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RIVER DISCHARGE IN SOUTH AMERICA:
AGREEMENT BETWEEN PROJECTED CHANGE AND RECENT ALTERATION

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RIVER DISCHARGE IN SOUTH AMERICA:

AGREEMENT BETWEEN PROJECTED CHANGE AND RECENT ALTERATION

Trabalho de Conclusão de Curso apresentado ao Instituto de Pesquisas Hidráulicas da Universidade Federal do Rio Grande do Sul como requisito para a obtenção do título de Engenheiro Civil

Orientador: Prof. Dr. Rodrigo Cauduro Dias de Paiva

Porto Alegre

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RIVER DISCHARGE IN SOUTH AMERICA:

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Trabalho de Conclusão de Curso em Engenharia Civil pela Universidade Federal do Rio Grande do Sul defendido e aprovado em 29/11/2021 pela Comissão Avaliadora composta por:

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À família, aos amigos e aos mentores que me acompanharam durante a graduação, a tornando uma fase pela qual tenho grande carinho.

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RESUMO

Mudanças climáticas se tornaram uma grande preocupação para a gestão de recursos hídricos nas últimas décadas. Eventos extremos (secas e cheias) na América do Sul, historicamente, causam prejuízos nas esferas social e econômica. Como padrões na hidrologia são influenciados pelo clima, entender o comportamento recente e futuro desse sistema é relevante para planejamentos a longo prazo. Esses padrões podem se dever tanto a ações antrópicas, quanto à variabilidade natural do clima. Eventos extremos de vazão recentes têm levantado a questão sobre sua procedência: se ocorrem devido a atividades antrópicas, ou a variações climáticas naturais. Para avaliar esse tópico, foram comparadas as alterações de vazões mínima, média e máxima de um período recente (1980-2019) com as de projeções climáticas (final do século XXI). Esse paralelo foi feito com o objetivo de avaliar a concordância entre as tendências desses períodos. A bacia Orinoco e as partes norte e oeste da bacia Amazônica mostraram discordâncias, majoritariamente, com uma tendência positiva (negativa) nas últimas décadas (final do século XXI), enquanto as bacias Tocantins-Araguaia, São Francisco e Atlântico NE Ocidental e a parte superior da bacia do Prata concordaram com um decréscimo de vazão nos dois períodos. A partir dessa análise, trouxemos uma hipótese de que regiões concordantes (discordantes) podem estar sofrendo influência antrópica (natural) no clima, se encaminhando para um estado de mudança mais permanente (incerto).

ABSTRACT

Climate change has become a great concern for water management sector over the past decades. Extreme events (floods and droughts) in South America have historically caused harm to social and economic fields. Since hydrology patterns are influenced by climate, understanding this system's recent and future behaviors is relevant for long term planning. These pattern alterations can either be due to anthropic or natural influences. Recent extreme events of river discharge in South America are raising a discussion of whether they can be attributed to climate change, or to natural variability. To address this issue, we compared recent past (1980-2019) trends to climate projections for river minimum, mean, and maximum discharges. This comparison was conducted with the objective of evaluation of the agreement between these periods' trends. Orinoco and upper -western Amazon basins presented strong disagreement, with positive (negative) trends in the last decades (projected for late 21st century), whereas Tocantins-Araguaia, São Francisco, Western Northeast Atlantic and upper La Plata basins agreed with discharge decrease in both periods. With this analysis, we bring a hypothesis that agreeing (disagreeing) regions may be experiencing impacts related to anthropic influence on climate (climate's natural variability), heading towards a more permanent change (uncertain future).

LISTA DE FIGURAS

LISTA DE EQUAÇÕES

SUMÁRIO

River discharge in South America: agreement between projected change and recent alteration

Vazão nos rios da América do Sul: concordância entre projeções de mudanças e alterações recentes

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ABSTRACT

Climate change has become a great concern for water management sector over the past decades. Extreme events (floods and droughts) in South America have historically caused harm to social and economic fields. Since hydrology patterns are influenced by climate, understanding this system's recent and future behaviors is relevant for long term planning. These pattern alterations can either be due to anthropic or natural influences. Recent extreme events of river discharge in South America are raising a discussion of whether they can be attributed to climate change, or to natural variability. To address this issue, we compared recent past (1980-2019) trends to climate projections for river minimum, mean, and maximum discharges. This comparison was conducted with the objective of evaluation of the agreement between these periods' trends. Orinoco and upper -western Amazon basins presented strong disagreement, with positive (negative) trends in the last decades (projected for late 21st century), whereas Tocantins-Araguaia, São Francisco, Western Northeast Atlantic and upper La Plata basins agreed with discharge decrease in both periods. With this analysis, we bring a hypothesis that agreeing (disagreeing) regions may be experiencing impacts related to anthropic influence on climate (climate's natural variability), heading towards a more permanent change (uncertain future).

Keywords: Climate natural variability, Climate change impacts, South America, Hydrology.

RESUMO

Mudanças climáticas se tornaram uma grande preocupação para a gestão de recursos hídricos nas últimas décadas. Eventos extremos (secas e cheias) na América do Sul, historicamente, causam prejuízos nas esferas social e econômica. Como padrões na hidrologia são influenciados pelo clima, entender o comportamento recente e futuro desse sistema é relevante para planejamentos a longo prazo. Esses padrões podem se dever tanto a ações antrópicas, quanto à variabilidade natural do clima. Eventos extremos de vazão recentes têm levantado a questão sobre sua procedência: se ocorrem devido a atividades antrópicas, ou a variações climáticas naturais. Para avaliar esse tópico, foram comparadas as alterações de vazões mínima, média e máxima de um período recente (1980-2019) com as de projeções climáticas (final do século XXI). Esse paralelo foi feito com o objetivo de avaliar a concordância entre as tendências desses períodos. A bacia Orinoco e as partes norte e oeste da bacia Amazônica mostraram discordâncias, majoritariamente, com uma tendência positiva (negativa) nas últimas décadas (final do século XXI), enquanto as bacias Tocantins-Araguaia, São Francisco e Atlântico NE Ocidental e a parte superior da bacia do Prata concordaram com um decréscimo de vazão nos dois períodos. A partir dessa análise, trouxemos uma hipótese de que regiões concordantes (discordantes) podem estar sofrendo influência antrópica (natural) no clima, se encaminhando para um estado de mudança mais permanente (incerto).

