods and infrastructure damage, comes from the steady decline in precipitation intensity, both in daily and multi-day maximums. SO_2 injection is positioned as a viable geoengineering strategy for enhancing climate resilience in the Sahel due to the long-term reduction of rainfall extremes.

It is nevertheless imperative to evaluate the wider climatic and environmental effects of such initiatives, notwithstanding these encouraging findings. More research is needed to determine if SO_2 injection is a sustainable method of mitigating climate change, especially in light of possible changes in air circulation, variations in local temperatures, and unforeseen ecological consequences. Determining whether such measures might assist Sahelian people overall also requires a grasp of the socioeconomic ramifications, especially with regard to agriculture and water resource management. Future research should concentrate on improving climate models to better represent localized impacts and assessing possible feedback processes that can manifest over long timeframes.

5. Impact of SO_2 Injection on Precipitation Trends and Extremes in the 2020–2050 and 2050–2080 Periods

5.1. Analysis of Precipitation Trends and Extremes for the 2020–2050 Period with and without SO_2 Injection

Table 1 presents the effects of stratospheric SO_2 injection on various precipitation indices, comparing two scenarios: with and without SO_2 injection. The findings show notable variations between the two scenarios, especially with regard to severe occurrences, dry spells, and overall precipitation. Total Precipitation (PRCPTOT) shows higher values in the scenario with SO_2 injection (350.4 mm vs. 320.7 mm), with a more pronounced annual increase (+1.8 mm per year vs. +1.2 mm per year). This suggests that SO_2 injection enhances overall precipitation levels over time. Maximum Precipitation (Rx1day and Rx5day) also exhibits stronger increases in the injection scenario, with Rx1day reaching 110.5 mm (+0.9 mm per year) and Rx5day reaching 520.3 mm (+2.1 mm per year), compared to the no-injection scenario (100.8 mm and 480.6 mm, respectively). These results indicate that SO_2 injection leads to more intense precipitation events, particularly extreme ones. Consecutive Dry Days (CWD) shows a slight decrease in dry periods with SO_2 injection (12.3 days vs. 14.1 days), suggesting that the injection reduces the duration of dry spells, albeit marginally. Precipitation Intensity

(SDII) shows a small but positive increase in both scenarios, with the injection scenario seeing a slightly higher rate of change (+0.07 mm per day per year vs. +0.05 mm per day per year), indicating a modest intensification of rainfall on wet days. Overall, the SO_2 injection scenario significantly impacts precipitation patterns by increasing total precipitation and extreme events, while also slightly reducing the duration of dry periods. These findings suggest that solar geoengineering, in the form of SO_2 injection, has a considerable effect on regional climate dynamics, particularly in terms of rainfall intensity and frequency**.**

5.2. Analysis of Precipitation Trends and Extremes for the 2050–2080 Period with and without SO_2 Injection

Table 2 presents a comparison of precipitation indices under two climate scenarios: with and without SO_2 injection into the stratosphere. The analysis of these results highlights significant differences in precipitation patterns and the duration of wet and dry periods.

The PRCPTOT index, representing total annual precipitation, is higher in the SO_2 injection scenario (370.1 mm) compared to the scenario without injection (340.3 mm). This increase of 29.8 mm suggests that SO_2 injection could slightly enhance annual precipitation. Additionally, the regression slope indicates a more pronounced rise in annual precipitation under the injection scenario (+2.0 mm per year compared to +1.4 mm per year), reinforcing the hypothesis of a stabilizing effect on rainfall patterns.

Regarding extreme precipitation events, the Rx1day (maximum 1-day precipitation) and Rx5day (maximum 5-day precipitation) indices also show higher values in the injection scenario. Rx1day increases from 110.9 mm without injection to 120.7 mm with injection, an 8.8% increase. Similarly, Rx5day rises significantly from 500.2 mm to 540.8 mm. These results suggest that, despite an overall increase in annual precipitation, SO_2 injection could intensify extreme rainfall events.

The CWD index (number of consecutive wet days) slightly decreases with SO_2 injection, from 13.5 days in the non-injection scenario to 11.7 days in the injection

Table 1. Comparison of Precipitation Indices for the 2020–2050 Period with and Without SO_2 Injection.

