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Simulation of the Effects of SO_2 Injection into the Stratosphere on Precipitation and Temperature Regimes in the Sahel, West Africa

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Abstract

To address global warming and its impact on the Sahel, particularly rising temperatures and changing precipitation patterns, this study explores Solar Radiation Management (SRM) through stratospheric aerosol injection (SAI). Using the IPSL-CM5A-LR model, we simulate the effects of SO_2 injection on temperature and precipitation. We analyze data across three scenarios: historical greenhouse gas concentrations, RCP4.5 without SO_2 injection, and RCP4.5 combined with SO_2 geoengineering (G3). Climate data for two future periods (2020-2050 and 2050-2080) are compared to historical data (1950-2005) to assess seasonal and spatial variations in climate parameters. This study aims to evaluate the impact of SAI on temperature and precipitation in the Sahel, comparing historical data with RCP4.5 and SAI scenarios. It seeks to determine SAI's effectiveness in mitigating warming and identify potential side effects on the region's climate from 2020 to 2080. Results indicate that stratospheric SO_2 injection in the Sahel moderates seasonal temperatures, sustaining reductions through 2050-2080. The injection stabilizes temperatures, especially in summer, potentially mitigating heat stress during the hot season. However, SAI exhibits varied impacts on precipitation patterns across seasons. While it enhances rainfall in June and July, it generally reduces precipitation intensity in May, June, and August. These effects underscore the complex interplay between SAI and regional climate dynamics. Overall, stratospheric SO_2 injection emerges as a promising tool for climate mitigation in the Sahel, offering both opportunities and challenges that warrant further investigation as global efforts to address climate change intensify. Understanding these dynamics is crucial for informed decision-making regarding climate intervention strategies in vulnerable regions like the Sahel.

Keywords

Geoengineering, Climate Change, Stratospheric Aerosol Injection, Global Warming, Sahel

1. Introduction

Increased global warming is perceived with evidence and projections indicate warmer climates. Extreme temperatures in the Sahel are expected to increase due to this global warming. Solar radiation management (SRM) has been proposed as a temporary method to combat global warming by reducing negative emissions (Kuswanto et al., 2021). Regardless of the fact that Africa contributes the least to global warming, African countries are strongly affected by global change (Niang et al., 2014). Temperature changes have had a significant impact on Africa (Niang et al., 2014). Central Africa saw an increase in precipitation, while precipitation decreased in large parts of southern Africa and the Sahel (Niang et al., 2014). In West Africa, changing precipitation patterns, rising temperatures and an increase in extreme events are already being observed. Over the past fifty years, temperatures in West Africa have increased, alongside an increase in global temperatures (Niang et al., 2014). The frequency of extreme precipitation has also increased over the past fifty years and is expected to continue to increase in the future (Mukherjee et al., 2018). According to Adeniyi (2016), a significantly wetter climate, a later start and false rainfall should be expected in the eastern Sahel, western West Africa and the central coast of Guinea, au-over West Africa, considering the 4.5 and 8.5 $W \cdot m^{-2}$ scenarios. These expected climate changes would have an impact on the productivity of poor farmers in West Africa who practice subsistence agriculture (Adeniyi, 2016). West Africans are already fighting against desertification which has taken away part of the Sahel, and the loss of flow capacity of rivers (Ezeife, 2014), However, solar geoengineering, also known as Solar Radiation Management (SRM), has been proposed as a potential strategy to temporarily combat global warming (Ezeife, 2014; Crutzen, 2006). There are many proposed SRM methods, but stratospheric sulfate aerosol injection (SAI) is the most commonly discussed. This method is based on observations that past volcanic eruptions cool the planet (Wigley, 2006; Budyko, 1977; Govindasamy & Caldeira, 2000). In this method, sulfur-based particles are injected into the stratosphere, which increases the albedo by reflecting some of the solar radiation. Volcanic eruptions such as those of Pinatubo (in the Philippines) in 1991 or El Chichon (in Mexico) in 1982 has been a great source of inspiration. According to one estimate, several hundred thousand kilograms of CO_2 could offset the impact of one kilogram of sulfur on global warming. To halve the radiative forcing caused by the 240 billion tonnes of carbon released by human activity and accumulated in the atmosphere since the industrial revolution, it would be enough to inject one million of tonnes of aerosols into the stratosphere. According to the designers of this idea, a fleet of twenty planes capable of carrying heavy loads and flying at an altitude of 20 km could disperse these aerosols (Keith, 2013). The injection of SO_2 into the stratosphere induces a series of atmospheric and radiative changes that directly influence temperature and precipitation. Sulfate aerosols increase the Earth's albedo, leading to a net cooling effect, which alters the thermal gradient and affects large-scale atmospheric circulation patterns. These changes impact convection processes, monsoon dynamics, and moisture transport, particularly in tropical regions such as the Sahel. Additionally, aerosol-cloud interactions can modify cloud microphysics, influencing precipitation formation and distribution. Understanding these mechanisms is crucial for assessing the regional climate responses to geoengineering interventions. Over the past decade, a large body of research has been conducted on the effects of SAI on climate change. Many of these studies suggest SAI could reduce the effects of climate change on global temperatures. As for precipitation, however, SAI may have side effects (Tilmes et al., 2013); as Irvine et al. (2019) emphasized the potential risks of SAI techniques compared to the risks posed by climate change in a recent review. Other studies have recently focused on the effects of IAS on sectors, such as agriculture (Pongratz et al., 2012; Xia et al., 2014; Yang et al., 2016; Proctor et al., 2018), public health (Effiong & Neitzel, 2016), hydrology (Dagon & Schrag, 2016) and economy (Harding et al., 2020). In this study, we aim not only to document the changes in temperature and precipitation resulting from SO_2 injection but also to analyze the physical mechanisms driving these changes. By examining alterations in radiative forcing, atmospheric circulation, and cloud processes, we seek to provide a more comprehensive understanding of how stratospheric aerosol injection affects the Sahelian climate. Here, we continue this effort to increase the participation of developing countries in MRS research. The objective is to understand how the injection of SO_2 into the stratosphere could affect precipitation and temperature regimes in the Sahel under climate change and climate engineering scenarios.

2. Data and Methodology

2.1. Study Area

The Sahel, a critically important geographic region, is located in West Africa. This strip of land stretches across several countries in the region, characterized by a subtle transition between the vast Sahara deserts to the north and the greener savannah areas to the south. It is a region that presents a wide variety of landscapes, climates and cultures. The Atlantic Ocean in the west and the Red Sea in the east form the huge region that is known as the Sahel. It encompasses countries such as Senegal, Mauritania, Mali, Burkina Faso, Chad, Sudan, and others. The region is bordered to the south by the Sudanian savannah and to the north by the Sahara. The landscapes of the Sahel range from arid, sandy deserts to more fertile lands suitable for agriculture (**Figure 1**).

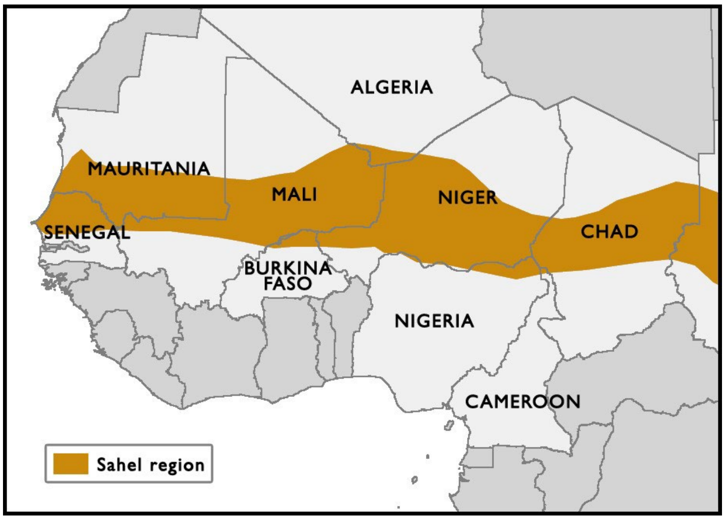


Figure 1. Map highlighting the Sahel zone.

2.2. Data Description

2.2.1. Simulation Scenario

As part of this study, we collected temperature and precipitation data from three distinct experiments. These data were analyzed for three different periods: future periods 2020-2050 and 2050-2080 and the reference historical period 1950-2005.

The two future scenarios studied are as follows:

- Scenario I_G3 (With SO_2 injection): This scenario involves the injection of sulfur dioxide (SO_2) into the stratosphere. Temperature and precipitation data were collected for the following seasons: cold season (December-January-February), hot season (March-April-May), rainy season (June-July-August) and Harmattan wind season (September-October-November).
- Scenario NO I_RCP4.5 (Without SO_2 Injection): this scenario does not include SO_2 injection. Temperature and precipitation data were also collected for the same seasons as in the I_G3 scenario.

Thus, the historical climatology data serve as a baseline to compare changes in future scenarios. For each season, we calculated the daily average of temperature and precipitation data for scenarios I_G3 and NO I_RCP4.5. This approach allowed us to examine the seasonal and spatial variations of climate parameters over the periods of 2020-2050 and 2050-2080, by comparing scenarios with no SO_2 injection to historical data. These temperature and precipitation data are essential for assessing potential climate changes in the study region over time.

2.2.2. Description of Simulation Model

For this study, we selected the IPSL-CM5A-LR simulation model to focus on understanding the specific impacts of SO_2 injection. Our primary objective is to thoroughly analyze these impacts using a single, well-documented model before conducting a comparative analysis with other models. This approach ensures a detailed comprehension of the mechanisms at play, as nearly all models indicate that SO_2 injection leads to a reduction in temperature. By using IPSL-CM5A-LR, which offers complete scenario coverage, including historical climatology, RCP4.5, and G3, we can systematically examine the outcomes under various conditions.

The IPSL-CM5A-LR model, a lower-resolution version (1.9˚ × 3.75˚) of the IPSL-CM5, integrates atmospheric, terrestrial, oceanic, and glacial components to simulate the Earth system (Dufresne et al., 2013). It utilizes the atmospheric general circulation model LMDZ with zoom capability (Krinner et al., 2005), enhancing the precision of regional climate simulations. The Geoengineering Model Intercomparison Project (GeoMIP) aims to understand the differences between climate models in assessing the impacts of geoengineering. As part of this effort, the G3 experiment combines RCP4.5 forcing with SO_2 injection starting in 2020. This involves the annual injection of 5 teragrams (Tg) of SO_2 into the stratosphere (16 - 25 km altitude) above the equator, from 2020 to 2069 (Kravitz et al., 2011). The choice of this altitude range is based on the fact that SO_2 must reach the stratosphere to ensure a sufficient lifetime and global dispersion of sulfate aerosols, which are key to inducing a cooling effect. Injection at lower altitudes would result in faster removal due to tropospheric processes such as precipitation and turbulence. Additionally, injection above the equator is motivated by its efficiency in distributing aerosols globally via stratospheric circulation (e.g., Brewer-Dobson circulation), maximizing the climate impact while reducing regional disparities. After 2069, SO_2 injection stops, and the simulation continues with standard RCP4.5 forcing until 2090 to observe the "climate rebound" effect. In this study, we assume a constant SO_2 injection rate (5 Tg per year), which simplifies the analysis of its effects on climate variables. However, in reality, an adaptive injection strategy, where the SO_2 injection rate is adjusted based on climate feedback (e.g., maintaining a target radiative forcing or temperature threshold), could be more representative of potential geoengineering deployment. Future work could explore variable injection scenarios that respond dynamically to evolving climate conditions, providing a more comprehensive understanding of the possible impacts of stratospheric aerosol injection. The historical climatology scenario (1950-2005) serves as a reference for evaluating changes in temperature and precipitation under future scenarios. The RCP4.5 simulation (without SO_2 injection) reflects changes in greenhouse gases and aerosols, resulting in a net radiative forcing of 4.5 $W \cdot m^{-2}$ by 2100 relative to pre-industrial levels (Taylor et al., 2012). This scenario is part of CMIP5 and is accessible through the Earth System Grid Federation. Historical precipitation and temperature simulations from IPSL-CM5A-LR are well-aligned with the CMIP6 multi-model mean for West Africa (Adeniyi, 2016; Adeniyi & Nweke, 2019; Zebaze et al., 2019), reinforcing its relevance for regional climate studies.

2.3. Methods

We used three methods for this study: the climate anomaly method, the graphical comparison method, and the SO_2 injection efficiency assessment.

2.3.1. Climate Anomaly

The climate anomaly method is commonly used in climatology and meteorology to evaluate variations in climate parameters over a given period. It involves calculating the difference between two sets of climate data, which makes it possible to identify climate change, abnormal weather phenomena and the impact of human activities on the climate. To calculate the climate anomaly, we performed the following operations: We calculated the differences between future scenarios without SO_2 injection (SI_RCP4.5) for two time intervals (2020-2050 and 2050-2080) and historical climatology (C_Hist) from the period 1950-2005. These differences allowed us to highlight variations from the average, thus identifying long-term climate trends and extreme events.

$$\text{Change} = (\text{NO I\_RCP4.5\_mean}) - (\text{C\_Hist\_mean}) \quad (1)$$

$$\text{Change} = (\text{I\_G3\_mean}) - (\text{NO I\_RCP4.5\_mean}) \quad (2)$$

$$\text{Relative change (\%)} = \text{I\_G3\_mean} - \text{NO I\_RCP4.5}_{\text{mean}}/\text{NO I\_RCP4.5}_{\text{mean}} \quad (3)$$

where:

- NO I_RCP4.5_meam represents the average of projection data without SO_2 injection scenario.
- C_Hist_mean represents the average of historical climatology.
- I_G3_mean represents the average of projection data with SO_2 injection scenario.

