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ASSESSMENT OF WATER AVAILABILITY IN THE PERIOD OF 100 YEARS AT THE HEAD OF THE SÃO FRANCISCO RIVER BASIN, BASED ON CLIMATE CHANGE SCENARIOS

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Keywords:
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Climate models

ABSTRACT

In the last century, changes in climate trends have been observed around the planet, which have resulted in alterations in the hydrological cycle. Studies that take into account the impact of climate change on water availability are of great importance, especially in Brazil's case, where water from rivers, beyond being destined for human consumption, animal watering and economic activities, has a great participation in electricity generation. This fact makes its energy matrix vulnerable to variations in the climate system. In this study, a flow analysis for the head of the São Francisco river basin was performed between 2010 and 2100, considering the precipitation data of the CCSM4 climate model presented in the Fifth Assessment Report (AR5) from the Intergovernmental Panel on Climate Change (IPCC). Projections of future flow were performed for the scenarios RCP4.5 and RCP8.5, based on the SMAP rain-flow model, followed by a comparative analysis with the present climate. In general, we can observe that the decades of 2010 to 2100 will be marked by the high levels of precipitation, interspersed by long droughts, in which the recorded flow will be lower than the Long Term Average (LTA) calculated for the basin. Therefore, new management strategies must be considered to maintain the multiple uses of the basin.

Palavras-chave:
Modelagem chuva-vazão
IPCC
CCSM4
SMAP
Modelos climáticos

AVALIAÇÃO DA DISPONIBILIDADE HÍDRICA NO PERÍODO DE 100 ANOS NA CABECEIRA DA BACIA DO RIO SÃO FRANCISCO, COM BASE EM CENÁRIOS DE MUDANÇAS CLIMÁTICAS

RESUMO

No último século, foram constatadas na Terra, mudanças de tendências no clima que implicaram em alterações no ciclo hidrológico. Estudos que considerem o impacto das mudanças climáticas na disponibilidade hídrica, portanto, são de grande importância, principalmente para o Brasil, onde a água de rios e mananciais, além de ser destinada para consumo humano, dessedentação animal e atividades econômicas, apresenta grande participação na geração de energia elétrica, fazendo com que a matriz energética do país esteja vulnerável às variações climáticas. Neste trabalho foi realizada uma análise de vazão para a cabeceira da bacia hidrográfica do rio São Francisco entre os anos de 2010 e 2100, considerando os dados de precipitação referentes ao modelo climático CCSM4 apresentado no Quinto Relatório de Avaliação (AR5) do Painel Intergovernamental sobre Mudanças Climáticas (IPCC). Foram efetuadas projeções de vazão futura para os cenários RCP4.5 e RCP8.5, a partir do modelo chuva-vazão SMAP, seguidas de uma análise comparativa com o clima presente. De modo geral, observou-se que o período entre as décadas de 2010 a 2100 será marcado pela ocorrência de elevados níveis de precipitação, intercalados por longas secas, em que a vazão registrada será inferior à Média de Longo Termo (MLT) calculada para a bacia. Desta forma, novas estratégias de gestão deverão ser consideradas para a manutenção dos múltiplos usos da bacia.

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INTRODUCTION

A series of changes in climate trends have been observed since 1950, with substantial variations in precipitation and temperature extremes (THORNTON *et al.,* 2014). According to Sohngen and Tian (2016), climate change is associated with a higher occurrence of forest fires and insect infestations. Tozato *et al.* (2015), in turn, highlight the impacts on the phenology, distribution, morphology, abundance and reproduction of species, while Ojima (2011) highlights the migratory movements and the spatial redistribution of the population caused by changes in the climate.

Regarding Brazil, Bolson and Haonat (2016) also emphasize how water governance is affected, causing a state of water insecurity, especially in the regions of the Semi-Arid and the western border of Rio Grande do Sul and Santa Catarina. Water availability in Brazilian basins is subject, therefore, not only to the management of its multiple uses, but also to future climate change.

Hydroelectricity is one of the most frequent uses of water resources in Brazil, corresponding to approximately 60% of the country's internal electricity supply (CANTELLE *et al.,* 2018). According to Da Silva *et al.* (2019), the use of water for energy generation is encouraged by the government, since it is a renewable source and has a low associated cost. However, the negative point is the dependence of the hydroelectric matrix on regional climatic conditions, as well as the management of local water resources.

In this context, we highlight the Fifth Assessment Report (AR5) made available by the Intergovernmental Panel on Climate Change (IPCC) in 2013 and which, based on extensive bibliography, brings a series of historical climate projections and scenarios of future evolution, from different evolutionary, technological and social lines.

Regarding precipitation, AR5 indicates, for example, a 22% reduction in the Northeast of Brazil and a 25% increase in southeastern South America. The IPCC (2013) also suggests a reduction in drinking water offering in dry subtropical territories, which would potentiate disputes over the use of hydrographic basins. This effect is similar to what happens with the São Francisco River, whose transposition aims to integrate its basin with those of the Northeast.

The frequent water deficit, characterized by low levels of precipitation and irregular distribution, represents a major problem for the states of the Northeast region, due to its consequences for public supply, agricultural, industrial and energy production (MARENGO *et al.,* 2016).

In this context, Miranda *et al.* (2017), Silva *et al.* (2020) and Silveira *et al.* (2013), aiming at a deeper analysis of the hydrological regime of the basins in the Northeast region, used climatological data presented by the IPCC, coupled to the Soil Moisture Accounting Procedure (SMAP) rainfall-runoff model (LOPES *et al.,* 1982). In all cases, the authors observed negative impacts on the flow regime of the basins, projecting a substantial reduction in water availability.

Considering this fact, it is plausible to establish a connection between climate change and changes in the water regime, paying attention to how they can affect the local socioeconomic development. Therefore, the objective of this study is to evaluate the scenarios of water availability for the head of the São Francisco river basin, from 2010 to 2100, based on the SMAP model and the rainfall data available in the IPCC AR5.

MATERIAL AND METHODS

São Francisco river basin

The São Francisco river basin crosses seven Brazilian Federative Units (Alagoas, Bahia, Federal District, Goiás, Minas Gerais, Pernambuco and Sergipe), as shown in Figure 1, totaling a drainage area of approximately 640,000 km^2, which corresponds to 8% of the Brazilian territory (CBHSF, 2016).

The São Francisco river extends for 2,863 km, from the Serra da Canastra in Minas Gerais, where its source is located, to its mouth in the Atlantic Ocean, and runs through 507 municipalities. With 54% of its territory located in the Semi-Arid region, the basin also covers the Caatinga, Cerrado and Atlantic Forest biomes, beyond coastal and island ecosystems (CBHSF, 2016).

According to the Köppen classification, the hot semi-arid climate (BSh) is predominant, characterized by rainy summers and dry winters, with transitions to the humid climate in certain regions of the basin. The average annual temperature ranges from 18 to 27 ºC, with an average rainfall of 1000 mm/year approximately and an average evapotranspiration of 896 mm/year (CBHSF, 2016). It is noteworthy that due to the extension of the basin, there is a great climatic variability, with the highest values of precipitation and evapotranspiration occurring in the south and the lowest in the north.

The São Francisco basin was divided into 4 physiographic zones or regions (High São Francisco, Upper Middle São Francisco, Lower Middle São Francisco and Low São Francisco), for planning and management purposes. These physiographic zones bring together a population of 14 million inhabitants. The population profile and the socio-economic reality, however, are quite diverse, with areas of high demographic density and high levels of income and urbanization, in contrast to sparsely populated, rural and low-income areas (IBGE, 2010).

In the High, Upper Middle and Lower Middle São Francisco, for example, there are relevant industrial zones, with emphasis on steel, mining, chemistry and textiles industries, in addition to agro-industrial centers for grains and fruit production, while in the Low São Francisco predominates agriculture and cattle farming as well as traditional fishing, strongly linked to the riverside economy.