Index	Scenario	Mean (mm or days)	Standard Deviation	Slope (per year)
PRCPTOT	With injection	350.4 mm	30.2 mm	+1.8 mm per year
	Without injection	320.7 mm	25.8 mm	+1.2 mm per year
Rx1day	With injection	110.5 mm	15.4 mm	+0.9 mm per year
	Without injection	100.8 mm	12.9 mm	+0.7 mm per year
Rx5day	With injection	520.3 mm	42.7 mm	+2.1 mm per year
	Without injection	480.6 mm	38.9 mm	+1.6 mm per year
CWD	With injection	12.3 days	2.1 days	–0.1 days per year
	Without injection	14.1 days	2.5 days	–0.05 days per year
SDII	With injection	14.8 mm per day	1.6 mm per day	+0.07 mm per day per year
	Without injection	13.5 mm per day	1.3 mm per day	+0.05 mm per day per year

Table 2. Comparison of Precipitation Indices for the 2050–2080 Period with and Without SO_2 Injection.

Index	Scenario	Mean (mm or days)	Standard Deviation	Slope (per year)
PRCPTOT	With injection	370.1 mm	34.6 mm	+2.0 mm per year
	Without injection	340.3 mm	28.5 mm	+1.4 mm per year
Rx1day	With injection	120.7 mm	18.2 mm	+1.1 mm per year
	Without injection	110.9 mm	15.7 mm	+0.8 mm per year
Rx5day	With injection	540.8 mm	46.3 mm	+2.4 mm per year
	Without injection	500.2 mm	41.5 mm	+1.8 mm per year
CWD	With injection	11.7 days	2.4 days	–0.15 days per year
	Without injection	13.5 days	2.8 days	–0.08 days per year
SDII	With injection	15.3 mm per day	1.8 mm per day	+0.09 mm per day per year
	Without injection	14.0 mm per day	1.5 mm per day	+0.06 mm per day per year

scenario. This reduction in wet spell duration suggests that SO_2 injection may lead to a more fragmented distribution of precipitation throughout the year, shortening prolonged wet periods.

Finally, the SDII index (simple daily intensity index) shows a slight decrease in the SO_2 injection scenario, dropping from 15.3 mm per day without injection to 14.0 mm per day with injection. This trend indicates a modest reduction in the average daily precipitation intensity, which could suggest a moderating effect of SO_2 injection on rainfall intensity.

Overall, the findings in **Table 2** suggest that SO_2 injection significantly influences rainfall patterns in the Sahel. It increases total annual precipitation and intensifies extreme rainfall events while reducing the duration of prolonged wet periods. These observations confirm that stratospheric geoengineering could be a potential strategy for mitigating extreme climatic conditions, although further research is needed to assess its long-term effects.

6. Discussion

The results obtained for the periods 2020–2050 and 2050–2080 show significant variations in climate indices under the "with injection" and "without injection" SO_2 scenarios. The injection of SO_2 tends to reduce the number of consecutive dry days (CDD) and increase the number of consecutive wet days (CWD), indicating a favorable modulation of rainfall patterns. This finding is consistent with the work of Abiodun et al. [30], who show that stratospheric SO_2 injection can reduce aridity and alter precipitation distribution in the Sahel.

Regarding annual total precipitation (PRCPTOT), our results indicate a slight increase in the scenario with SO_2 injection, although the overall trend remains relatively stable. This phenomenon is also reported by Visioni et al. [31], who emphasize that stratospheric aerosol injection can slightly increase precipitation by mitigating tropospheric warming. However, the exact impact depends on local climate feedbacks and atmospheric circulation mechanisms.

Extreme precipitation indices, particularly the daily maximum precipitation (Rx1day) and five-day maximum precipitation (Rx5day), show slightly lower values in the scenario with injection. This suggests that SO_2 injection can reduce the intensity of extreme precipitation events, thereby reducing the risk of flash floods. These results are in line with those of Kravitz et al. [32], who observe that solar radiation modification mitigates precipitation intensity peaks by reducing energy input into the troposphere.

Regarding the average precipitation intensity (SDII), a slight decrease is observed in the scenario with SO_2 injection, indicating that while precipitation events may be more frequent, they could be less intense. This observation aligns with the findings of Tilmes et al. [33], who show that climate engineering through aerosol injection influences precipitation intensity without drastically changing total volume.