2.3.2. Graphical Comparison

The graphical comparison method involves visually representing different climate data series using graphs. This makes it possible to visually compare variations, trends and relationships between climate data over a specific period. In our study, we compared temperature and precipitation data using line graphs.

2.3.3. Efficiency of SO_2 Injection

The effectiveness of SO_2 injection is used to assess the impact of SO_2 injection (AI_G3) on reducing the projected warming in the SI_RCP4.5 scenario. To do this, we analyzed the near-surface air temperature response as well as precipitation efficiency. The effectiveness of SO_2 injection was evaluated using the following formula:

$$E = \text{NO I\_RCP4.5\_mean} - C_{\text{Hist}_{\text{mean}}} / \text{I\_G3\_mean} - C_{\text{Hist}_{\text{mean}}} \quad (4)$$

This formula compares the differences between the simulations of near-surface air temperature and precipitation in the I_G3 scenario with those of the historical climatology from 1950 to 2005. The results obtained were then compared to the climate response of the difference between the NO I_RCP4.5 scenario and historical climatology. This method allows us to evaluate the effectiveness of SO_2 injection into the stratosphere in terms of reducing warming compared to the NO

I_RCP4.5 scenario.

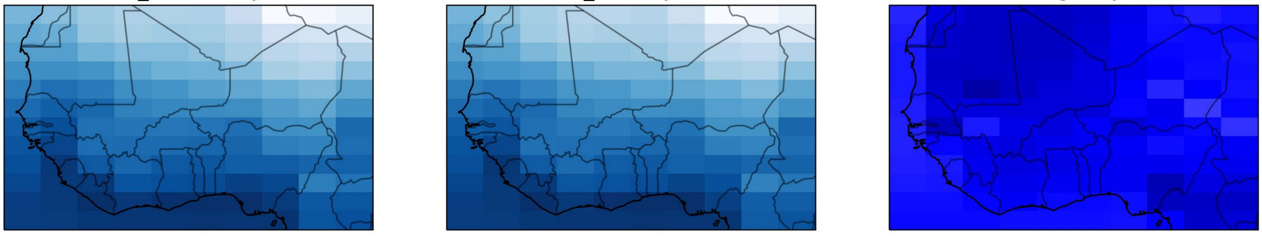
3. Results

3.1. Seasonal Variations in Temperature and Precipitation: A Comprehensive Analysis Across All Seasons

In this part, the impacts of anthropogenic forcing at mean level SI_RCP4.5 on temperature and precipitation regimes and the extent to which temperature and precipitation regimes have been affected relative to historical time are presented. The projected changes in temperature over the different seasons namely the cold dry season (DJF), the hot dry season (MAM), the rainy season (JJA) and the transitional season between the cold season and the rainy season (SON) and temperature variations are shown in figures

3.1.1. Seasonal Temperature Analysis: Comparison between the Past and the Future (1950-2005 vs 2020-2050)

We observe that in the NO I_RCP4.5 scenario, significant warming is predicted across West Africa compared to the historical period of 1950-2005. Cold seasons (DJF) show widespread warming, but the Sahel experiences the highest warming during the hot season (MAM). The warming is more marked in the zone below 10˚N. The greatest warming is also projected during the rainy season (JJA), with significant increases in the Sahel and Sahara. This temperature increase is mainly caused by human activities, particularly the use of fossil fuels such as coal, oil and natural gas and also other human activities, such as deforestation, intensive agriculture and industrial protection, as contributing to global warming. We state conclusively that human activities are the primary cause of global warming observed over the past decades. This statement is in agreement with the global scientific consensus which attributes climate change to increasing concentrations of greenhouse gases, mainly carbon dioxide (CO_2), the result of human activity. In conclusion, our results show significant warming predicted in the West African region for the period 2020-2050, in the absence of SO_2 injection. This warming is particularly marked in the Sahel and the Sahara, with potential consequences on the climatic and environmental conditions of the region. Additionally, we highlight the central role of human activities, particularly the use of fossil fuels, in this warming, underscoring the need to reduce greenhouse gas emissions to mitigate climate change in this region (Figure 2).



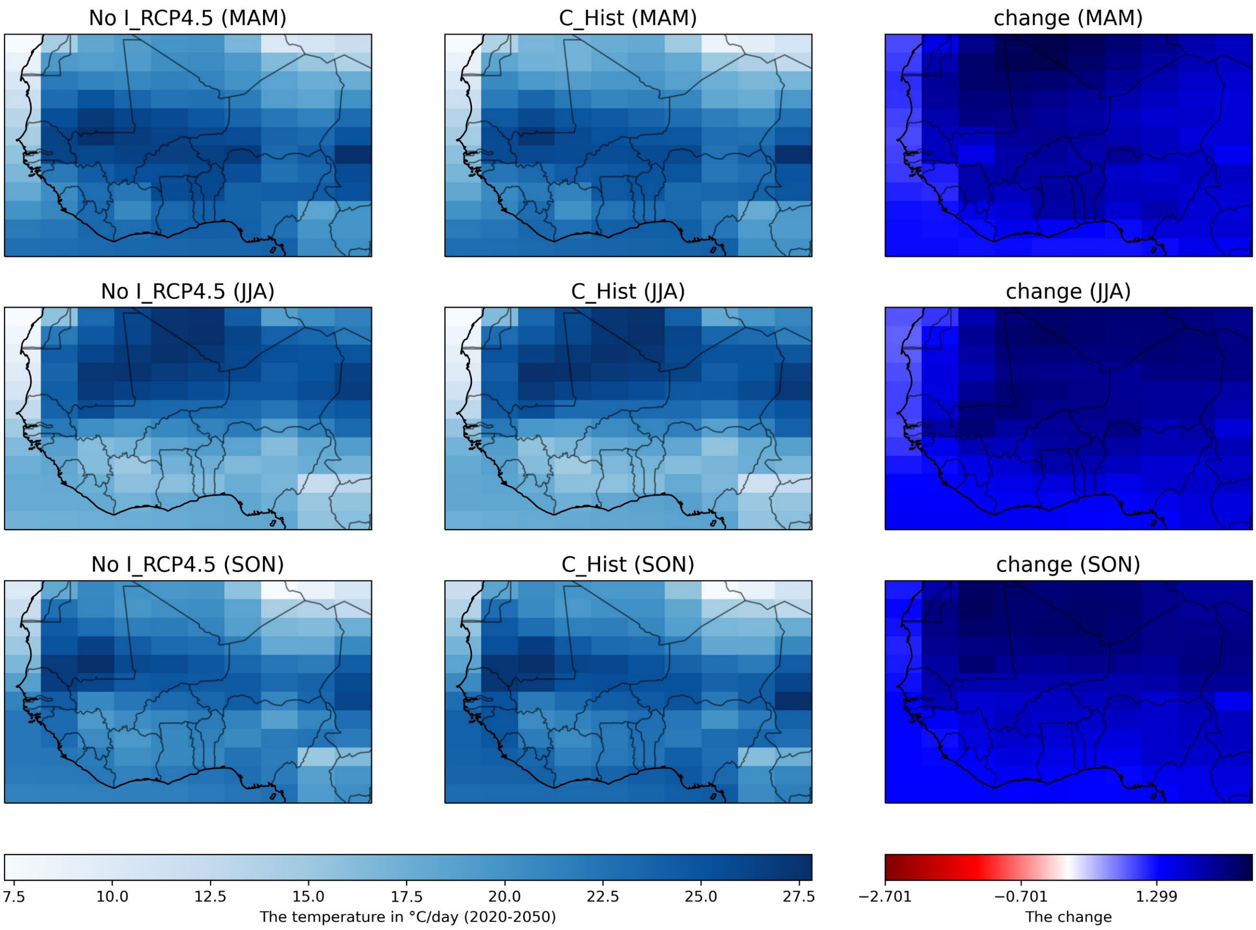


Figure 2. Comparative seasonal map of temperature variations (2020-2050 vs. 1950-2005).

3.1.2. Seasonal Analysis of Temperatures: Comparison between the Past and the Future (1950-2005 vs 2050-2080)

It is interesting to observe the seasonal temperature variation in the period 2050-2080 and compare it to the previous period of 2020-2050. Our study shows that both datasets (2020-2050 and 2050-2080) accurately simulate seasonal and spatial temperature trends in West Africa. This suggests a good agreement of temperatures in West Africa. This suggests good agreement between observations and simulations, reinforcing the credibility of the results. We observe that the highest temperatures are recorded in most of West Africa for the period 2020-2050, with particularly high values along the Sahelian strip and in the Sahara Desert. However as shown in Figure 3, our analysis reveals that the 2050-2080 period is warmer than the 2020-2050 period. This highlights a continuing warming trend in the region. This increase in temperatures could have a significant impact on the region. Higher temperatures can contribute to extreme weather events, such as heat waves, droughts, and changes in precipitation patterns. These climate changes can have repercussions on agriculture, water resources, biodiversity, human health and the economy of the region. We observe that the period 2050-2080 is warmer than the period 2020-2050 confirms the long-term global warming trend. This highlights the importance of taking climate change mitigation measures, such as reducing adaptation strategies to deal with the inevitable impacts of climate change. In summary, our results highlight a continued increase in temperatures in the West African region, with potential implications for the region's climate, environment and societies. This development highlights the urgency of action to mitigate the causes of climate change and to prepare for the challenges that arise from it.

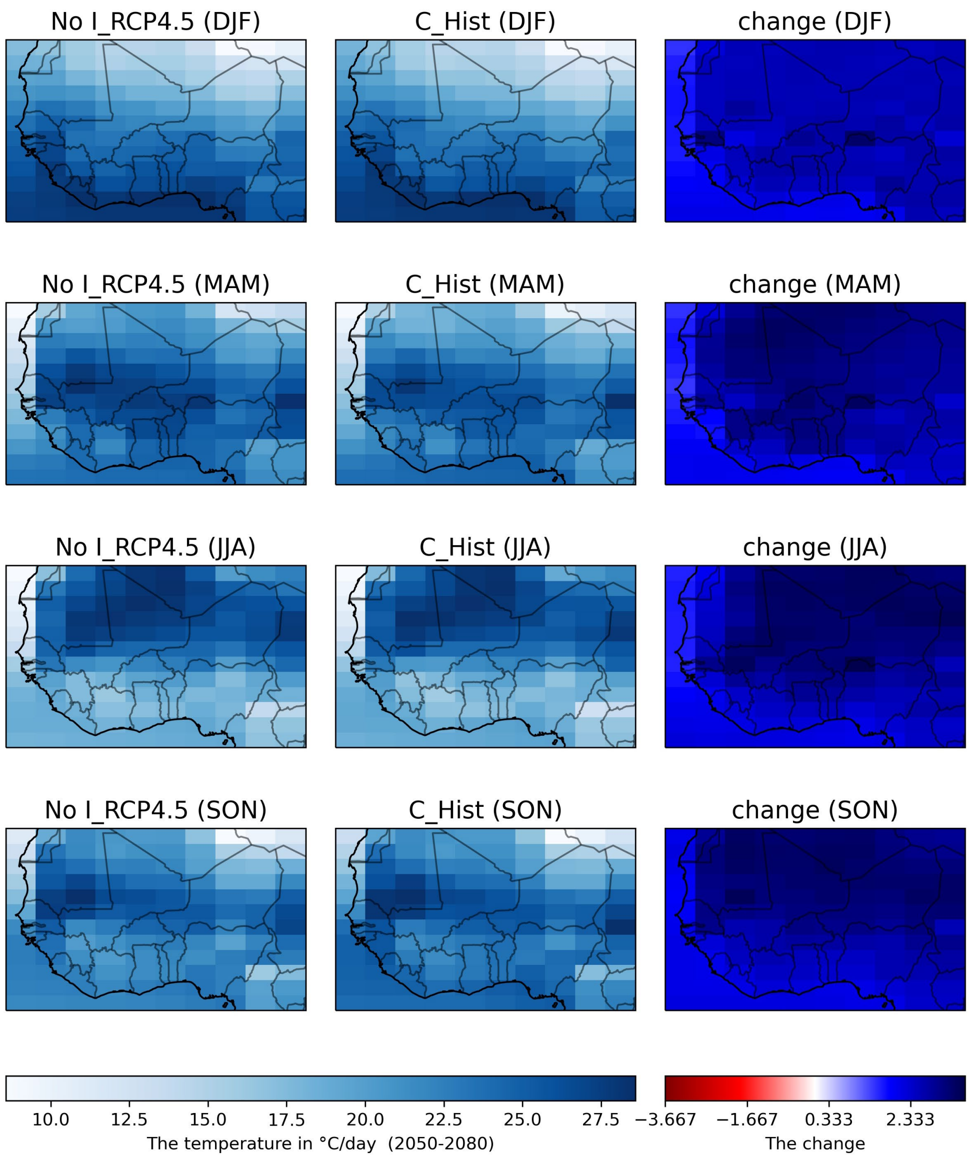


Figure 3. Comparative seasonal map of temperature variations (2050-2080 vs. 1950-2005).

3.1.3. Seasonal Analysis of Precipitation: Comparison between the Past and the Future (1950-2005 vs 2020-2050)

For precipitation climatology (1950-2005): During the dry season (DJF, MAM), precipitation ranged between 0 and 3 mm/day, with the lowest precipitation levels recorded. This suggests a relatively dry period for these seasons during this timeframe.

