



# La Plata Basin Hydroclimate Response to Solar Radiation Modification With Stratospheric Aerosol Injection

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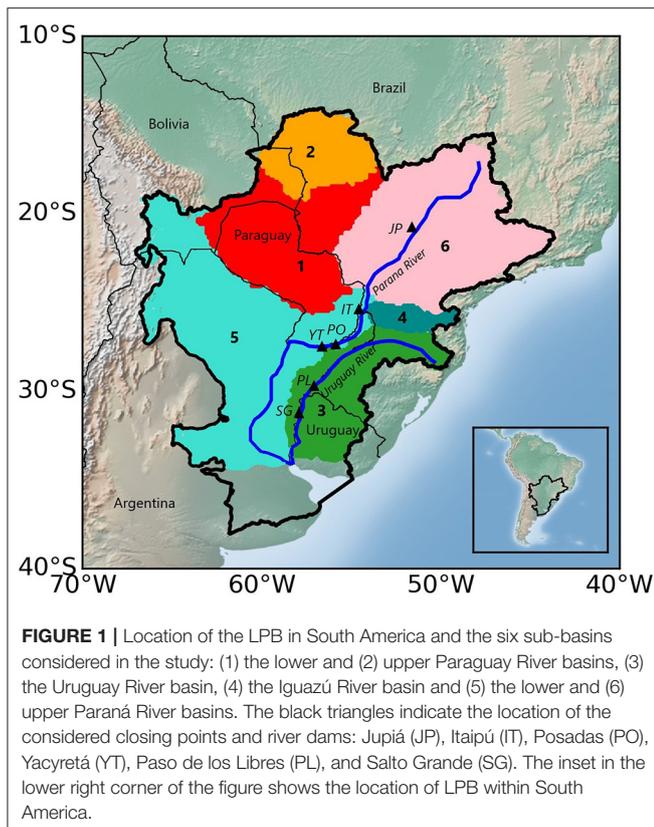
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This study analyses the La Plata Basin (LPB) hydroclimate response to Solar Radiation Modification (SRM) with Stratospheric Aerosol Injection (SAI) in terms of changes in mean and extreme temperature, rainfall, and river flows simulations from the Geoengineering Large Ensemble (GLENS). The GLENS data used consists of three members simulations of a single model under the high anthropogenic emission scenario RCP8.5 with and without sulfur injection in the tropical stratosphere. The response of such an intervention is compared to a historical period (1980–2010) and to projections under the RCP8.5 scenario for two time slices: 2021–2050 and 2051–2080. The analysis of changes in extreme temperature and precipitation focuses on a subset of climate indices from the Expert Team of Climate Change Detection and Indices (ETCCDI). To determine the possible effects of SRM in the LPB water cycle, we use the distributed Variable Infiltration Capacity (VIC) hydrologic model in combination with daily extreme temperature and precipitation outputs from GLENS. Systematic errors in both fields were corrected by the application of a statistical bias correction method. Results show robust impacts on the water cycle of the LPB due to SRM implementation, particularly associated with increased precipitation over the northern part of the region and a general reduced warming compared to the RCP8.5 scenario. These variations would lead to regional-dependent responses in the river flows, mostly related to reductions in the severity of the extremely low flow conditions. Additionally, under the SRM scenario a reduction in extreme precipitation and a cooling effect on extreme temperatures could be expected over the LPB.

**Keywords:** climate change, extremes, solar geoengineering, GLENS, hydrologic model, South America

## INTRODUCTION

The La Plata Basin (LPB) is a transboundary river basin in South America, situated between  $\sim 67^{\circ}\text{W}$  and  $43^{\circ}\text{W}$  and  $15^{\circ}\text{S}$  and  $38^{\circ}\text{S}$  latitude (Figure 1). It is bounded to the west by the Pampean ridges and the pre-mountain range of the Andes and to the northeast and the east by the Brazilian Plateau and the Serra do Mar, respectively. It is the fifth largest freshwater basin in the world, and the second in the continent, after the Amazon basin.



During the last decades, this region experienced a robust positive precipitation trend attributed to the increase of anthropogenic greenhouse gases (Vera and Díaz, 2015; Zhang et al., 2016; GHG). Also, the LPB has been subject to other climate trends such as increased precipitation and river flows as well as extreme temperatures and rainfall (Barros et al., 2015; Cavalcanti et al., 2015; Dai, 2016; Cerón et al., 2021). Consequently, large areas along the margins of the middle and lower sections of the Paraná and Uruguay rivers, the main tributaries of La Plata River in terms of discharges, were subject to large floods that led to critical streamflow and considerable damage (Barros et al., 2015). As a result of an increase in the atmospheric GHG concentration, the LPB is projected to get warmer in the upcoming decades, with a more noticeable temperature increase in its northern half section. At the same time, projections suggest that there would be an increase in precipitation, mainly over the southern part of the basin (Montroull et al., 2018; Zaninelli et al., 2018). Additionally, a trend toward a gradual increase in streamflow was found for most of the rivers (Saurral et al., 2013; Betts et al., 2018) with more frequent and longer-lasting fluvial flooding events in the lower basin (Camilloni et al., 2013).

In addition to mitigation and adaptation and considering the ambitious climate targets of the Paris Agreement to limit global warming to well below 2°C and pursue efforts to limit it to 1.5°C compared to the preindustrial era (UNFCCC, 2015), other options for counteracting climate change have

been proposed, such as climate interventions in the form of geoengineering (Crutzen, 2006; Wigley, 2006; MacCracken, 2009; Keith and MacMartin, 2015). Solar radiation modification (SRM) is a geoengineering strategy suggested to intentionally reduce the sun's incoming radiation and to cool the climate. SRM implementation has been presented as a possible pathway to avoid some of the worst consequences of global warming and to meet the Paris Agreement warming targets (Lawrence et al., 2018) while society transitions to carbon-free energy solutions. However, SRM is a controversial strategy and would come with benefits but also risks and concerns, and socio-political implications. Quantifying these potential benefits and risks must occur prior to any implementation of SRM. For example, it has been found that while the intensity of the global hydrological cycle is expected to enhance in response to GHG-induced warming due to the increases in lower tropospheric water vapor and net downward radiative flux (Held and Soden, 2006), solar geoengineering would lead to a less intense global water cycle with potentially significant changes in regional precipitation patterns (Bala et al., 2008; Robock et al., 2008; Tilmes et al., 2013; Dagon and Schrag, 2016).

