Stratospheric Sulfate Aerosols impacts on West African monsoon precipitation using GeoMIP Models

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Abstract

Stratospheric Aerosol Geoengineering (SAG) is proposed to offset global warming; the use of this approach can impact the hydrological cycle. We use simulations from Coupled Model Intercomparison Project (CMIP5) and Geoengineering Model Intercomparison Project (G3 simulation) to analyze the impacts of SAG on precipitation (P) and to determine its responsible causes in West Africa and Sahel region. CMIP5 Historical data are firstly validated, the results obtained are consistent with those of observations data (CMAP and GPCP). Under the Representative Concentration Pathway (RCP) scenario RCP4.5, a slight increase is found in West Africa Region (WAR) relative to present-day climate. The dynamic processes especially the monsoon shifts are responsible for this change of precipitation. Under RCP4.5, during the monsoon period, reductions in P are 0.86%, 0.80% related to the present-day climate in the Northern Sahel (NSA), Southern Sahel (SSA) respectively while P is increased by 1.04% in WAR. Under SAG, 3.71% of P change (decrease) was associated with a -3.51 value of efficacy in the West African Region (AR). Under G3, a significant decrease of P is found in the West African region. This decrease in monsoon precipitation is mainly explained by changes in dynamics, which leads to weakened monsoon circulation and a shift in the distribution of monsoon precipitation. This result suggests that SAG deployment to balancing all warming can be harmful to rainfall in WAR if the amount of SO_2 to be injected in this tropical area is not taken into consideration.

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Key Points:

• We determine the changes of West African Summer Monsoon precipitation using stratospheric aerosol geoengineering injections climate models

• Increase of precipitation is observed under global warming while its decrease is obtained with stratospheric aerosol geoengineering models

• These changes of West African Summer Monsoon precipitation are mainly driven by the dynamic processes

Abstract

Stratospheric Aerosol Geoengineering (SAG) is proposed to offset global warming; the use of this approach can impact the hydrological cycle. We use simulations from Coupled Model Intercomparison Project (CMIP5) and Geoengineering Model Intercomparison Project (G3 simulation) to analyze the impacts of SAG on precipitation (P) and to determine its responsible causes in West Africa and Sahel region. CMIP5 Historical data are firstly validated, the results obtained are consistent with those of observations data (CMAP and GPCP). Under the Representative Concentration Pathway (RCP) scenario RCP4.5, a slight increase is found in West Africa Region (WAR) relative to present-day climate. The dynamic processes especially the monsoon shifts are responsible for this change of precipitation. Under RCP4.5, during the monsoon period, reductions in P are 0.86%, 0.80% related to the present-day climate in the Northern Sahel (NSA), Southern Sahel (SSA) respectively while P is increased by 1.04% in WAR. Under SAG, 3.71% of P change (decrease) was associated with a -3.51 value of efficacy in the West African Region (AR). Under G3, a significant decrease of P is found in the West

African region. This decrease in monsoon precipitation is mainly explained by changes in dynamics, which leads to weakened monsoon circulation and a shift in the distribution of monsoon precipitation. This result suggests that SAG deployment to balancing all warming can be harmful to rainfall in WAR if the amount of SO_2 to be injected in this tropical area is not taken into consideration.

Plain Language Summary:
Stratospheric aerosol geoengineering deployment has been proposed to reduce temperature increase in the context of global warming but its impacts on the hydrological cycle and its mains causes need to be strengthened on the regional scale. While the exact effects of Stratospheric aerosol geoengineering on the water cycle are uncertain, various studies suggest that there could be harmful, its consequences can cause considerable changes in regional rainfall. Climate simulations (Coupled Model Intercomparison Project: CMIP5 and Geoengineering Model Intercomparison Project GeoMIP) are used in this work to quantify their impacts on the monsoon rainfall in West Africa. We determine the changes in precipitation and its responsible mechanisms for these changes in West Africa during summer using Stratospheric Aerosol Geoengineering. Under global warming, while a slight decrease in rainfall is observed in the Sahel region. Under Stratospheric Aerosol Geoengineering, a significant decrease in rainfall is obtained over the West Africa region and the Sahel region. The main processes responsible for the changes of P under SAG are determined based on the decomposition approach, results show that changes in precipitation are largely related to changes in the dynamic processes (monsoon circulation).

Keywords: West Africa, monsoon precipitation, climate change, geoengineering, GeoMIP, G3, RCP4.5,

1. Introduction:

Climate Geoengineering is a set of some methodologies, known according to the literature as a potential way to reduce the most dangerous changes to Earth's climate as a result of large greenhouse gas increases (Launder, Brian & Thompson, J. Michael T, 2010).

Stratospheric sulfate Aerosols Geoengineering (SAG) is one of the geoengineering methods (Lenton & Vaughan, 2009) that lead to the reduction of global warming Robock et al. (2009) proved that this method could be relatively low cost, especially in comparison with the cost of mitigation, potentially making this idea attractive to policymakers and stakeholders. The reduction of incoming shortwave radiation is also called Solar Radiation Management (SRM). However, Robock et al. (2009), Tilmes et al.(2013), Kravitz et al 2013 empathized that stratospheric geoengineering with sulfate aerosols could have casual and consequences of possible impacts on the hydrological cycle, then the region of Monsoon precipitation could be impacted.. Most of the previous studies have been interested in the determination of geoengineering impacts on precipitation on the global scale (Kravitz et al., 2013; Tilmes, et al., 2013, Govindasamy and Caldeira 2000) have reported the reduction of the hydrological cycle with SAG applications. Although certain research works have been done, few of these works have focused on the mechanism responsible for changes in monsoon precipitation under SRM. Therefore, there is still a need to implement the analysis of the hydrological cycle on a regional scale under SRM and to determine the mechanisms responsible for changes in P using the existing climate models.

The West African monsoon (WAM) is a system of Earth's climate, that involves interconnections between the atmosphere, the biosphere, and the hydrosphere over many time scales during the boreal summer (e.g. Nicholson and Grist 2003; Redelsperger et al. 2006). It is part of the global monsoon system, which regulates atmospheric humidity and heat budgets in low latitudes. It is the major source of water for agriculture in West Africa (Froidurot & Diedhiou, 2017), it is the principal determinant of agricultural production in densely populated areas where the economy is dependent on subsistence farming. The WAM precipitation is characterized by moisture fluxes derivation from different sources comprising the soil moisture and the atmospheric moisture flux convergence (Gong & Eltahir, 1996; Lélé et al., 2015; Mera et al., 2014). Some previous works investigated the atmospheric moisture over the WAM, (Pomposi et al. (2015) observed that changes in moisture flux convergence, as well as the circulation process within the higher precipitation region and along the monsoon border, are associated with the precipitations changes within the Intertropical Convergence Zone (ITCZ). (Xue & Shukla .(1993) demonstrated that the role of continental surfaces is linked by the soil moisture and precipitation in the WAM region. In the West African monsoon (WAM) zone, the role of continental surfaces is fully verified due to the close relationship associated with soil moisture and precipitation (Xue & Shukla, 1993). Interesting descriptions of the WAM hydrology and dynamics have been described in many works (J. L. Redelsperger et al., 2001).

The West African (WA) Monsoon precipitation variability poses a constraint to the water resources, vegetation, and food security and its long-term state over periods of few years to several decades has been investigated thoroughly (Abiodun et al., 2008; Janicot, 1992; Lamb, 1982; Nicholson, 2013; Okoro et al., 2018; Sanogo et al., 2015). The WAM precipitation results from the moisture fluxes originating from many sources during the summer season. More than 80% of the annual rainfall occurs during June–September when the intertropical front is northward position, but the total precipitation has annual variations (Le Barbé et al., 2002). WAM region frequently suffers from droughts, which cause water deficiencies and disrupt the agriculture sector; this is the only sector that provides both food and income for the majority of rural households. The impact of these droughts and the controversy concerning their causes has prompted climatologists to offer a variety of hypotheses including changes in the ITCZ latitude position, tropical Atlantic sea surface temperature anomalies, energy balance changes. The WAM contributes to the majority of summer precipitation in the Sahel(Dong & Sutton, 2015). The WAM's transition to its strong phase is related to wind forcing, evaporation, Sea Surface Temperature (SST) positive feedback (S.P. Xie, 1999): warming in SST in the northern part of Atlantic relative to that of southern drives stronger-westerly winds forcing and intensify the WAM, which reduces surface evaporation north of the equator and enhances it in the South, amplifying the interhemispheric SST gradient.