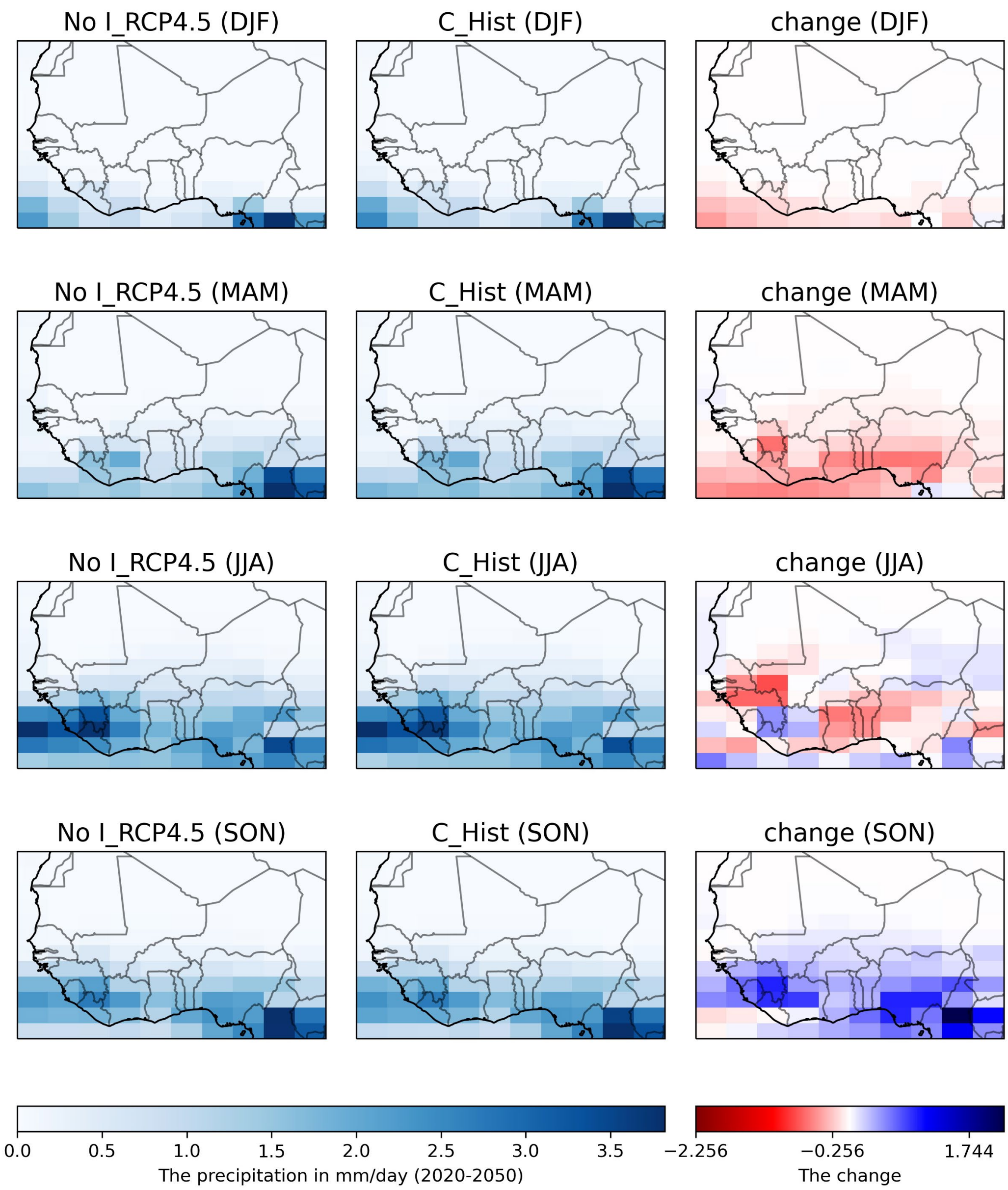


Figure 4. Comparative seasonal map of precipitation variations (2020-2050 vs. 1950-2005).

For the scenario without injection (SI_RCP4.5) of (2020-2050): During the rainy season (JJA), we notice that in this scenario, humidity is simulated below the Sahel, while drought is simulated above it. As shown in **Figure 4**, this indicates a significant change in precipitation distribution due to the climate change scenario, with increased humidity in some regions and drought in others. We observe an increase in rainfall of up to 20% across southern West Africa. This indicates a positive response to precipitation in these areas in response to climate change. However, as illustrated in **Figure 4**, we also notice a reduction in precipitation over the Sahel towards the Sahara, with a significant reduction of 20% to 80% expected during the rainy season. We relate this to regional warming, which leads to higher evaporation than precipitation, exacerbating drought conditions. This observation suggests a negative impact of climate change on precipitation in these northern regions.

A correlation between temperature and precipitation during certain seasons, such as April, July, and September, is observed, which aligns with the findings of Cong and Brady (2012). This suggests that higher temperatures are associated with lower precipitation levels for these species. In summary, our results show that climate change, as simulated in the SI_RCP4.5 scenario, causes significant variations in the distribution of precipitation, with increases in some areas and marked reductions in others. Higher regions and increased evaporation. These results highlight the importance of taking climate change into account in planning water resources management and adaptation to potential impacts.

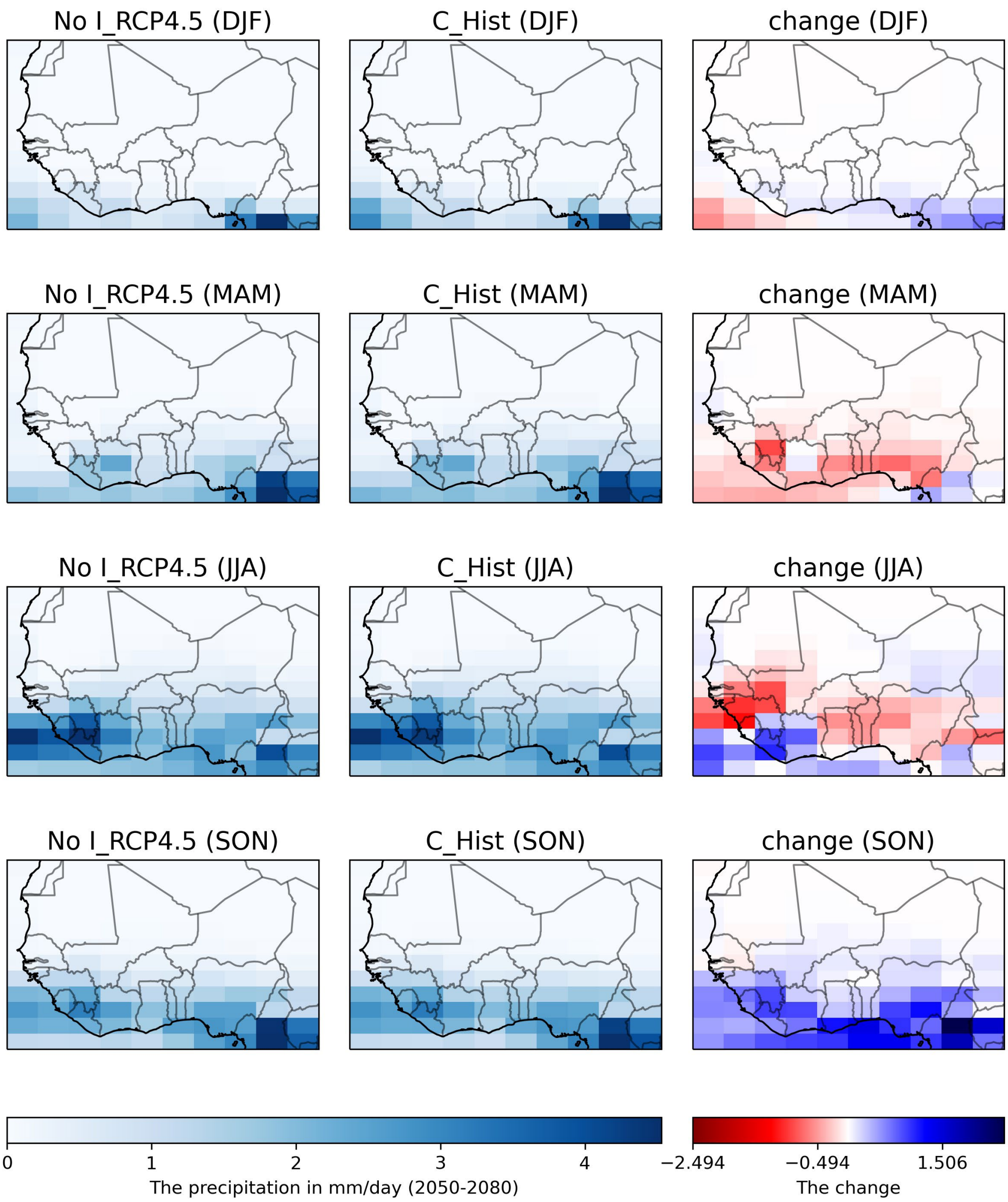


Figure 5. Comparative seasonal map of precipitation variations (2050-2080 vs. 1950-2005).

3.1.4. Seasonal Analysis of Precipitation: Comparison between the Past and the Future (1950-2005 vs 2050-2080)

Figure 5 shows the differences in period average precipitation (JJA) between the future period (2050-2080) and the historical period. We are observing a possible increase in precipitation in the Sahel region. This is consistent with previous work (Fontaine et al., 2011), CMIP3 model and other authors (Monerie et al., 2013; James & Washington, 2013), CMIP5 models which also predicted an increase in precipitation in this region. The increase in precipitation in the central Sahel is generally associated with the strengthening of continent-ocean temperature gradients, an accentuation of monsoon winds and converging moisture fluxes in the Sahel. This phenomenon is consistent with an increase in convection and atmospheric lift, which could explain the increase in rainfall. We observe a decrease in precipitation in the west of the Sahel, which is in contrast to the increase observed in the central Sahel. These regional variations in precipitation could be due to local factors, such as variations in sea surface temperatures or atmospheric currents. Precipitation is greater in the Sahel between July and August, a period centered on the Sahelian rains, as well as in October. The increase in precipitation in SON is associated with an increase in convergence, indicating a strengthening of the monsoon system from July to October. In conclusion, our results indicate projected changes in precipitation distribution in the Sahel region for the period 2050-2080. The increase in precipitation in the central Sahel and the decrease in the western Sahel suggest significant variations that could have significant impacts on agriculture, the environment and local communities in the region. Understanding these predicted climate changes is essential to taking appropriate adaptation measures.

3.2. Future Climate with and without SO_2 Injection: Comparative Analysis of Seasonal Temperatures and Precipitation

In this part, the impacts of AI_G3 on the projected warming in the RCP4.5 scenario and the projected changes in temperature and precipitation regimes in the RCP4.5 scenario are presented.

3.2.1. Comparison of Temperatures between SO_2 Injection and Absence Scenarios (2020-2050)

During the four seasons (DJF, MAM, JJA, SON), the scenario with SO_2 injection (AI_G3) is able to reduce the predicted increase in temperature in the scenario without injection (SI_RCP4.5). As shown in **Figure 6**, cooling prevails in virtually all countries in the domain, with a cooling amplitude between 0˚C and 1.2˚C. This confirms the effectiveness of SO_2 injection in mitigating temperature increases. Reduction of the increase in temperatures: during the four seasons (DJF, MAM, JJA, SON), the scenario with SO_2 injection (AI_G3) succeeds in reducing the predicted increase in temperatures compared to the scenario without injection (SI_RCP4. 5). This reduction in temperature increase is observed throughout the studied area. The cooling effect is generally present in all countries in the region, with a cooling amplitude ranging from 0˚C to 1.2˚C. This indicates SO_2 injection has a significant impact on reducing temperatures. For specific seasons: During

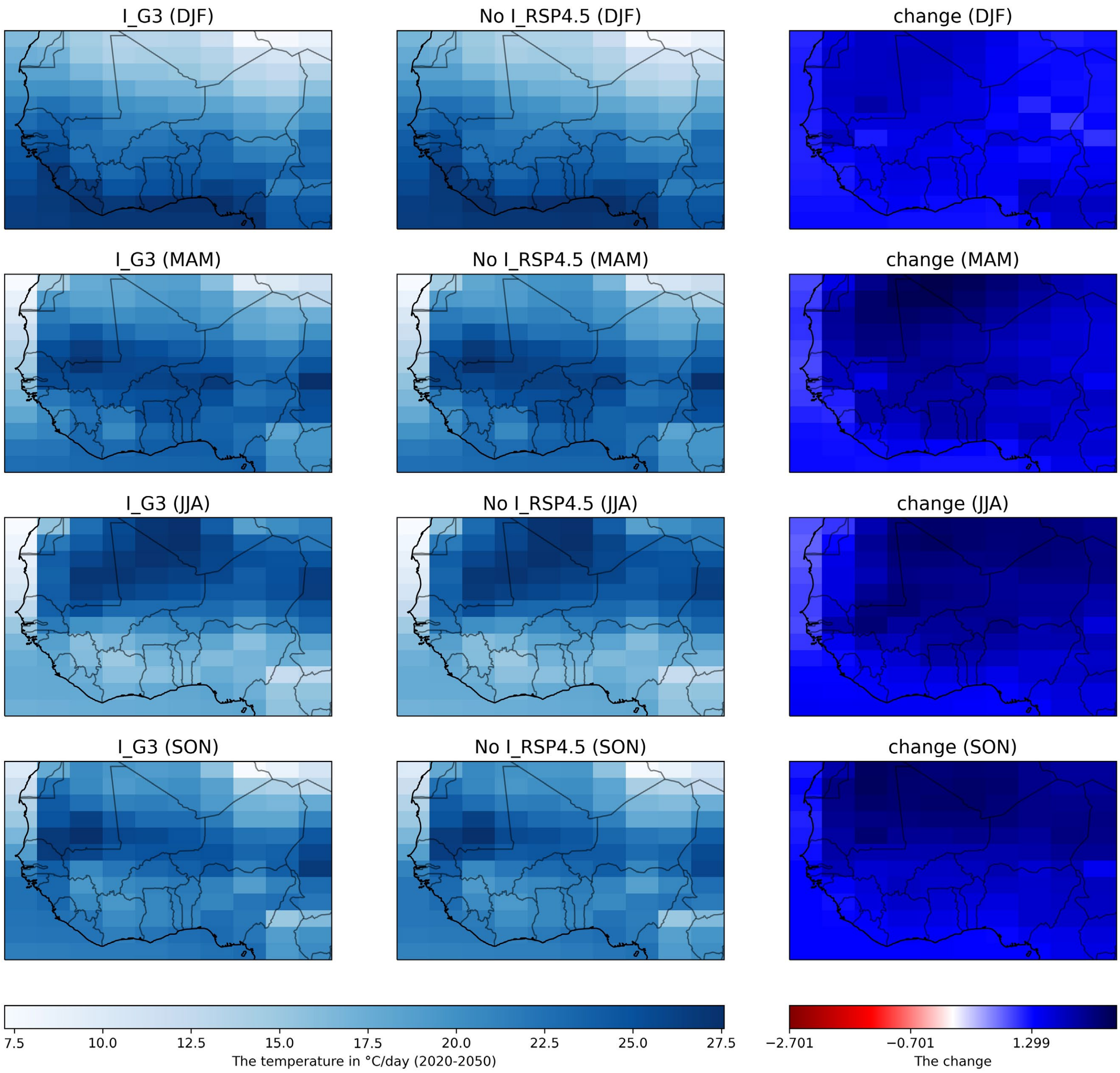


Figure 6. Comparative seasonal map of temperatures under SO_2 injection scenario (2020-2050).