Palavras-chave: Variabilidade natural do clima, Impactos de mudanças climáticas, América do Sul, Hidrologia.

INTRODUCTION

Hydrology is mostly regulated by climatologic drivers, such as precipitation and evapotranspiration. Despite these variables' behavior being highly inconstant in short term, they present long term patterns, upon which most of water management planning takes place. Changes in these long term patterns impose challenges for water management. According to Intergovernmental Panel on Climate Change's (IPCC) latest report (2021), climate has been suffering notorious influence of human activities over the last two centuries. These interactions alone are estimated to have contributed with approximately 1.07 ^{o}C for the increase of global surface temperature between 1850-1900 and 2010-2019 (IPCC, 2021). IPCC 6th Assessment Report (AR6) (2021) mentioned other significant changes that can be almost certainly attributed to anthropic actions, such as the increase of precipitation over land, the increase in Sea Surface Temperature (SST) and the consequent retreat of glaciers. These evidence are supported by paleoclimate reanalysis, associated with observational and computational products that allow extensive time series reconstruction (IPCC, 2021).

A common way to address climate change impacts is through General Circulation Models (GCM), or even Regional Climate Models (RCM), which simulate future conditions of Earth's atmosphere and oceans. Several scientific studies in the field of hydrology have assessed the effect that climate change may have on water resources by applying these simulation's results as inputs for hydrologic models (Brêda et al., 2020; de Jong et al., 2021; Moragoda & Cohen, 2020; Ribeiro Neto et al., 2016; Sorribas et al., 2016). Sorribas et al. (2016) forced MGB-IPH model over the Amazon basin (Paiva et al., 2013) with predictions from CMIP5 considering a high Greenhouse Gases (GHG) emission scenario, RCP 8.5 (IPCC, 2014). With a similar approach, Brêda et al. (2020) forced the continental scale version of MGB-IPH for South America's territory, MGB-SA (Siqueira et al., 2018), with data from RCP 8.5 and RCP 4.5 (moderate GHG emission).

Despite the impacts caused by anthropic activities, climate presents important natural variability throughout time (interannual, decadal, and multi-decadal). Low-frequency SST patterns are related to oceanic phenomena such as Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) and influence rainfall and, therefore, discharge behavior throughout time (Bartiko, 2020; Castino et al., 2017; Pasquini & Depetris, 2007; Perez et al., 2021; Rocha & de Souza Filho, 2020; Valdés-Pineda et al., 2018). For instance, Castino et al. (2017) stated that ENSO imposes a first-order influence on river discharge in tropical and subtropical Andean region. Many studies document an increase in river discharge on southeastern South America occurred in the 1970s and relate it to positive anomalies in ENSO and PDO and negative ones in AMO (Castino et al., 2017; Perez et al., 2021; Rocha & de Souza Filho, 2020). The understanding and prediction of such phenomena and its effects on continental hydrological processes can greatly benefit the water management sector, from water permitting policies to the operation of hydroelectric plants.

Hydrology plays an important role in socioeconomic field in general. However, due to the hydroelectric potential, the hydroclimatic global and regional relevance and the magnitude of South America, this science deserves special attention in the continent. Taking Brazilian territory as instance, the region's mean discharge is around 255,000 m^3/s, from which 80 % are in the Amazon basin (ANA, 2020). The country has 4,466 reservoirs registered, from which 35 % are destined for irrigation, 22 % for power generation and 18 % for human consumption (ANA, 2020). Between 2012 and 2017, some regions in Brazil have experienced lower rainfall than average, significantly affecting reservoirs' volume and operation. Following a moderated volume recovery in 2018, after December 2019, country's National Integrated System (SIN) active storage reached its lowest value in 5 years (ANA, 2020). Water and Sanitation National Agency's (ANA) Report (2020) stated that many Brazilian regions presented low precipitation in the year of 2019, especially the Paraguay and Paraná basins, in the last one many water supply systems nearly collapsed. Rocha & de Souza Filho (2020) showed that there has been a consistent decrease in the inflow from key reservoirs of Brazilian hydroelectric power system, such as Sobradinho (Furnas), in the northeast (southeast) region. These changes are likely to be related to AMO and PDO cold-warm phase shifts (Rocha & de Souza Filho, 2020), but, since these phenomena are also influenced by climate, it is difficult to dissociate changes due to anthropic influence on climate from those due to natural variability. South America presented extreme events (e.g., Amazon River flood and Pantanal drought) in the last two years (2021 and 2020). However, extreme events are also documented on a more distant past. This raises the question of whether the main cause of recent events is the anthropic influence on climate, or climate's natural variability.

OBJECTIVE

The present study aims to analyze and compare river's minimum, mean and maximum recent discharge alterations (between 1980-1999 and 2000-2019) and trends (1980-2019) with climate change impacts on river discharge projected for the end of 21st century. This approach intends to investigate which regions and river streams could be experiencing impacts related to natural variability and those that can be already impacted by permanent climate change. The hypothesis we brought (OU discuss) is that regions which present same sign for recent discharge alteration and alterations projected for late 21st century may be already experiencing climate change impacts, and those that present opposite signs may be more influenced by natural variability.

METHODOLOGY

The analysis consisted in determining recent (1980-2019) discharge trends through MGB-SA dataset. We evaluated average and statistically significant alteration and validated it with observation data and other studies. These results were, then, compared to climate projections for late 21st century, and analyzed over its signal agreement between both periods (recent and future). This session explains the process more thoroughly.