In summary, SO_2 injection appears to have a stabilizing effect on Sahelian rainfall regimes by reducing dry periods and moderating extreme precipitation. However, these effects vary across climate indices and require further studies to better understand long-term implications. These results support previous conclusions regarding the potential and challenges of using SO_2 injection as a tool for mitigating regional climate impacts [29,33].

7. Conclusions

This study examined the climatic effects of stratospheric sulfur dioxide (SO_2) injection on the Sahel region by comparing two scenarios: one with SO_2 injection (G3) and one without (RCP4.5), using IPSL-CM5A-LR model simulations. The results show that SO_2 injection leads to notable modifications in precipitation patterns. In particular, the annual total precipitation on wet days (PRCPTOT) tends to be more stable in the injection scenario, while the non-injection scenario shows a sharper decline over time. This suggests that SO_2 injection may help moderate long-term reductions in rainfall. However, the analysis of extreme precipitation indices, such as Rx1day and Rx5day, reveals slightly lower values in the injection scenario, implying less intense but potentially more frequent precipitation events. Results related to the CWD (Consecutive Wet Days) index show a significant reduction in the duration of consecutive wet days due to SO_2 injection. This reduction in wet-day duration could decrease the risk of prolonged flooding while affecting soil moisture and groundwater recharge, with important implications for water resource management in the region. Furthermore, SO_2 injection appears to modulate the persistence of wet periods due to the cooling effect induced by SO_2 aerosols, which may suppress convective activity. Regarding the SDII (Simple Daily Intensity Index), which measures precipitation intensity on wet days, the results suggest that SO_2 injection could slightly increase the intensity of daily precipitation. Although this increase is modest, it could enhance the risk of flooding in certain areas while improving soil moisture and water availability for crops during wet periods. These findings highlight that solar geoengineering, while effective in reducing certain aspects of global warming, can have complex and region-specific consequences. In the Sahel, where livelihoods are closely tied to rainfall variability, such interventions could disrupt local hydro-climatic systems. Although SO_2 injection may offer some benefits in stabilizing total precipitation, its impacts on precipitation extremes remain uncertain and could have unintended consequences. Further investigations are needed to explore the underlying mechanisms driving these regional effects. Future research should focus on multi-model comparisons, long-term simulations, and a deeper understanding of how geoengineering influences large-scale atmospheric dynamics, particularly the West African monsoon. In this context, the findings of this study reinforce the importance of caution and comprehensive evaluation before considering large-scale implementation of solar geoengineering strategies.

Author Contributions

Conceptualization, T.S.C. and C.D.; methodology, T.S.C. and S.S.; software, T.S.C.; validation, T.S.C., C.D., S.S., and I.T.; formal analysis, T.S.C. and C.D.; investigation, T.S.C.; resources, S.S. and T.S.C.; data curation, T.S.C.; writing—original draft preparation, T.S.C.; writing—review and editing, T.S.C.; visualization, T.S.C. and C.D.; supervision, I.T. and S.S.; project administration, C.D. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used in this study were downloaded from the public ESGF Data platform. They are accessible via the following link: https://esg-dn1.nsc.liu.se/search/esgf-liu/.

Acknowledgments

The International Science Program (ISP/IPPS) provided research resources and workspace for this study through its granted research group MAL: 01, and we are grateful to the anonymous reviewers whose feedback helped to make the paper better.

Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

SO_2	Sulphur dioxide
SAI	Stratospheric Aerosol Injection
Rx1day	Recorded x maximum precipitation over 1 day
Rx5day	Recorded x maximum precipitation over 5 days
SDII	Simple Daily Intensity Index
SRM	Solar Radiation Management (modification du rayonnement solaire)
RCP4.5	Representative Concentration Pathway 4.5
G	“Global”
GeoMIP	Geoengineering Model Intercomparison Project
IPSL-CM5A-LR	Institut Pierre Simon Laplace Coupled Model version 5A - Low Resolution
PRCPTOT	Precipitation Recorded Composite Precipitation Total
Tg	Terra gramme
ETCCDI	Expert Team on Climate Change Detection and Indices
NO I_RCP4.5	Without SO_2 Injection
CMIP5	Coupled Model Intercomparison Project Phase 5
CWD	Consecutive Wet Days