The São Francisco basin also has relevant hydroelectric use along its main course, represented by nine plants in operation, five of which with a reservoir (Itaparica, Queimado, Retiro Baixo, Sobradinho and Três Marias), and all members of the National Interconnected System (SIN). For this reason, it constitutes an important base for the supply of electric energy in the Northeast region and in the country (ANA, 2020).

For this study, therefore, we decided to analyze the São Francisco river basin due to its strategic importance for human supply, animal drinking, agro-industrial production and electrical energy generation in northeastern Brazil.

Data collection

The monthly data of observed natural flow and evapotranspiration were obtained from the National

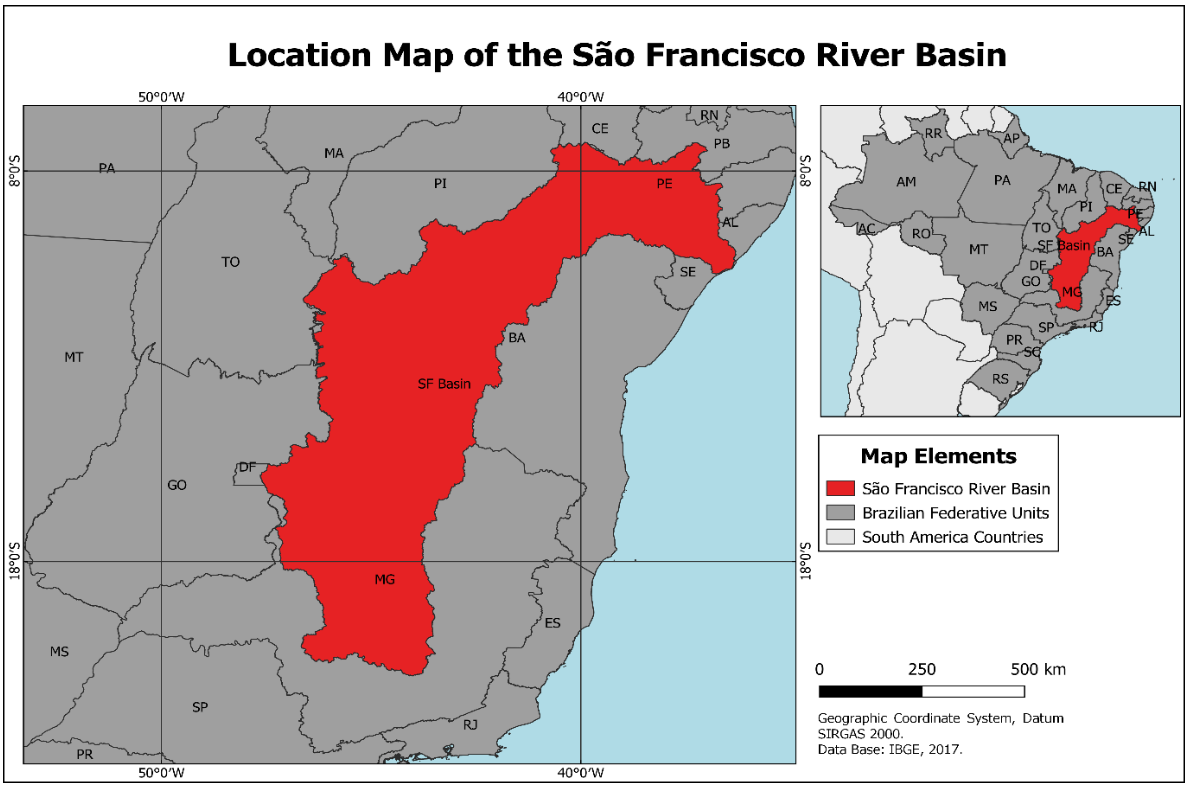

Figure 1. Location map of the São Francisco river basin in the context of the Brazilian territory

Electric System Operator (ONS) in order to use the SMAP rainfall-runoff model (LOPES *et al.,* 1982), in its monthly version. The precipitation data, in turn, were made available by the National Water and Basic Sanitation Agency (ANA), through the HidroWeb system. Since the data provided by ONS are already treated and refer only to hydroelectric plants reservoirs, we decided to focus the flow projection analysis only on the reservoir of the Três Marias Hydroelectric Plant, located at the head of the São Francisco river.

Considering the inventory of the national stations, 23 rains gauges located within the aforementioned reservoir area were chosen, as can be seen in Figure 2. Such selection was based on a period of coincident data, so that an uninterrupted series from 1985 to 2004 and with a percentage of failures below 12% was obtained.

To assess the reliability of the data, an outlier detection was performed, with values greater than 95% of the rainfall distribution being highlighted for each analyzed month. The highlighted data that were considered extremely high when compared to the other rain gauges, were then excluded and treated as failures. These, in turn, were filled with the average of the values of the three nearest rain gauges and located in similar climatological regions, according to the regional weighting method (BERTONI; TUCCI, 2001).

Precipitation data for the IPCC model, in turn, were obtained from the World Data Center for Climate (WDCC) platform, hosted by the German Climate Computing Center (DKRZ) and maintained by its long-term archiving service. Historical data from 1931 to 2004 and data for future projections from 2010 to 2100 of the RCP8.5 and RCP 4.5 scenarios were downloaded on this platform.

Considering that the data files were in .netCDF extension, whose format is not compatible with the SMAP model used in this study, it was necessary to use the MATLAB software to convert them into text files. In this step, only the precipitation data

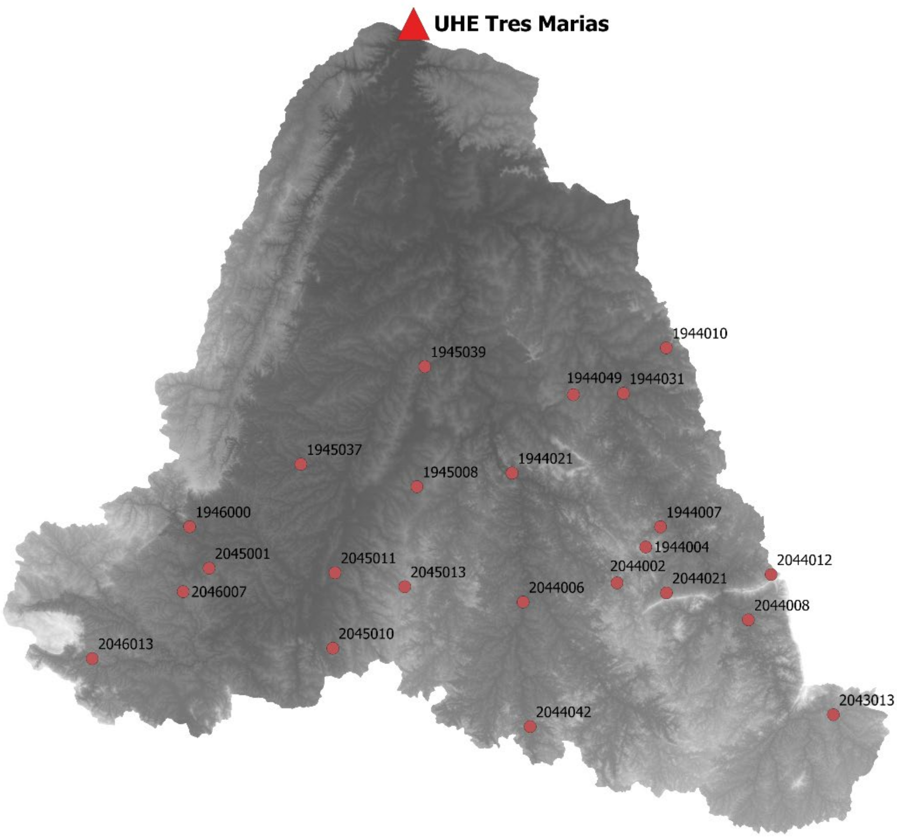

Figure 2. Spatial representation of the selected rain gauges at the head of the São Francisco river basin. The selected pluviometers are upstream of the Três Marias Hydroelectric Power Plant, aiming to standardize the drainage area that is object of the analysis of precipitation conversion into flow, since the obtaining of natural flow and evapotranspiration data was based on the plant area

whose latitude and longitude points were located within the limits of the São Francisco river basin were converted.