Hydrologic and hydrodynamic Model for Large Basins (MGB-SA)

For this analysis, we chose to work with a distributed hydrologic model, which possesses a discretization of the assessed area in homogeneous portions and river routing. This brings vantage in GIS visualization, allowing punctual assessments. As we aimed to get a general overview on South American rivers, it was used a continental scale version of MGB-IPH, MGB-SA, developed by Siqueira et al. (2018). MGB-SA is a fully coupled hydrologic-hydrodynamic model made for South America's territory. It represents the river system by streams of approximately 15 km extent and a drainage area equal or superior to 1,000 km². Each river reach is associated with a unit catchment, which is discretized in Hydrological Response Units (HRU), areas that share soil, vegetation and land use and cover characteristics. The vertical water balance is calculated for each HRU, and the resulting runoff is propagated downstream by using two methods: a linear reservoir approach for hillslope routing, and a 1D local inertial (hydrodynamic) method for river routing. (Siqueira et al., 2018). The model uses as rainfall and runoff input data the Multi-Source Weighted Ensemble Precipitation (MSWEP, v1.1), a 3-hourly dataset of combined satellite, reanalysis and daily gauge data. As input for climate variables used to define evapotranspiration (ET), it was used mean monthly data (1961-1990) from Climate Research Unit Global Climate v.2. MGB-SA was validated for discharge, water level, terrestrial water storage (TWS) and ET, obtaining satisfactory results according to multiple efficiency metrics (Siqueira et al., 2018). This process generated a river flow time series from 1990 to 2010.

The present study used a time series based on MGB-SA (Siqueira et al., 2018), containing some adjustments in its database and an extension of the assessment period, resulting in a discharge time series from 1979 to present (2021). The first version of the MGB-SA model was calibrated with MSWEP v1 precipitation data (Beck et al., 2017), however this database has become outdated, as it only provides precipitation data until 2015. Therefore, the time series was extended using precipitation data from the GPM IMERG (Skofronick-Jackson et al., 2017), which had to be bias-corrected in order to present a precipitation distribution similar to the original precipitation database (MSWEP). The period evaluated was 1980-2019. The first year (1979) was not considered due to the influence of model's initial condition over discharge values.

Recent discharge alteration

Recent discharge alteration was analyzed using MGB-SA modeled time series divided into two periods: 1980-1999 and 2000-2019. Then, the alteration was calculated as the percentual difference between discharge's mean values from each period. This process was made for minimum, mean and maximum annual discharges. Alteration values within the range ±10 % were considered neutral.

Even though MGB-SA's river discharges were validated by Siqueira et al. (2018), it was not found studies that analyzed alteration of the model's discharges broadly. Wongchuig Correa et al. (2017) confirmed the capability of MGB-IPH to represent interannual variability in terms of minimum, mean, and maximum values in the Amazon basin. However, it was needed to compare the alterations of simulated and observed discharges to see if further analyses were feasible. The observed data used for this comparison was from ANA's discharge gauges, in Brazilian territory. The gauge selection criterium was based on data quality and availability in each one of the reference periods and is detailed in the following section.

River gauge selection

Data quality

Gauge selection was based on ANA's database (15,536 gauges), which passed through a series of automatic filters in order to remove measurements that presented incoherent values of discharge. The filters applied are presented below:

- Negative streamflow: measurements less than zero were changed to "missing data".
- Unrealistic streamflow: values larger than 1,000 mmd^{-1} were considered incoherent with reality, and so were changed to "missing data". To this analysis, it was considered the catchment areas.
- Abrupt zero: identified if there were 0 m^3s^{-1} instead of "missing data". This verification considered intermittent rivers by evaluating the frequency curves. In the case of streamflow being larger than zero in 90% of the time, measurements equal to zero are considered "missing data". Otherwise, in the case of previous time step being larger than a threshold (defined as 50 m^3s^{-1}), the measurement equal to zero is considered an abrupt zero, and, thus, converted to "missing data".
- Constant values: identified if there were long periods of constant discharge values. For each value in the series, it was quantified how many times that value was repeated. In case this value presented 50% more repetitions in sequence than 95% of the remaining ones, it was substituted for "missing data".

Furthermore, gauges with drainage area lower than 1,000 km² were removed. This consideration was necessary due to MGB-SA model resolution. This process resulted in an ensemble of about 1,250 gauges.

Data availability

Gauges were also filtered by data availability in each period considered (1980-1999 and 2000-2019). This process consisted in discarding years with less than 80 % of data and then discarding gauging stations that had more than 25 % of years discarded for at least one of the periods considered. This resulted in a sample of 581 discharge gauges (Figure 2).

Significant changes

We addressed the statistical significance of discharge alteration through two methods: (i) Student's t-test (Student, 1908) and (ii) Mann Kendall test (Kendall, 1975; Mann, 1945). Both methods were applied for a 5 % level of significance, and they are described in the following topics.

Student's t-Test

This analysis consisted in comparing the two 20-year samples used to define discharge alteration (1980-1999 and 2000-2019) and determining whether they were statistically different or not. Student's t-test compares sample's mean and variance values. T value is defined by the difference between samples' means divided by the combined variance of both groups. The H_0 hypothesis ($mean_{1980\text{-}1999}=mean_{2000\text{-}2019}$) is rejected if the t-value obtained is greater in module than the inverse of the bicaudal probability for given significance level (α=0.05) and degrees of freedom ($N_{1980\text{-}1999}+N_{2000\text{-}2019}-2=38$).

Mann-Kendall Test

We also assessed discharge's trend between 1980 and 2019 through Mann-Kendall (MK) test (Kendall, 1975; Mann, 1945). MK test is a nonparametric statistical analysis for monotonic trend detection in a sample, and it has been extensively used for trend detection of hydroclimatic variables (Ahmad et al., 2018; Araújo Silva, 2011; Bartiko, 2020; Ricardo et al., 2013; Wongchuig Correa et al., 2017; Xu et al., 2003; Yue & Pilon, 2004). As a nonparametric test, MK is less suitable than parametric ones for normally distributed data, however, this difference is not substantial (Yue & Pilon, 2004). The method is described by the following equations, for a time series $X\ (1, 2, \ldots, n)$.

$$S=\sum_{k=1}^{n-1}\sum_{j=k+1}^{n} sign(X_j-X_k) \qquad (1)$$

$$V(S)=\frac{1}{18}\left[n(n-1)(2n+5)-\sum_{i=1}^{g}e_i(e_i-1)(2e_i+5)\right] \qquad (2)$$

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{V(S)}}\,, if\ S>0\\ 0\,, if\ S=0\\ \dfrac{S+1}{\sqrt{V(S)}}\,, if\ S<0\end{cases} \qquad (3)$$

Eq. (1) compares each term of a sample with all its subsequent terms, summing all these comparisons' signs (±1). The second term of Eq. (2) is used when there are ties in the sample, where g is the number of tie groups and e is the number of ties in the i^{th} group (Machiwal & Jha, 2012). Ties were not considered in the study, being applied just the first term of Eq. (2). Then, the result of $|Z|$ (absolute value of Eq. (3)) is compared to $Z_{1-\frac{\alpha}{2}}$, where, if greater, there is a significant change with Z's sign for an α level of significance.