References

[1] Alley, R.B., Clark, P.U., Huybers, P., et al., 2003. Abrupt climate change. Science. 299(5615), 2005–2010. DOI: https://doi.org/10.1126/science.1081056

[2] Robock, A., Oman, L., Stenchikov, G.L., 2008. Re-

gional climate responses to geoengineering with tropical and Arctic SO2 injections. Journal of Geophysical Research: Atmospheres. 113(D16), D16101. DOI: https://doi.org/10.1029/2008JD010050

[3] Huynh, H.N., McNeill, V.F., 2024. The potential environmental and climate impacts of stratospheric aerosol injection: a review. Environmental Science: Atmospheres. 4(2),114–143. DOI: https://doi.org/10.1039/D3EA00134B

[4] Tilmes, S., Müller, R., Salawitch, R., 2008. The sensitivity of polar ozone depletion to proposed geoengineering schemes. Science. 320(5880), 1201–1204. DOI: https://doi.org/10.1126/science.1153966

[5] Rasch, P.J., Tilmes, S., Turco, R.P., et al., 2008. An overview of geoengineering of climate using stratospheric sulphate aerosols. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 366(1882), 4007–4037. DOI: https://doi.org/10.1098/rsta.2008.0131

[6] Jones, A., Haywood, J., Boucher, O., 2009. Climate impacts of geoengineering marine stratocumulus clouds. Journal of Geophysical Research: Atmospheres. 114(D10), D10106. DOI: https://doi.org/10.1029/2008JD011450

[7] Xia, L., Robock, A., Tilmes, S., et al., 2016. Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate. Atmospheric Chemistry and Physics. 16(3), 1479–1489. DOI: https://doi.org/10.5194/acp-16-1479-2016

[8] Kravitz, B., Robock, A., Jones, A., et al., 2015. The Geoengineering Model Intercomparison Project (GeoMIP): A review. Wiley Interdisciplinary Reviews: Climate Change. 6(6), 907–924. DOI: https://doi/epdf/10.1002/asl.316

[9] Twumasi-Ankrah, M. J., Zhan, J., Asamoah, E.F., 2024. Mapping ecoregional vulnerability to climate change for Africa. Science of the Total Environment, 953, 176219. DOI: https://doi.org/10.1016/j.scitotenv.2024.176219

[10] Jones, A., Haywood, J., Boucher, O., et al., 2010. Geoengineering by stratospheric SO_2 injection: results from the Met Office HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE. Atmospheric Chemistry and Physics. 10(13), 5999–6006. DOI: https://doi.org/10.5194/acp-10-5999-2010

[11] Alamou, A.E., Obada, E., Biao, E.I., et al., 2022. Impact of Stratospheric Aerosol Geoengineering on Meteorological Droughts in West Africa. Atmosphere. 13(2), 234. DOI: https://doi.org/10.3390/atmos13020234

[12] Dai, A., 2013. Increasing drought under global warming in observations and models. Nature Climate Change. 3(1), 52–58. DOI: https://doi.org/10.1038/nclimate1633

[13] Jones, A., Haywood, J.M., Jones, A.C., 2017. Impacts of hemispheric solar geoengineering on tropical cyclone frequency. Nature Communications. 8, 1382. DOI : https://doi.org/10.1038/s41467-017-01606-0

[14] Bonou, F.K., Da-Allada, C.Y., Baloitcha, E., et al., 2023. Stratospheric sulfate aerosols impacts on West African monsoon precipitation using GeoMIP models. Earth's Future. 11(11), e2023EF003779. DOI: https://doi.org/10.1029/2023EF003779

[15] Alamou, E.A., Zandagba, J.E., Biao, E.I., et al., 2022, Impact of Stratospheric Aerosol Geoengineering on Extreme Precipitation and Temperature Indices in West Africa Using GLENS Simulations. Journal of Geophysical Research: Atmospheres. 127(9), e2021JD035855. DOI: https://doi.org/10.1029/2021JD035855

[16] Kravitz, B., Robock, A., Tilmes, S., et al., 2013. Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres. 118(15), 8320–8332. DOI: https://doi.org/10.1002/jgrd.50646

[17] MacMartin, D.G., Kravitz, B., Visioni, D., 2021. Solar geoengineering and the implications for regional climates. Nature Climate Change. 11(1), 26–31.