Increased WAM, induced by anthropogenic greenhouse gas and aerosol forcing, may have led to a significant increase in Sahel precipitation since the 1980s (Dong & Sutton, 2015). Under RCP 8.5, approximately 80% of CMIP5 models agree on a modest drying rate of around 20% over the westernmost Sahel (15°W–5°W), whereas approximately 75% of models agree on an increase in precipitation between 0°E and 30°E over the Sahel, with a wide amplitude distribution (Roehrig et al., 2013). The projected reinforcement of WAM is related to a robust expansion of warming over the Sahel by around 10%-50% over the global mean (Roehrig et al., 2013). Several works basing on SAG emphasized that the offset of global warming may cause a reduction of global precipitation (Bala et al., 2008; Govindasamy & Caldeira, 2000; A. C. Jones et al., 2018; Robock et al., 2008; Tjiputra et al., 2016; Xu et al., 2020, Odunlami et al., 2020). Some of these works pointed out the weakening of precipitation over the monsoon land regions such as the West African Summer Monsoon region under SAG (e.g., Cheng et al., 2019; Dagon & Schrag, 2016, 2017; Haywood et al., 2013; Niemeier et al., 2013; Robock et al., 2008; Tilmes et al., 2013). Recent work by Pinto et al.(2020) argued that the application of SAG will impact temperature and rainfall means and extremes over sub-Saharan Africa using simulations GLENS. They found agree that the use of SAG leads to a reduction in temperature means and extremes precipitations, it has been shown that the use of SAG in the northern hemisphere only could affect the hydrological cycle in the Sahel, while the SAG injection in only the Southern Hemisphere may increase significantly the Sahel vegetation productivity (Haywood et al., 2013). These authors showed that the injection of SAG in only one hemisphere may impact the position of the Inter tropical Convergence Zone (ITCZ). Some Recent studies demonstrated that the control of temperature variation through multiple aerosol injections at several latitudes, as in the Geoengineering Large Ensembles (GLENS) simulations (Tilmes et al., 2018), may lead to reduce shifts in the latitude of the ITCZ and related rainfall (Cheng et al., 2019; Kravitz et al., 2017, 2019; MacMartin et al., 2019; Tilmes et al., 2018; Xu et al., 2020) Interpreting variations in global mean precipitation, Kravitz et al.(2013) described the changes in the surface and atmospheric energy budgets using GeoMIP simulations (Kravitz et al., 2011) and they reported that changes in precipitation could be attributed to a decrease in the mean flux of evaporative moisture and increased moisture convergence, particularly over land regions. Furthermore, using GeoMIP simulations, Kravitz et al.(2013) and Tilmes and et al.(2013) reported the large decline in land evaporation in most regions associated with the global decline in precipitation, this is not the case in the rainfall regions of the summer monsoon, such as the West Africa region, whereas summer monsoon rainfall is influenced by both regional and large scale processes. Consequently, the mechanisms responsible for changes in West African Monsoon Summer precipitation need to be implemented. Changes in tropical precipitation can be demonstrated through the decomposition into the contributions of thermodynamic and dynamic processes (e.g., Weller et al., 2019), and the decomposition methodology of (Chadwick et al., 2013, 2016) can be used to identify the related contribution of these two terms (Da-Allada et al., 2020; Chadwick et al., 2016; Kent et al., 2015; Lazenby et al., 2018; Monerie et al., 2019). Using this method, changes in tropical precipitation, under climate change, have been largely associated with changes in the dynamic component indicating changes in the position (Chadwick et al., 2016; Kent et al., 2015). Due to the great importance of West African Summer Monsoon (WASM) precipitation on agriculture productivity, the magnitudes and patterns of WAM system responses to geoengineering need to be investigated regionally, and climate modeling should be a helpful way in this analysis. The use of climate geoengineering is expected to balance the warming resulting from increasing concentrations of greenhouse gases with a corresponding decrease in solar absorption (Crutzen, 2006) associated with precipitation reduction. Geoengineering atmosphere models basing on sulfate aerosols also show changes in stratospheric dynamics and chemistry caused by SRM (Heckendorn et al., 2009; Tilmes et al., 2009). Recently, Da-Allada et al. (2020) found that the dynamic process is the main mechanism responsible for the change of WASM using GLENS simulations. By subdividing the West African region into three sub-regions, they found that the deployment of SAG in North of Sahel (NSA) and South of Sahel (SSA) could be effective while their application in West Africa Region (WAR) can be over effective.

In the current study, the changes under SRM on West African Monsoon precipitation have been determined using GeoMIP (G3/G4) and Coupled Model Intercomparison Project CMIP5 (Historical, RCP4.5) simulations after validation with CMAP and GPCP observations. These impacts of SRM are determined in the context of global warming and climate geo-engineering with their main causes to explain the changes obtained. The rest of the manuscript is organized as follows, Methods and data , the section in which present the set of data and methods used in this study. Results describe the validation of historical simulation in regards to CMAP and GPCP observations. The impacts of SRM on WAM precipitation are presented in this same section under different simulations. The potential mechanisms explaining the changes in monsoon precipitation have been determined basing IPSL-CM5A-LR due to availability of specific humidity with higher vertical resolution. The Discussion section is dedicated to the results discussion. Finally, the conclusion presents a summary of the results obtained in this paper.

2. Methods and data

Ten CMIP5 era climate models with 2 experiments (Historical and RCP4.5 simulations) are analyzed in this paper; these models are listed in Table 1. These Historical CMIP5 models are extracted from the global data for West Africa during the monsoon period (Fig .1). Two observations data of precipitation data (GPCP and CMAP) have been used for the comparison with historical data. This set of models have been chosen due to the availability of GeoMIP (G3/G4) simulations associated with CMIP5 simulations. These distributions of Historical precipitation in West Africa staring from 1986 to 2005 (20 years). The analysis focuses on the seasonal average of West African Monsoon precipitation mainly during boreal summer, the monsoonal season starting from July to October (JASO) according to (Da-Allada et al., 2020; Gaetani et al., 2017) in this area. For each model, daily or monthly data from (historical experiments of CMIP5 models) are analyzed jointly with RCP4.5 (CMIP5). The CMIP5 models have different simulations; their Historical simulations are the simulations of the recent past (Sheffield et al., 2013). The CMIP5 Historical simulations are the simulation in which all forcing have been applied to the models, including anthropogenic greenhouse gas concentrations. The historical simulation began from multicentury preindustrial control runs and configured with the observed atmospheric composition evolution (anthropogenic and natural sources) The RCP4.5 is the Representative Concentration Pathway (RCP 4.5) with a scenario that provides stabilization to radiation forcing at 4.5 $W.m^{-2}$ in with future projection starting from 2006 to 2100 without ever exceeding that value. This simulation incorporates historical emissions and land cover information. We used in this study the GeoMIP climate era models with two experiments (G3/G4) simulations. G3 is a combination with RCP4.5 forcing, starting in 2020, gradual ramp-up the amount of SO_2 or sulfate aerosol injected, to keep global average temperature nearly constant (Kravitz et al., 2011). G4 is a combination with RCP4.5. Starting from 2020, it requires continuous injection of SO_2 through the lower stratosphere to the equator at a rate of 5 Tg SO_2 per year (Kravitz et al., 2011, Bürger et al., 2015, Clarke et al., 2021). We used monthly RCP4.5 and G3 and G4 simulations, monthly historical P simulations of CMIP5 have been compared with the observations for model validation over 1986 and 2005.

The changes in rainfall have been calculated through the difference between all the existing ensemble members of RCP4.5 over 2050–2069 and the baseline (present-day climate: 2010–2029) under global warming. Under SAG, changes of P have been quantified through the difference between the only ensemble member of G3 (2050-2069) and baseline (Table 1). We select this future period (2050-2069) as the distribution of SO_2 injection rates converges around 2050 (MacMartin et al., 2019). The baseline period is 20 years (2010–2029), which is considered as the period more suitable for present–day climate. The statistical significance of the rainfall changes is determined using a two-tailed Student's t-test and the standard error is used to provide an estimate of the error in the rainfall changes

The Earth System Models (Dufresne et al., 2013), has been generally developed in different institutions. IPSL-CMA5-LR, is one of the atmospheric models based on LMDZ5 (Hourdin et al., 2013), with different horizontal resolution and vertical levels. The ocean model coupled with that of atmospheric is NEMOv3.2 (Madec, 2016), in ORCA2 configuration. The performances of the oceanic component in the coupled configuration are presented in Mignot et al. (2013) for the case of IPSL-CMA5-LR. More information on this model can be found in the special issue in Climate Dynamics (http://link.springer.com/journal/382/40/9/) for a collection of studies describing various aspects and components of the model as well as its performance. The high resolution IPSL-CMA-LR for the specific humidity, the version with CMIP table (CFday) of geoengineering model has been used to determine the potential mechanisms to the impact of SRM on the West African Monsoon Precipitation. NCAR Climate Variability Diagnostics Package (Phillips et al., 2014), or diagnostics such as the cloud regime metric (Williams and Webb, 2009) developed by the Cloud Feedback MIP (CFMIP) community.

The availability of high vertical resolution of specific humidity (Hus) at different levels of pressure in IPSL–CM5A-LR is an advantage for the determination of mechanisms responsible for P changes using decomposition methods. The main variables extracted from each simulation in this work are monthly precipitation (P). Additional parameters such as daily wind velocity (V), specific humidity (q) has been used due to the high vertical resolution of CF convention simulation of IPSL-CM5A-LR. For the validation of Historical simulation, Monthly precipitation data used in this study were obtained from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) dataset (P. Xie & Arkin, 1997) from 1979 to 2018, Global Precipitation Climatology Project (GPCP) data estimates on a 2.5 × 2.5 degree latitude/longitude (Huffman et al., 1997) were used in this study. Precipitation change (ΔP) has been decomposed into dynamical (ΔPdyn), thermodynamical (ΔPtherm) and non-linear cross components (ΔPcross) according to Chadwick et al.(2016) to access the causes of precipitation changes in WA under SRM. In reality, this method assumes that the precipitation is dominated by convection in tropical region (Chadwick et al., 2016; Monerie et al., 2019). The precipitation, P, is considered as P = M*q, where M* is defined as a proxy for convective mass flux from the boundary layer to the free troposphere (Held & Soden, 2006; Kent et al., 2015; Lazenby et al., 2018), M* = P/q, and q is near surface specific humidity, then, the change in rainfall , then, ΔP c is decomposed as :

$$\Delta P = M^*\Delta q + q\Delta M^* + \Delta q\Delta M^* \quad (\text{Eq .1})$$

$$= \Delta P\text{therm} + \Delta P\text{dyn} + \Delta P\text{cross}$$

where erm + ΔPdyn + ΔPcross thermodynamic change due to the specific humidity changes (q), ΔPdyn represents the dynamic change from circulation changes (M*), and ΔPcross is the term due to the changes in both specific humidity and circulation. Further decomposition of ΔPdyn allows us to document changes due to shifts in the pattern of circulation (ΔPshift) or the mean tropical circulation (ΔP_{weak}), as

$$\Delta P_{dyn} = \Delta P_{weak} + \Delta P_{shift} \quad \text{(Eq 2)}$$

$$\Delta P_{weak} = q\Delta M^*_{weak} \quad \text{(Eq 3)}$$

$$\Delta P_{shift} = q\Delta M^*_{shift} \quad \text{(Eq 4)}$$

$$\Delta M^*_{weak} = -\alpha M^* \quad \text{(Eq 5)}$$

where α = (tropical mean ΔM^*)/tropical mean M^* is the change in the weak of the mean tropical circulation. Note that although ΔM^* is a scalar, ΔP_{weak} is provided for each grid point by multiplying by the reference moisture field. ΔM^*_{shift} is calculated by the difference ΔM^* and ΔM^*_{weak}.