Since sample's autocorrelation can affect MK test results (Bartiko, 2020; Wongchuig Correa et al., 2017; Yue et al., 2002), we performed the Trend Free Pre-Whitening (TFPW) method (Yue et al., 2002). This process consists in correcting eventual lag-1 autocorrelation in a series through the following equations.

$$\beta=median\left(\frac{x_j-x_i}{j-i}\right)\ \forall\ i<j \qquad (4)$$

$$Y_t=X_t-\beta t \qquad (5)$$

$$Y_t'=Y_t-\phi Y_{t-1} \qquad (6)$$

$$Y_t''=Y_t'+\beta t \qquad (7)$$

Eq. (4) is a comparison between $x_j(2, 3, \ldots,\ j)$ to all its predecessors x_i, being x a term of the time series and $j>i$. The median of these values results in the slope of its linear trend β. Then, the slope effect is subtracted from the sample (Eq. (5)), resulting in a new sample Y_t . This sample is tested for autocorrelation on lag-1 and striped of its influence by Eq. (6), where ϕ is the autocorrelation value for lag 1. Finally, Eq. (7) adds the linear trend effect to Y_t', resulting in Y_t'', a sample with no autocorrelation and with the same linear trend effect as the original one. When the sample does not present autocorrelation on lag-1 or a linear trend, MK test can be applied on the original series.

Climate projections

For the intended comparison between climate's recent and future conditions, we selected multiple research that encompassed climate change impacts over South America's hydrology (Brêda et al., 2020; de Jong et al., 2021; Ribeiro Neto et al., 2016; Sorribas et al., 2016; Zaninelli et al., 2019). From the selected studies, the main comparison was made upon South America Climate Change Impacts (SACCI), conducted by Brêda et al. (2020). This is because Brêda et al. (2020) also used MGB-

SA for their analysis, making possible to compare results for the same river reaches. Despite this advantage, the study has only assessed mean values, leaving a gap of information regarding minimum and maximum discharges, which were needed to be compared with other research's results.

The studies selection was made mainly through bibliographic research, but it also counted with consultation of YARA platform (https://www.labhidro.ufsc.br/yara/yara.html) (Borges de Amorim et al., 2020). This website displays results from a synthesis procedure on 42 climate change impacts related articles conducted by Borges de Amorim & Chaffe (2019), which evaluated the ensemble's results on consistency, quantity, and quality aspects. The results are shown for 12 main Brazilian basins. The following topics describe SACCI's study more thoroughly, and also describe the main climate projections for South America's hydrology.

SACCI Overview

Brêda et al. (2020) assessed climate change impacts on multiple long-period hydroclimate variables at the end of 21st century. For this analysis, the authors forced MGB-SA model with bias corrected data from an ensemble of 25 GCMs from CMIP5 (IPCC, 2014). Their analysis was based on two periods of 20 years: 1986-2005 and 2081-2100. The Greenhouse Gases (GHG) emission scenarios evaluated were RCP 4.5 and RCP 8.5, each corresponding respectively to a 4.5 W/m^2 and an 8.5 W/m^2 radiation increment. SACCI's results were divided between mean and significant changes and coefficient of variation for each scenario. The significance level was defined as 5 %. The climate change impact results were presented for the following variables: (i) temperature, (ii) precipitation, (iii) evapotranspiration, (iv) runoff, (v) aridity index and (vi) river discharge. An agreement analysis between the GCMs ensemble was conducted for precipitation and river discharge, in which it was considered to be an agreement if 2/3 of the GCMs showed the same alteration signal, towards wetter or dryer conditions. The results for river discharge were evaluated for a river network with drainage area > 10,000 km^2 (less detailed than MGB-SA's default one). This filter was applied in face of results' significant uncertainty when analyzing streams with drainage area < 10,000 km^2.

Other projections

Many studies have found that South America is likely to suffer decrease in water availability in most of its territory, except for southeastern region (south Brazil), which is the most consistent outlier to this behavior (Brêda et al., 2020; de Jong et al., 2021; de Queiroz et al., 2016, 2019; Ribeiro Neto et al., 2016; Sorribas et al., 2016; Zaninelli et al., 2019). In general, the most affected regions are Amazon, Orinoco and upper Paraguay basins, with consistent decrease in minimum, mean and maximum discharges, northeastern South America, with decrease (increase) in minimum and mean (maximum) discharges, and southeastern South America, with consistent increase of minimum, mean and maximum discharges.

Amazon River shows a negative alteration of 8 % on mean streamflow near its outlet, mainly due to the severe discharge decrease of its southern tributaries, especially on Tapajós and Xingu basins (Brêda et al., 2020). This strong negative behavior is corroborated by Sorribas et al. (2016), who also analyzed extreme discharges. Minimum discharge is expected to decrease in practically all basin's extent, whereas maximum discharge shows positive anomalies mainly on upper and western regions, with negative trends in southern and southeastern tributaries of Amazon River. Ribeiro Neto et al. (2016) did not show such intense signal over southeastern Amazon Basin for Q_{95}, instead, they obtained the strongest anomalies over Solimões basin. The pattern for Q_{10} is more similar to the one observed by Sorribas et al. (2016). As Ribeiro Neto et al. (2016) analyzed two GCMs separately, Sorribas et al. (2016) conducted their study over a five-model ensemble. Another difference between their methods is that, despite using the same hydrological model, Sorribas et al. (2016) used hydrodynamic modelling, whereas Ribeiro Neto et al. (2016) did not consider river routing in their analysis.

