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ASSESSING FUTURE SCENARIOS OF WATER AVAILABILITY USING CMPI5 HIGH RESOLUTION CLIMATE MODELS – CASE STUDY OF THE ALTO TIETÊ BASIN

AVALIANDO CENÁRIOS FUTUROS DA DISPONIBILIDADE HÍDRICA UTILIZANDO MODELOS CLIMÁTICOS DE ALTA RESOLUÇÃO CMIP5 – ESTUDO DE CASO DA BACIA DO ALTO TIETÊ

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ABSTRACT

Global climate change and extreme climate variability directly affect the hydrological cycle and rainfall variability, which highlights the importance of studying climatic conditions as a support for water resource management in regions with low water availability, such as the Upper Tietê River Basin (Bacia Hidrográfica do Alto Tietê – BHAT). This study aims to present a diagnosis for BHAT water availability conditions in future climate scenarios, based on the high-resolution models CMCC-CM, MIROC4h, ETA-MIROC5, and ETA-HADGEM2-ES, for the time slices 2020-2040, 2041-2070, and 2071-2099, in order to provide climate information for BHAT's management. The main results showed a clear upward trend in the average annual temperatures. For the RCP8.5 scenario, the average annual increase was 0.5°C from 2006 to 2099. Precipitation showed high interannual variability without a specific defined trend. The average annual flow showed a slight positive trend in the period 2006–2099. However, it also presented a decrease in the monthly average flow in the wet period (13%) and an increase in the dry period (9.7%), compared to the historical data simulated for the time slice 2020–2040 of the RCP8.5 scenario. However, the annual increase in BHAT water availability at future scenarios should not be sufficient to meet the growing demand for water in the region. Therefore, it is necessary to evaluate water availability based on other high-resolution climate models, in order to evaluate uncertainties, and in other regions with different supply systems that provide water to the São Paulo Metropolitan Region, identifying alternative water supply sources.

Keywords: climate projections; CMIP5; water availability; water resources management; Upper Tietê River Basin.

RESUMO

As mudanças climáticas globais e a variabilidade climática extrema impactam diretamente o ciclo hidrológico e a variabilidade de precipitação, tornando importante o estudo de condições climáticas como subsídio ao gerenciamento de recursos hídricos em regiões com baixa disponibilidade hídrica, como a Bacia Hidrográfica do Alto Tietê (BHAT). O estudo teve por objetivo apresentar um diagnóstico das condições de disponibilidade hídrica na BHAT, utilizando cenários climáticos futuros dos modelos de alta resolução CMCC-CM, MIROC4h, ETA-MIROC5 e ETA-HADGEM2-ES, nos *time slices* 2020-2040, 2041-2070 e 2071-2099, de forma a fornecer informações climáticas para gestão da BHAT. Os principais resultados mostraram uma clara tendência de aumento das temperaturas médias anuais, sendo que para o cenário RCP8.5, verificou-se um incremento médio anual de 0,5°C de 2006 até 2099. Já a precipitação apresentou alta variabilidade interanual, sem tendência específica definida. A vazão média anual mostrou leve tendência de aumento no período 2006–2099, porém com diminuição das vazões médias mensais no período úmido (13%) e aumento destas no período seco (9,7%), em comparação com os dados históricos simulados no *time slice* 2020-2040 do cenário RCP8.5. No entanto, o acréscimo anual na disponibilidade hídrica da BHAT nos cenários futuros não deve ser suficiente para acompanhar a crescente demanda por água na região. Mostra-se, assim, necessária a avaliação da disponibilidade hídrica com base em outros modelos climáticos de alta resolução, a fim de avaliar as incertezas, e nas regiões dos demais sistemas de abastecimento da Região Metropolitana de São Paulo, identificando fontes alternativas de abastecimento de água.

Palavras-chave: projeções climáticas; CMIP5; disponibilidade hídrica; gestão de recursos hídricos; Bacia Hidrográfica do Alto Tietê.

INTRODUCTION

Climate changes are characterized based on weather variations in multiple time scales and directly affect the planet's hydrological cycle and precipitation variability, thus being able to impact availability and scarcity of water in several regions of the globe, from local to regional scales (GESUALDO *et al*., 2019). Water scarcity, in its turn, can impact other departments, such as public water supply and hydroelectric sectors (SILVEIRA *et al*., 2018).