Although the technical and financial feasibility of SRM is still under debate, a key area of concern is the insufficient knowledge about the potential impacts at regional scale. Stratospheric aerosol injection (SAI) is one SRM method that aims to replicate the cooling effect of volcanoes by spraying reflective sulfate particles into the stratosphere (e.g., Brovkin et al., 2009; Robock et al., 2013). Different studies show that maintaining global mean temperatures at a given level by SRM through SAI results in diverse regional climate impacts (Robock et al., 2008; Simpson et al., 2019; Da-Allada et al., 2020; Odoulami et al., 2020; Pinto et al., 2020; Abiodun et al., 2021). Recently, Irvine and Keith (2020) studied the fraction of regions where SAI could exacerbate or moderate climate impact when SAI is applied to halve the warming produced by doubling CO<sub>2</sub>. They found that almost none of the four analyzed variables (annual mean temperature, yearly maximum temperature, maximum annual precipitation rate and precipitation minus evaporation) are exacerbated when averaged over the Intergovernmental Panel on Climate Change (IPCC) Special Report on Extremes (SREX) regions (Seneviratne et al., 2012). This is the case for the southern South America (SSA) region of which the LPB is part. However, this result cannot be extrapolated to the LPB as SSA is large enough to encompass sub-regions with different climate regimes leading to a recent update of the IPCC climate reference regions (Iturbide et al., 2020).

The objective of this paper is to evaluate the LPB hydroclimate response to SRM in comparison to a high emission scenario in terms of changes in water availability, mean temperature and rainfall, and hydrological and climate extremes using simulations from the Geoengineering Large Ensemble (GLENS). The structure of the manuscript is as follows: the study area, methods and data used in this analysis are explained in section study area, data and methodology, the main results are shown in section results, and a discussion and conclusions are provided in section discussions and conclusions.

## STUDY AREA, DATA, AND METHODOLOGY

### Study Area

The LPB covers 3.1 million km<sup>2</sup>, comprising southern Brazil, southeastern Bolivia, a great part of Uruguay, Paraguay, and an extensive area of central and northern Argentina. It can be divided into six sub-basins: lower and upper Paraguay, Uruguay, Iguazú, lower and upper Paraná. The three main river systems in the LPB are: the Paraguay River, with an annual average flow of 2,800 m<sup>3</sup>/s at Asunción, the Paraná River with an annual average flow of 12,000 m<sup>3</sup>/s at Itaipú and the Uruguay River, with an annual average flow of 4,700 m<sup>3</sup>/s at Salto Grande. These latter two rivers come together to form La Plata River, draining into the southwestern Atlantic Ocean, with an average output of 25,000 m<sup>3</sup>/s. The Paraná River has a drainage basin of 2.6 million km<sup>2</sup> while the Uruguay River basin is the only large river in the LPB that is not a tributary of the Paraná, and its area covers around 10% of the LPB area. Both the Paraguay and the Iguazú rivers end at the Paraná River.

The LPB population is estimated at ~110 million inhabitants that represents about 60 percent of the combined population of the five countries of the basin. It hosts 50 big cities, 75 dams and more than 30 large hydropower plants that produce around 73% of the total energy demand (Popescu et al., 2014). The LPB is the core of the southeastern South American region with socio-economic activities like agriculture and livestock that generate around 70% of the per capita Gross Domestic Product of the LPB countries.

### Models

#### Climate Model

The Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) project (Tilmes et al., 2018) includes a suite of simulations made with the Community Earth System Model using the Whole Atmosphere Community Climate Model CESM1 (WACCM) as its atmospheric component (Mills et al., 2017). The model horizontal resolution is 0.95° latitude × 1.25° longitude, with 70 vertical layers extending up to 145 km altitude. The simulations consist in simultaneous injection of sulfur dioxide into the stratosphere at four locations, 30°S, 15°S, 15°N, and 30°N at 180°E and at an altitude around 5 km above the climatological tropopause height at the injection latitudes. The goal of the GLENS geoengineering simulations was to maintain the global mean surface temperature and the interhemispheric and equator-to-pole surface temperature gradients at 2020 levels over the period 2020–2099 under the high GHG emission scenario RCP8.5 (Meinshausen et al., 2011). The GLENS data used here consists of three members that use prescribed GHG forcing concentrations following the RCP 8.5 (control simulations) and three members that also follow the RCP8.5 scenario combined with increasing sulfur injections for the geoengineering (feedback simulations). A more detailed description of the data and simulations used in this study is available in Tilmes et al. (2018).

#### Hydrologic Model

The distributed Variable Infiltration Capacity (VIC) hydrology model (Liang et al., 1994; Nijssen et al., 1997) is used to assess the potential impacts of SAI on the hydroclimate of LPB. The model's inputs are information on soil type, topography, and vegetation, and daily information on selected meteorological variables (daily maximum and minimum temperatures and precipitation). Its skill to simulate the main hydrologic features of various basins worldwide has been proved extensively (e.g., Mattheussen et al., 2000; Wood et al., 2002) and it has already been successfully applied to the LPB as well (Su and Lettenmaier, 2009; Saurral, 2010; Montroull et al., 2018). Soil type and vegetation information were obtained from the 5-min Global Soil Data Task dataset of the Distributed Active Archive Center (2000) and the University of Maryland's 1-km Global Land Cover product (Hansen et al., 2000), respectively. Topography data was taken from the Global 30 arc-second elevation (GTOPO30) dataset (United States Geological Survey, 1997).