It is noteworthy that the aforementioned scenarios were defined by the World Climate Research Program (WCRP), according to the total radiative pathways associated with atmospheric emissions, and based on future projections of population growth and technological development. These data provide an estimate of the radiative forcing in the year 2100, compared to conditions prior to the Industrial Revolution (TAYLOR *et al.,* 2012).

The RCP4.5 scenario proposes the stabilization of the levels of radiative forcing up to 4.5 W/m² shortly after 2100 and, therefore, it is assumed to be more conservative and directed towards sustainable development. The RCP8.5 scenario proposes the stabilization of the radiative forcing up to 8.5 W/m²; therefore, it is assumed a more pessimistic scenario, in which fossil fuels will continue to be the largest source of energy during the 21st century (VAN VUUREN *et al.*, 2011).

Bias removal

The CCSM4 model (Community Climate System Model) was used for the precipitation projections. This model consists of the fourth version of the CCSM family of models, developed by the National Center for Atmospheric Research (NCAR) in the United States.

The CCSM4 is a coupled Atmosphere-Ocean General Circulation Model (AOGCM), part of the fifth phase of the Coupled Model Intercomparison Project (CMIP), and has already been employed in climate simulation studies, showing good performance and satisfactory results for precipitation projections (ISLAM *et al.,* 2017; THIBEAULT *et al.,* 2014).

A summary of the main characteristics of its atmospheric and oceanic components can be seen in Table 1.

Due to the systematic errors inherent to AOGCMs, it was necessary to remove the bias in order to improve the results of the simulations and reduce the performance errors of the model (FERNÁNDEZ BOU *et al.,* 2015; DA SILVA *et al.*, 2019). According to Meyer and Jin (2016), in their study, the bias removal in CCSM4 model promoted an improvement of the model's limitations, resulting in a great convective activity and a more representative seasonal distribution of precipitation.

For the bias correction in this study, it was used the linear scaling methodology, described by Fernández Bou *et al.* (2015) in their study regarding the flow forecast for the head of the Uruguay river basin. Initially, the monthly average rainfall observed and projected for the years from 1985 to 2004 was calculated, since this was the period of precipitation data in which the calibration and validation of the SMAP model was performed. Subsequently, through Equation 1, a relationship between the observed and projected rainfall averages was established in order to obtain a difference coefficient for each month of the year.

$$C_m = 1 + \frac{(P_{obsm} - P_{projm})}{P_{projm}} \quad (1)$$

Where,
C_m = correction coefficient for the month m;
P_{obsm} = observed average rainfall for the month m, considering the basin area; and
P_{projm} = projected average rainfall for the month m, considering the basin area;

Then, through Equation 2, the correction coefficients were applied to the monthly

Table 1. Characteristics of the atmospheric and oceanic components of the CCSM4

CCSM4	
Atmosphere Component	Resolution of 1.25° x 0.9°
	26 layers in the vertical direction
	Coupler to exchange fluxes and information
Ocean Component	Resolution of 1.11° in the zonal direction
	Meridional resolution ranging from 0.27° to 0.5°
	60 vertical levels with 20 layers in the upper ocean

precipitation data of the RCP4.5 and RCP8.5 future scenarios. The corrected rainfall was then used as input for the SMAP model.

$$P_j(t) = P_{projm}(t) \times C_m \quad (2)$$

Where,
$P_j(t)$ = corrected rainfall after the bias removal for the month m;
P_{projm} = projected average rainfall for the month m, considering the basin area; and
C_m = correction coefficient for the month m;

SMAP model calibration and validation

SMAP (Soil Moisture Accounting Procedure) is a hydrological, conceptual and deterministic model, developed by Lopes *et al.* (1982) to simulate the rainfall-runoff transformation.

It is also considered a mathematical and concentrated model, or concentrated with semi-distributed application, based on the principle of mass conservation and on the concept of water balance. In this model, the transfer equations are only in function of time, with the spatial distribution of precipitation represented by the weighted distance of each rain gauge.

In its monthly version, the SMAP consists of two mathematical reservoirs: Soil reservoir (unsaturated zone) and Groundwater reservoir (saturated zone). This version is characterized by having its transfer functions updated every month, being adapted to the use of optimization tools, to maximize the overall efficiency coefficient.

Considering the mathematical characteristic of the model, the reservoirs can be described by a series of equations, in order to obtain the total runoff projected. All the equations used in the SMAP operation, as well as the main physical and temporal parameters, can be found in the work of Fernández Bou *et al.* (2015), regarding the runoff projections for the Uruguay river basin.

In order to use SMAP in its monthly version, we inserted the monthly precipitation totals made available by ANA, so that 60% were destined for calibration and 40% destined for model validation. The data for each station were arranged so that the calibration period would begin in the same month in which a drought scenario was observed, respecting the basin seasonality.

Subsequently, we inserted the monthly natural flow and evapotranspiration data, provided by ONS, referring to the Três Marias Hydroelectric Power Plant. Then, the initialization parameters of the model and their respective limits were defined, as well as the upper and lower limits for the spatial and temporal weight of the rain gauges. The initial basic flow (ebin) and the initial moisture rate (tuin) were manually calibrated, so that the curves of the observed flow and the flow calculated by the model were in phase.

The SMAP calibration was completed with the optimization of the model, using the Microsoft Excel® SOLVER tool. In this tool, the objective function was defined, as well as the parameters and limits to be considered, in order to obtain the combination of factors, which, respecting the characteristics of the basin, resulted in the highest global efficiency coefficient value.

A similar procedure, but without the optimization step, was adopted for the model validation. The same limits and parameters of the calibration were considered, changing only the data period, ebin and tuin.

After the calibration and validation processes, the precipitation data from January 1931 to December 2005, referring to the CCSM4 model were inserted in the SMAP. The objective of this step was to verify if the simulated flow for the present climate was similar to the observed natural flow data. This comparison was made through the analysis of the period in common between the data, that is, the period in which the SMAP calibration and validation was done, by calculating the Mean Absolute Error (MAE) and the Mean Absolute Percentage Error (MAPE).

Then, the bias removal was performed to eliminate the systematic errors, establishing a relationship between the observed and projected rainfall averages, in order to obtain a difference coefficient for each month of the year. This correction coefficient was applied to the precipitation data of the future scenarios – RCP4.5 and RCP8.5 – in order to obtain more robust forecasts. The SMAP performance metrics can be found in the study performed by Fernandez Bou *et al.* (2015).

After the bias correction, the SMAP was run for the period from 2010 to 2100, for both RCP4.5 and RCP8.5 scenarios, generating future flow projections for the head of the basin. The average, standard deviation and flow plus two standard deviations (95% of the distribution) were then calculated. Subsequently, simulated future flow graphs were generated, with the comparison between the average monthly flows simulated and observed.

Climate variability

The analysis of climate variability is an extremely important factor for short and long term forecasts, since it allows to understand the changes in the oceanic and atmospheric circulation, establishing the most critical forcing. The study of this variability is also essential to determine the anthropogenic influence on global climate change observed since the Industrial Revolution.

However, several studies show that model simulations are still unable to replicate the observed spatial patterns and their magnitude, underestimating or overestimating the natural climate variability (KRAVTSOV *et al.*, 2018; SWANSON *et al.*, 2009). In his work on the Atlantic Multidecadal Oscillation (AMO), for example, Kravtsov (2017) observed pronounced differences in relation to climatic variability observed in the 21st century and to that simulated by the CMIP5 models.