the cold season (DJF), significant cooling is simulated, and it spatially shifts northward. During the hot season (MAM), SO_2 injection led to a significant reduction in temperature, with a maximum decrease of 1.2˚C observed in the Sahara and Sahel. This reduction in temperature is of variable intensity in the region studied, ranging from 0.8 to 1.2. This means that the Sahara and the Sahel, where it reaches 1.2˚C, while in other regions, it is a little less marked at 0.8˚C. We also note that the southern study area experienced a lesser decrease in temperature compared to the northern study area, indicating some geographic variation in the effects of SO_2 injection on temperature. During the rainy season (JJA), the degree of cooling is greater, with a temperature reduction of 0.4˚C to 1.2˚C. This reduction is particularly marked between the ocean and the southern coast. This significant reduction in temperature is observed between the ocean and the southern coast on the one hand, and the Sahel and Sahara on the other. This means that regions between these two geographic areas experienced notable cooling compared to pre-industrial internal variability. During the Harmattan wind season (SON), we observe that the injection of SO_2 led to a decrease in temperature in the studied region. This decrease is significant, with values of up to 1.19˚C in certain parts, such as the Sahara of Mali, Algeria and Mauritania. We observe that the north and south of Niger did not experience any change in temperature after the injection of SO_2, while the rest of the area shows a decrease in temperature varying from 0.5˚C to 1˚C. The impact of SO_2 injection on temperature during the Harmattan wind season is therefore clearly significant, with marked reductions in temperature in several study regions. This seasonality in the effects of SO_2 injection on temperature is crucial to understanding how this intervention can influence the climate in the region. Geographic variations are seen in different regions, with a greater decrease in some areas compared to others. For example, the Sahara and Sahel show more marked temperature reductions. This reduction in temperature can be attributed to two scientific reasons: sunlight reflection and light scattering. Sulfate aerosols generated by SO_2 injection can reflect some of the sunlight and scatter the light, thereby reducing solar radiation reaching cooling. In summary our analysis of the map shows that SO_2 injection has a significant effect in reducing temperatures in the region studied, with seasonal variations can be attributed to the effects of sulfate aerosols on the reflection and scattering of sunlight. These observations are important for understanding the potential impact of SO_2 injection on regional climate and temperature variations.

3.2.2. Comparison of Temperatures between SO_2 Injection and Absence Scenarios (2050-2080)

We observe that the reduction in temperature is notable and even more pronounced than in the previous period (2020-2050), as illustrated in **Figure 7**. This indicates a significant cooling effect. The results suggest that SO_2 injection is effective in maintaining temperatures at levels similar to those of the previous period, bringing future temperatures (2050-2080) closer to historical values. This supports the idea that SO_2 injection can help stabilize temperatures over time.

As shown in **Figure 7**, during all seasons (DJF, MAM, JJA, SON), the AI_G3 experiment reduces the temperature increase simulated in the SI_RCP4.5 scenario. This highlights the positive impact of SO_2 injection throughout the year. The cooling amplitude is greater during the cold and hot seasons, varying between 0.4˚C and 1.5˚C, demonstrating that the cooling effect is more pronounced during specific times of the year.

We observe that the cooling is significant compared to the pre-industrial internal variability, mainly over the ocean during the cold season. However, this significant cooling shifts northward during the rainy season. Our analyzes clearly demonstrate that SO_2 injection has a positive impact on temperature reduction, thus stabilizing future temperatures. It also highlights significant seasonal and geographic variations, highlighting the effectiveness of this intervention in mitigating predicted temperature increases. This information is essential to understanding how climate change can be managed and the potential implications for the region.

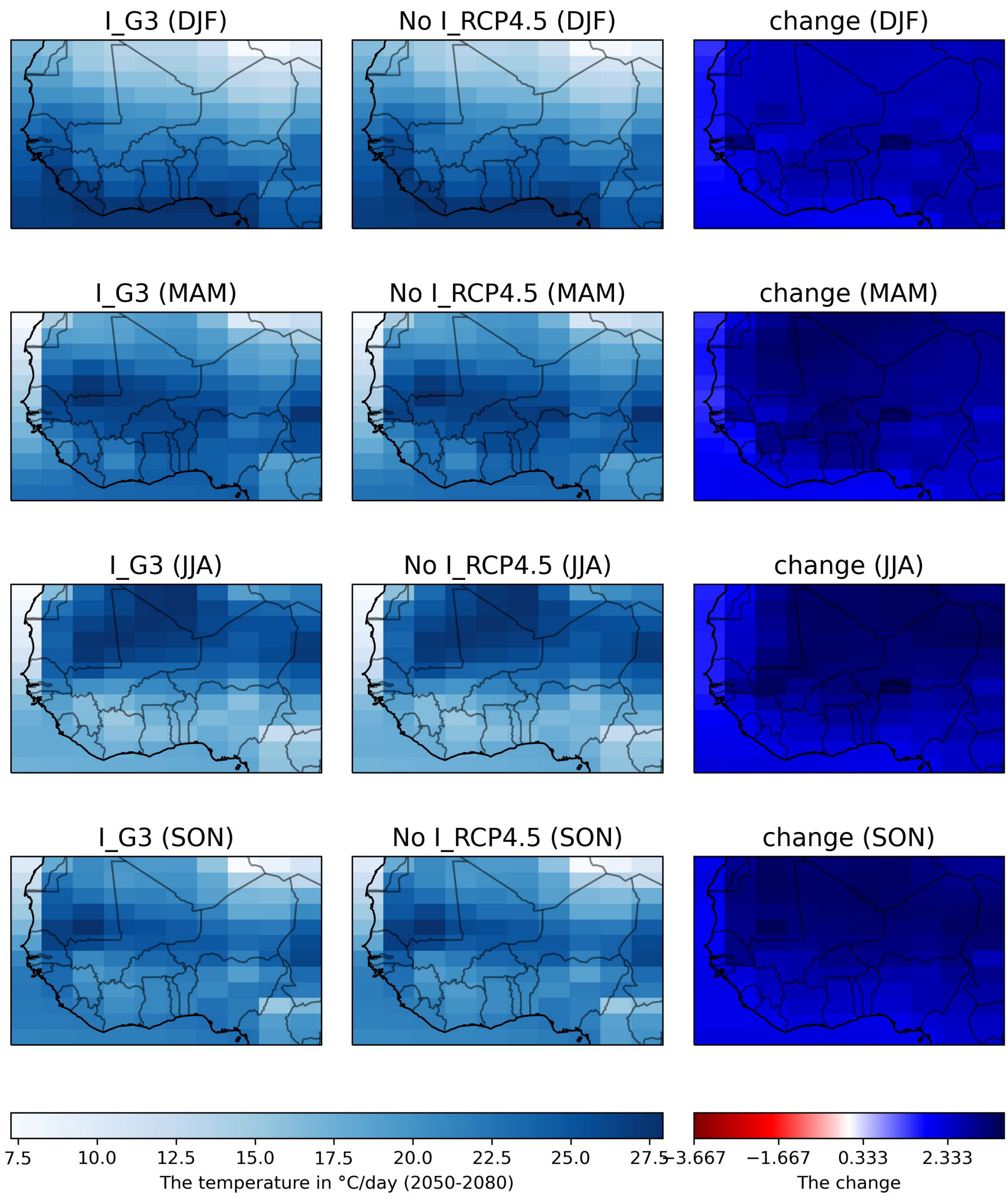


Figure 7. Comparative seasonal map of temperatures under SO_2 injection scenario (2050-2080).

3.2.3. Seasons Under the Influence of SO_2: Comparison of Precipitation between SO_2 Injection and Absence Scenarios (2020-2050)

The effects of SO_2 injection on precipitation patterns can vary significantly depending on geographic regions, seasons, atmospheric conditions, and other factors. Figure 8 illustrates the impact of SO_2 injection on the precipitation regime across different seasons: the cold season (**DJF**), the hot season (**MAM**), the rainy season (**JJA**), and the period of Harmattan winds (**SON**). Cold Season (DJF): the change brought by SO_2 injection is not significant during the cold season (DJF). This means that, overall, there is no notable difference in precipitation between the scenarios with and without SO_2 injection. We observe only a small decrease in precipitation of 10% in the south of the region studied, towards the ocean. This decrease could indicate a slight reduction in rainfall, although this reduction is relatively small (10%) and may not have a significant impact on local conditions. We observe that in the north and center of the study region, there is no change in precipitation during the cold season. This suggests that SO_2 injection has no discernible effect on precipitation in these areas. Cold season (DJF) shows that SO_2 injection does not have a significant impact on precipitation during the cold season in the studied region. The slight variations observed, such as the small decrease in precipitation in the south, are not large enough to have a major impact on the overall precipitation pattern during this period. However, it is important to note that these results are specific to the cold season and may differ between seasons and geographic regions. Hot Season (MAM): the map (MAM) shows that after the injection of SO_2, the south of the studied area, towards the ocean, experienced a decrease of 20%. This significant decrease in precipitation in the south suggests that SO_2 injection has an impact on the precipitation regime during the warm season. On the contrary, the north of the study area, there is no significant change in precipitation in this region. The (MAM) map suggests that SO_2 injection impacts precipitation during the hot season in West Africa. This influence is manifested by a significant decrease of 20% in precipitation in the south of the studied domain, while the north of the domain, where there is no precipitation, does not show a significant change. Rainy Season (JJA): with SO_2 injection does not result in significant changes in simulated precipitation compared to the scenario without injection (SI_RCP4.5) during the rainy season in the northern Africa zone from West. The injection of SO_2 leads to a reduction in precipitation in parts of the Sahel Senegal, northern Guinea Conakry and southern Mali. Ghana, Togo, Benin and northern Nigeria will experience a decrease in precipitation while southern Guinea Conakry and the northern and central Ivory Coast. This variation in precipitation can have implications for agriculture, water availability and other environmental aspects in the region. Harmattan Wind Season (SON): There are no significant changes in precipitation simulated by SO_2 injection compared to the scenario without Sahel injection to the Sahara during the Harmattan Wind Season (SON). In the southern part of the domain, where the injection of SO_2 causes cooling, precipitation governs positively during the Harmattan wind season (SON). The cooling causes increased precipitation by bringing moisture to the region. This is part of Cong and Brady's hypothesis that temperature and precipitation may have a negative correlation. However, significant changes are observed below the Sahel all the way to the ocean. Overall, our analysis shows that the effects of SO_2 injection vary across seasons and geographic regions. These results highlight the importance of understanding the potential impacts of SO_2 injection on seasonal precipitation patterns, as this can have important consequences for agriculture, water availability and the ecology of the Sahel region. However, it is also important to note that methodological challenges may arise, such as dividing by zero for the dry season, and that these simulations should be interpreted with caution.