Looking at northeast region, Tocantins basin presented significant decrease for mean discharge, while Parnaíba and São Francisco basins did not show statistical significance (Brêda et al., 2020). Ribeiro Neto et al. (2016) observed slight (severe) decreases in most of northeast region (Tocantins River mouth) for extreme discharges, except for a small portion of Northeast Atlantic basin, which presented an increase in Q_{10}, indicating intensification of extreme events. In southeast South America (Uruguay basin), it is likely to occur an increment of minimum, mean and maximum discharges (Brêda et al., 2020; de Jong et al., 2021; Ribeiro Neto et al., 2016), consisting in the most extensive area that points towards wetter conditions. As for the central part of the continent, Brêda et al. (2020), Ribeiro Neto et al. (2016) showed either inconclusive or weak signs of alteration, appearing to be a transition zone from dryer conditions (north and northeast) to wetter conditions (southeast). Some zones of central basins may present a non-neutral condition. Upper (lower) Paraná and Paraguay basins show negative (positive) trends, as river's sensitivity to precipitation pass from lower to higher values, respectively (Brêda et al., 2020; Ribeiro Neto et al., 2016).

Some studies addressed discharge changes indirectly through precipitation and evapotranspiration, or even through hydropower potential production (de Jong et al., 2021; Queiroz et al., 2019; Zaninelli et al., 2019), presenting generally the same projections of wetter/dryer condition along South America. Turning the attention to changes in hydroelectric plants, the pattern observed is extremely similar, if not the same, to discharge's and runoff's, since it is assessed through dams' inflow stream. The plants most likely to present downward production are in the north and northeast regions of South America. For instance, Belo Monte dam, located in Xingu River, may show a decrease in its production, since Xingu River basin is probably walking towards dryer conditions (Brêda et al., 2020; de Jong et al., 2021; de Queiroz et al., 2019; Sorribas et al., 2016).

RESULTS

Recent discharge alteration

Earlier, we presented the methods implemented to assess river discharge mean (percentual difference between mean values) and significant (Student's t-test) alterations, and discharge significant trends (MK test). Significant alterations and trends were displayed in the same maps (Figure 1 - bottom), where river reaches in blue (red) showed positive (negative) values for at least one of both methods (Student's t-test and MK test), whereas the grey ones did not show significant results for neither of them. Figure 1 (top) displays the mean alteration between 1980-1999 and 2000-2019 for (a) minimum, (b) mean and (c) maximum discharges in the last decades.

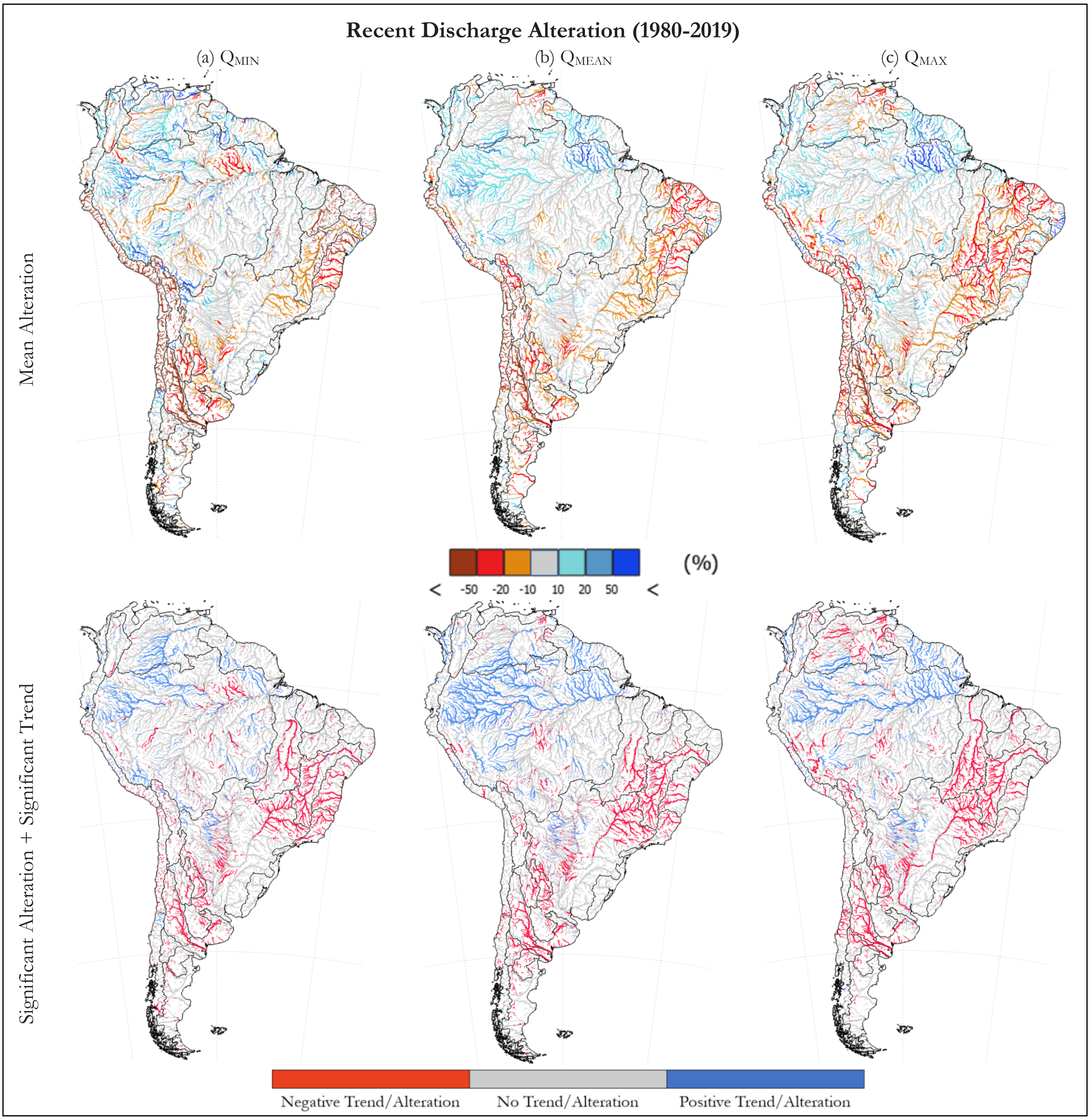

Figure 1. Mean alterations and significant trends and alterations (α=0.05) for (a) minimum, (b) mean, and (c) maximum discharges for the period 1980-2019.