Considering these facts, we decided to analyze the discrepancy between natural variability and that modeled for the head of the São Francisco river basin. For this analysis, graphs were created containing the standard deviation of the simulated flow for the period from 1931 to 2005. Graphs for the observed flow for the same period and the projected flow for the decades between 2010 and 2100 were also plotted. Finally, we compared the monthly standard deviation calculated for the RCP4.5 and RCP8.5 climate change scenarios.

RESULTS AND DISCUSSION

Bias renoval analysis

The calculation of the Mean Absolute Error (MAE) and the Mean Absolute Percentage Error (MAPE) from the uncorrected results and the observed flow data, for the common period from 1975 to 2005 was performed in order to better understand the simulated flow results for the present climate.

It should be noted that despite the historical round being performed for the entire period of data provided by CCSM4 (1931-2005), the comparison between MAE and MAPE was made considering only the years between 1975 and 2005, extrapolating the SMAP calibration and validation interval (1985-2004), in order to obtain a complete period of 30 years. This period is considered by the World Meteorological Organization (WMO) as sufficient to identify the characteristic patterns of a climate parameter. The values obtained can be seen in Table 2.

We can observe in Table 2 that the use of the correction coefficient in the precipitation data increased the average monthly flows projected by the model for the head of the São Francisco river basin, bringing them closer to the monthly observed flow in the same period and decreasing the average errors associated with the data.

This analysis is compatible with that observed by Miranda *et al.* (2017), when simulating flows for the São Francisco river basin with the AOGCM MIROC, regionalized by the RegCM climate model. The authors pointed out that the removal of precipitation bias also promoted an improvement in the statistical performance indexes, increasing the efficiency coefficient of the SMAP model by

Table 2. Comparison between Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE) with and without bias correction

	Mean Average 1975-2005	With no correction	With correction
HEAD OF THE SÃO FRANCISCO RIVER BASIN	Observed (m^3/s)	706.18	706.18
	Simulated (m^3/s)	449.23	632.07
	Mean Absolute Error (MAE)	463.23	453.57
	Mean Absolute Percentage Error (MAPE)	64.68	57.21

more than 350%.

It should also be noted that the bias removal, although successful, was very expressive, indicating that while CCSM4 adequately captures the precipitation regime over the head of the basin, the simplifications inherent to its cumulus parameterization, convection and cloud microphysics do not allow the model to reach the same precipitation totals observed.

Average flow analysis

From the detection of the systematic average errors of the model in the present climate simulation, the adjustment coefficients were used in the simulations of the CCSM4 for the period from 2010 to 2100. The averages of these differences are shown in Figure 3. We can observe that for the present climate (1931-2005) the curves referring to the observed average flow and the simulated average flow show similar behavior, with peaks and valleys in phase.

It is also noteworthy that, although the simulated average flow curve differs from the average flow observed in the wet period, there is no relevant variation during the dry period. Therefore, regarding the present climate, the results reinforce that observed by Silveira *et al.* (2016), in their study on the analysis of precipitation and temperature for the São Francisco basin, based on the IPCC-AR5 models. According to the authors, the CCSM4 is able to correctly representing seasonality, with a correlation greater than 0.9 to the basin climatology and a mean squared percentage error of less than 3.0%.

In relation to the RCP4.5 scenario, we can observe that the projected flow from 2041 to 2070 increases considerably in the first months of the year, distancing itself from the observed flow. This result is also consistent with that obtained by Silveira *et al.* (2016) when evaluating the same period, in which the authors highlight a variation in precipitation anomalies between 10% and -20%.

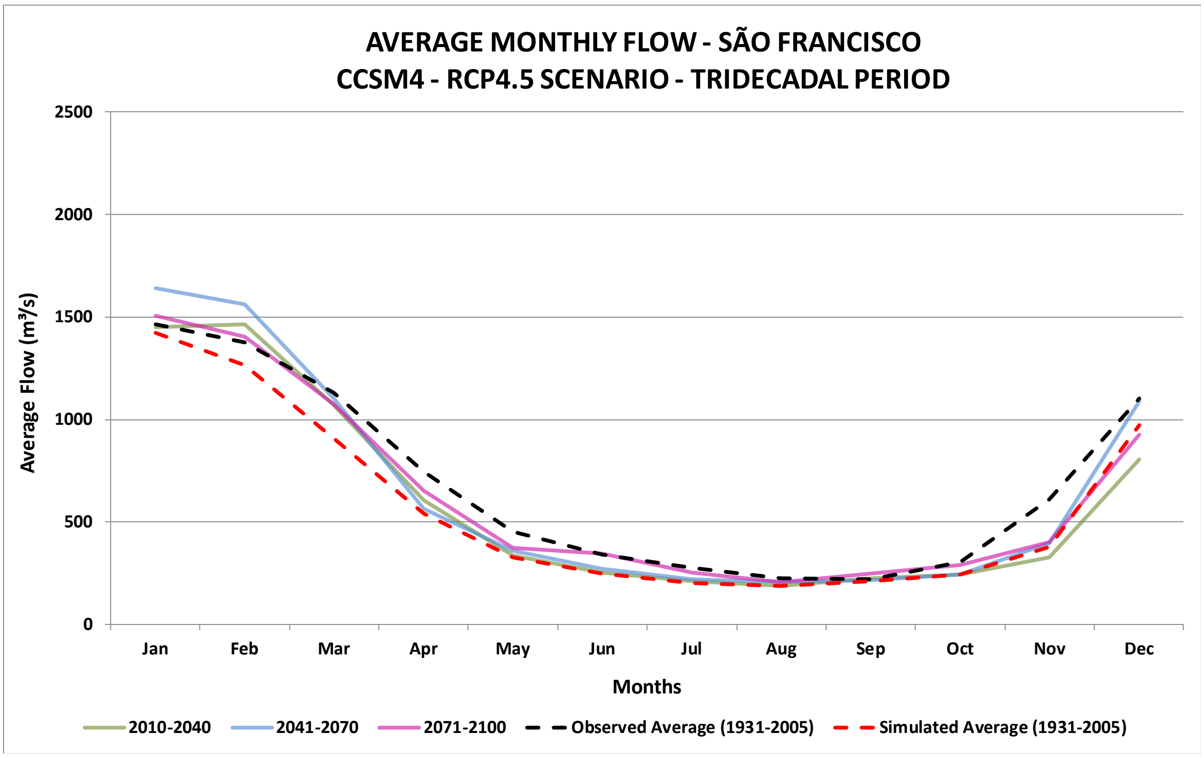

Figure 3. Comparison between the average monthly flows simulated by the SMAP model for the head of the São Francisco river basin. The black dotted curve refers to the average flow observed for the present climate (1931-2005), while the red dotted curve represents the average projected flow by the model for the present climate. The green, blue and lilac curves represent, respectively, the future flow projections of the RCP4.5 scenario of CCSM4 for the periods 2010-2040, 2041-2070 and 2071-2100

Regarding the values of monthly average flow, we can observe that at the beginning of the century (Figure 4) a single extreme event is expected to occur, associated with the year 2024, in which the flow exceeds 3500 m³/s. It is also worth mentioning several periods of scarcity, with emphasis on the periods from 2013 to 2015 and from 2024 to 2028, where the projected flow is less than 95% of the distribution. For the second third of the century, the main expected flow events are related to the years 2036 and 2057, in which the flow exceeds 4000 m³/s. There are also years marked by drought, such as 2070 and 2071, where the projected flow is less than 100 m³/s. Still according to the model, at the end of the century there will be some extreme events, mainly in the years 2079 and 2080, in which the flow will reach a value higher than 3000 m³/s. For the period between 2073 and 2076, 2086 and 2090, 2099 and 2100, the expected flow will remain below average.