The VIC model, setup as in Saurral (2010), was forced using the daily meteorological data from GLENS after a re-gridding into a regular 1/8°latitude × 1/8°longitude grid to increase the horizontal resolution of the hydrological simulations. To overcome the biases in GLENS climate simulations as the input data for the VIC model, we used the method developed for the Inter-Sectoral Impact Model Intercomparison Project Phase 2b (ISIMIP2b; Frieler et al., 2017). This bias correction method adjusts the daily variability of simulated climate data to observations preserving the climate signal (long-term trend) using a constant offset for air temperature and a multiplicative correction factor in the case of precipitation. Different temperature and precipitation databases were used for the bias correction: the CLARIS LPB database (Penalba et al., 2014) and the Global Precipitation Climatology Project (GPCP; Adler et al., 2003) version 2.3 for precipitation and the WFDEI dataset (Weedon et al., 2014) for temperature. The calibration period for the bias correction process was 1980–1990, while the validation period was 1991–2000. Outputs from VIC consist of daily, monthly, and annual mean values of evapotranspiration and surface and sub-surface runoff which are integrated afterwards using a routing model (Lohmann et al., 1998) to derive streamflow data at selected closing points in two sub-basins: Jupia, Itaipú and Posadas for the Paraná River sub-basin, and Paso de los Libres and Salto Grande for the Uruguay River sub-basin (**Figure 1**). Some of the points were selected because there are large hydropower plants in or close to these locations (the Itaipú, the Yacyretá, and the Salto Grande river dams) and any relevant variation in the rivers' flows could have severe consequences on the energy production. The Itaipú reservoir on the Paraná River is shared between Brazil and Paraguay. It is the largest dam in the basin with a total capacity of 29,000 million m<sup>3</sup> and it is one of the largest hydroelectric plants in the world with a total installed capacity of 14,000 MW. The Yacyretá dam, also on the Paraná River and 100 km downstream of Posadas, is located on the border between Argentina and Paraguay. The total capacity of the dam is 21,000 million m<sup>3</sup>. The

**TABLE 1** | Subset of the temperature and precipitation extreme indices from ETCCDI used in this study.

Index	Description	Index definition	Unit
TNn	Coldest daily Tmin	Annual minimum value of daily minimum temperature	°C
TNx	Warmest daily Tmin	Annual maximum value of daily minimum temperature	°C
TXn	Coldest daily Tmax	Annual minimum value of daily maximum temperature	°C
TXx	Warmest daily Tmax	Annual maximum value of daily maximum temperature	°C
RX5day	Wettest consecutive 5 days	Annual maximum of consecutive 5-day (cumulative) precipitation amount	mm
CDD	Consecutive dry days	Annual maximum number of consecutive days when precipitation <1 mm	days

hydropower generated by this dam, which has a total capacity of 3,200 MW, is mainly used by Argentina. The Salto Grande dam, on the Uruguay River, is placed on the border between Argentina and Uruguay, and has a capacity of 5,500 million m<sup>3</sup>. The power plant has a total capacity of 1,890 MW, which covers part of the power demand of Argentina and more than half of the power needs of Uruguay (FAO, 2016).

## Climate Extreme Indices

The analysis is focused on a subset of six extreme climate indices from the Expert Team of Climate Change Detection and Indices (ETCCDI, Frich et al., 2002; Klein Tank et al., 2009; Zhang et al., 2011) summarized in **Table 1**. The indices were selected in order to characterize different aspects of daily temperature and precipitation extremes with recurrence times of a year or less. They have been widely used previously, both for observed weather (Donat et al., 2013) and model outputs from different CMIPs (e.g., Sillmann et al., 2013; Kim et al., 2020) and geoengineering simulations (e.g., Curry et al., 2014; Ji et al., 2018; Pinto et al., 2020).

## Projections

Changes in selected mean hydrometeorological variables (maximum and minimum temperature, precipitation, evapotranspiration, runoff, and river discharges) and in extreme indices derived from GLENS and from the VIC model over the LPB are calculated by computing the difference between the three-member ensemble mean values for two future 30-year periods (2021–2050 and 2051–2080) and the mean values over the historical period, 1980–2010. Projected changes are assumed robust when the absolute value of the multi-member ensemble mean of the computed differences exceeds the standard deviation of the changes in the individual ensemble members. The latter definition of robustness was applied in previous studies