Table 1: List of Models used in this work

Models	G3(members)	G4 (members)	Historical (Members)	Rcp45(members)	Reference
BNU-ESM	1	1	1	1	(Verten-stein et al., 2010)
CanESM2	Not available	3	4	10	(Chylek et al., 2011)
CSIRO-MK3L-1-2	Not available	3	4	3	(Parth et al., 2016)
GISS-E2-R	3	3	9	3	Schimidt et al., 2014
HadGEM2-ES	3	3	4	4	(Collins et al., 2011)
IPSL-CMA-LR	1	Not available	6	5	Dufresne et al.(2013
MIROC-ESM	1	1	3	3	(Watanabe et al., 2011)
MIROC-ESM-CHEM	Not available	9	1	9	(Watanabe et al., 2011)
MPI-ESM-LR	3	Not available	3	3	Mauritsen et al., 2019
NorESM1-M	2	1	3	1	Bentsen et al., 2013
GEOSCCM		3	Not available	3	Douglass et al., 2004
CNRM-ESM1		4	1	4	Séférian et al., 2016

-G3, G4 and RCP4.5 simulations: 2050-206

- Baseline simulations (RCP4.5): 2010-2029
- CMIP5 historical simulations: 1986-2005:

1. Results and Discussion

3.1 validation of historical simulation

Historical simulations basing on Precipitation from CMIP5 models have been compared with GPCP and CMAP observations over the same period (Fig. 1. and 2). Most of the CMIP5 simulations used in this work are relatively in the agreement with the observations (CMAP, GPCP), the maxima of precipitation in the West African region are mostly represented approximately over the band located between 10°S to 10°N during African Monsoon period, although some differences in the position of the maxima of P appears in the extension of high precipitation southward from one simulation to another (Fig. 1). All historical simulations present a slight underestimation from one subregion to another in West Africa region (Fig. 1). The CSIRO simulation exhibits a higher underestimation of rainfall while CNR-ESM1 presents an overestimation of rainfall compared with GPCP and CMAP (Fig 2). However, the zone of the P maxima zone is well represented. Mostly, all models agree with the maxima of P distribution, from the ocean to the countries with an intensification of P during the monsoonal period (with the values reaching ~10 mm.d^{-1})

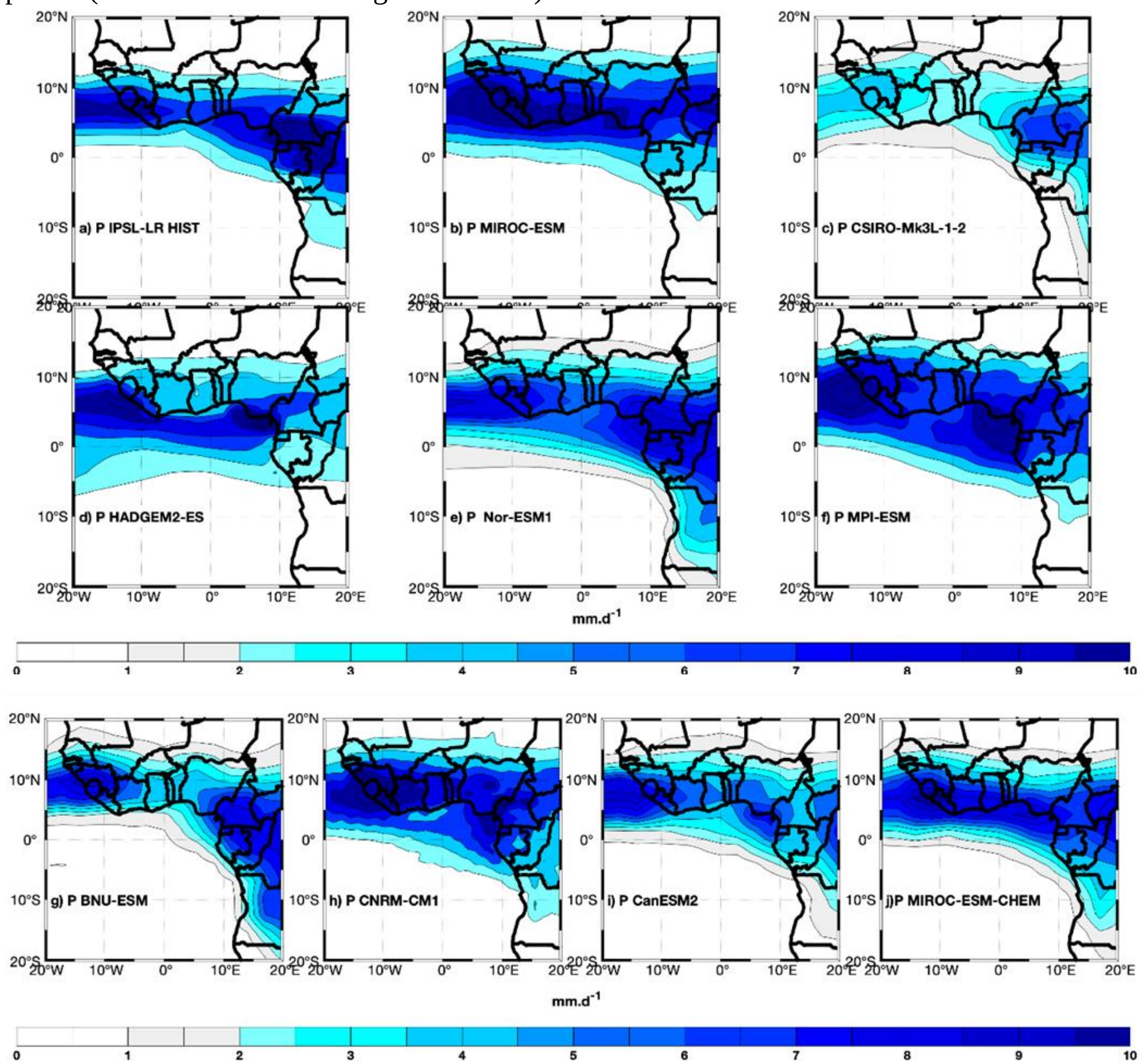

Figure 1: Spatial distributions of monthly precipitation (mm. day -1.) averaged over 1986-2005 between July and October in West Africa from **a)** to **j**) from CMIP5 models

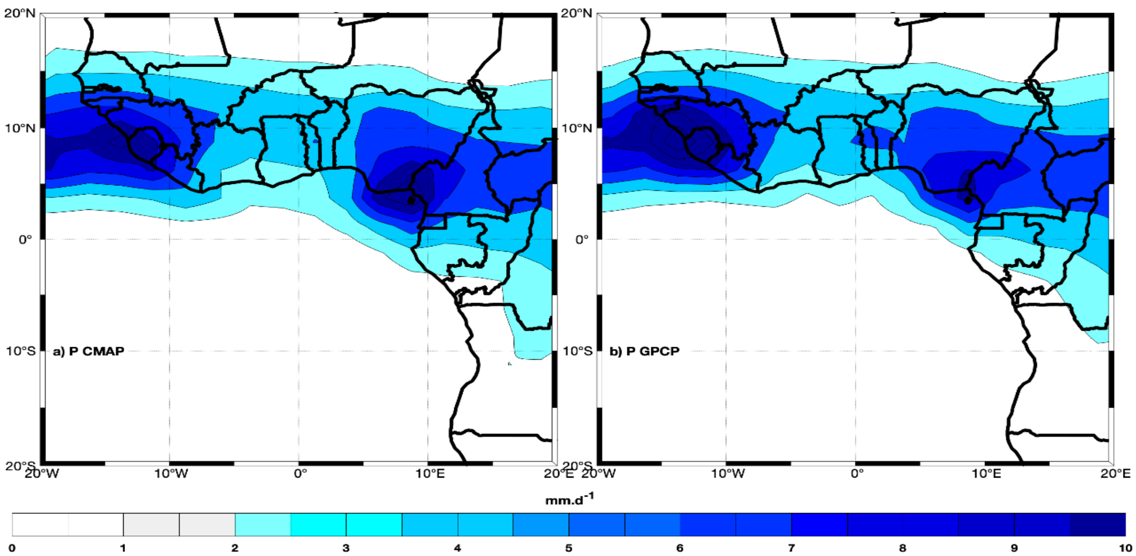

Figure 2: Spatial distributions of monthly precipitation (mm. day -1.) averaged over 1986-2005 between July and October in West Africa from **a** to i) from CMAP and GPCP data

The performances of each Historical CMIP5 precipitation in West Africa are statistically summarized basing on Taylor diagram (Fig. 3) to identify the models which are close with observation data. This diagram provides a concise statistical evaluation of the degree of pattern correspondence between the models and observations regarding their Pearson's correlation (Cor), root-mean-square error (RMSE), and the ratio of their variances (STD). All simulations reproduce the monsoonal precipitation referenced CMAP precipitations, but also to GPCP observations. in West Africa (Fig. 3).

Figure 3: Taylor diagrams showing monthly precipitation averaged over 1986-2005 between July and October in West Africa. The red dot denotes the CMAP observations data.

The analysis of precipitation biases is described through the estimation of the difference between each model and the CMAP observations. Negative changes (~ 5 $mm.day^{-1}$) have been observed over West Africa and Sahel region from one model to another. IPSL-CM5A-LR, MIROC-ESM-CHEM, HadGEM2-ES, MPI-ESM, Nor-ESM1, BNU-ESM, CanESM2 all show an underestimation of precipitation over the Sahel region while a modest overestimation can be observed over West Africa and coastal regions (Fig. 4). CSIRO-Mk3L-1-2 mostly shows strong underestimation compare to the observation over the West Africa and the Sahel region. The ensemble simulations of CMIP5 models show that their historical simulations are less rainy over Sahel region while strong precipitations are distributed over some coastal countries and the southern part of West Africa.