[18] Riahi, K., van Vuuren, D.P., Kriegler, E., et al., 2017. The shared socio-economic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change. 42, 153–168. DOI: https://doi.org/10.1016/j.gloenvcha.2016.05.009

[19] Krinner, G., Viovy, N., de Noblet-Ducoudré, N., et al., 2005. A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system. Global Biogeochemical Cycles. 19(1), GB1015. DOI: https://doi.org/10.1029/2003GB002199

[20] Kravitz, B., Robock, A., Boucher, O., et al., 2011. The Geoengineering Model Intercomparison Project (GeoMIP). Atmospheric Science Letters. 12(2), 162–167. DOI: https://doi.org/10.1002/asl.316

[21] Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society. 93(4), 485–498. DOI: https://doi.org/10.1175/BAMS-D-11-00094.1

[22] Adeniyi, M.O., 2016. The consequences of the IPCC AR5 RCPs 4.5 and 8.5 climate change scenarios on precipitation in West Africa. Climatic Change. 139(2), 245–263. DOI: https://doi.org/10.1007/s10584-016-1774-2

[23] Adeniyi, M.O., Nweke, G.C., 2019. Performance of CMIP5 models in temperature simulation over West Africa. Journal of Nigerian Association of Mathematical Physics. 49, 147–158.

[24] Zebaze, S., Jain, S., Salunke, P., et al., 2019. Assessment of CMIP5 multimodel mean for the histori-

cal climate of Africa. Atmospheric Science Letters. 20(8), e926. DOI: https://doi.org/10.1002/asl.926

[25] Dufresne, J.L., Foujols, M.A., Denvil, S., et al., 2013. Climate change projections using the IPSL-CM5 Earth system model: from CMIP3 to CMIP5. Climate Dynamics. 40(9–10), 2123–2165. DOI: https://doi.org/10.1007/s00382-012-1636-1

[26] Zhang, X., Alexander, L., Hegerl, G.C., et al., 2011. Indices for monitoring changes in extremes based on daily temperature and precipitation data. Wiley Interdisciplinary Reviews: Climate Change. 2(6), 851–870. DOI: https://doi.org/10.1002/wcc.147

[27] Niemeier, U., Timmreck, C., 2015. What is the limit of climate engineering by stratospheric injection of SO_2?. Atmospheric Chemistry and Physics. 15(16), 9129–9141. DOI: https://doi.org/10.5194/acp-15-9129-2015

[28] Visioni, D., MacMartin, D.G., Kravitz, B., et al., 2020. Seasonally modulated stratospheric aerosol geoengineering alters the climate outcomes. Geophysical Research Letters. 47(13), e2020GL088337. DOI: https://doi.org/10.1029/2020GL088337

[29] Haywood, J.M., Jones, A., Bellouin, N., et al., 2013. Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. Nature Climate Change. 3(7), 660–665. DOI: https://doi.org/10.1038/nclimate1857

[30] Abiodun, B.J., Odoulami, R.C., Sawadogo, W., et al., 2021. Potential impacts of stratospheric aerosol injection on drought risk managements over major river basins in Africa. Climatic Change. 169(31), 1–16. DOI: https://doi.org/10.1007/s10584-021-03268-w

[31] Visioni, D., MacMartin, D.G., Kravitz, B., 2021. Is turning down the sun a good proxy for stratospheric sulfate geoengineering? Geophysical Research Letters. 48(7), e2021GL092696. DOI: https://doi.org/10.1029/2020JD033952

[32] Kravitz, B., Robock, A., Tilmes, S., et al., 2017. Climate model response to stratospheric aerosol geoengineering. Journal of Climate. 30(1), 276–299.

[33] Tilmes, S., Fasullo, J., Lamarque, J.-F., et al., 2013. The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres. 118(19), 11036–11058. DOI: https://doi.org/10.1002/jgrd.50868

[34] Potts, M., Zulu, E. M., Wehner, M., et al., 2013. Crisis in the Sahel – Possible Solutions and the Consequences of Inaction. OASIS Initiative: University of California, Berkeley. April 9, 2013. Available from: https://africaportal.org/wp-content/uploads/2023/05/Crisis_in_the_Sahel.pdf