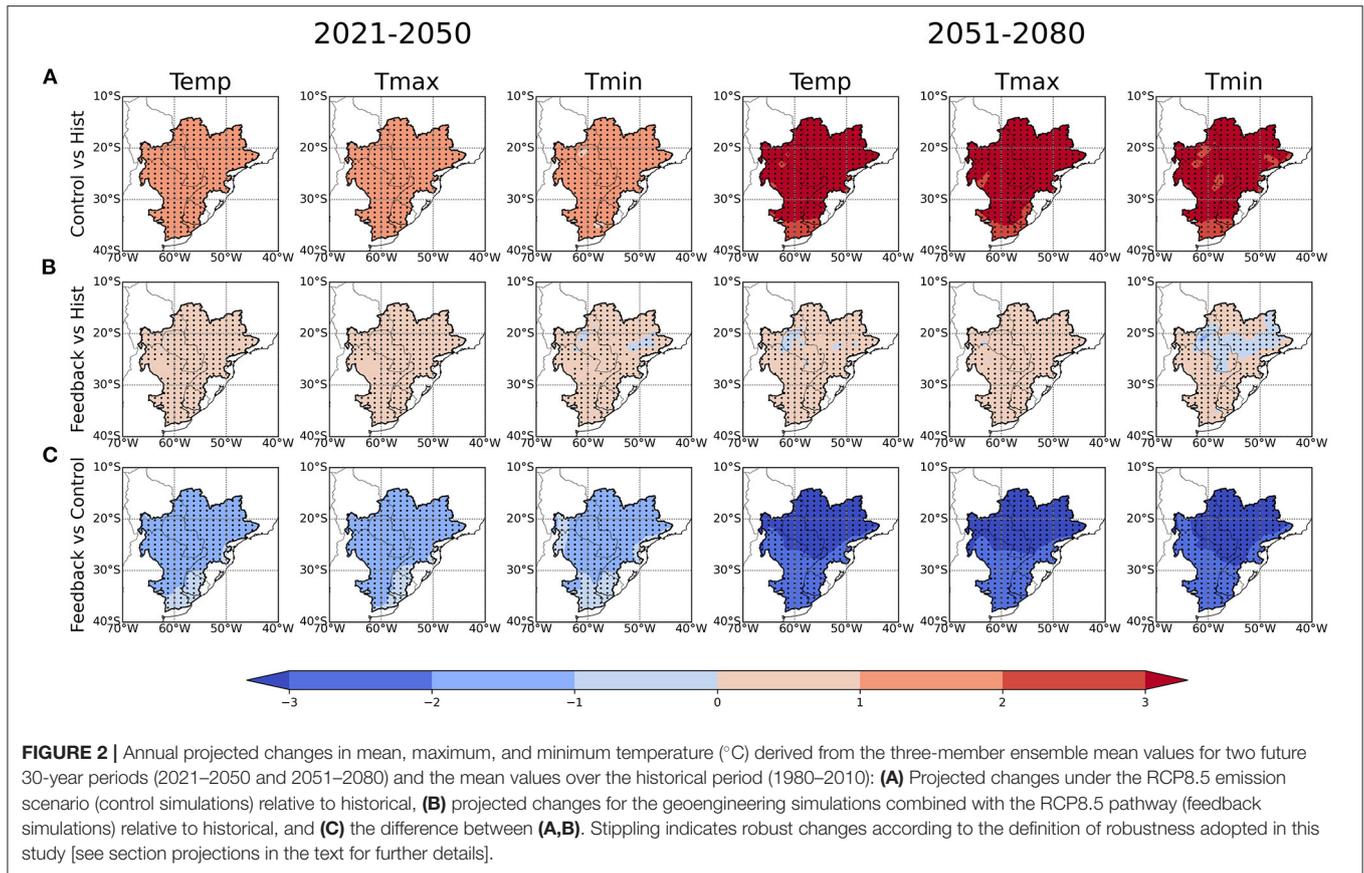
(Meehl et al., 2007; Donnelly et al., 2017; Montroull et al., 2018). Robust changes are stippled in the maps presented in section results.

## RESULTS

### Mean Climate

The deployment of SAI as simulated by the GLENS feedback experiment results in much smaller regional annual temperature changes than the RCP8.5 simulations (control) for both future time slices (**Figure 2**). Under the RCP8.5 scenario (**Figure 2A**) there is over the whole basin a robust and almost uniform warming in the mean, maximum and minimum temperatures in the range of 1–2°C for the 2021–2050 period, which increases to more than 3°C for 2051–2080. However, for this last period the increases in the three temperature variables are less (between 2 and 3°C) but still robust in a limited area of the southern section of the basin. With values under 1°C for the two time slices, temperature changes in a SAI scenario (**Figure 2B**) are mostly positive and robust but, as expected, they are moderate in comparison with the RCP8.5 one. There are only small areas where there is a cooling effect of the SAI in comparison with the historical period. This is more noticeable in the yearly minimum temperature for the 2051–2080 period with a temperature decrease smaller than –1°C in the northern central region. Overall, the result of contrasting the feedback and control simulations is robust and shows almost the same magnitudes and spatial patterns for the mean, maximum and minimum temperatures (**Figure 2C**). For the 2021–2050 period, SAI results in a temperature decrease between –1°C and –2°C in most of the LPB with the lowest changes (up to –1°C) in the southeastern corner. The cooling is more extreme for the medium future (2051–2080) in the northern half section of the basin (more than –3°C) and between –2°C and –3°C in the south. This asymmetric north–south response in temperature could be related to the different land cover between both regions (Abelen et al., 2015) and consequently in the albedo feedback.

**Figure 3** shows the projected changes of annual mean precipitation, evapotranspiration and runoff for the control and feedback experiments and for the comparison between them. Regarding precipitation, for the 2021–2050 period under the RCP8.5 scenario (**Figure 3A**) parts of the basin are likely to feature robust increases in rainfall between 0.1 and 0.3 mm/day at the border between the upper Paraguay and Paraná sub-basins in the northern section of the LPB and in the west area that represents the south limit between the same sub-basins. Robust positive changes are larger (up to 0.5 mm/day) and cover a more extensive area of the lower Paraguay and upper Paraná sub-basins for the 2051–2080 period. Toward the south of the LPB, including lower Paraná and Uruguay basins, there are small non-robust decreases in both time slices. Evapotranspiration changes are mostly positive and robust (around 0.1 mm/day for the 2021–2050 period and up to 0.5 mm/day for 2051–2080) in the northern section of the upper Paraná and Iguazú sub-basins and in the Uruguay basin upstream of Salto Grande. The only negative and non-robust changes are in the lower Paraná and Paraguay, the same region with negative changes in precipitation.