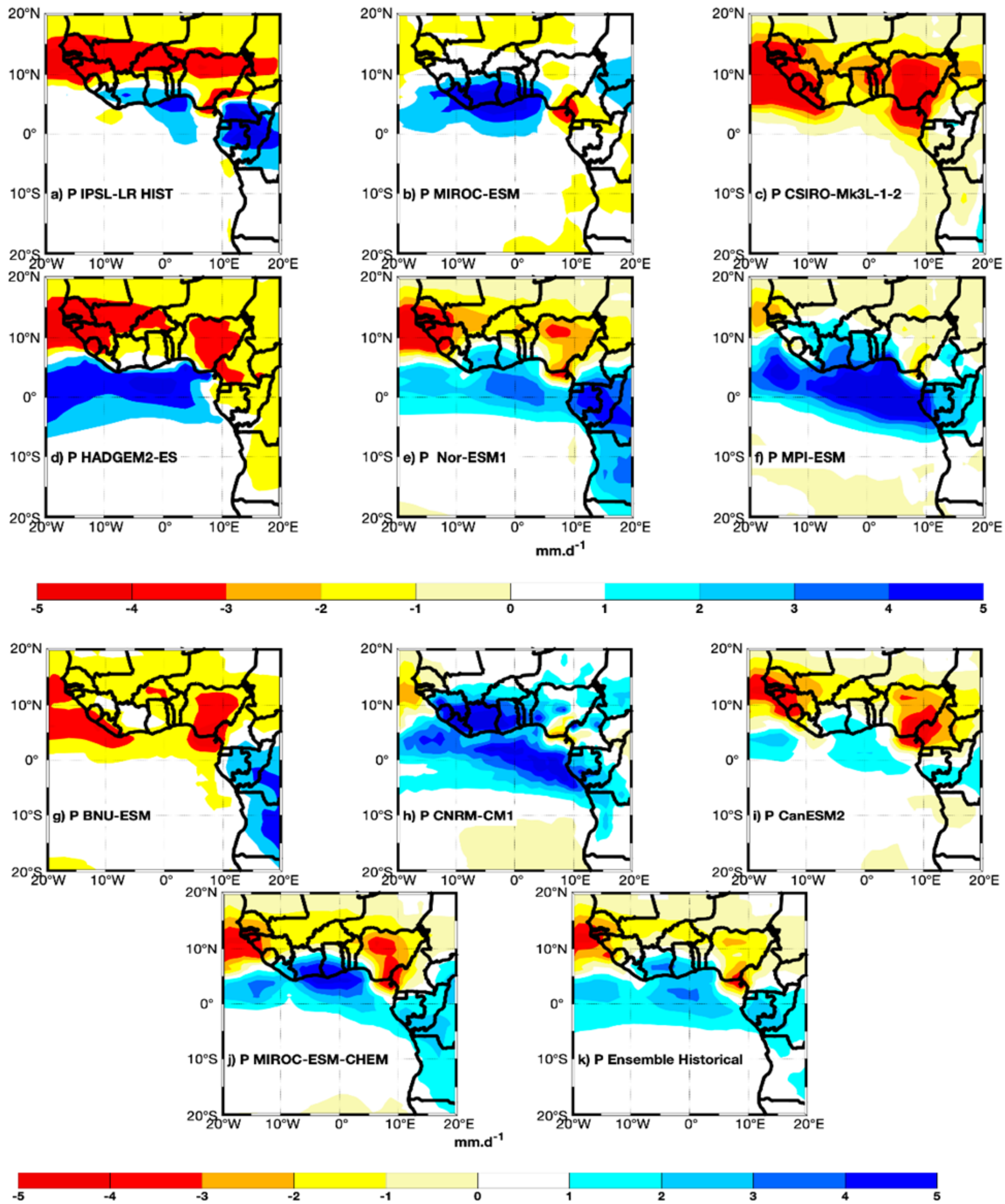

Figure 4: Difference of precipitation between Models and CMAP observations between July and October

3. 2 Impact of global warming and Stratospheric aerosol injection on monsoon P

The changes of precipitation under different G3 simulations have been estimated by calculating the difference between G3 and baseline simulations (RCP4.5, from 2010 to 2029). Most of the models present the decrease of precipitation over the West Africa region (Fig.5), and Sahel region following by GIESS-E2R simulation which presents also increase of precipitation mainly over West Africa. Due to the high influence of both previous models, the ensemble G3 simulations show a slight increase in precipitation under the present-day simulation. The Table 2 below presents the different values of the difference between each G3 simulations and the baseline simulation, the mean bias error (MBE) and their root mean square error (RMSE)

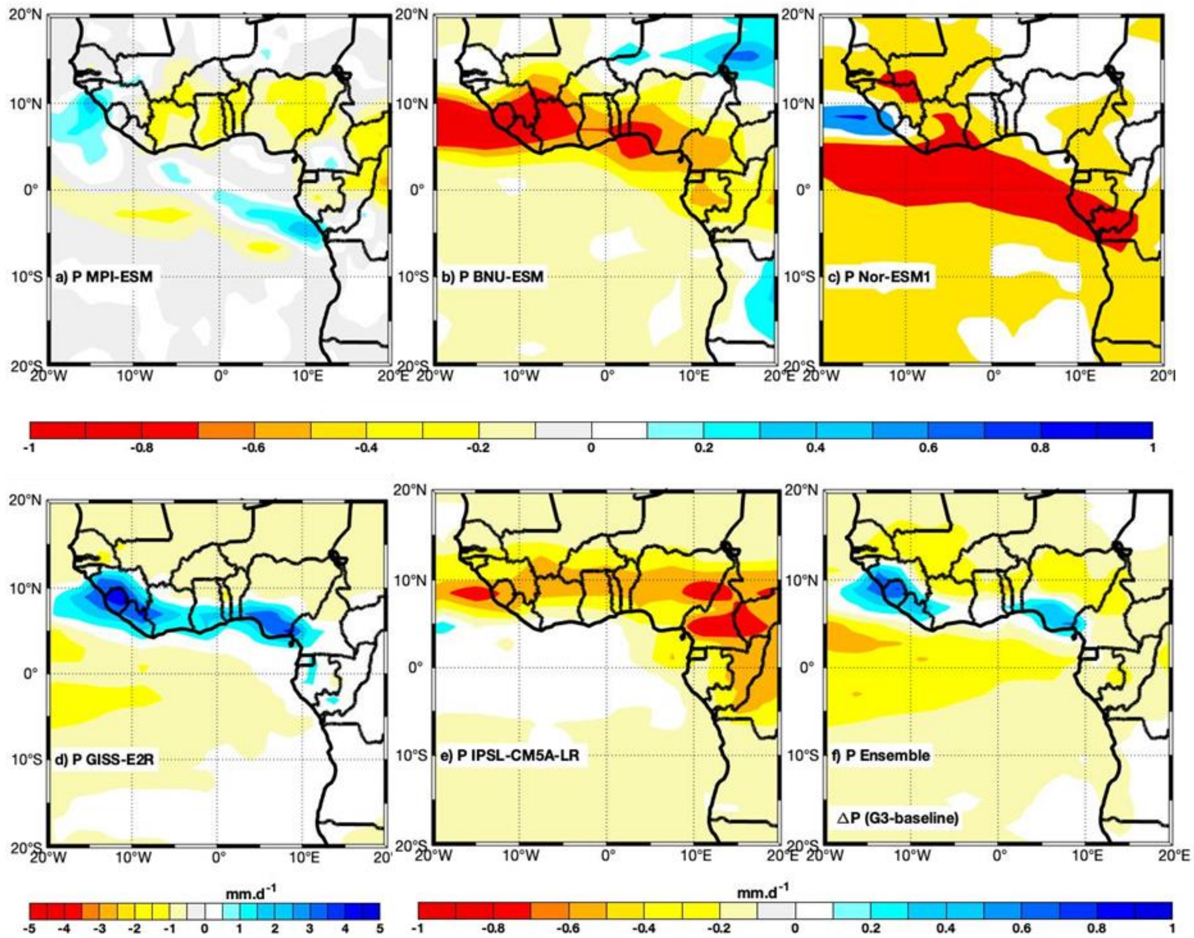

Figure 5: Changes of precipitation between Models and baseline(G3-baseline) simulations during the monsoon period

Table 2: Mean bias error (MBE) and root mean square error (RMSE) between G3 and baseline simulations. All MBE values are significant (t-test, $p<0.05$)

Model	MBE	RMSE	Percentage (%)
MPI-ESM	-0.2007	0.0597	2.4

BNU-ESM	-0.2572	0.0323	6.8
Nor-ESM1	-0.6305	0.1324	8.9
HadGEM2-ES	3.3784	0.3784	
GISS-E2R	0.3176	0.0916	6.8
IPSL-CM5A-LR	-0.0450	0.1145	0.64
Ensemble	0.4452	0.0559	7.8

G4 simulations are the second scenarios analyzed in this study as one of the SAG scenarios. The changes of precipitations are also estimated by retrieving its associated baseline (Fig.6). The models, BNU-ESM, CSIRO-Mk3L-1-2 and GEOSCM show relatively the decrease (~1mm.day-1) of precipitations over West Africa and Sahel regions. However. MIROC-ESM, MIROC-ESM-CHEM present the increase of P over Sahel region.This set of models affect the ensemble simulation which presents a higher increase of precipitation over West Africa and G4 simulation (Table 3). All these mean bias errors (MBE) are tested statistically significant student test ($p<0.05$) except that of GEOSCCM.

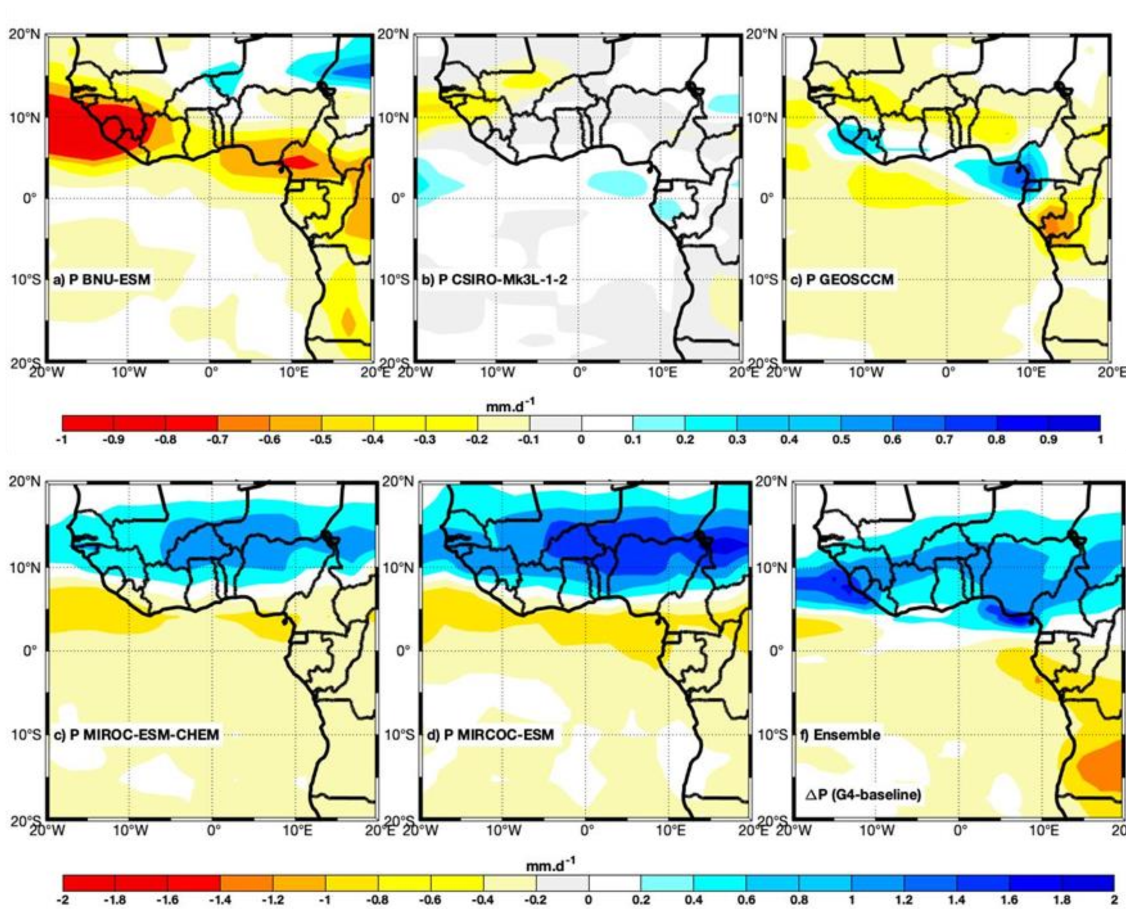

Figure 6: Changes of precipitation between Models and baseline(G4-baseline) simulations during monsoon period