Therefore, we can observe in this period a low oscillation of the flow series, and it is not possible to clearly define a trend. Such analysis is compatible with that performed by Guimarães *et al.* (2016), in their study on climate projections for Brazilian Northeast region, based on CMIP5 models. After analyzing the projections of several models for the future climate, the authors also concluded that the changes in the average precipitation in the RCP4.5 scenario were small, with no significant reduction trend.

Regarding the RCP8.5 scenario in Figure 5, we can observe that the projected future average flows from 2010 to 2040 will always be lower than the average flows observed and projected for the present climate (1931-2005), reaching values below 500 m³/s in the dry months. We can also verify that the projected future flows from 2041 to 2070 and from 2071 to 2100 are noticeably higher than the average in almost every month, increasing significantly in the wet period and, in some cases, exceeding 2000 m³/s.

This result was also observed by Silveira *et al.* (2013), when evaluating the performance of

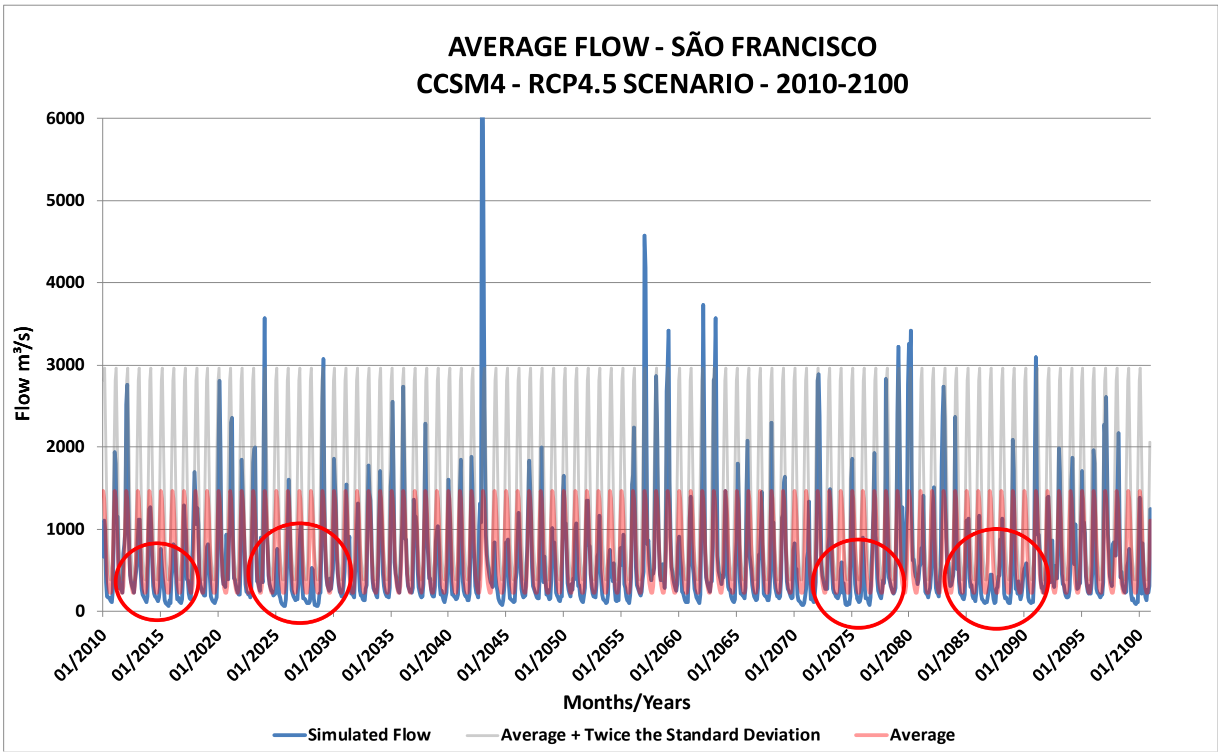

Figure 4. Results of simulated monthly future flow for the period from 2010 to 2100 of RCP4.5 scenario for the head of the São Francisco river basin, represented by the dark blue curve. The observed natural average flow for the present climate (1931-2005), represented by the red curve, is shown as the basis of comparison, and this flow plus two standard deviations (95% of the distribution) is represented by the gray curve

the CMIP5 models for the Brazilian Northeast for the RCP8.5 scenario. According to the authors, in most models analyzed, the greatest impacts were obtained in December, January and February. Sales *et al.* (2015), in their study on projections of precipitation changes in the Northeast region, also found a similar behavior, with the CMIP5 models projecting a precipitation reduction in winter and spring in the medium and long term, and the increase of rain in the summer.

Concerning the average flow values, some extreme events are predicted at the beginning of the century (Figure 6) in which the projected flow is greater than 95% of the distribution, with emphasis on the years 2024 and 2036, where the flow reaches values above 4000 m³/s. There are also periods marked by water scarcity, such as the bienniums from 2014 to 2015 and 2033 to 2034, where the flow rate is lower than the observed average, reaching values close to 100 m³/s. For the second third of the century, few relevant extreme events are also expected, the main ones referring to the years 2059, 2066 and 2068, where the flow exceeds 4900 m³/s. Water scarcity periods are also foreseen, with emphasis on the years 2041 to 2042, 2051 to 2055 and 2063 to 2064, in which the flow rates are below the observed average. The end of the century is marked by several extreme events, especially in the year 2093, where the projected flow reaches 5000 m³/s. The years 2071 and 2087 are also noteworthy, in which the flow is less than 200 m³/s.

Guimarães *et al.* (2016) also observed more pronounced changes in precipitation in the RCP8.5 scenario. According to the authors, despite the spread between the simulations, there was a tendency of dryness increase over the Northeast region during this century. The same was pointed out by Silveira *et al.* (2016), when reporting greater dispersion among the trends of the CMIP models in this scenario. The authors pointed out, however, that most models project a greater range of oscillations between 2071 and 2100, indicating the occurrence of extreme events in this period, a fact also observed in the present analysis.