From the river streams where it was not found significant trend, 69% (minimum discharge), 73% (mean discharge) and 67% (maximum discharge) were within the neutral range of +/- 10%. And from the ones within the neutral range, 14% (minimum discharge), 18% (mean discharge) and 14% (maximum discharge) presented significant trend. In general, the neutral range of ±10 % represents the non-significant changes, especially for minimum and mean discharges. As for maximum discharges, Student's t-test and MK test showed a positive anomaly in most of Amazon River extension, which was within mean alteration's neutral band (Figure 1). As seen in the maps, most regions' patterns agree between minimum, mean, and maximum discharges, and northeast, southwest, and north areas are the ones that most show significant trends and alterations in natural river flow.

Caution is necessary for interpreting results regarding MK test. Chen & Grasby (2009) showed that MK test applied on short time series may not represent discharge's real long-term trends. This is due to the influence of low-frequency oscillations in ocean phenomena over rainfall and river regimes. This can be especially problematic when the extent of data's record is less than half wavelength of river discharge's low-frequency oscillation in a given locality (Chen & Grasby, 2009). The authors stablished that the trend of river discharge time series shorter than 60 years should be analyzed with this limitation in mind.

AMO and PDO presented phase durations not longer than 35 years in the period from 1931 to 2016, with, respectively, 2 and 4 shifts during this time, according to a change point analysis (Rocha & de Souza Filho, 2020). ENSO did not exhibit any change point in the series, therefore, it did not present long term oscillation in the analysis, unlike AMO and PDO. However, it is associated to PDO's phase shift (cold-warm) in 1975 (Rocha & de Souza Filho, 2020). The study showed that PDO had high correlation with more recent river flow values, despite pointing that this result should be treated carefully. Taking these statements in consideration, the period 1980-2019 was considered satisfactory for streamflow trends representation, since it is >30 years and it encompasses AMO's and PDO's long-term phase durations.

Validation

Agreement between observed and simulated discharge alteration

To evaluate MGB-SA's representation of discharge alteration, the same procedure was applied for ANA's observation data and the model's simulation data. Then, we compared their results at the respective river reaches. The degree of agreement between observed and simulated alteration was categorized in 4 classes: (i) Agreement, (ii) Partial Agreement, (iii) Disagreement and (iv) Partial Disagreement.

(i) Both alterations have equal sign and are higher (lower) than +10 % (-10 %), or both are within the neutral range (± 10%).
(ii) One alteration is higher (lower) than +10 % (-10 %) and the other is within the neutral range and has equal sign.
(iii) Both alterations are out of the neutral range and have opposite signs.
(iv) One alteration is higher (lower) than +10 % (-10 %) and the other is within the neutral range and has opposite sign.

The result of this validation is displayed in Figure 2. Maximum discharge presented the highest values for *Partial Disagreement* (15.3 %) and *Disagreement* (4.8 %). Still, this was considered a satisfactory result, since almost 80 % of the gauges presented *Agreement* or *Partial Agreement*. Disagreeing gauges did not surpass 13 % (9 %) for minimum (mean) discharge. With this analysis, we considered MGB-SA capable of representing alterations in river flow.

Other studies

Aiming to validate the method applied in a larger scale, we compared discharge's trend and alteration with studies of river discharge trends over South America. Many authors have assessed past and recent trends in hydrology time series over different South American basins and regions (Bartiko, 2020; Castino et al., 2017; Fleischmann, 2021; Perez et al., 2021; Wongchuig Correa et al., 2017).

River discharge in La Plata basin showed significant increase in early 1970s, associated with positive (negative) ENSO and PDO (AMO) phases (Castino et al., 2017; Perez et al., 2021; Rocha & de Souza Filho, 2020). Perez et al. (2021) proposed that was not until 1995 that the region presented a decrease trend of hydrological variables. After this period, La Plata basin presented mostly negative trends of river discharge (Perez et al., 2021; Rocha & de Souza Filho, 2020). However, the Andean side (western) shows an increase of river discharge for the same latitude range (Castino et al., 2017). Northeastern South America presents a consistent negative trend of river discharge over a large area (Bartiko, 2020; Rocha & de Souza Filho, 2020).

Wongchuig Correa et al. (2017) assessed discharge trends in the Amazon basin from 1981-2010. They observed positive trends of mean and maximum discharge mostly over north and northwestern regions from the basin. As for southern Amazon basin, the study showed negative trends, especially for minimum and mean discharges (Wongchuig Correa et al., 2017). Fleischmann (2021) presented results of an inundation area increase of 20 % in central Amazon from 1980 to 2020, associated to a raise of rainfall over basin's north region. This increased precipitation would be related to a hydroclimate shift in late 1990s in which lead to historic water level records in June 2021 (Fleischmann, 2021). The spatial pattern of these trends matches the one found by Wongchuig Correa et al. (2017).