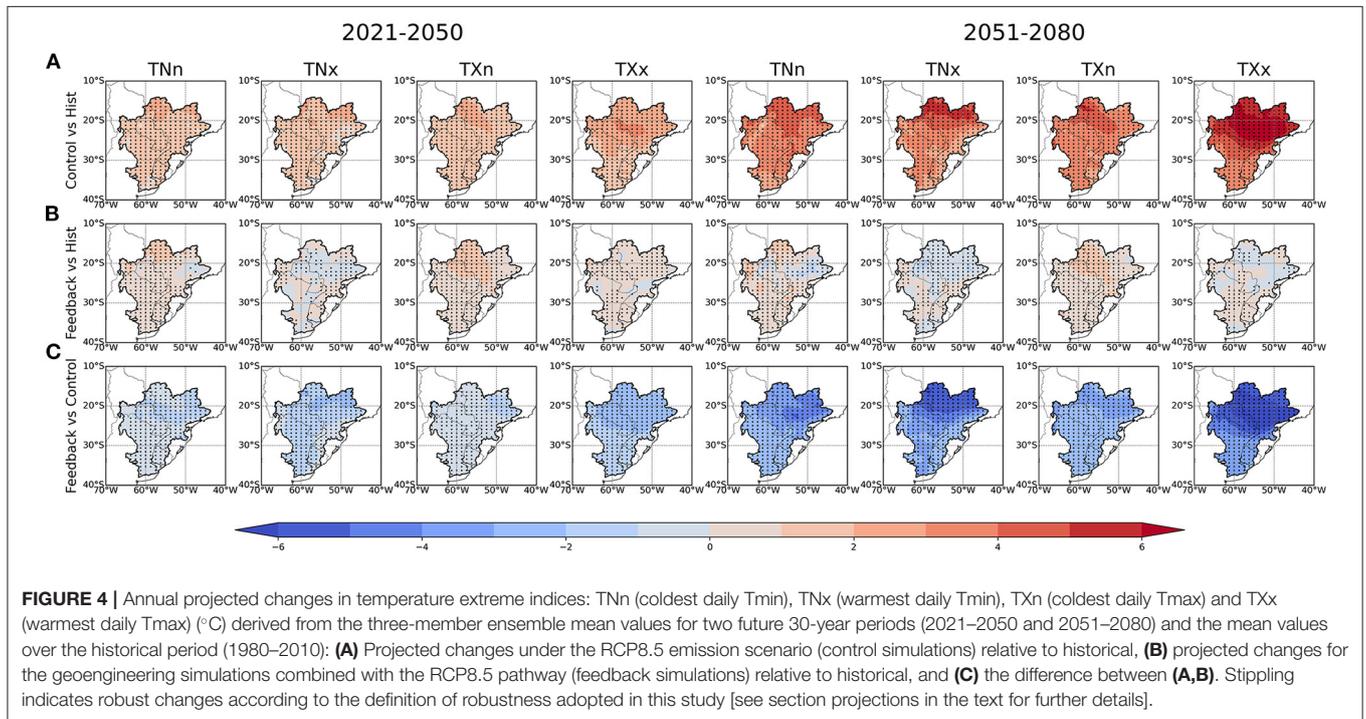
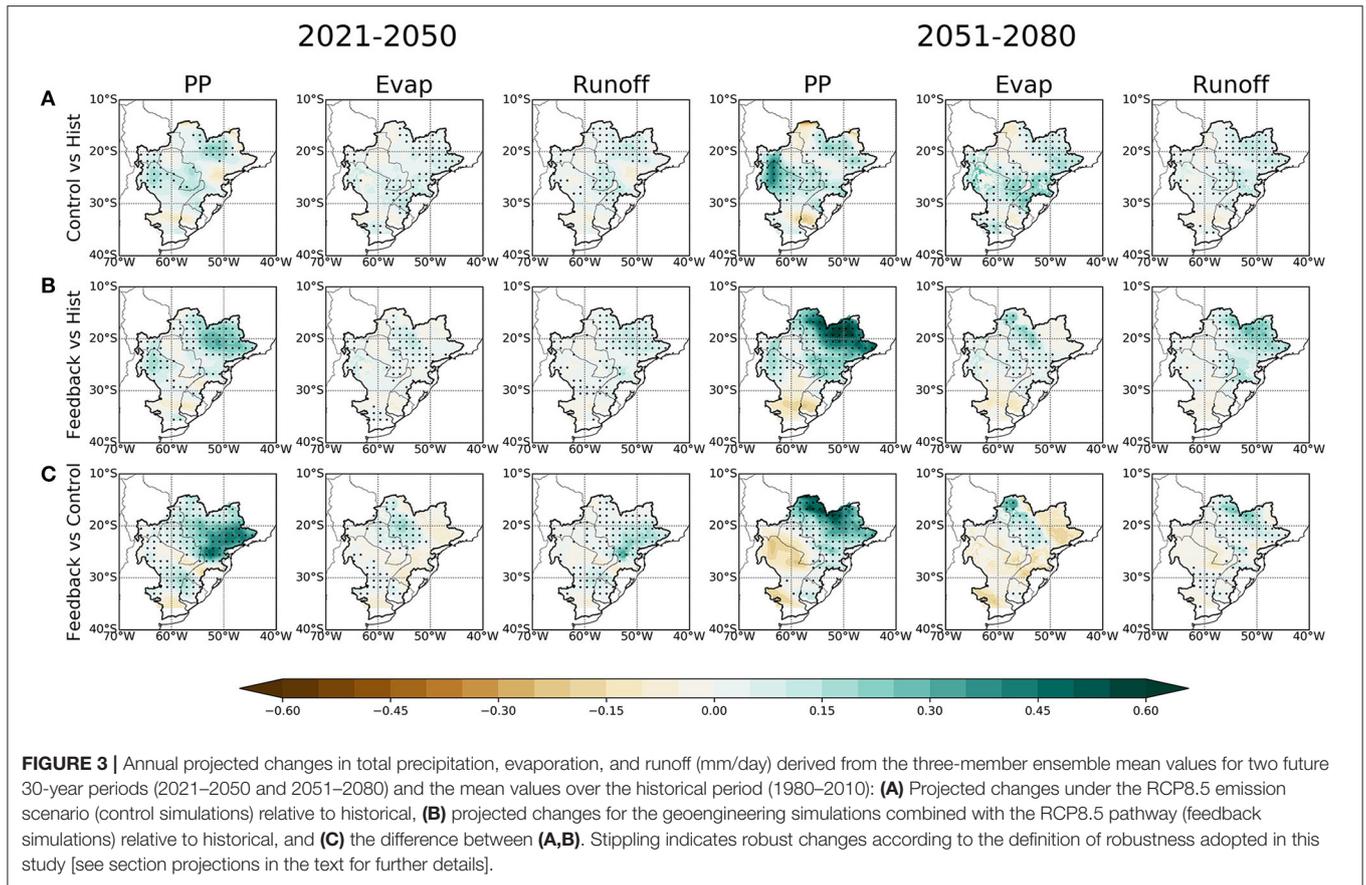