Table 3: Mean bias error (MBE) and root mean square error (RMSE) between G4 and baselines simulations, all values are significant (t-test, p<0.005) except the MBE of GEOSCCM

Model	MBE (mm.day^{-1})	RMSE((mm.day-1)	Percentages (%)
MIRCOC-ESM	-0.5030	0.1033	6.5
HadGEN2-ES	3.4157	0.3452	
BNU-ESM	-0.2992	0.0551	6
CSIRO-Mk3L-2-2	0.0677	0.0342	2.6
MIROC-ESM-CHEM	-0.4450	0.0778	7
GEOSCCM	0.0073	0.0893	0.01
Ensemble	0.3865	0.2387	6.4

3.2.1 Precipitations changes under global warming (RCP45-baseline)

Under global warming, the changes of precipitation have been estimated by calculating the difference between each RCP4.5 model and its baseline simulation. Different trends of precipitations changes have been observed over West Africa and the Sahel region (Fig. 7). The ensemble simulation exhibits mostly the increase of precipitation over West Africa and Sahel region. The results vary from one model to another. Negatives changes are observed over West Africa and the Sahel region with MPI-ESM, BNU-ESM, Nor-ESM1, and MIRCOC groups Models (Table 4). This trend of precipitations with these simulations is opposite to that of the rest of RCP4.5 simulations and the ensemble simulations.

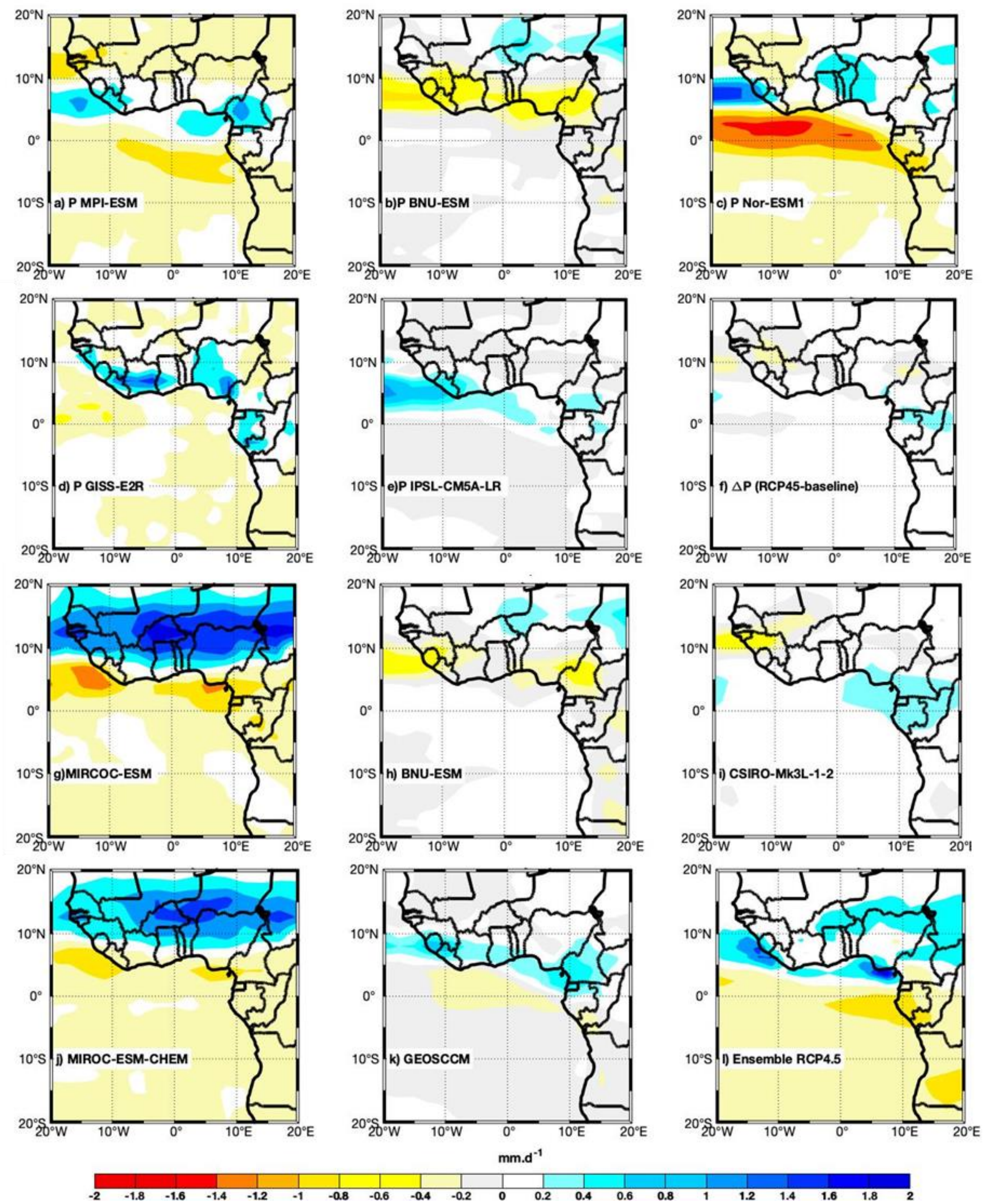

Figure 7: Changes of precipitation between Models and baseline (RCP4.5-baseline) simulations during the monsoon period

Table 4: Mean bias error (MBE) and root mean square error (RMSE) between RCP4.5 and baseline simulations

Model	MBE	RMSE	Percentage of changes (%)
MPI-ESM	-0.1392	0.1323	1.6
BNU-ESM	-0.0781	0.0518	2.1
Nor-ESM1	-0.4599	0.1228	6.6
GISS-E2R	0.0895	0.0651	1.9
IPSL-CM5A-LR	0.2376	0.1205	3.4
MIROC-ESM	-04945	0.0785	6.4
CSIRO-Mk3L-2-2	0.1867	0.1867	7.2
MIROC-ESM-CHEM	-0.3174	0.663	5
GEOSCCM	0.0279	0.0001	0.04
Ensemble	0.4294	0.0534	10

The IPSL-CM5A-LR models are used in this work to analyze the mains mechanism driven precipitations changes under SAG and global warming. The reason for that choice is basing on the availability of specific humidity data at pressure levels near 950hPa in IPSL-CM5A-LR as used in (Da-Allada et.al, 2020). In this work, RCP4.5 simulations have been chosen as G3 simulations derived directly from RCP4.5. Under RCP4.5 at global warming conditions, the monsoonal precipitation change is determined by computing the difference of P between two different periods (RCP4.5: 2050–2069) relative to baseline (RCP4.5: 2010-2029) as recently done by Da-Allada et al. (2020) with GLENS simulations. An increase in summer monsoon precipitation is most observed toward the oceanic zone adjacent to the West Africa region (Fig. 8a) associated with the slight increase of P in West African region. All the West Africa countries are not affected by this P change on P, it is important to note that this increase observed is not statistically significant. However, the main processes responsible for the P changes (ΔP) under RCP4.5 is due to monsoon precipitation shifts distribution (ΔPshift), otherwise the dynamic process (Fig 8b-d) similar mechanism with the results of Da-Allada et al. (2020) who also found the dynamic process as the mains mechanism responsible of P change under RCP8.5 with GLENS simulations. The ΔPcross contribution is low toward to precipitation changes (Fig. 8c). The increase of ΔPtherm distribution is also observed from the equator toward the north part, this pattern also contributes slightly to the change of P observed under global warming (Figs. 8b and 8g). This pattern of ΔPtherm is explained by the increase of specific humidity (Fig 8a and 8b). ΔPdyn distribution shows mostly a decrease between 5°- 10°N. A slight decrease (~ -0.1 mm.day^{-1}) appears over the Sahel region (Both North and South region) under RCP4.5 simulation, contrary patterns have been recently found by Da-Allada et al. (2020).