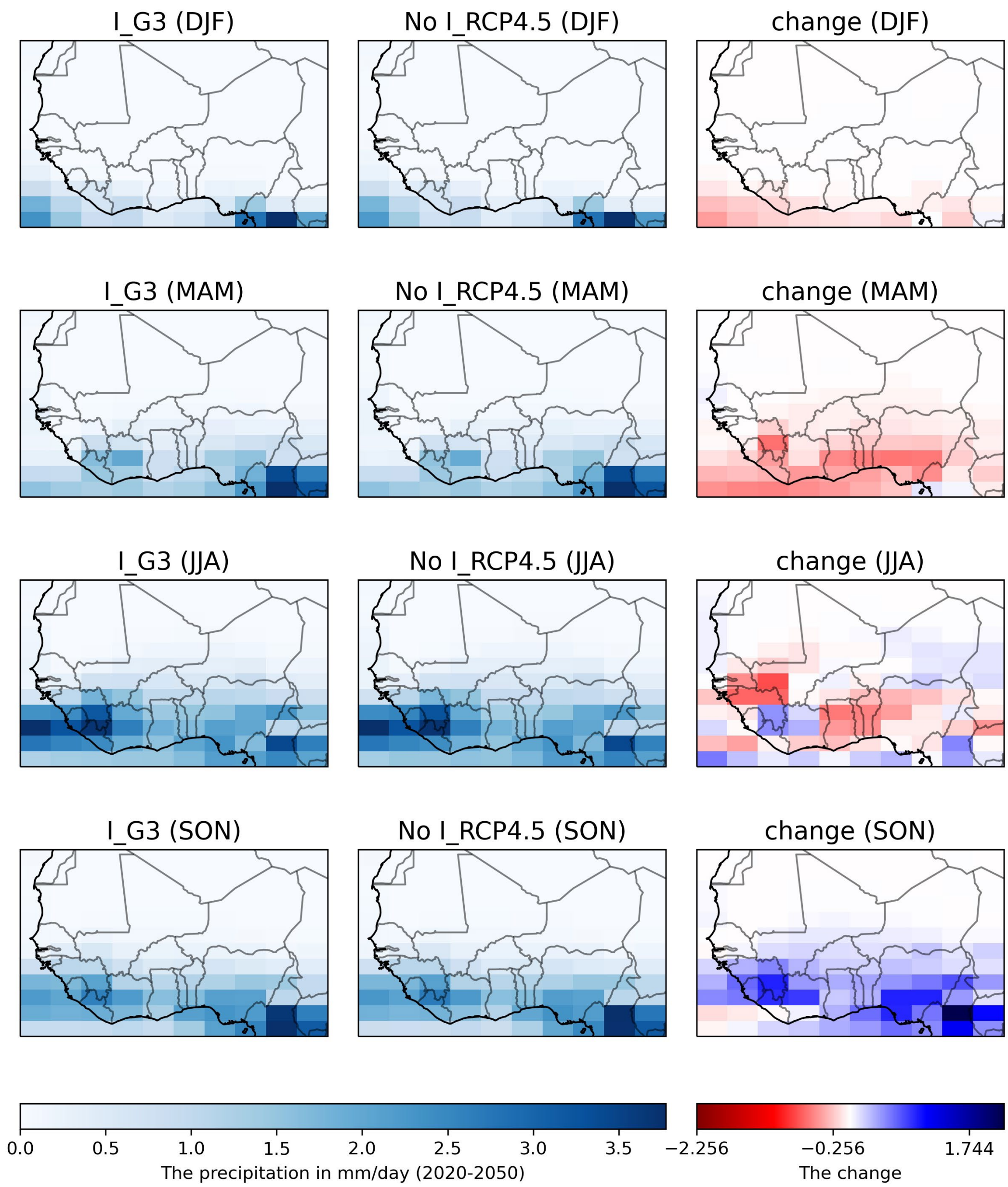


Figure 8. Comparative seasonal map of precipitation under SO_2 injection scenario (2020-2050).

3.2.4. Seasons Under the Influence of SO_2: Comparison of Precipitation between SO_2 Injection and Absence Scenarios (2050-2080)

In **Figure 9**, we present the analysis of precipitation for the second period (2050-2080) during different seasons, specifically focusing on the cold season (DJF), hot season (MAM), and rainy season (JJA). For the second period of 2050-2080 during

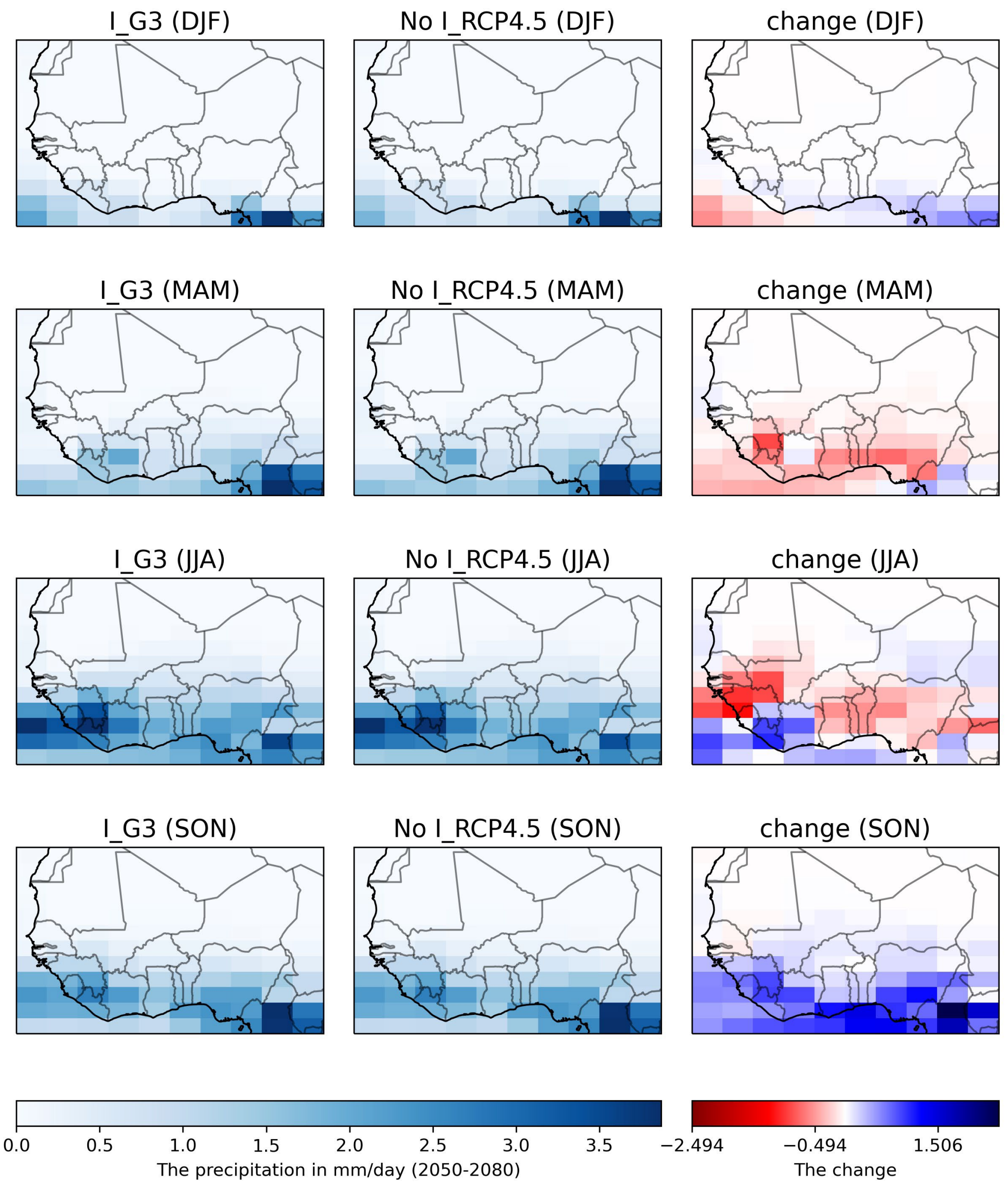


Figure 9. Comparative seasonal map of precipitation under SO_2 injection scenario (2050-2080).

the cold season (DJF), our analysis suggests similar trends to that of the first period with a slight change in The results show that in the Sahel towards the Sahara during the cold season (DJF), an undefined percentage of precipitation variation is observed due to division by zero (0 mm/day of precipitation). This suggests that there is no precipitation during this time in these regions. Hot Season (MAM): The (MAM) map shows that SO_2 injection has a significant impact on precipitation during the hot season in West Africa. There is a significant decrease of 20% in precipitation in the south of the studied area. In contrast, the north of the domain, the north of the domain, where there is no precipitation, does not show a significant change, which is consistent with the absence of precipitation in this region. Rainy Season (JJA): We observe a reduction in precipitation in Senegal towards eastern Mali, southern Guinea-Conakry, with a reduction of up to 52% during the rainy season. This reduction can have significant implications for agriculture and water availability in these regions. However, it is noted that during the rainy season, an increase in precipitation is simulated in southern Côte d'Ivoire, southern Guinea-Conakry and Liberia, with percentage increases of up to more than 20%. Harmattan Wind Season (SON): During the season (SON), a significant increase in precipitation is observed in the south of the study area, with very significant changes reaching a value of 90% to 150% increase in rains. This increase may impact water availability and agriculture during this period In summary, our observations show that SO_2 injection has varied effects on precipitation in different seasons in West Africa. There is a significant decrease during the warm season (MAM) in the south, a reduction during the wet season (JJA) in some regions, but also an increase in precipitation during this period in other regions. During the Harmattan season (SON), a significant increase in precipitation is observed in the south of the study area. These variations have important implications for the region regarding water management and agriculture.

3.3. Future Climate with and without SO_2 Injection: Analysis of Daily Variations in Temperature and Precipitation

3.3.1. Daily Climate Projection (2020-2050): Effects of SO_2 Injection on Future Temperatures

The G3 experiment in Figure 10 shows the temporal evolution of the daily average near-surface air temperature for the period 2020-2050 of the simulation with SO_2 injection (green line), and for the simulation without SO_2 injection (blue line) and the difference between the two scenarios (red line) for 2020-2050. January: Temperatures vary from 17˚C to 19˚C, and the temperature scenarios with and without injection are almost overlapping, with a difference of less than 0.25˚C. It appears that SO_2 injection does not have a significant effect on temperatures in January. February: Temperatures increase slightly, from 19˚C to 21˚C. However, around mid-February, there is a temperature decrease of around 0.5˚C, which continues until the end of the month. The injection of SO_2 can be associated with this decrease in temperature. March and April: Temperatures continue to rise, reaching 23˚C to 28˚C in March and 28˚C to 30˚C in April. The injection of SO_2 appears to have a cooling effect, with a decrease of around 0.15˚C in May. May and June: In May, temperatures vary from 29˚C to 32˚C, with a decrease of 0.15˚C due to SO_2 injection. In June, temperatures increase further, reaching 32˚C to 34˚C, but injection continues to dominate, with a decrease of 0.5˚C. July and August: in July, temperatures decrease slightly, from 34˚C to 31˚C, with a predominant influence from the injection of SO_2, leading to a decrease of 0.5˚C. In August, temperatures stabilize around 29˚C to 30˚C, with the injection trying to maintain the temperature. September: temperatures vary from 30˚C to 28˚C, with SO_2 injection dominating but trying to stabilize the temperature without injection. October, November and December: Temperatures continue to drop, falling from 28˚C to 25˚C in October, from 25˚C to 20˚C in November, and from 20˚C to 18˚C in December. The temperature scenarios with and without injection are superimposed, indicating that SO_2 injection does not have a significant effect on temperatures during these months. In summary, our analysis suggests that SO_2 injection has variable effects on temperatures throughout the year, with periods of cooling and stabilization, particularly during the wet season months. However, it appears that the effects of SO_2 injection are not uniform and depend on the season. This detailed analysis of seasonal variations and temperatures is essential to understand the impact of this geoengineering method on the climate of the Sahel.

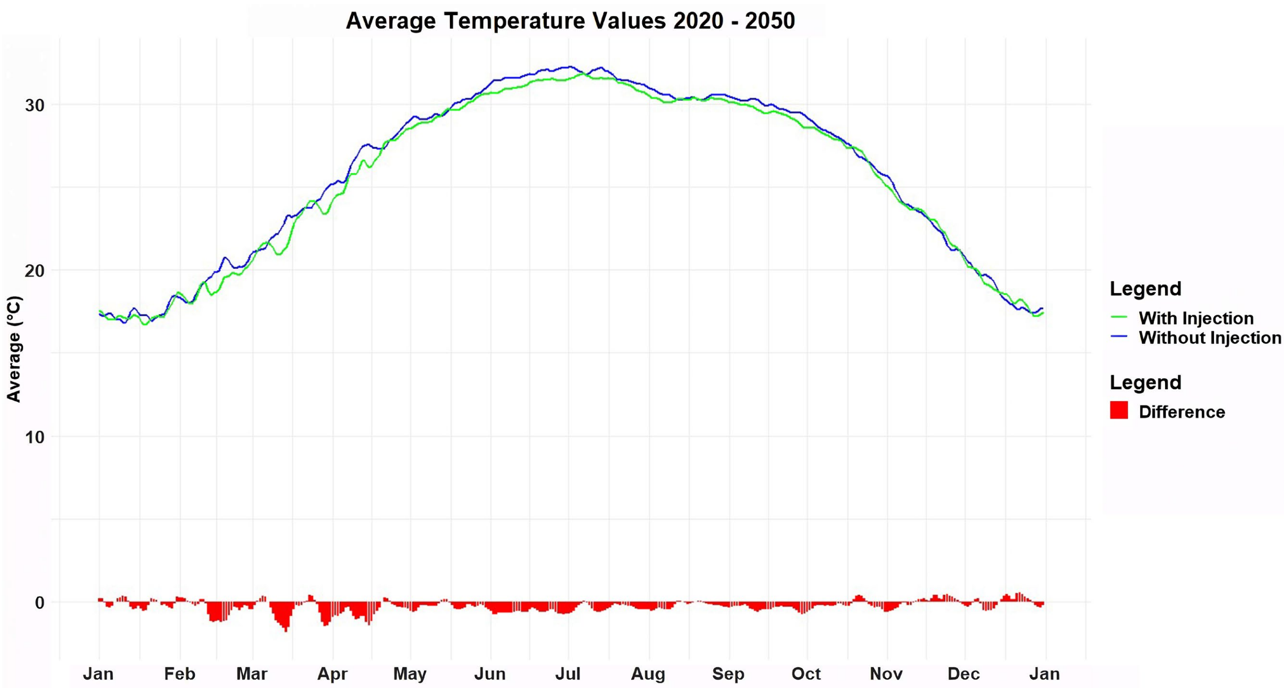


Figure 10. Daily comparison of temperatures with and without SO_2 injection (2020-2050).