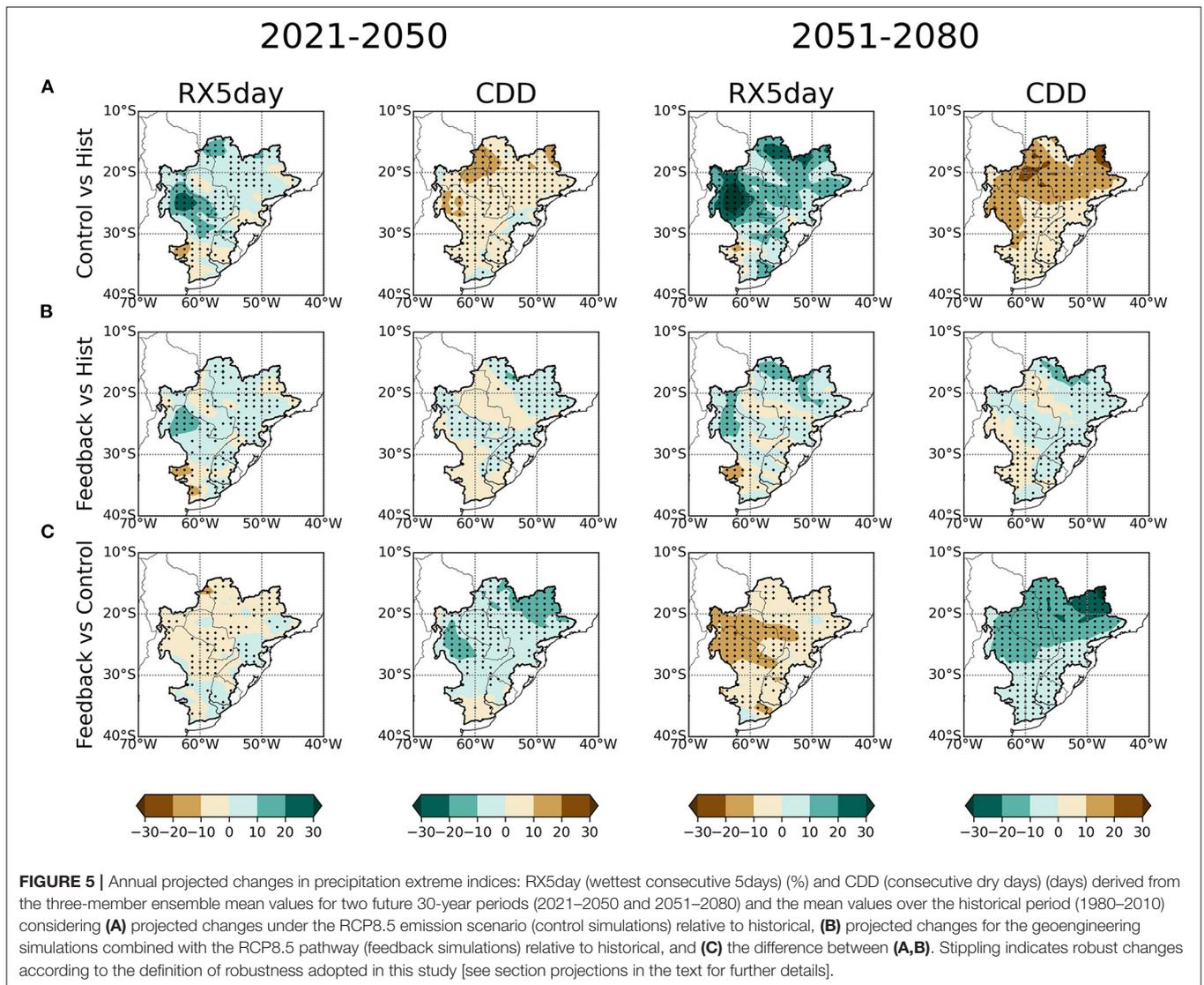
Finally, changes in runoff for the control simulations are quite similar to those in precipitation and evapotranspiration: in the areas where precipitation is projected to increase, runoff changes are positive in both periods. The precipitation response to SAI (**Figure 3B**) is not uniform geographically: robust increases to the north of the LPB in the upper Paraná and Paraguay sub-basins and reductions in the lower Paraná and Uruguay sub-basins in both periods. In comparison with the control simulation (**Figure 3C**), projected changes have higher magnitude indicating a robust wetting of a large fraction of the LPB basin for the near term and a dipole for the long term: more rainfall in the upper Paraná and Paraguay, Iguazú and southern Uruguay and drying in the lower Paraná and northern Uruguay sub-basins. The overall effect of SAI is to increase evapotranspiration and runoff in vast areas of the LPB (**Figure 3B**) that compared with the RCP8.5 scenario results in robust higher magnitudes of runoff in the Paraguay, Uruguay, and most of the Paraná sub-basins (**Figure 3C**). This is the case particularly for the 2051–2080 period. Consequences on river flows will be discussed in section river discharges.

## Extreme Climate

This section presents results for the six ETCCDI indices describing temperature and precipitation extremes presented in section models. For the control simulations, the projected increases in TNn, TNx, TXn and TXx, are robust across the

whole basin for the two time slices (**Figure 4A**). The spatial pattern of changes in TNn, TNx, and TXn are similar with the largest increases exceeding  $2^{\circ}\text{C}$  over the northern section of the LPB for the 2021–2050 period and higher than  $4^{\circ}\text{C}$  in most of the basin for the 2051–2080. TXx exhibits the largest changes that are maxima in the section of the basin north of  $30^{\circ}\text{S}$  reaching up to  $4^{\circ}\text{C}$  for the first period and above  $6^{\circ}\text{C}$  for the second one. The same relation of projected changes in TNn and TXx were identified in this region for the end of the twenty-first century using a multi-model ensemble from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Sillmann et al., 2013). Under the SAI scenario, the projected changes in the four temperature indices are moderate (**Figure 4B**). The magnitude of the changes is significantly weaker when compared to projected changes in the control simulations (**Figure 4A**) and generally smaller than  $2^{\circ}\text{C}$  for the two periods. For all the indices except TXn there are some areas where temperatures are smaller compared to historical values. This is evident for TNx with robust negative changes between  $-1^{\circ}\text{C}$  and  $-2^{\circ}\text{C}$  in the upper Paraná and Paraguay sub-basins for the period 2051–2080. The comparison between the feedback and control simulations (**Figure 4C**) shows that the cooling effect of the SAI in comparison with the RCP8.5 scenario is robust and reaches the highest magnitude up to  $-6^{\circ}\text{C}$  for TNx and TXx over the upper Paraná and Paraguay sub-basins for the last period. Overall, regional temperature extremes under the SAI