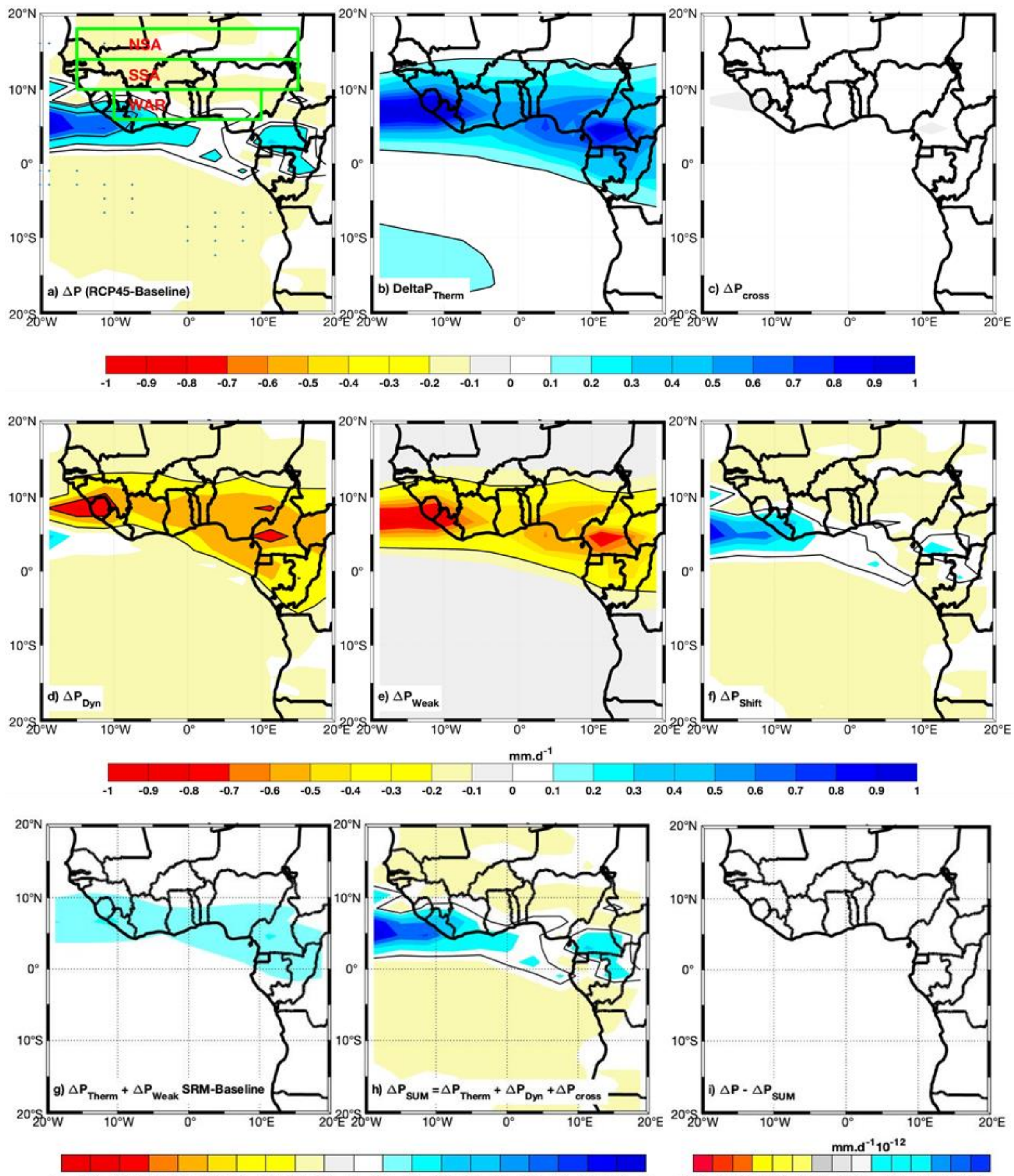

Figure 8: (a) Changes in monsoon precipitation under RCP4.5 related the baseline with its different terms, (b) thermodynamic (ΔPtherm), (c) nonlinear cross term (ΔPcross) and (d) dynamic (ΔPdyn). The dynamic component (ΔPdyn) is decomposed into (ΔPweak) and (ΔPshift). The Fig 8.g presents the sum of ΔPtherm+ ΔPweak, h) presents the sum of ΔPtherm + ΔPcross+ ΔPdyn, the difference between Fig8.a (the model precipitation change) and Fig8.h (the sum of all the components of precipitation change).

ΔPdyn term has been decomposed according to Equation 2 by dissociating this term into a term associated with the weakened low-level monsoon (ΔPweak) and a term associated with the local dynamic feedback in charge of monsoon precipitation shifts distribution (ΔPshift). The spatial distribution of ΔPweak presents the constrat pattern with ΔPtherm (Fig. 8.b and 8.e). The amplitude of ΔPtherm is dominant over that of ΔPweak, as their sum remains positive (Fig 8.g). The distribution of ΔPshift has a similar patterns trend as that of P (Figs. 8.a and 8.f). The ΔPshift has a similar pattern of distribution as the ΔP, thus ΔPshift component of ΔPdyn is responsible for the changes in ΔP. The change of precipitation under RCP4.5 based on the decomposition method is similar to the change in P (Figs 8.a and 8.h) and their difference is null (Fig. 8i), emphasizing that the decomposition method used is consistent to demonstrate changes in West African Monsoon precipitation. The similar concept has been used by Da-Allada et al. (2020) to explain the changes basing on P decomposition. In conclusion, the changes in precipitation under RCP4.5 are mainly driven by the dynamic process.

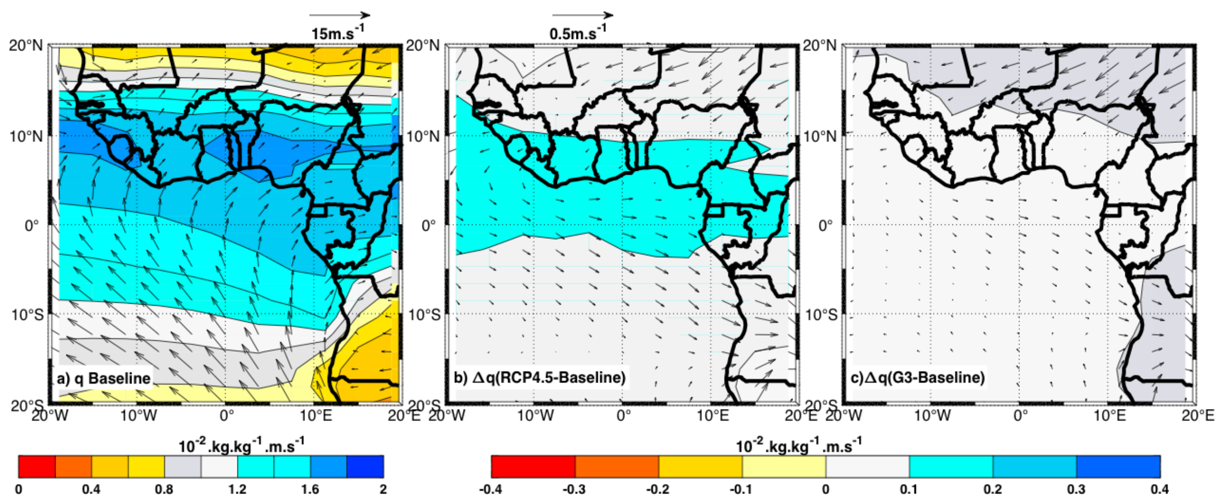

Figure 9: Spatial distributions of average monthly near surface specific humidity (in color) and surface wind field (vectors) at 955 hPa for the baseline simulation over 2010-2029, b) differences (relative to the baseline) in mean surface specific humidity (color) and near-surface wind (vectors) under RCP4.5, 2050-2069 at same pressure level and c) same as in b with G3 simulation)

3.3- Impacts of P changes and its main causes under G3

Under SAG, the spatial monthly distribution of P in G3 simulation relative to that of baseline shows the decrease in summer monsoon precipitation in West African regions (Fig.

10.a) This change of P is similar to that obtain in Da-Allada et al. (2020) who determined the decrease of P under G3 simulation of GLENS model over this region. This precipitation change is also significant in West African Countries (Fig. 10.a). As in the RCP4.5, the contribution of ΔPcross to precipitation changes is also negligible under G3 simulations (Fig. 10.c). ΔPtherm does not contribute to precipitation change under G3 due to the lower difference in the near-surface specific humidity compared with the baseline (Fig. 9.c and Fig 9.b). The contribution of dynamic terms (both weak and shift terms) explains the change in P under G3, from both components, the ΔPweak component has a similar magnitude as that of P, but it is also noted the contribution ΔPshift with a decrease (~0.2 $mm.day^{-1}$), therefore both these terms of dynamic terms can explain the decrease in precipitation (Figs. 10.a, 10.e and 10.f). Their contribution is largely associated with the low-level land-sea temperature contrast (Da-Allada et al., 2020). The change in monsoon rainfall under G3 primarily based on the decomposition approach is equal to the change in precipitation simulated (Figs. 10.a and 10.h) and the difference between these two terms is negligible (Fig. 10.i). In conclusion, under G3, change in precipitation is explained by the dynamical process, that leads to weakened monsoon circulation of the monsoon precipitation distribution and a shift in the monsoon precipitation.