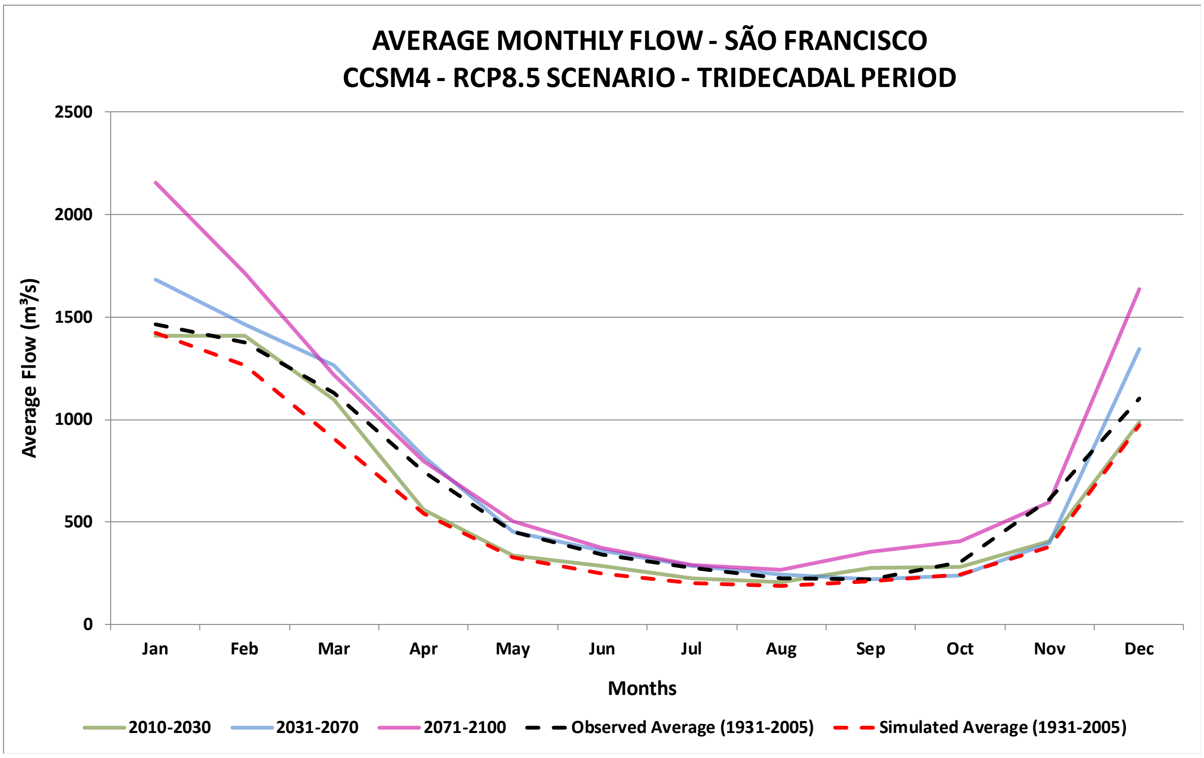

Figure 5. Comparison between the average monthly flows simulated by the SMAP model for the head of the São Francisco river basin. The black dotted curve refers to the average flow observed for the present climate (1931-2005), while the red dotted curve represents the average projected flow by the model for the present climate. The green, blue and lilac curves represent, respectively, the future flow projections of the RCP8.5 scenario of CCSM4 for the periods 2010-2040, 2041-2070 and 2071-2100

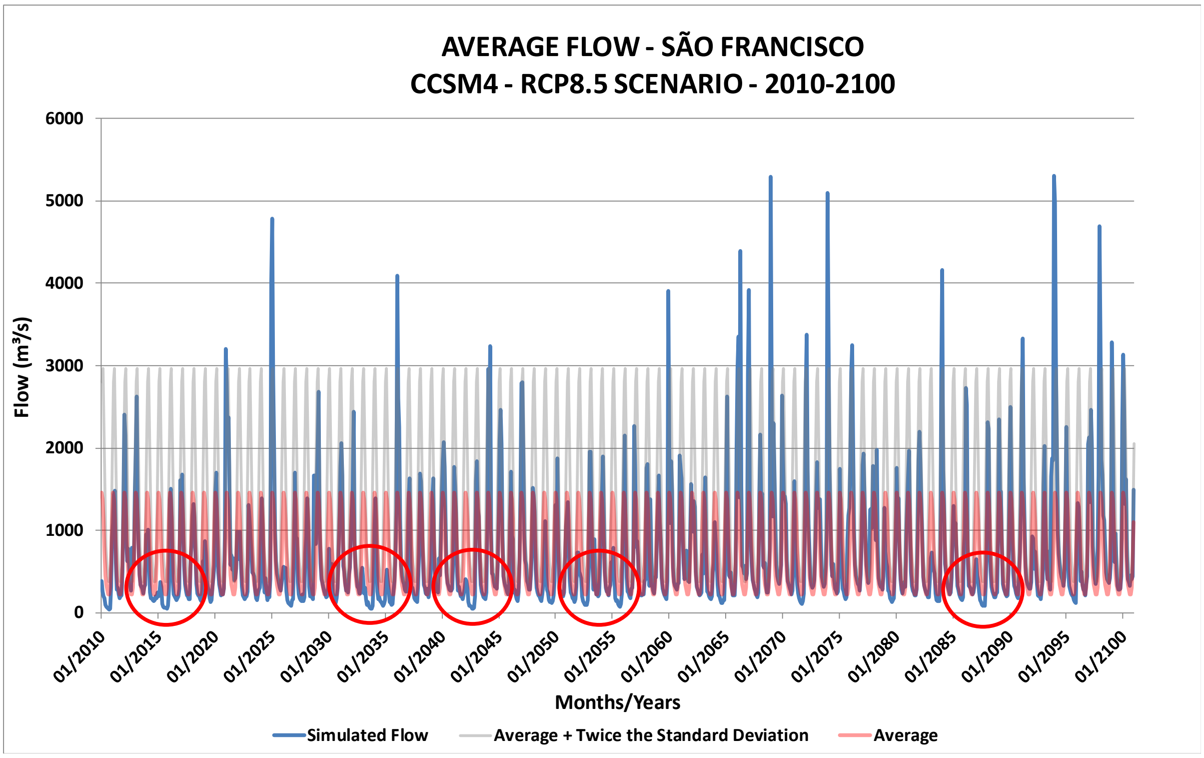

Figure 6. Results of simulated monthly future flow for the period from 2010 to 2100 of RCP8.5 scenario for the head of the São Francisco river basin, represented by the dark blue curve. The observed natural average flow for the present climate (1931-2005), represented by the red curve, is shown as the basis of comparison, and this flow plus two standard deviations (95% of the distribution) is represented by the gray curve

Analysis of climate variability

Regarding the analysis of climate variability for the head of the São Francisco river basin in Figures 7 and 8, referring to the RCP4.5 and RCP8.5 scenarios respectively, we can observe that the wet period presents the highest standard deviation between the simulated and observed flows for the present climate, as well as the highest values of projected future flow, mainly in January and December. In relation to the dry period, there is also a lower deviation between all flows compared, with results below 150 m³/s.

These results are compatible with those obtained by Sales *et al.* (2015), in their study on precipitation and temperature projections for Brazilian Northeast, considering the CMIP5 models and the RCP8.5 scenario. The authors observed that the greatest variations occurred in the wet season, with the highlight being the predominance of positive anomalies.

It is also noteworthy that, in both RCP4.5 and RCP8.5 scenarios, the present climate simulations are comparable to those observed, despite presenting lower values in almost every month, which demonstrates the robustness of the CCSM4 and its good capacity to simulate natural climate variability. It is also remarkable that in the present climate simulations the variability of projected flows was closer to that observed in the RCP4.5 scenario, with the standard deviation of the future scenarios higher than the simulated for the climate present in most months.

Miranda *et al.* (2017) also reached a similar conclusion when employing IPCC precipitation data and the SMAP model for the assessment of the hydrological regime for the head of São Francisco river. As pointed out by the authors, the temporal variability of precipitation predicted by the models for the present climate is usually lower than that observed in nature.

The increase in the variability of the time series, showed by the standard deviation, is also clear in the future climate simulations, indicating a greater concentration of events at the ends of the distribution.