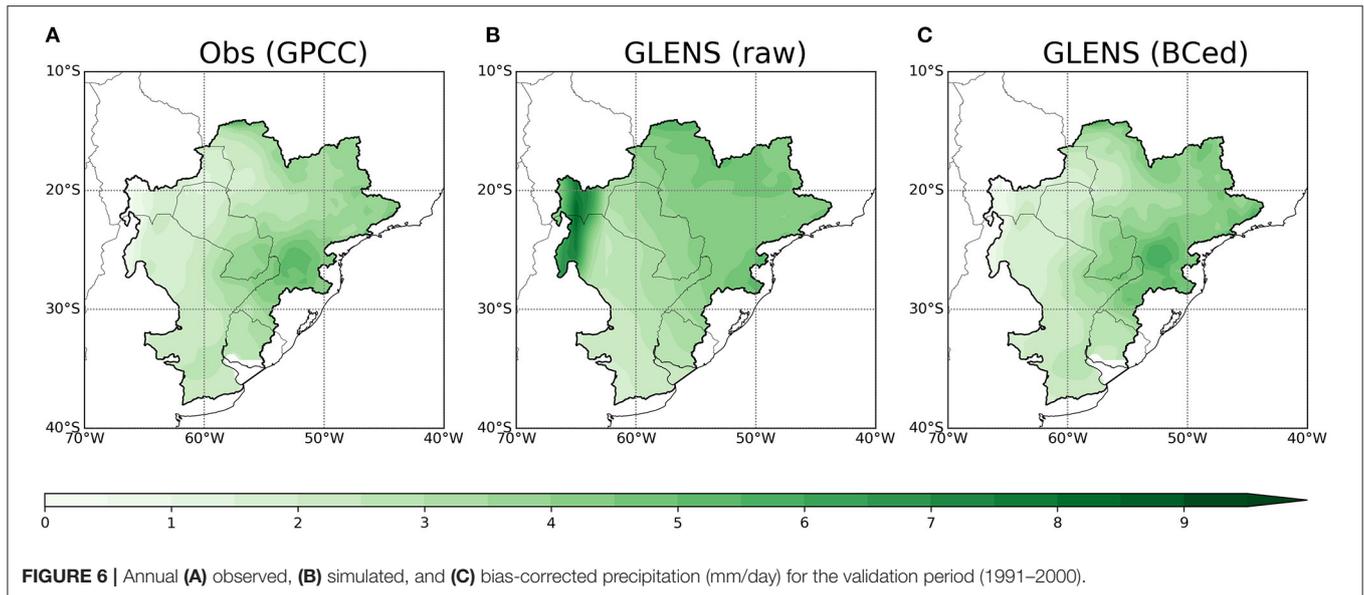
and increased GHG scenario as represented by the feedback simulations almost offsets the warming under RCP8.5 at the LPB keeping the spatial mean temperature increases for TNn, TNx, and TXx with magnitudes lower than 1°C.

**Figure 5** shows the projected changes in the precipitation indices RX5day and CDD at annual timescales in response to increases in GHG and SAI forcing and the differences between both. Under the RCP8.5 scenario (**Figure 5A**), changes in RX5day show a quite similar spatial pattern as the yearly mean precipitation (**Figure 3A**) with robust increases over most of the basin with greater magnitudes (up to 30%) for the second period. Similarly, the annual maximum number of consecutive dry days CDD shows robust increases for the two time slices reaching more than 10 days for 2051–2080 in a large section of the basin. Changes in RX5day associated with the SAI forcing are moderate in comparison to the control simulations (**Figure 5B**) reducing the magnitude over most of the basin. The effect on

CDD is different and in some regions like the upper Paraná sub-basin to the north of the LPB, there are robust decreases in the 2021–2050 period. The area of the LPB with robust negative changes in CDD is more extensive for the 2051–2080 period although there are robust positive changes in the southernmost region of the Paraná sub-basin and in the western section of the Uruguay sub-basin. The contrast in the projected changes of RX5day and CDD derived from the feedback and control simulations (**Figure 5C**) indicates that the SAI forcing moderates the magnitude of both indices resulting in a greater reduction in CDD in the northern section of the LPB over the upper Paraná and Uruguay sub-basins for the last period.

## River Discharges

The changes in temperature, precipitation, evapotranspiration, and runoff described previously under different forcing scenarios will certainly impact the annual mean streamflow of the main



rivers of the LPB. This section presents the projected changes in the mean and extreme flows of the Paraná River at the closing points of Jupiá, Itaipú, and Posadas and in Paso de los Libres and Salto Grande on the Uruguay River (see **Figure 1** for the location of the closing points). The atmospheric input data for the hydrologic modeling are the bias-corrected GLENS control and feedback simulations of the daily minimum and maximum temperatures and precipitation. Maximum and minimum simulated temperatures are highly spatially correlated with observations for the validation period for both uncorrected and corrected data ( $>0.9$  in all cases) indicating a good performance of the GLENS temperature simulations and not significant value added by the bias correction method (Figures not shown). **Figure 6** shows the yearly mean precipitation fields in the LPB derived from the GPPC database, and from GLENS uncorrected and bias-corrected outputs for the validation period (1991–2000). It is important to stress that the observed data presented in this figure played no role in the computation of corrected data and it is shown only for comparison and validation. It is evident that the corrected field is quite similar to the observations. In particular, it can be noted that the biases are well-removed over the region with steep terrain of the pre-mountain range of the Andes. Also, both the location and magnitude of the precipitation maximum over the Iguazú sub-basin are adequately represented after the bias correction.