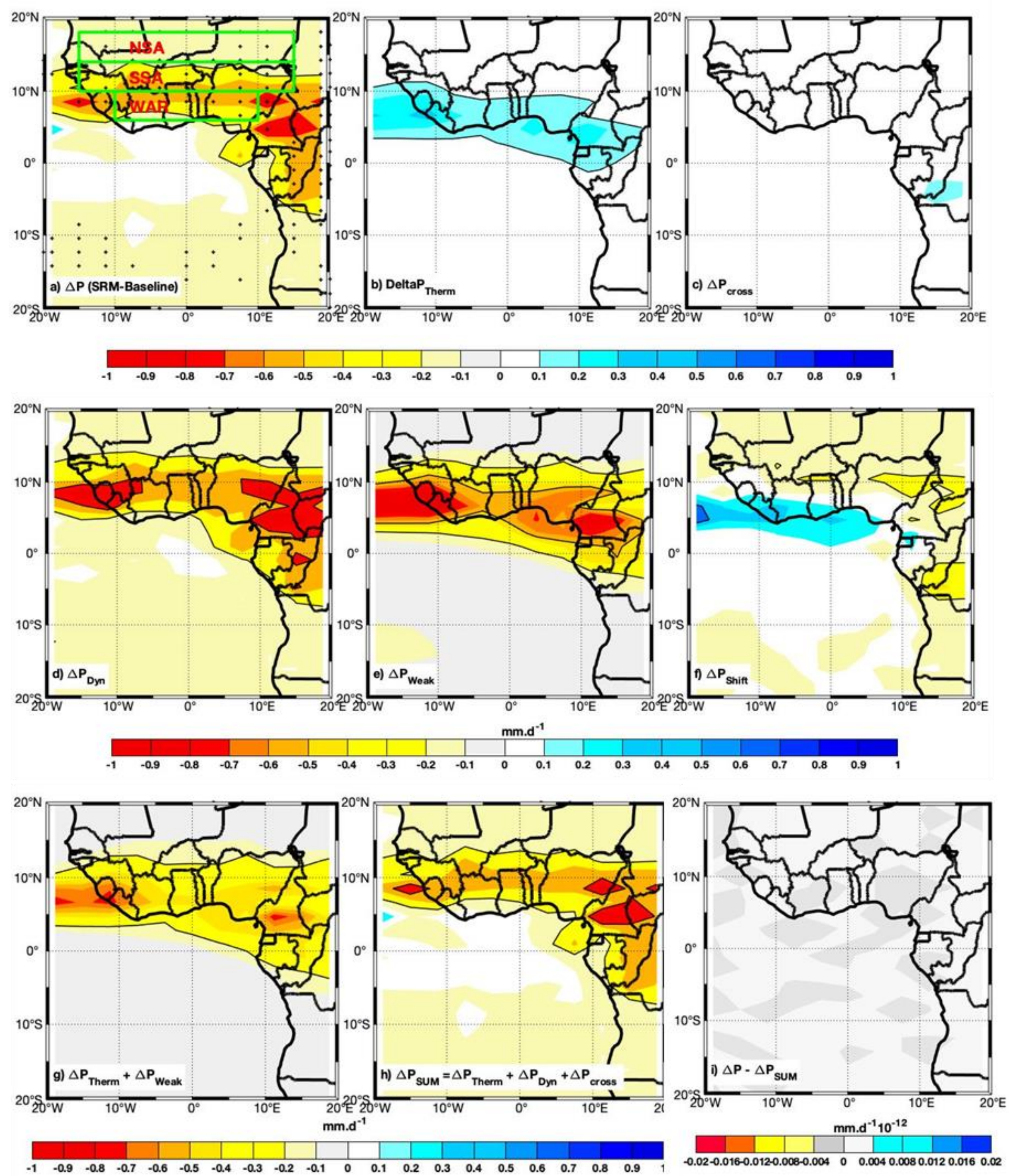

Figure 10: (G3 – Baseline) similar to Fig 8.

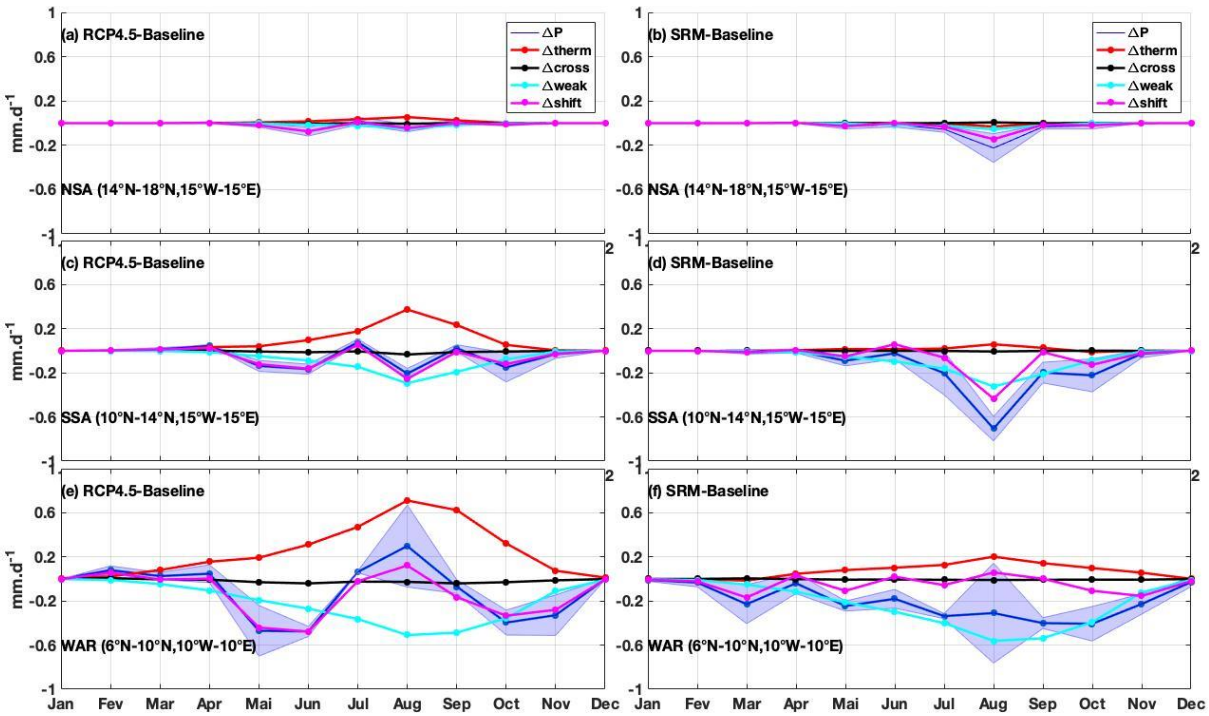

Figure 11: Seasonal cycles of precipitation changes and the different components of precipitation changes (see Figure 8) under RCP4.5 (left column) and G3 (IPSL-CMAP-LR) (right column) relative to the baseline for the Northern of Sahel (a and b), Southern of Sahel (c and d), and the Western Africa region (e and f). Here the nonlinear component of precipitation (ΔPcross) is added and the blue shaded areas indicating the standard error on the term of precipitation changes. Changes in precipitation are obtained as in Figures 8 and 10. All units are mm. day $^{-1}$.

The changes in P using IPSL-CMAP-LR simulations (CMIP5 and GeoMIP) with its different components decomposition for three different regions (NSA, SSA, and WAR) have been presented in West Africa (Fig. 11) similar to those defined by Da-Allada et al. (2020) who considered in their work the Northern Sahel (NSA; 18°N–14°N, 15°W–15°E), the Southern Sahel (SSA; 14°N–10°N, 15°W–15°E), and the Western Africa region (WAR; 6°N–10°N, 10°W–10°E). Under RCP4.5, slight decreases of P have been found (0.005 ± 0.075 i.e. 0.86%) and (0.03 ± 0.17 i.e. 0.8 %) in the NSA and SSA but these changes are not significant (Fig. 4.a , Fig. 10.a and 10.c) over both sub-regions contrary to those of Da-Allada et al.(2020) which found significant increase with GLENS simulations. Otherwise the increase of P (0.09±0.29 i.e. 1.04 %) has been obtained in Western Africa Region (WAR) similar trend variation in agreement with that of Da-Allada et al. (2020). This result suggests that under RP.4.5, the increase will be moderated in WAR. Under SAG with G3 simulation, during summer period, the precipitation decreases (0.10± 0.12 i.e. 17.4%) and (0.36± 0.29 8.47 %) respectively in the NSA and SSA, this pattern is not similar to that found by Da-Allada et al.(2020) in NSA but found a slight decrease in SSA during the summer period with GLENS Simulation These results in both regions may be taken with reserve due to the non-significant change under RCP.4.5 and baseline, however Da.-Allada et al. (2020) found that deployed the SAG in these regions will be effective. The decrease by and (0.34± 0.25 i.e. 3.71%) have been noted in WAR while Da. Allada et al. (2020) obtained 0.72 ± 0.27 mm (10.87%) of decrease over this sub-region. Their decrease in P is higher than that obtained in this study, this may be due to the use of RCP8.5 simulations have accentuated effect on P. In these three regions, during the boreal summer, changes in precipitation relative to the baseline for RCP4.5 and G3 are important comparing with those of evaporation (Fig. 12) over SSA and WAR. The changes in rainfall are larger than those of evaporation in SSA and WAR regions while the change in rainfall is similar to that of evaporation in NSA region. These results are similar to those observed in Da-Allada et al. (2020) using GLENS simulation. The physical processes responsible for rainfall changes in precipitation under RCP4.5 are associated with the changes in the monsoon circulation that shifts monsoon precipitation (shift component in Fig.11). Under G3 simulation, in the three regions, changes in precipitation have the same trend as the weakened component of dynamic precipitation change (Fig.11).

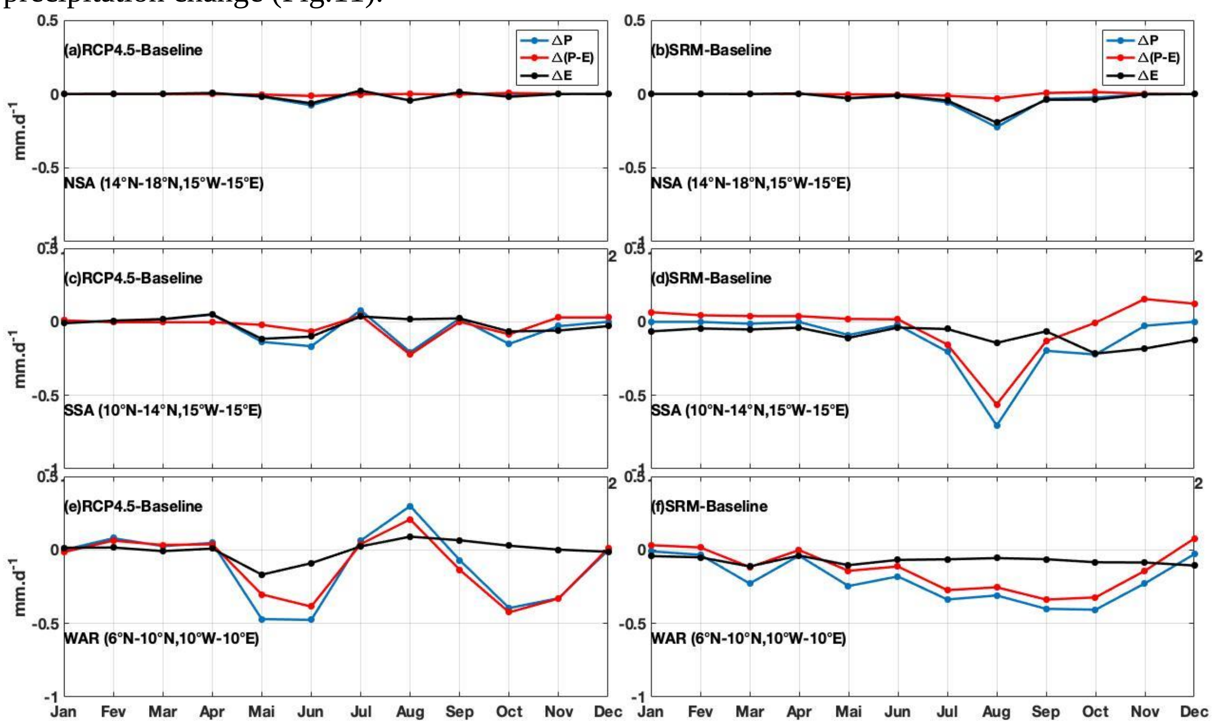

Figure 12: Monthly variability of precipitation, precipitation-evaporation and evaporation changes (relative to the present-day climate simulation) under RCP4.5 (left column) and G3 (right column) for the Northern of Sahel (a and b), Southern of Sahel (c and d), and the Western

Africa region (e and f). Changes are for the period 2050–2069 relative to the present-day similation. All units are mm. Day^{-1}

Recently, Cheng et al. (2019) computed the boreal summer efficacy of geoengineering, which balance the impacts of high GHGs emissions (ratio of Geoengineering–High-GHGs difference over that of HighGHGs–Baseline) for precipitation. The efficacy value >-1 leads to under compensation induced by geoengineering relative to baseline whereas the efficacy value <-1 suggests geoengineering leads to over compensation relative to baseline. In this work, we did not calculate the efficacy for NSA and SSA due to non-significant changes of P found under RCP4.5; therefore, we only focused our calculation in WAR. We obtained the mean efficacy value of precipitation equal to $-3.51 <-1$ (high over compensation) in WAR, this result is similar to that found recently by Da-Allada et al. (2020).