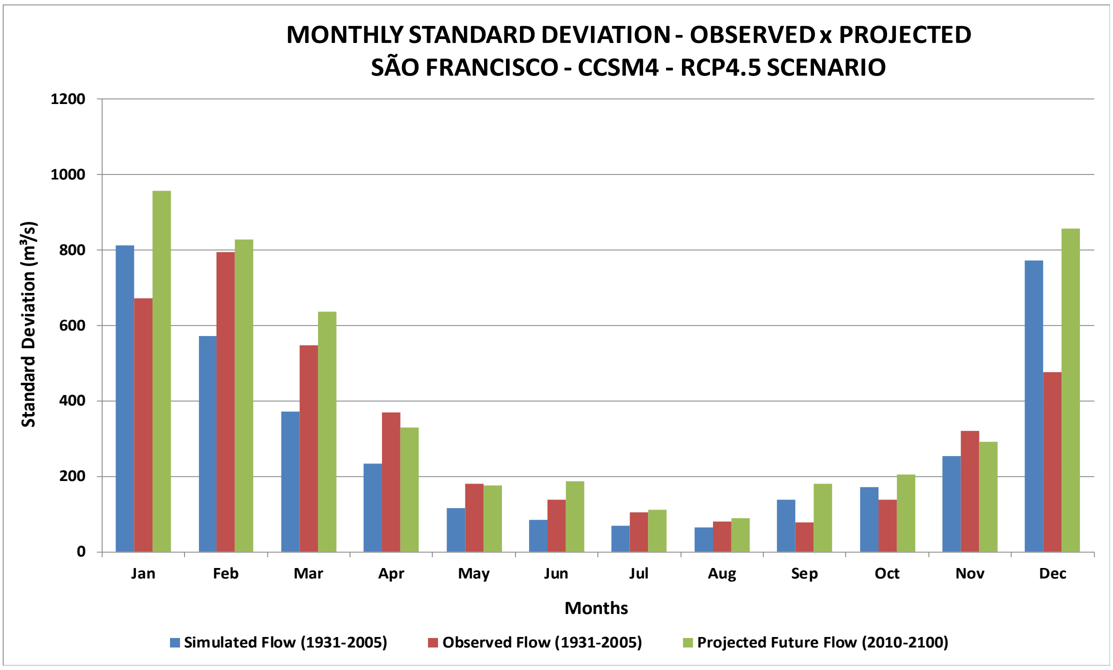

Figure 7. Comparison between the monthly standard deviation of the flows predicted by the SMAP model for the historical period and the IPCC RCP4.5 scenario of the CCSM4, and the monthly observed average flow, provided by ONS, for the head of the São Francisco river basin. The red columns refer to the standard deviation of the observed flow (1931-2005), while the blue ones correspond to the standard deviation of the simulated flow for the present climate (1931-2005). The green columns represent the standard deviation of the projected future flow (2010-2100)

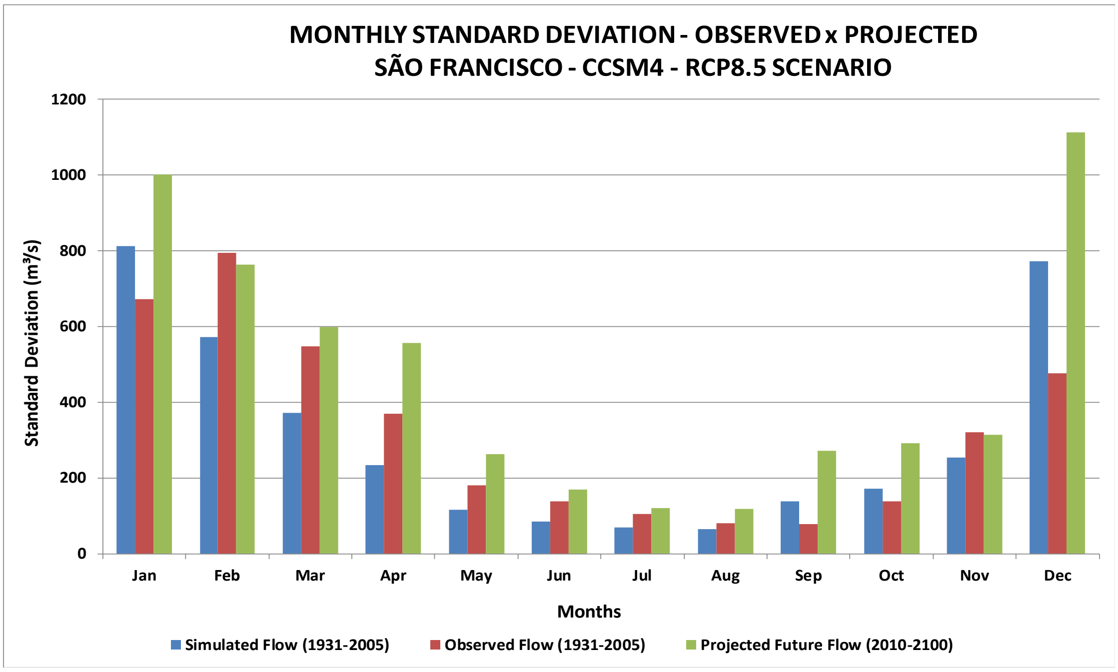

Figure 8. Comparison between the monthly standard deviation of the flows predicted by the SMAP model for the historical period and the IPCC RCP8.5 scenario of the CCSM4, and the monthly observed average flow, provided by ONS, for the head of the São Francisco river basin. The red columns refer to the standard deviation of the observed flow (1931-2005), while the blue ones correspond to the standard deviation of the simulated flow for the present climate (1931-2005). The green columns represent the standard deviation of the projected future flow (2010-2100)

CONCLUSIONS

- After analyzing the projections generated for the head of the São Francisco river basin, it is necessary to emphasize that the biggest problem is the poor flow distribution over the next century. The existence of years with flows greater than 95% of the distribution for the basin may imply serious structural problems, causing floods, disease outbreaks and crises in urban logistics. Otherwise, prolonged periods with flow rates below the average can directly affect the multiple uses of the basins, also implying a reduction of storage in the reservoirs that compose the SIN and causing conflicts between municipalities and states.
- These results reinforce the one already presented by Alves *et al.* (2013), in their study on the variation of the historical flow series of the National Electric System Operator (ONS). According to the authors, in an analysis performed from 1900 to 2011, it was already possible to observe a negative trend or low frequency variability in the Northeast region flows, which could result in the reduction of local hydroelectricity production capacity in the long term.
- The same was pointed out by Sobral *et al.* (2018), in an analysis from 1964 to 2016 of the Sobradinho reservoir, also located in the São Francisco river basin. The authors highlighted the trend of decreasing rainfall totals since the 1980s, with a significant reduction in 2001 of the volume of water in the reservoir, configuring the beginning of a water scarcity situation.
- Regarding the analysis of the CCSM4 model, we concluded that its projected results for the present climate are consistent with the observed natural flows, indicating that its future projections are robust. It is also noteworthy that although the bias correction – responsible for removing systematic errors from the model – has been accentuated, the variability simulated by the model is compatible with that observed.
- In particular, there is an increasing tendency of extreme flow events, mainly in the last two thirds of the century, where flows above 4000 m^3/s occur. These are interspersed with long periods of drought, in which the flow reaches values below 100 m^3/s.
- These events are quite extreme when compared to the Long Term Average (LTA) of the basin, which is 690 m^3/s, also obtained between 1931 and 2005. These perceptions are consistent with the predictions of the last Assessment Report (IPCC, 2013), which affirms the reduction of precipitation in northeastern Brazil and the extension of drought periods in South America.
- A similar conclusion was reached by Valério and Júnior (2015), when assessing the effects of climate change on the flow regime in the Paraguaçu river basin, located in Bahia. Based on data from the IPCC climate models, including CCSM3 (previous version of CCSM4), the authors observed great variability and a flow reduction tendency, mainly at the end of the century.
- Thus, the observed trends suggest the need for a more assertive management of the São Francisco river basin, aiming at the continuity of all its uses. Therefore, new control strategies should be considered, such as the construction of accumulation reservoirs for water supply during the years when scarcity is expected and the creation of new technologies that reduce productive and supply losses.

AUTHORSHIP CONTRIBUTION STATEMENT

COUTINHO, P.E.: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing; CATALDI, M: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

AGÊNCIA NACIONAL DE ÁGUAS – ANA. Sistema Interligado Nacional – Bacia do rio São Francisco. Brasília: Agência Nacional de Águas, 2020.

ALVES, B.; SOUZA FILHO, F.A.; SILVEIRA, C.S. Análise de Tendências e Padrões de Variação das Séries Históricas de Vazões do Operador Nacional do Sistema (ONS). **Revista Brasileira de Recursos Hídricos**, v. 18, n. 4, p. 19-34, 2013.

BERTONI, J.C.; TUCCI, C.E.M. Precipitação. In.: Hidrologia: ciência e aplicação, Org. Carlos E.M. Tucci, 2ª ed., 2. reimpr., Porto Alegre: Ed. Universidade/UFRGS: ABRH, 2001.