In recent decades, both frequency and intensity of drought occurrences around the world have significantly raised, most likely due to the increase in the global mean temperature. Climate conditions characterized by the occurrence of extreme events implied major impacts in South America, for example, the drought in Brazil's northeast region from 2010 to 2016. In addition, there was a second major drought event in Brazil's southeast region in 2014 and 2015 (MARENGO; BERNASCONI, 2015; MARENGO *et al*., 2018; CALADO; VALVERDE; BAIGORRIA, 2019).

Thus, the study and dissemination of climate conditions can help to drive adaptation and impact mitigation plans and water management policies (BORK *et al*., 2017), if they are objective enough to be considered by the authorities involved in decision-making processes. This information can be used, for example, for watersheds management, in order to provide benefits for the preservation of these natural resources, reducing the risks of natural disasters (CABRERA *et al*., 2009).

The drought of 2014–2015 in Brazil's southeast region adversely affected the water availability of the Cantareira System, the largest water supply system in the São Paulo Metropolitan Region (SPMR). It reflected over the current management of water resources from Upper Tietê River Basin (*Bacia Hidrográfica do Alto Tietê* — BHAT) and the need for risk reduction (FISCH; SANTOS; SILVA, 2017; OTTO *et al*., 2015; NOBRE *et al*., 2016; CALADO; VALVERDE; BAIGORRIA, 2019).

The BHAT covers most of SPMR's portion, which is composed by 39 cities, and 35 of which are inserted into Alto Tietê's region (FABHAT, 2014). Given the importance of this river basin and the regional water availability, several researches have already been produced so far in order to provide climatic information diagnosis and projection of future scenarios, subsidizing the management of water resources. In the study by Lira and Cardoso (2018) on the trend of river flows in the main Brazilian hydrographic basins, for the period 1931–2014, an increase in the quarterly flow in winter and spring at Tietê river basin was observed, with statistical significance, in addition to a smaller increase in annual flow, when compared to other sub-basins of Paraná River.

Pereira's *et al*. research (2008) evaluated results from the Hydrometeorological Forecast System (HFS) regarding the BHAT, including short- and immediate-term forecast obtained through numerical modeling on a local scale. Moreover, in Calado, Valverde and Baigorria's research (2019), teleconnection indicators were evaluated, such as the El Niño phenomenon, the Pacific Decadal Oscillation (PDO) and extreme events in the variability of the seasonal precipitation and flow in the Cantareira System region.

Silva and Valverde (2017) developed another study on the use of future climatic scenarios information for the management of BHAT, which evaluated the regional water availability for future scenarios based on a global climatic model from the Meteorological Research Institute — Japanese Meteorological Agency (MRI-JMA) for A2 emission scenario and an empirical hydrological model. It has been verified that, for the future period comprehended between 2017 and 2039, the variability in both precipitation and temperature in BHAT will lead to an increase in the variability of the seasonal flow, which indicates the susceptibility to floods and inundations in the summer and water scarcity events in the fall and winter (SILVA; VALVERDE, 2017).

A recent study published by Gesualdo *et al*. (2019) investigated the influence of climate changes on water availability in Jaguari River Basin (JRB), part of the Cantareira System, which is the main source of freshwater to nine million people in SPMR. Making use of a conceptual hydrological model and a conjunction of future projections generated by seventeen General Circulation Models (GCM) for two Intergovernmental Panel on Climate Changes (IPCC) (RCP4.5 and RCP8.5), it was found that a greater interannual variability for the flow is expected, from January to March, as well as an extension of the drought season until November (currently from June to September), with a decrease of over 50% in October, indicating October and November as the most vulnerable months to water scarcity.

The use of climate models for the study of water availability is an important tool for the integrated and preventive management of water resources, in order to evaluate the resilience of a specific region to the impacts of climate changes and to increase the management potentialities aiming water security, despite the existence of uncertainties related to this sort of model to forecasting future climate scenarios (SILVA; VALVERDE, 2017). Therefore, the importance of producing studies that generate complementary results for the use of climate models to evaluate water availability in the BHAT is highlighted, such as the application of other climate models to assess the climate variability through several future scenarios.