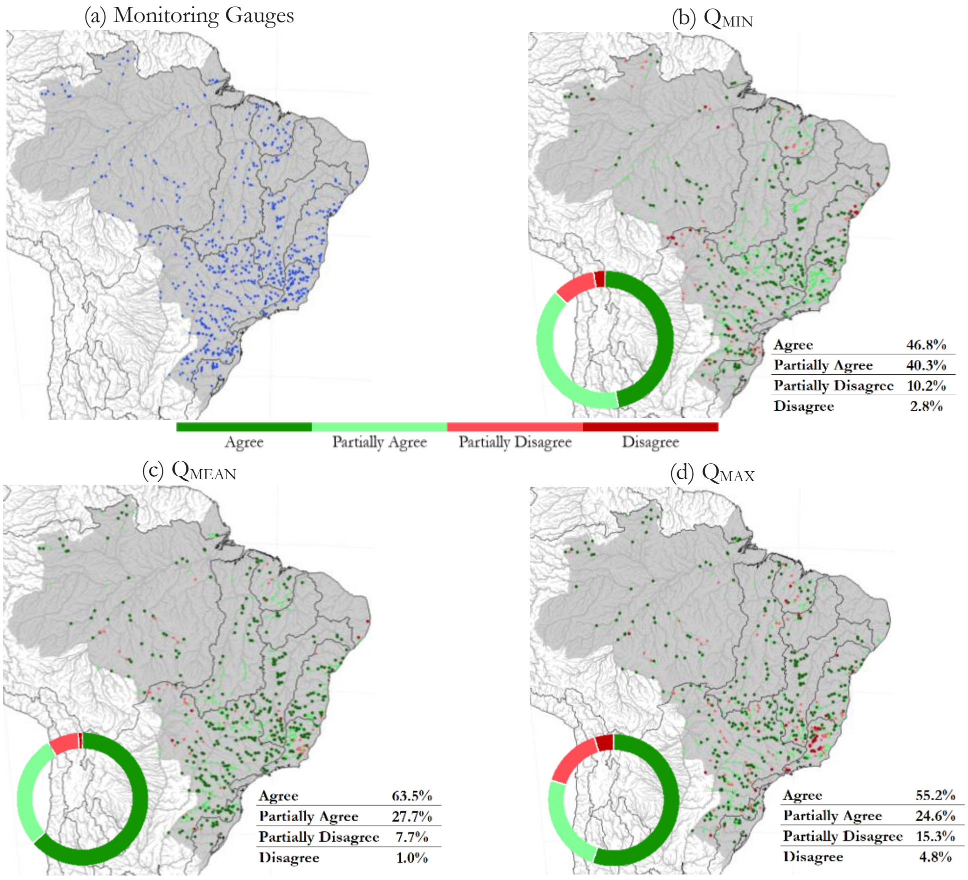

Figure 2. (a) Spatial distribution of the 581 gauges used for MGB-SA's validation and agreement results for (b) minimum, (c) mean, and (d) maximum discharges.

Focusing on Brazilian territory, the northeast, central and upper-southeast regions present well spread downward trends in magnitude and frequency of flood events, whereas north and south regions show upward trends (Bartiko, 2020). This pattern was also observed by Rocha & de Souza Filho (2020), that evaluated changes in key Brazilian hydropower reservoir systems: Furnas (southeast), Sobradinho (northeast), Tucuruí (north) and Itaipu (south). The authors pointed to a uniform trend behavior on northeast (negative) and south (positive) regions, with the area in between presenting a transition from one state to the other.

The present study shows patterns similar to the referred ones, especially in South America's north and northeast regions, in which discharge alteration and trend were more substantial. As for southeastern South America (southern Brazil), our results for streamflow changes did not match the strong positive signal presented by Bartiko (2020) and Rocha & de Souza Filho (2020). This can be due to method limitations, or even to dataset characteristics and/or issues.

Recent alteration vs. Climate projections

This item presents the results of the comparison between discharge trends observed in a period from 1980 to 2019 and projected for the end of 21st century. We were able to compare mean discharge alteration directly (stream by stream) with Brêda et al. (2020) results, since they also used MGB-SA in their assessment and provided their river network's result shapefile. The comparison was displayed in form of agreement between recent alteration and future projection signals (similarly to what was done with ANA's gauge data and MGB-SA simulation data previously). The result was represented by the following categories: (i) Agreement, (ii) Partial Agreement, (iii) Disagreement, (iv) Partial Disagreement and (v) Undefined. The first 4 categories are the same representation seen on Figure 2, as for class (v), it stands for river streams for which the GCM ensemble did not converge to an alteration signal. Figure 3 exhibits the impacts over mean discharge obtained by Brêda et al. (2020), alongside its agreement with 1980-2019 mean discharge trends for (a) RCP 4.5 and (b) RCP 8.5 scenarios. It is worth mentioning that changes between GHG emission scenarios are given mainly by alteration intensity and not in its signal, as observed in the studies of Brêda et al. (2020) and Ribeiro Neto et al. (2016).