BOLSON, S.H.; HAONAT, A.I. A governança da água, vulnerabilidade hídrica e os impactos das mudanças climáticas no Brasil. **Veredas do Direito**: Direito Ambiental e Desenvolvimento Sustentável, v. 13, n. 25, p. 223-248, 2016.

CANTELLE, T.D.; LIMA, E.C.; BORGES, L.A.C. PANORAMA DOS RECURSOS HÍDRICOS NO MUNDO E NO BRASIL. **Revista em Agronegócio e Meio Ambiente**, v. 11, n. 4, p. 1259-1281, 2018.

COMITÊ DA BACIA HIDROGRÁFICA DO RIO SÃO FRANCISCO – CBHSF. Plano de Recursos Hídricos da Bacia Hidrográfica do Rio São Francisco – Atualização 2016-2025. Belo Horizonte: Secretaria do Comitê, 2016.

DA SILVA, F.N.R.; ALVES, J.L.D.; CATALDI, M. Climate downscaling over South America for 1971-2000: application in SMAP rainfall-runoff model for Grande River Basin. **Climate Dynamics**, v. 52, p. 681-696, 2019.

FERNÁNDEZ BOU, A.S.; DE SÁ, R.V.; CATALDI, M. Flood forecasting in the upper Uruguay River basin. **Natural Hazards**, v. 79, n. 2, p. 1239-1256, 2015.

GUIMARÃES, S.O.; COSTA, A.A.; VASCONCELOS JÚNIOR, F.C.; SILVA, E.M.; SALES, D.C.; ARAÚJO JÚNIOR, L.M.; SOUZA, S.G. Projeções de Mudanças Climáticas sobre o Nordeste Brasileiro dos Modelos do CMIP5 e do CORDEX. **Revista Brasileira de Meteorologia**, v. 31, n. 3, p. 337-365, 2016.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE). Censo Brasileiro de 2010. Rio de Janeiro: IBGE, 2010.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Genebra, Suiça, 2013.

ISLAM, S.; TANG, Y. Simulation of different types of ENSO impacts on South Asian Monsoon in CCSM4. **Climate Dynamics**, v. 48, n. 3-4, p, 893-911, 2017.

KRAVTSOV, S. Pronounced differences between observed and CMIP5 simulated multidecadal climate variability in the twentieth century. **Geophysical Research Letters**, v. 44, n. 11, p. 5749-5757, 2017.

KRAVTSOV, S.; GRIMM, C.; GU, S. Global-scale multidecadal variability missing in state-of-the-art climate models. **Climate and Atmospheric Science**, v. 1, n. 34, 2018.

LOPES, J.; BRAGA, B.; CONEJO, J. SMAP – a simplified hydrological model, applied modelling in catchment hydrology. In: Singh (ed) Water Resources Publications, 1982.

MARENGO, J.A.; CUNHA, A.P.; ALVES, L.M.A seca de 2012-15 no semiárido do Nordeste do Brasil no contexto histórico. **Revista Climanálise**, v. 4, n. 1, 2016.

MEYER, J.D.D.; JIN, J. Bias correction of the CCSM4 for improved regional climate modeling of the North American monsoon. **Climate Dynamics**, v. 46, n. 9-10, p. 2961-2976, 2016.

MIRANDA, N.M.; CATALDI, M.; SILVA, F.N. R. Simulation of the Hydrological Behavior of the São Francisco River Headwaters Using the SMAP and RegCM Models. **Anuário do Instituto de Geociências – UFRJ**, v. 40, n. 3, p. 328-339, 2017.

OJIMA, R. As dimensões demográficas das mudanças climáticas: cenários de mudança do clima e as tendências do crescimento populacional. **Rev. bras. estud. popul.**, v. 28, n. 2, p. 389-403, 2011.

SALES, D.C.; PEREIRA, J.M.R. Projeções de mudanças na precipitação e temperatura no nordeste brasileiro utilizando a técnica de downscaling dinâmico. **Rev. bras. meteorol.**, v. 30, n. 4, p. 435-456, 2015.

SILVA, M.V.M.; SILVEIRA, C.S.; SILVA, G.K.; PEDROSA, W.H.V.; MARCOS JÚNIOR, A.D.; SOUZA FILHO, F.A. Projections of climate change in streamflow and affluent natural energy in the Brazilian hydroelectric sector of CORDEX models. **Revista Brasileira de Recursos Hídricos**, v. 25, p. 1-15, 2020.

SILVEIRA, C.S.; SOUZA FILHO, F.A.; MARTINS, E.S.P.R.; OLIVEIRA, J.L.; COSTA, A.C.; NOBREGA, M.T.; SOUZA, S.A.; SILVA, R.F.V. Climate change in the são francisco river basin. **Revista Brasileira de Recursos Hídricos**, v. 21, n. 2, p. 416-428, 2016.

SILVEIRA, C.S.; SOUZA FILHO, F.A.; COSTA, A.A.; CABRAL, S.L. Avaliação de desempenho dos modelos do CMIP5 quanto à representação dos padrões de variação da precipitação no século XX sobre a região Nordeste do Brasil, Amazônia e bacia do Prata e análise das projeções para o cenário RCP8.5. **Revista Brasileira de Meteorologia**, v. 28, n. 3, p. 317-330, 2013.

SOBRAL, M.C.M.; ASSIS, J.M.O.; OLIVEIRA, C.R.; SILVA, G.M.N.; MORAIS, M.; CARVALHO, R.M.C. Impacto das mudanças climáticas nos recursos hídricos no submédio da bacia hidrográfica do rio São Francisco - Brasil. **REDE - Revista Eletrônica do PRODEMA**, v. 12, n. 03, p. 95-106, 2018.

SOHNGEN, B.; TIAN, X. Global climate change impacts on forests and markets. **Forest Policy And Economics**, v. 72, n. 5, p. 18-26, 2016.

SWANSON, K.L.; SUGIHARA, G.; TSONIS, A.A. Long-term natural variability and 20th century climate change. **Proceedings of the National Academy of Sciences**, v. 106, n. 38, p. 16120-16123, 2009.

TAYLOR, K.E.; STOUFFER, R.J.; MEEHL, G.A. An overview of CMIP5 and the experiment design. **American Meteorological Society**, v. 93, n. 4, p. 485-498, 2012.

THIBEAULT, J.M.; SETH, A. A Framework for Evaluating Model Credibility for Warm-Season Precipitation in Northeastern North America: A Case Study of CMIP5 Simulations and Projections. **Journal of Climate**, v. 27, n. 2, p. 493-510, 2014.

THORNTON, P.K.; ERICKSEN, P.J.; HERRERO, M.; CHALLINOR, A.J. Climate variability and vulnerability to climate change: a review. **Global Change Biology**, v. 20, n. 11, p. 3313-3328, 2014.

TOZATO, H.C.; MELLO-THÉRY, N.A.; DUBREUIL, V. Impactos das Mudanças Climáticas na Biodiversidade Brasileira e o Desafio em Estabelecer uma Gestão Integrada para a Adaptação e Mitigação. **Revista Gestão & Políticas Públicas**, v. 5, n. 2, p. 309-331, 2015.

VALÉRIO, E.; JÚNIOR, C. Avaliação dos efeitos de mudanças climáticas no regime hidrológico da bacia do rio Paraguaçu, BA / Evaluation of the effects of climate change on the hydrological response of the Paraguaçu river basin. **Revista Brasileira de Recursos Hídricos**, v. 20, n. 4, p. 872-887, 2015.

VAN VUUREN, D.P.; EDMONDS, J.; KAINUMA, M.; RIAHI, K.; THOMSON, A.; HIBBARD, K.; HURTT, G.C.; KRAM, T.; KREY, V.; LAMARQUE, J.F. The representative concentration pathways: an overview. **Climatic Change**, v. 109, n. 1-2, p. 5-31, 2011.