3.3.2. Daily Climate Projection (2050-2080): Effects of SO_2 Injection on Future Temperatures

The results for the second period of 2050-2080 highlight significant changes in temperature depending on the months of the year, comparing the scenarios with and without SO_2 injection. Figure 11 January: SO_2 injection induces a significant decrease in temperature in January, with a difference of up to 2˚C. This means that the injection helps maintain cooler temperatures during this month. February: In February, the cooling effect of SO_2 injection is also significant, with a difference ranging from 0.5˚C to 1.5˚C compared to the situation without injection. March and April: The months of March and April show a notable decrease in temperature thanks to the injection of SO_2, with variations of 1˚C to 2˚C in March and 1.5˚C to 2˚C in April. May: In May, SO_2 injection maintains slightly lower temperatures, with a difference of up to 0.5˚C after injection. June to November: These months show a significant decrease in temperature after SO_2 injection, with a drop of 2˚C. this suggests that the injection is particularly effective in maintaining cooler temperatures during hot seasons. July and August: although temperatures without injection decrease slightly, SO_2 injection helps stabilize temperatures, with differences of 1˚C to 1.5˚C. September: In September, SO_2 injection maintains cooler temperatures, with a difference of 1˚C to 2˚C compared to the situation without injection. October to December: These months also show a significant decrease in temperature after SO_2 injection, with differences of up to 2.5˚C in November. Overall, the results indicate that SO_2 injection has a significant cooling effect on temperatures throughout the year, with significant seasonal variations. This geoengineering method appears particularly effective in maintaining lower temperatures during rainy months, which may have positive implications for mitigating the effects of heat waves and high temperatures during the hot season The average temperature has cooled, which is in line with other research on the impact of several geoengineering trials. For example, a study by Curry et al. calculated PDFs in the same way as our method but for the globe and focused on the mean temperature differences between the GeoMIP G1 (Curry et al., 2014) experiments. Therefore, this feature implies that with injection significantly mitigates the additional increase in average temperature caused by the scenario without injection in the Sahel in West Africa.

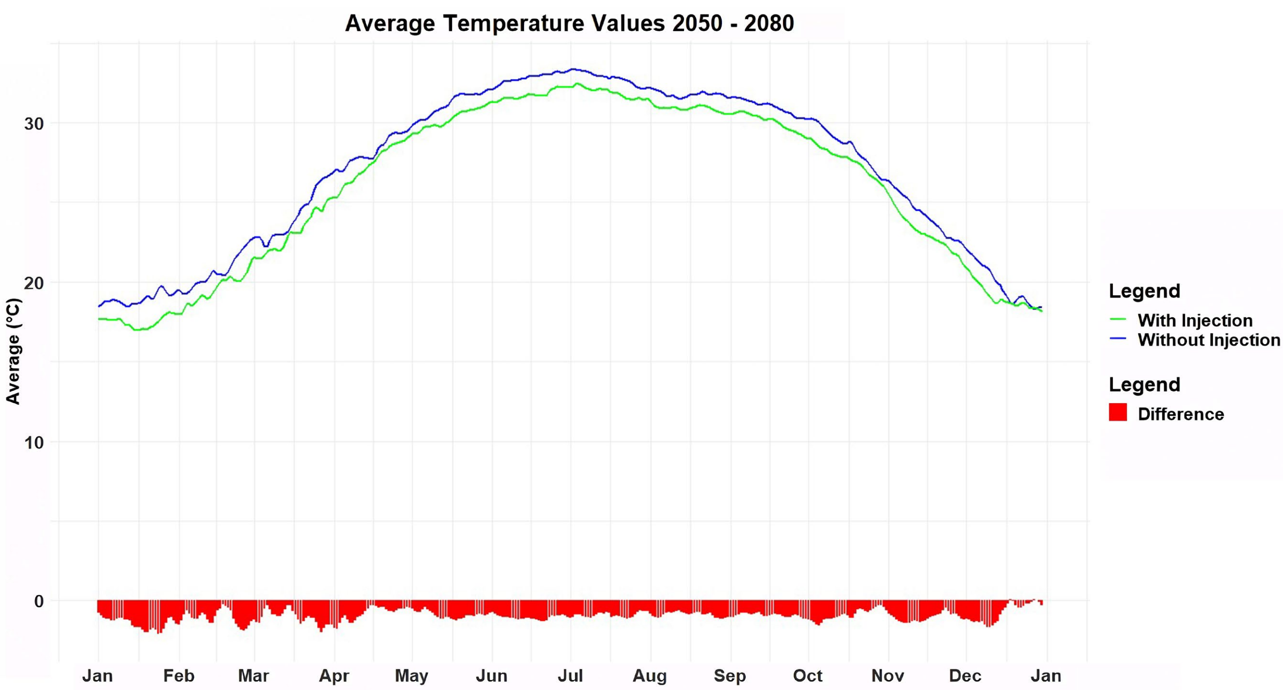


Figure 11. Daily comparison of temperatures with and without SO_2 injection (2050-2080).

3.3.3. Daily Climate Projection (2020-2050): Effects of SO_2 Injection on Future Precipitation

January to April: no precipitation is observed in the Sahel region from January to April, whether with or without injection with or without SO_2 injection May: In May, a slight peak in precipitation is observed, with daily average values varying from 0 to 0.02 mm. However, the change between with and no SO_2 injection scenarios is not significant. June: The month of June shows an increase in precipitation compared to May. Without SO_2 injection, the daily average values vary from 0.125 to 0.30 mm, while with injection, they vary from 0.15 to 0.5 mm. The injection of SO_2 seems to have a positive effect on precipitation in June, with an increase in daily average values (from 0.125 to 0.23 mm) compared to the scenario without injection. July: In July, precipitation continues to increase, reaching daily average values ranging from 0.30 to 075 mm without injection and from 0.45 to 1.10 mm with SO_2 injection. The first week of July shows a decrease in precipitation (0.30 mm) with SO_2 injection, but then there is a gradual increase (0.20 mm) until the beginning of August. August: in August the effect of SO_2 injection appears to be negative, with a decrease in precipitation compared to the scenario without injection, the average values vary from 0.45 to 1.40 mm, while with injection, they vary from 0.6 to 1.26 mm. September and October: The months of September and October also show negative effects of SO_2 injection on precipitation, with a decrease in values ranging from 0.20 to 0.50 mm compared to the scenario without injection. November and December: in November and December, the daily average values return to approximately 0 mm and the effect of SO_2 injection is not significant on precipitation for these two months. In summary, SO_2 injection appears to have a variable impact on precipitation in the Sahel region over the months. It seems to favor an increase in precipitation in August, September and October. However, it is essential to note that natural climate variations may also play a role, and other factors must be considered for a complete understanding of these changes. Average precipitation in the Sahel changes by −0.5% and there is also a net reduction in land precipitation, with large reductions around September and October in the Sahel and smaller reductions around

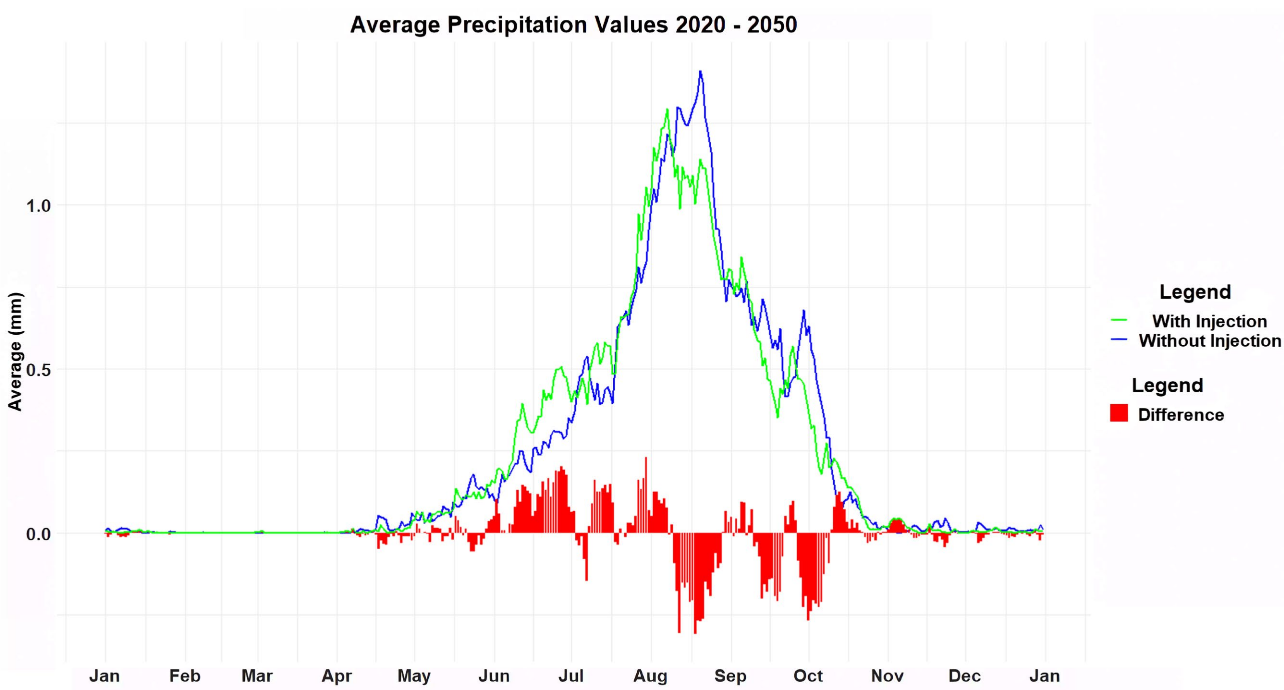


Figure 12. Comparison of daily precipitation with and without SO_2 injection (2020-2050).

May and July with injection. However with no injection an increase in precipitation in the months of June and August. Average daily precipitation in the Sahel is reduced by 0.4 to 0.7 mm/day; although there is little impact on terrestrial precipitation Figure 12: although the distribution of changes generally tends to oppose that due to increased GHGs, they are much smaller in magnitude. Average precipitation in the Sahel is reduced by about 2.3%, from 0.7 to 0.5 mm per day^{-1}, and the strong reduction in precipitation over the Sahel is still evident Figure 12, which would have serious consequences for the Sahel, as indicated by the impact on nuclear power plants. On the other hand, there is a general increase in precipitation with low values.

3.3.4. Daily Climate Projection (2050-2080): Effects of SO_2 Injection on Future Precipitation

January to mid-April: it is noted that there is no precipitation observed in the Sahel from January to mid-April for this time of year. This may indicate a prolonged dry season early in the year, which may have implications for water availability for ecosystems and human activities. Variations in the intensity and period of precipitation: Figure 13 highlights variations in the intensity and period of precipitation in the Sahel region. It is observed that the precipitation intensity decreases during the peak precipitation period, especially in May, June and September, in the scenario without injection compared to the simulations with SO_2 injection. This decrease in intensity during these months can have consequences for agriculture, groundwater recharge and other water-related aspects. On the other hand, Figure 13 indicates that the Sahel zone also shows a decrease in precipitation intensity during the peak precipitation period, especially in May,

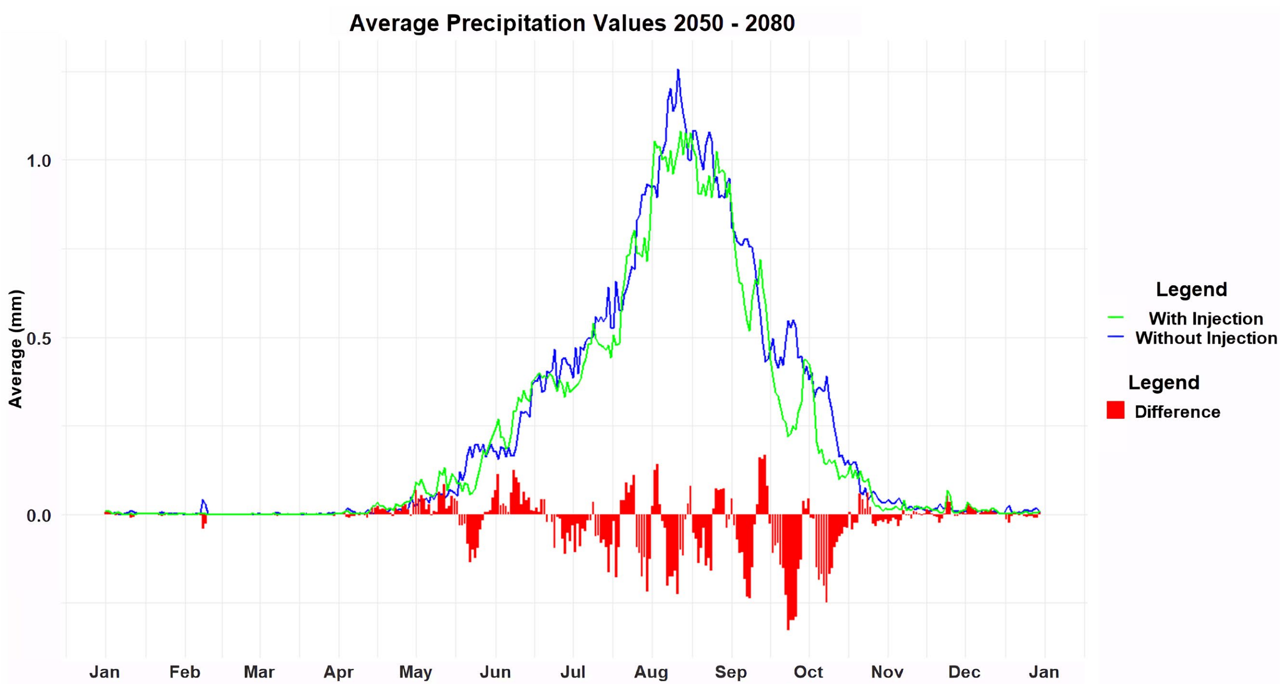


Figure 13. Comparison of daily precipitation with and without SO_2 injection (2050-2080).

June and August, in the scenario with SO_2 injection. This means that the effect of SO_2 injection does not seem to attenuate the decrease in precipitation intensity during these months. Overall, **Figure 13** suggests that the period 2050-2080 in the Sahel region is characterized by a prolonged dry season at the beginning of the year, a decrease in the intensity of precipitation during the peak months, and variations in precipitation patterns, which can have significant consequences on water availability, and the ecology of the region. The effect of SO_2 injection does not necessarily appear to mitigate these trends.