Discussion

In this study, the historical precipitation of CMIP5 models have been validated by comparing these models with CMAP and GPCP observation. The changes of precipitation under climate change and climate geo-engineering through the application of Stratospheric Aerosol Geoengineering have been determined over West Africa and Sahel region using RCP4.5 and G3/G4 models from GeoMIP simulations. These (G3/G4) GeoMIP simulations are the simulation with which SAG have been deployed. The possible impacts of SAG and the present-day scenario on precipitations within the period of (2050-2069) have been analyzed. The main mechanisms of rainfall changes have been determined using IPSL-CMA5-LR (due to availability of specific humidity data near 950hPa) basing on the methods used in Da-Allada et al. (2020).

All CMIP5 models are relatively in agreement with CMAP and GPCP precipitation. Their general patterns in estimating West African Monson precipitation mainly during July and October is comparable with observations. However, underestimation and overestimation of precipitation are also pointed out over some regions of West Africa from one model to another. CSIRO-Mk3L-1-2, BNU-ESM models present an underestimation of rainfall over the whole West Africa and Sahel Region while MPI-ESM, CNRM-CM1 models present slightly overestimation of precipitation over these regions. Statistically, the ensemble simulations of all the models shows underestimation of P in term of their behavior in estimating WAM. Recently Da-Allada et al. (2020) reported some underestimation of GLENS simulation compared with CMAP and GPCP rainfall. These model biases over certain regions of West Africa and Sahel region could be explained by the poor simulation of orographic forced ascent or the large uncertainty in the model precipitation estimates over this region (Akinsanola & Zhou, 2018; Diallo et al., 2016, Da-Allada et al.,2020).

The analysis of the precipitation changes shows relatively the decrease of precipitation over

West Africa (Table 2, & table 3) under SAG while under global warming, most of simulations shows the increase of precipitation compared with present- day simulations (Table 4). MIROC-ESM an MIROC-ESM-CHEM show increase of precipitation under G4 simulations. This is due to the biases in these models. The decrease of precipitation is observed under global warming condition (RCP4.5) with some of RCP4.5 simulations, however, the ensemble simulation and must of simulation agree with P increase under global warming (Table 4). Recently increase of precipitation has been observed under global warming (RCP8.5) and decrease of P under SAG in Da-Allada et al. (2020) using GLENS simulations. Some of opposite trend presented in this study could be explained by some higher biases in such models. Dike et al. (2014) have pointed out the overestimation of precipitation biases in some climate models over West Africa. They associated the reason to the fact that these models do not capture the changes in the Sea Surface Temperature within the Gulf of Guinea, which modulates the African monsoon circulation. These biases have revealed that the transition phase of African monsoon circulation is not well-represented by the model. However, this model simulates well the seasonal variability of precipitation in this region during summer monsoon precipitation period.

The decomposition methods (Da-Allada et al., 2020, Monerie et al. 2020, Kent et al. 2015; Chadwick et al. 2016; Rowell and Chadwick 2018) used in this work are consistent to investigate the possible causes of precipitation. This method allows understanding of the mechanisms that driven precipitation change in terms of dynamic and thermodynamic changes. Under RCP4.5, the increase of Precipitation in IPSL-CM5A-LR simulations is explained by the dynamic process. A similar result has been obtained by Da-Allada et al. (2020) to explain the changes basing on P decomposition. This method has not been applied to other models used in this work as they have lower vertical resolution and there are missing of specific humidity at near-surface pressure level in these models except IPSL-CM5A-LR model

Under SAG, we obtained previously with this model, the decrease of precipitation in West Africa and Sahel region. The dynamic terms (both weak and shift terms) are mainly responsible for the precipitation change. Recently, Da-Allada et al. (2020) emphasized that their contribution is largely associated with the low-level land-sea temperature contrast.

This work is based on precipitation changes under global warming and SAG with G3 and G4 scenarios that have been performed using CMIP5 and GeOMIP for the first time in West Africa. Recently similar work has been done using GLENS simulations in Da-Allada et al. (2020). The GLENS models show relatively the same spatial trend of shifts and changes in magnitudes of the precipitation features obtained with IPSL-CM5A-LR simulations. Monerie et al. (2020) using RCP8.5 of CMIP5 models found that the change in precipitation is explained by dynamical term of P decomposition. We found also a similar mechanism for the precipitation change under global warming, this change of P is explained by dynamic process mainly the shift component of precipitation This is similar to that obtained in Da-Allada et al. (2020) using RCP8.5 scenarios of GLENS simulations. The change of precipitation under SAG using

GeoMIP remains also the same patterns. Under GLENS, Da-Allada reported the changes in the West African Summer Monsoon precipitation which are largely explained by the reduction in land-sea thermal contrast in the lower troposphere that leads to weakened monsoon circulation and a northward shift of the monsoon precipitation patterns.

Most of CMIP5 and GeoMIP model data analysis shows that precipitation will increase over the Sahel and West African region under global warming while decrease of precipitation appears mostly under SAG. Decomposing precipitation helps to determine the mains causes of precipitation change. Basing on the decomposition methods, we fund that the change in precipitation is explained dynamical processes using IPSL-CM5A-LR model. This is consistent with Da-Allada. (2020), who found a similar behavior but using GLENS simulations, our results strengthen their finding with other climate model mainly the GeoMIP simulations. However due to biases in climate models, some of these models present opposite trend of precipitation changes (from Table 2 to table 3). This is due to the fact that some climate models such as CMIP5 and hereafter GeoMIP present significant uncertainties on their behavior representing the African Monsoon precipitation in Sahel region and also in African region (Monerie et al. (2020).

The hydrological cycle in this region can be affected by the deployment of SAG. Thus, the application of SAG in West African region using both G3 and CMIP5 simulations will over compensate the changes in precipitation in the Western Africa region. This recommends counterbalancing all warming would be going excessively far if the objective were to reestablish the Western Africa monsoon precipitation; rather, this would require restricting SAG arrangement to balancing 1/3 of RCP4.5 warming as previously proposed in Da-Allada et al. (2020) using RCP8.5 and G3 simulation of GLENS model. As the connection between global mean warming and regional precipitation change is dependent upon enormous vulnerabilities, this model outcome ought to be taken with consideration in the monitoring of future climate.

Conclusion

This paper contributes to the analysis of monsoon precipitation on precipitation changes and the mechanisms responsible of these changes during boreal summer in West Africa using CMIP5 and GeoMIP simulations. In general, all models reproduce relatively the monsoon precipitation patterns compared with to observations data all models agree with the intensification of P during West African Monsoon period. IPSL-CMA5 –LR simulations have been used in this study to investigate the mains mechanism inducing changes of precipitation under global warming and climate geo-engineering. An increase in summer monsoon precipitation is slightly observed over West Africa Region and most accentuated over coastal zone adjacent to West Africa countries located below 10°N under RCP4.5. These changes on monsoon P under RCP4.5 are mainly driven by the dynamic process. Under G3 simulation, the decrease above 5°N during boreal summer has been reported in West Africa and Sahel region. This change of P under G3 precipitation is mainly explained by the dynamic process (both shift and weak term), which leads to a weakened monsoon circulation and a shift in the distribution of monsoon precipitation.

Three specific regions have been considered, NSA, the SSA, and the WAR similar to that of Da-Allada et al. (2020). Under RCP4.5, during the monsoon period, non-significant precipitation decreased by (0.005 ± 0.075 i.e. 0.86%) and (0.03 ± 0.17 i.e. 0.8 %) are reported at NSA and SSA respectively while rainfall increase of P (0.09±0.29 1.04 %) compared with present-day simulation in WAR region. However, with G3, relative to the baseline, the WASM rainfall, the precipitation decreases (0.10± 0.12 i.e. 17.4%) and (0.36± 0.29 i.e 8.47 %) respectively in the NSA and SSA while the decrease by and (0.34± 0.25 i.e. 3.71%) has been noted in WAR. Due to the non-significant changes over NSA and SSA, the efficacy mean has been considered only for WAR region. Using SAG will therefore have no major effect in the Sahel regions (NSA and SSA), whereas it can be over effective in the WAR. The mean efficacy ratio of SAG (−3.51) determined during the monsoon period suggests a high over compensation in WAR. In the West Africa Region, if the goal were to reestablish the Western African Monsoon precipitation, this work recommends that the organization of SAG ought to be restricted to balance 1/3 of RCP4.5, as previously suggested by Da-Allada et al. (2020)

In agreement with previous studies (e.g., Da-Allada et al, 2020, Cheng et al., 2019), our results showed that WASM precipitation decrease also under G3 simulation as they recently found with GLENS simulations. This study is a contribution to the determination of the physical processes responsible for precipitation changes in the WAR using G3. Our findings indicated that changes in precipitation in this region are largely led by the changes in the monsoon circulation which derive from the reduction of the thermal gradient induced by the application of SAG. Understanding the mechanism of the precipitation decrease will contribute to improve and implement the strategies for stratospheric aerosol injection to mitigate the effect of SAG on precipitation changes.

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Conflicts of Interest: The author declares no conflict of interest.

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