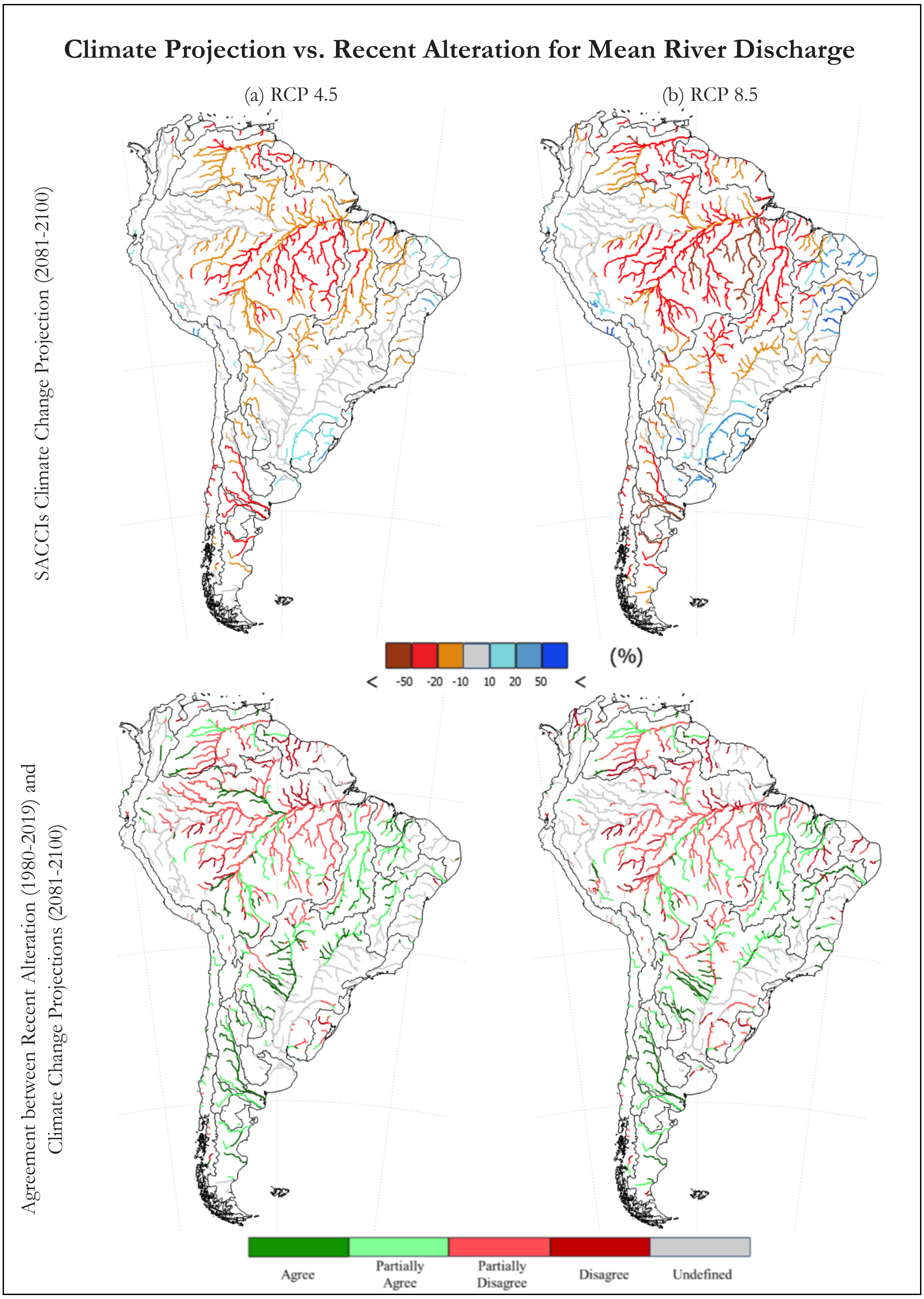

Figure 3. SACCI's climate projections for mean discharges and its agreement with alteration (MGB-SA) between 1980-1999 and 2000-2019.

Both agreement maps have similar patterns, which is expected, since most differences between the scenarios are given by intensity of change, not by signal. Northern basins, such as Amazon and Orinoco show disagreement in results, with climate projections indicating decrease in river discharge, whereas recent alteration indicates the opposite. As for Northeastern and upper Central regions (São Francisco, Tocantins-Araguaia, Western Northeast Atlantic and upper La Plata basins) show wide agreement between past and future periods, both indicating decreasing river discharge.

Extreme discharges were compared more generally than the average one, lacking river stream resolution level analysis. Amazon basin presents disagreement in most of its territory for minimum streamflow, being projected to have significant decrease in its eastern region. On the other hand, the basin is expected to have significant increase in maximum discharge in its western portion, mainly in upper Amazonas River, and also in its northern region, behavior which matches trends simulated in 1980-2019. Northeastern South America recent trends agree with projected decreases (in both minimum and maximum discharges) in most of its extension. Our results for lower Paraíba River show a positive alteration for maximum discharge, which corroborates to Ribeiro Neto et al. (2016) findings, even not being the expected for most of the region. As for southeastern South America (southern Brazil), our study disagrees with the steady increase projected for mean and extreme discharges. However, it must be noted that the recent trends we found disagree with other studies' evidence, demanding awareness when treating this result. Southern South America basins and basins that drain Central Andes were not analyzed, since MGB-SA does not consider snowmelt in its simulation, process which is relevant in said localities (Brêda et al., 2020; Siqueira et al., 2018).

Here are addressed the study's limitations and prospects. What is considered to be the main issue is the extent of the period assessed (40 years), since MK test may not represent true discharge trend in periods shorter than 60 years (Chen & Grasby, 2009). We also evaluated discharge alteration by comparing two 20-year samples, which are shorter than the usual climatological normal period (30 years). MGB-SA dataset's uncertainties and performance metrics were not directly addressed, nor were defined confidence bands for discharge alteration. We addressed this issue by assuming a ±10 % threshold to report a discharge change. Since our assessment focused on change's signal and not on its absolute value, it was considered that the neutral range encompassed method's uncertainties. As for prospects, this analysis could be reconducted for other hydrologic variables, over a longer time series, and it could be compared to new climate projections studies, as these assessments evolve over the years.

CONCLUSIONS

The comparison between discharge trends from 1980 to 2019 and the ones projected for late 21st century showed some regions with uniform behavior, and others with more irregular patterns. Northern South America climate projections mostly disagreed with recent alteration for minimum, mean, and maximum discharges. As for continent's northeast region, it presented wide agreement with 1980-2019 behavior. As recent past discharges indicate wetter conditions at Amazon basin, climate projections present several decreases in minimum and mean discharges (maximum discharge is also expected to decrease, however the negative alteration is more restricted to eastern and southeastern regions) (Brêda et al., 2020; de Jong et al., 2021; Ribeiro Neto et al., 2016; Sorribas et al., 2016). As for northeastern basins (Tocantins-Araguaia, São Francisco, and Western Northeast Atlantic), discharge alteration points towards drier conditions according to recent past and future periods (Brêda et al., 2020; de Jong et al., 2021; Ribeiro Neto et al., 2016), agreeing in most of their extension. Climate projections for central South America show a transition zone from drier conditions (upper portion) to wetter conditions (bottom portion). This can be seen as the GCMs disagree on projections for lower Paraná and Paraguay rivers. This transitional pattern was also seen in recent alteration, except for southeastern South America, which did not show positive anomalies in our analysis, disagreeing with climate projections for the region (Brêda et al., 2020; de Jong et al., 2021; Ribeiro Neto et al., 2016), though we found our results for the region to be dissonant from other studies (Bartiko, 2020; Rocha & de Souza Filho, 2020).

The study discussed climate's natural and anthropogenic changes influence on hydrology in recent decades. Aiming to bring evidence towards one effect or the other over different South American regions, we compared simulated discharge alteration through 1980-1999 and 2000-2019 to alteration projected for the end of 21st century. If both periods' (recent past and future) anomaly signals agree, the evidence cannot discard the influence of climate change in recent years, perhaps indicating a more steady trend or alteration for next decades. If there is a disagreement, it could be assumed that climate projections for the long term are imposing minor influence in front of climate's natural variability recently and future conditions are uncertain.

The relevance of this topic is given by the very importance of South America's hydrology. Hydropower plants are the main asset for energy production in Brazil, and their management involves long term planning. The evidence brought in the present study can help to construct future scenarios of dam operation. Knowing whether climate projections stand for a more probable state or not, water management sector could prepare more adequately for the future.

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