3.4. Effectiveness of Stratospheric SO_2 Injection in the Sahel

This section uses the framework mentioned previously in Section 2.3.2 to investigate the effectiveness of G3 in reducing the projected warming in the AI_RCP4.5 scenario by analyzing the near-surface air temperature response. Additionally, precipitation efficiency is examined to determine the efficiency of G3. This is accomplished by comparing simulations of near-surface air temperature and precipitation from G3 to those from climatology from 1950 to 2005. Finally, the results are compared to the climate response.

3.4.1. Seasonal Effectiveness of SO_2 Injection on Temperatures (2020-2050)

According to the results of our analysis, the injection of sulfur dioxide (SO_2) into the stratosphere is effective in almost all seasons **Figure 14**, including the following seasons: During Cold Season (DJF): Results indicate that SO_2 injection is effective during the cold season, which could mean it helps mitigate the effects of climate change or meet other specific environmental objectives The hot season (MAM): the effectiveness of SO_2 injection seems to be maintained in the hot season (MAM). This may be important given that hot dry seasons (HDS) are often associated with heat waves. Rainy season (JJA): Our analysis suggests that SO_2 injection is also effective during the rainy season. This period is crucial for many regions regarding harvests and environmental conditions. The Harmattan wind season (SON): even in the transition season between the cold season and the rainy season (SON), the results show that SO_2 injection remains effective. This may have implications for climate stability and weather conditions during this period.

3.4.2. Seasonal Effectiveness of SO_2 Injection on Temperatures (2050-2080)

Our result shows that the injection of sulfur dioxide (SO_2) into the stratosphere is effective in all seasons, with higher values than the first period (2020-2050), this indicates that this geoengineering method seems have a positive and lasting impact on temperature reduction. The fact that the effectiveness persists over a second period (2050-2080) see **Figure 15** indicates that the advantages of SO_2 injection are not ephemeral, but rather sustainable in the long term. This can be an important asset in the context of the fight against climate change. If effectiveness is maintained across seasons over time, this suggests that this approach may help reduce seasonal variations in climate conditions, which could be beneficial for temperature reduction.

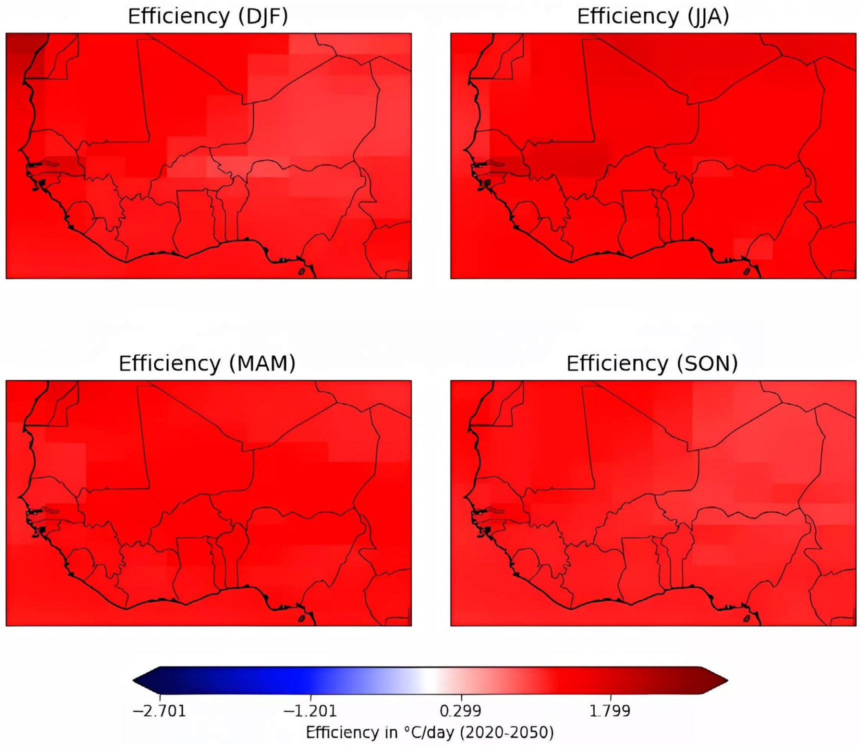


Figure 14. G3 efficiency map over different seasons from 2020-2050.

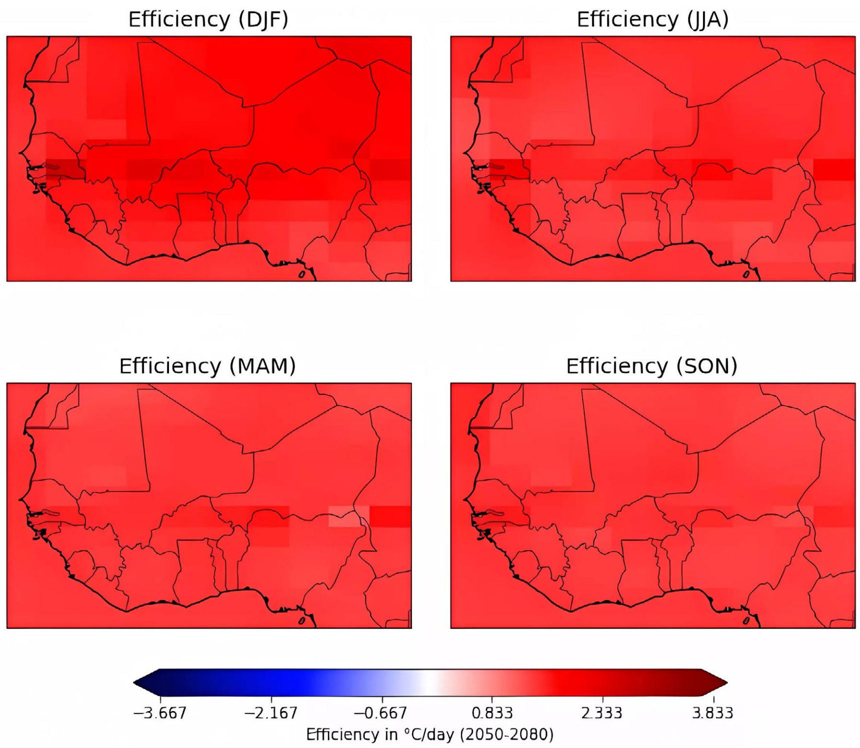


Figure 15. G3 efficiency map over different seasons from 2050-2080.

3.4.3. Seasonal Effectiveness of SO_2 Injection on Precipitation (2020-2050)

The results of our SO_2 injection efficiency maps for precipitation in West Africa from 2020-2050 depending on the seasons. Our observations show significant seasonal variations in the region where this geoengineering method is effective. Cold season (DJF): We observed that the effectiveness of SO_2 injection varies in West Africa during the cold season (DJF). It is effective in parts of southern Ivory Coast, near the ocean, while other parts show mixed results, suggesting some complexity in the effects on rainfall during this season. The hot season (MAM): for the hot season (MAM), our results indicate that the effectiveness of SO_2 injection is mixed, with areas where it is effective and others where it is not. This may reflect the seasonal variability of precipitation in the region. Hot season (MAM): results show that SO_2 injection is mainly effective during the rainy season (JJA) in West Africa, with the exception of the Mauritania area, particularly near the west coast of the Atlantic Ocean. This could have implications for the rainy season in the region. The Harmattan wind season (SON): for the transition season between the cold season and the rainy season (SON), we found that the efficiency of SO_2 injection is high in most of the West Africa, with the exception of the Malian Sahara, Algeria and eastern Niger. This may indicate that this method helps improve rainfall during this season. It is important to note that seasonal variations in rainfall in West Africa are influenced by many complex climatic factors, including monsoons, ocean currents and atmospheric systems. The results we obtained suggest that SO_2 injection can have varying effects depending on season and region, highlighting the importance of considering complexity when evolving this geoengineering method (Figure 16).

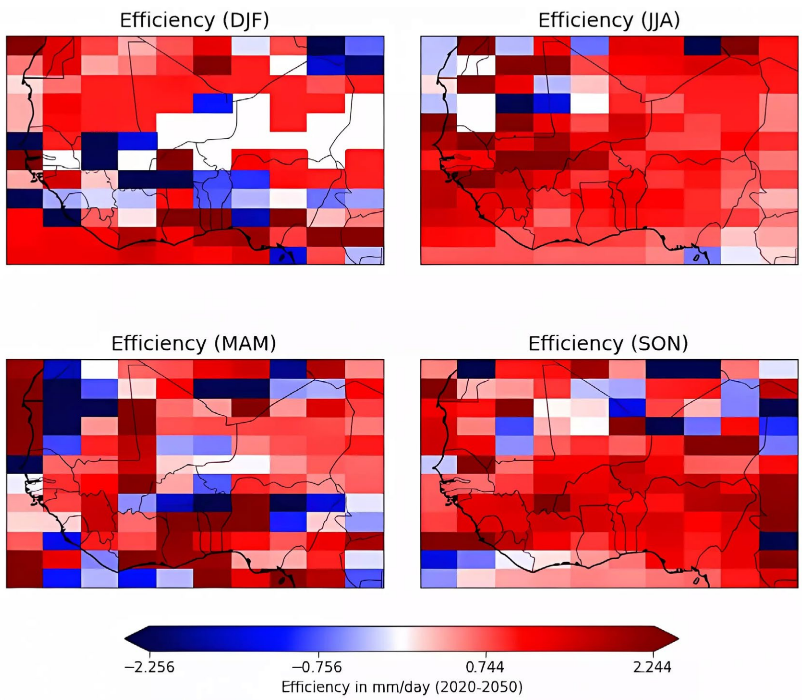


Figure 16. Map of G3 effectiveness for precipitation changes (2020-2050).

3.4.4. Seasonal Effectiveness of SO_2 Injection on Precipitation (2020-2080)

The results concerning the effectiveness of SO_2 injection for precipitation in West Africa for the period 2050-2080 depending on the seasons. Our observations show changes compared to the previous period and significant seasonal variations in the regions where G3 is effective. Cold season (DJF): We find that the effectiveness of SO_2 injection during the cold dry season (DJF) in West Africa has changed compared to the previous period. This time it is not effective in certain regions, notably the Ivory Coast, Togo, Ghana, Cameroon, central Nigeria, most of Niger, eastern Mali and Chad. This variation may be linked to climate change or other factors. Hot season (MAM): For the hot dry season (MAM), results again indicate that the effectiveness of SO_2 injection is mixed, with some areas where it is effective and less effective in others. Rainy season (SON): We find that SO_2 injection is mainly effective during the rainy season (JJA) in West Africa, with the exception of the Mauritania area, northern Coast Ivory, Cameroon and certain other regions. This suggests that this method may impact the rainy season in the region, although variations remain. The Harmattan wind season (SON): for the transition season between the cold season and the rainy season (SON) our results again show a variable effectiveness of SO_2 injection, with areas where it is effective, particularly in Ivory Coast, Guinea and near the ocean. These results show that the effectiveness of SO_2 injection on rainfall in West Africa can vary considerably depending on the season and region, as well as compared to the previous period. Climate change, atmospheric factors and other variables can influence these variations (Figure 17).

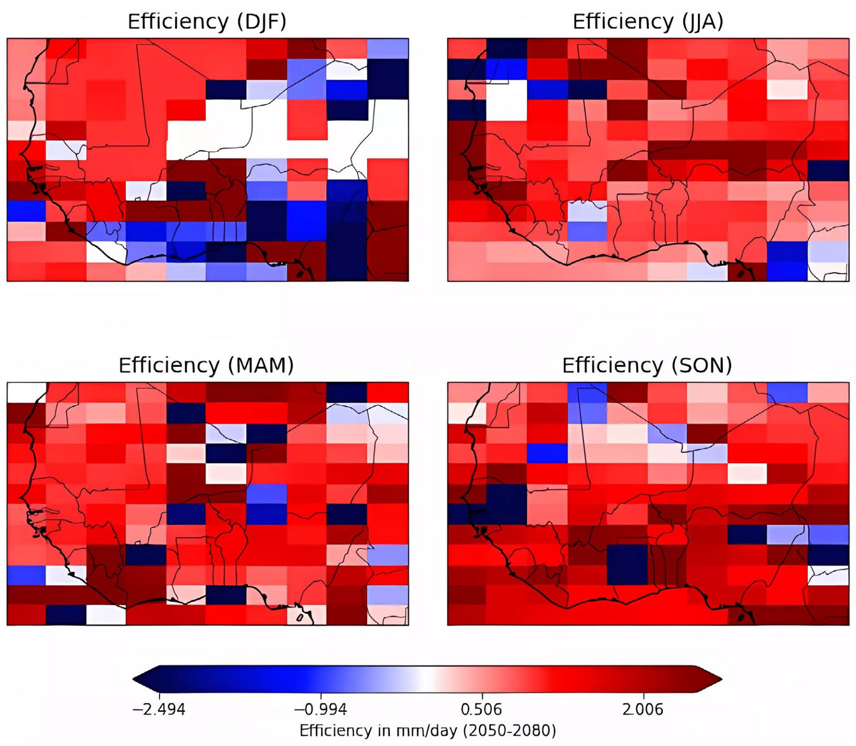


Figure 17. Map of G3 effectiveness for precipitation changes (2050-2080).

4. Discussion

4.1. Implications of Projected Climate Change for Communities and Society

4.1.1. Implications of Projected Temperature Changes for Communities and Society

The study's findings show that adding sulphur dioxide (SO_2) to the atmosphere can dramatically decrease temperatures in the Sahel and Sahara regions (Robock et al., 2008; Niemeier & Timmreck, 2015). For example, during the hot season (March-April-May), temperatures can drop by up to 1.2˚C in some regions, while during the rainy season (June-August-September), temperatures can drop by 0.4˚C to 1.2˚C between the ocean and the southern shore (Robock et al., 2008; Niemeier & Timmreck, 2015).