The projected changes in the annual mean and extreme flows of the Paraná and Uruguay rivers at the selected points for the control and feedback simulations and the periods 2021–2050 and 2051–2080 are presented in **Tables 2, 3**. Flows are computed as the ensemble mean of the hydrologic simulations resulting from the three members of the GLENS outputs. Minimum and maximum flows are defined as the 5th and 95th percentiles, respectively. The positive changes in rainfall in the upper-middle Paraná River basin under the SAI feedback scenario (**Figure 3B**)

**TABLE 2 |** Changes in the mean (Qmean), extremely low (represented by the 5th percentile; Q5) and extremely high (95th percentile; Q95) Paraná River streamflow simulated by the VIC hydrology model considering control vs. historical and feedback vs. historical GLENS simulations.

	2021–2050			2051–2080		
	Qmean	Q5	Q95	Qmean	Q5	Q95
<b>JUPIÁ</b>						
Control vs. historical	0	7	6	–1	–4	14
Feedback vs. historical	11	54	4	21	75	9
<b>ITAIPIÚ</b>						
Control vs. historical	0	–12	3	–1	–14	10
Feedback vs. historical	10	17	4	21	29	13
<b>POSADAS</b>						
Control vs. historical	0	–9	7	–1	–8	12
Feedback vs. historical	10	18	5	20	33	14

Results are shown for periods 2021–2050 and 2051–2080 separately and for the three closing points in the Paraná River: Jupiá, Itaipú and Posadas. Values are indicated in % of change.

lead to a uniform increase close to 10% (20%) in the mean flow of the river at the three closing points in 2021–2050 (2051–2080) relative to the historical period (**Table 2**). At the same time, this is accompanied by a marked increase in the value of the 5th percentile in both future periods, reaching a maximum of 75% at Jupiá in 2051–2080. Without SAI (control scenario), changes are mostly negative for these low flow conditions, which would translate into even lower streamflow values under drought conditions compared to the historical period. Interestingly, the magnitude of increase is much smaller for the extremely high flows (95th percentile) and only reach 4–5% in 2021–2050 and 9–14% in 2051–2080, which are comparable to values obtained under the RCP8.5 scenario. Results for the Uruguay River (**Table 3**) show a different behavior, since geoengineering

**TABLE 3** | As in **Table 2** but for the closing points in the Uruguay River: Paso de los Libres and Salto Grande.

	2021–2050			2051–2080		
	Qmean	Q5	Q95	Qmean	Q5	Q95
<b>PASO DE LOS LIBRES</b>						
Control vs. historical	–1	–1	–5	–5	–11	–2
Feedback vs. historical	0	8	0	4	6	6
<b>SALTO GRANDE</b>						
Control vs. historical	–1	–4	–6	–5	–14	–6
Feedback vs. historical	0	0	–3	4	0	–2

strategies would lead to minor changes in the mean river flows (0–4% depending on the future period under consideration) while also bringing an increase in the 5th percentile flow values and little variations (ranging from –3 to 6%, depending on the period and closing point considered) in the 95th percentile flow values.

## DISCUSSIONS AND CONCLUSIONS

This article provides a first overview of the LPB hydroclimate response to SAI using simulations from the Geoengineering Large Ensemble (GLENS) Project. The goal of the geoengineering simulations was to maintain the global mean surface temperature and the interhemispheric and equator-to-pole surface temperature gradients at 2020 levels under a RCP8.5 GHG scenario by simultaneously injecting sulfur dioxide in the stratosphere at four locations.

Results show that, relative to the historical conditions (1980–2010), SAI can offset the projected increase in the magnitude of mean and extreme temperatures when compared to the RCP8.5 scenario for the periods 2021–2050 and 2051–2080. The cooling effect of SAI is more significant in the northern section of the basin. The response of SAI on precipitation is not uniform geographically, indicating an increase in the northern sector of the LPB including the upper Paraná and Paraguay sub-basins and a reduction to the south in the lower Paraná and Uruguay sub-basins. In terms of precipitation extremes, they are projected to decrease with different magnitudes depending on the location, but in general under the SAI scenario a reduction can be expected in both RX5day and CDD.

The possible effects of SAI on the LPB water cycle were assessed with the VIC hydrologic model in combination with daily extreme temperature and precipitation outputs from GLENS. SAI mostly increases mean and extreme flows of the main rivers of LPB with respect to the historical period and the RCP8.5 scenario. Still, it is worth noting that over the Paraná River the marked increase in the extremely low flow values (5th

percentile) under SAI in the upcoming decades (2021–2080) would become accompanied by smaller increases in the extremely high values (95th percentile), suggesting a reduction in the flow variability of the river and less severe drought conditions over the basin. However, this latter advantage could come at the expense of a slightly larger risk of flooding under extremely high flow conditions.

In conclusion, the overall effect of solar geoengineering in LPB, as derived from the single climate model considered in the GLENS experiment, is to reduce climate impacts associated with high GHG emissions for most of the basin, although for some areas it could make them worse compared to the RCP8.5 scenario without SAI: i.e., increase in high flows of the Paraná River at Itaipú dam and for the 2021–2050 period more dry days in the southern section of the basin. Therefore, even within the LPB, SAI involves trade-offs, as some regions will experience a greater compensation of the anthropogenic global mean temperature rise than others that could see drawbacks, leading to concerns about equity and climate justice. However, considering that results were obtained from multiple ensemble members of a single climate model, more research is needed assessing geoengineering simulations from different climate models.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

IC conceived this paper and wrote it. NM and RS performed the hydrological simulations. CG conducted the analysis of the extreme indices. All authors contributed to the article and approved the submitted version.

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