These findings are consistent with the observations of the recent drought in the Sahel, which has been attributed in part to natural climate variability and industrial SO_2 emissions (Giannini et al., 2013). However, it is crucial to highlight that the influence of SO_2 injection on precipitation is more complicated and may differ depending on the region and season. For example, a recent study found that SO_2 injections in the stratosphere can create significant droughts in the Sahel, but injections in the southern hemisphere can provide more abundant precipitation in the region (Haywood et al., 2013). These findings highlight the necessity of considering internal climate variability and the societal repercussions of such actions.

In terms of social and community ramifications, SO_2 injection into the atmosphere may have significant effects on economic activities and local communities. Temperature reduction, for example, can improve living circumstances for rural communities, but it can also have an impact on agricultural productivity and water management systems (Robock et al., 2008; Niemeier & Timmreck, 2015). It is therefore critical to discuss and consider the needs and concerns of local communities before implementing such initiatives (Williams & Morrow, 2009).

Furthermore, the ethical implications of stratospheric SO_2 injection must be carefully examined. Issues related to governance, unintended consequences, and equity remain central concerns in discussions on geoengineering. The decision-making process surrounding the deployment of such techniques requires inclusive governance frameworks that involve local populations, policymakers, and scientists. Additionally, unintended consequences such as shifts in precipitation patterns leading to droughts in certain regions must be anticipated to mitigate adverse effects. Lastly, equity concerns arise as the benefits and risks of SO_2 injection may not be distributed evenly across regions, potentially exacerbating socio-economic disparities. Addressing these ethical dimensions is crucial for ensuring a responsible.

4.1.2. Implications of Projected Precipitation Changes for Communities and Society

The findings of this study indicate that injecting sulphur dioxide (SO_2) into the atmosphere might have a varying influence on precipitation in the Sahel. Although SO_2 injection can increase precipitation in some months, it can also decrease precipitation in others. This emphasizes the necessity of considering the internal variability of the climate and the social ramifications of such actions (Robock et al., 2008).

In terms of social and community ramifications, SO_2 injection into the atmosphere may have significant effects on economic activities and local communities. For example, more precipitation can improve living circumstances for rural inhabitants, but it can also have an impact on agricultural productivity and water management systems. It is therefore critical to discuss and consider the needs and concerns of local communities before implementing such initiatives (Niemeier & Timmreck, 2015).

The findings of this study are consistent with observations of the recent drought in the Sahel, which has been attributed in part to natural climate variability and industrial SO_2 emissions (Haywood et al., 2013). However, it is crucial to highlight that the influence of SO_2 injection on precipitation is more complicated and might vary depending on the region and season. For example, a recent study found that SO_2 injections in the stratosphere might induce significant droughts in the Sahel, but injections in the southern hemisphere can provide more abundant precipitation in the region (Haywood et al., 2013).

5. Conclusion and Recommendation

The results of this study highlight the impact of SO_2 injection on the climate of the Sahel region in West Africa during two distinct periods: 2020-2050 and 2050-2080. Observations demonstrate that SO_2 injection has significant effects on temperatures and precipitation in this region, with major implications for climate management. For temperature, during the first period (2020-2050), the injection of SO_2 could induce a notable reduction in temperatures, with seasonal variations. The effectiveness of this intervention was highlighted by the dominance of Ai_G3 compared to SI_RCP4.5, with temperature reductions varying from 0.15˚C to 1.25˚C. The second period (2050-2080) confirmed the trend of reducing temperatures with continuous decreases that could range from 1.15˚C to 2˚C. These results reveal the effectiveness that SO_2 injection could have in mitigating predicted temperature increases, while highlighting the need to closely monitor these trends. For precipitation, precipitation in the Sahel could be significantly affected by the injection of SO_2. During both periods, a reduction in average precipitation is projected, with major implications for the region. The dry season could be particularly affected, with a reduction in the intensity of precipitation during the months at the beginning and end of the winter season. Additionally, significant variations in precipitation patterns are predicted, which could have significant consequences on water availability and the ecology of the region. Importantly, SO_2 injection did not appear to attenuate these trends, highlighting the complexity of the effects on precipitation. For implications, the results of this study highlight the importance of understanding the seasonal and regional effects of SO_2 injection on the Sahel climate. These variations could have repercussions on the management of water, agriculture and the ecology of the region. However, it is essential to take into account the potential methodological challenges associated with these simulations. In short, this research provides crucial information on the effect of SO_2 injection on the climate of the Sahel in West Africa. The results highlight the need to closely monitor changes in temperature and precipitation in the region, while developing adaptation and mitigation strategies to deal with future climate change. This understanding is essential to guarantee the resilience and well-being of the populations of the Sahel in a context of global upheaval. The effectiveness of SO_2 injection in mitigating change must be continuously evaluated. It is essential to continue research into the effects of this technology and monitor its potential impacts on precipitation and local ecosystems.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

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,* 245-263. https://doi.org/10.1007/s10584-016-1774-2

Adeniyi, M. O., & Nweke, G. C. (2019). Performance of CMIP5 Models in Temperature Simulation over West Africa. *Journal of the Nigerian Association of Mathematical Physics, 49,* 147-158

Budyko, M. I. (1977). Present-Day Climatic Changes. *Tellus, 29,* 193-204.

Cong, R., & Brady, M. (2012). The Interdependence between Rainfall and Temperature: Copula Analyses. *The Scientific World Journal, 2012,* Article ID: 405675. https://doi.org/10.1100/2012/405675

Crutzen, P. J. (2006). Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma? *Climatic Change, 77,* 211-220. https://doi.org/10.1007/s10584-006-9101-y

Curry, C. L., Sillmann, J., Bronaugh, D., Alterskjaer, K., Cole, J. N. S., Ji, D. et al. (2014). A Multimodel Examination of Climate Extremes in an Idealized Geoengineering Experiment. *Journal of Geophysical Research: Atmospheres, 119,* 3900-3923. https://doi.org/10.1002/2013jd020648

Dagon, K., & Schrag, D. P. (2016). Exploring the Effects of Solar Radiation Management on Water Cycling in a Coupled Land-Atmosphere Model. *Journal of Climate, 29,* 2635-2650. https://doi.org/10.1175/jcli-d-15-0472.1

Dufresne, J., Foujols, M., Denvil, S., Caubel, A., Marti, O., Aumont, O. et al. (2013). Climate Change Projections Using the IPSL-CM5 Earth System Model: From CMIP3 to CMIP5.

Climate Dynamics, 40, 2123-2165. https://doi.org/10.1007/s00382-012-1636-1

Effiong, U., & Neitzel, R. L. (2016). Assessing the Direct Occupational and Public Health Impacts of Solar Radiation Management with Stratospheric Aerosols. *Environmental Health, 15,* Article No. 7. https://doi.org/10.1186/s12940-016-0089-0

Ezeife, N. D. (2014). Projected Impact of Global Warming on West Africa: Case for Regional and Transnational Adaptive Measures. *Annual Survey of International & Comparative Law, 20,* Article 9.

Fontaine, B., Roucou, P., & Monerie, P. (2011). Changes in the African Monsoon Region at Medium-Term Time Horizon Using 12 AR4 Coupled Models under the A1B Emissions Scenario. *Atmospheric Science Letters, 12,* 83-88. https://doi.org/10.1002/asl.321

Giannini, A., Salack, S., Lodoun, T., Ali, A., Gaye, A. T., & Ndiaye, O. (2013). A Unifying View of Climate Change in the Sahel Linking Intra-Seasonal, Interannual and Longer Time Scales. *Environmental Research Letters, 8,* Article ID: 024010. https://doi.org/10.1088/1748-9326/8/2/024010

Govindasamy, B., & Caldeira, K. (2000). Geoengineering Earth's Radiation Balance to Mitigate CO_2-Induced Climate Change. *Geophysical Research Letters, 27,* 2141-2144. https://doi.org/10.1029/1999gl006086

Harding, A. R., Ricke, K., Heyen, D., MacMartin, D. G., & Moreno-Cruz, J. (2020). Climate Econometric Models Indicate Solar Geoengineering Would Reduce Inter-Country Income Inequality. *Nature Communications, 11,* Article No. 227. https://doi.org/10.1038/s41467-019-13957-x

Haywood, J. M., Jones, A., Bellouin, N., & Stephenson, D. (2013). Asymmetric Forcing from Stratospheric Aerosols Impacts Sahelian Rainfall. *Nature Climate Change, 3,* 660-665. https://doi.org/10.1038/nclimate1857

Irvine, P., Emanuel, K., He, J., Horowitz, L. W., Vecchi, G., & Keith, D. (2019). Halving Warming with Idealized Solar Geoengineering Moderates Key Climate Hazards. *Nature Climate Change, 9,* 295-299. https://doi.org/10.1038/s41558-019-0398-8

James, R., & Washington, R. (2013). Changes in African Temperature and Precipitation as-Sociated with Degrees of Global Warming. *Climatic Change, 117,* 859-872.

Keith, D. W., & Parker, A. (2013). The Fate of an Engineered Planet. *Scientific American, 308,* 34-36. https://doi.org/10.1038/scientificamerican0113-34

Kravitz, B., Robock, A., Boucher, O., Schmidt, H., Taylor, K. E., Stenchikov, G. et al. (2011). The Geoengineering Model Intercomparison Project (GeoMIP). *Atmospheric Science Letters, 12,* 162-167. https://doi.org/10.1002/asl.316

Krinner, G., Viovy, N., de Noblet-Ducoudré, N., Ogée, J., Polcher, J., Friedlingstein, P. et al. (2005). A Dynamic Global Vegetation Model for Studies of the Coupled Atmosphere-biosphere System. *Global Biogeochemical Cycles, 19,* GB1015. https://doi.org/10.1029/2003gb002199

Kuswanto, H., Kravitz, B., Miftahurrohmah, B., Fauzi, F., Sopahaluwaken, A., & Moore, J. (2021). Impact of Solar Geoengineering on Temperatures over the Indonesian Maritime Continent. *International Journal of Climatology, 42,* 2795-2814. https://doi.org/10.1002/joc.7391

Monerie, P., Fontaine, B., & Roucou, P. (2013). Expected Future Changes in the African Monsoon between 2030 and 2070 Using Some CMIP3 and CMIP5 Models under a Medium-Low RCP Scenario. *Journal of Geophysical Research: Atmospheres, 117,* D16111. https://doi.org/10.1029/2012jd017510

Mukherjee, S., Aadhar, S., Stone, D., & Mishra, V. (2018). Increase in Extreme Precipitation Events under Anthropogenic Warming in India. *Weather and Climate Extremes, 20,* 45-

53. https://doi.org/10.1016/j.wace.2018.03.005

Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, A., Lennard, C., Padgham, J., & Urquhart, P. (2014). Africa. In *Climate Change. Impacts, Adaptation, and Vulnerability. Part: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Inter-Governmental Panel on Climate Change* (pp. 1199-1265). Cambridge University Press.

Niemeier, U., & Timmreck, C. (2015). What Is the Limit of Climate Engineering by Stratospheric Injection of SO_2? *Atmospheric Chemistry and Physics, 15,* 9129-9141. https://doi.org/10.5194/acp-15-9129-2015

Pongratz, J., Lobell, D. B., Cao, L., & Caldeira, K. (2012). Crop Yields in a Geoengineered Climate. *Nature Climate Change, 2,* 101-105. https://doi.org/10.1038/nclimate1373

Proctor, J., Hsiang, S., Burney, J., Burke, M., & Schlenker, W. (2018). Estimating Global Agricultural Effects of Geoengineering Using Volcanic Eruptions. *Nature, 560,* 480-483. https://doi.org/10.1038/s41586-018-0417-3

Robock, A., Oman, L., & Stenchikov, G. L. (2008). Regional Climate Responses to Geoengineering with Tropical and Arctic SO_2 Injections. *Journal of Geophysical Research: Atmospheres, 113,* D16101. https://doi.org/10.1029/2008jd010050

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,* 485-498. https://doi.org/10.1175/bams-d-11-00094.1

Tilmes, S., Fasullo, J., Lamarque, J., Marsh, D. R., Mills, M., Alterskjær, K. et al. (2013). The Hydrological Impact of Geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres, 118,* 11036-11058. https://doi.org/10.1002/jgrd.50868

Wigley, T. M. L. (2006). A Combined Mitigation/Geoengineering Approach to Climate Stabilization. *Science, 314,* 452-454. https://doi.org/10.1126/science.1131728

Williams, E. N., & Morrow, S. L. (2009). Achieving Trustworthiness in Qualitative Research: A Pan-Paradigmatic Perspective. *Psychotherapy Research, 19,* 576-582. https://doi.org/10.1080/10503300802702113

Xia, L., Robock, A., Cole, J., Curry, C. L., Ji, D., Jones, A. et al. (2014). Solar Radiation Management Impacts on Agriculture in China: A Case Study in the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres, 119,* 8695-8711. https://doi.org/10.1002/2013jd020630

Yang, H., Dobbie, S., Ramirez-Villegas, J., Feng, K., Challinor, A. J., Chen, B. et al. (2016). Potential Negative Consequences of Geoengineering on Crop Production: A Study of Indian Groundnut. *Geophysical Research Letters, 43,* 11786-11795. https://doi.org/10.1002/2016gl071209

Zebaze, S., Jain, S., Salunke, P., Shafiq, S., & Mishra, S. K. (2019). Assessment of CMIP5 Multimodel Mean for the Historical Climate of Africa. *Atmospheric Science Letters, 20,* e926. https://doi.org/10.1002/asl.926