Thus, the objective of this study was to present a diagnosis of the water availability conditions in BHAT for future climate scenarios based on high-resolution models, for the time slices 2020–2040, 2041–2070, 2071–2099. Therefore, it is believed that this type of study might serve as subsidy for the management of water resources in one of the most populated river basins in SPMR, where the water demand for the population's subsistence might be affected by the extreme climate variability, in a context of global climate changes.

STUDY AREA, DATA AND METHODOLOGY

The study area covers the totality of BHAT, which is located upstream from the Pirapora dam, comprehending a total draining area of 5,868 km^2, until the source of Tietê River in Paraitinga River, in Salesópolis, as illustrated in Figure 1. It counts with a total mean precipitation of 1,400 mm/year, presenting a wet period from November to March and a drought period from June to August, with contribution of important affluent rivers, such as Pinheiros River. It consists of 34 highly urbanized cities, with a total population of around 20 million inhabitants and, therefore, a mean demographic density of 3,000 inhabitants/km^2, considering the total river basin draining area. The elevated population contingent and the expressive economic potential of industries and services make the demand for water resources in the river basin approximately twice as big as its availability. The water demand in the region raises due to the increasing population growth, despite the low rate growth due to the high consolidation degree of the basin's urbanization and the higher levels of consumption of the local population, classifying the basin as one of most critical in the state of São Paulo. Eight water supply systems are responsible for supplying the basin's population: the Cantareira System; Alto do Tietê and Rio Claro Systems; Guarapiranga-Billings, Grande and Cotia Systems (FUSP, 2009; FAHBAT, 2014).

In order to achieve this study's goal, which is the analysis of the basin's future scenarios of water availability, in terms of tributary flow, temperature and precipitation data were analyzed in monthly scale from two global models of high spatial resolution from the Coupled Model Intercomparison Project – Phase 5 (CMIP5).

The CMIP5 is a project of the Working Group on Coupled Modeling (WGCM), from the World Climate Research Programme (WCRP), with the contribution of the Analysis, Integration and Modeling of the Earth System Project (AIMES) from the International Geosphere Biosphere Programme (IGBP). The project's objective is to produce a high-quality set of multimodal data, available for free, in order to promote the progress in the knowledge concerning climate changes and variability. The CMIP5 high-resolution models selected for this study were the Italian CMCC-CM and the Japanese MIROC (TAYLOR; STOUFFER; MEEHL, 2012). The application of high-resolution models is recommended for researches that need to evaluate climate conditions and to identify extreme events in small regional areas (TAYLOR; STOUFFER; MEEHL, 2009), such as the BHAT covered area.

For that reason, this study also used data from two regional climate models, both developed by the *Centro de Previsão de Tempo e Estudos Climáticos do Instituto Nacional de Pesquisas Espaciais* (CPTEC/INPE): The Eta-MIROC5 and Eta-HadGEM2-ES, which respectively use the global models MIROC5 and HadGEM2-ES from CMIP5 as boundary conditions (CHOU *et al*., 2014b).

The CPTEC/INPE regional models were developed within the scope of the research group PROJETA (Projections of climate change for South America which were regionalized by the ETA Model), based on the automation of the extraction process and availability of data generated by CPTEC/INPE of regionalized climate projections for Brazil. The temperature and precipitation simulations of the Eta-MIROC5 and Eta-HadGEM2-ES models, available through PROJETA, were considered in this study for RCP4.5 and RCP8.5 emission scenarios (CHOU *et al*., 2014b; CHOU *et al*., 2014a; LYRA *et al*., 2018).

Greenhouse gas emission scenarios are used in climate studies to provide plausible future projections of global climate change, considering numerous variables, including socioeconomic and technological changes, energy and soil use, as well as quantifications of greenhouse gas emissions and air pollutants. They are used as input data in the configuration of climate models and as a basis for assessing possible climate impacts, mitigation options, and cost management.

The IPCC's fifth report used the Representative Concentration Pathways (RCP), which are a set of scenarios capable of calculating different levels of greenhouse gas emissions, considered as the radiative forces associated with climate models, including also projections of emissions and concentrations of pollutants and land use, also forcing climate change. These concentrations

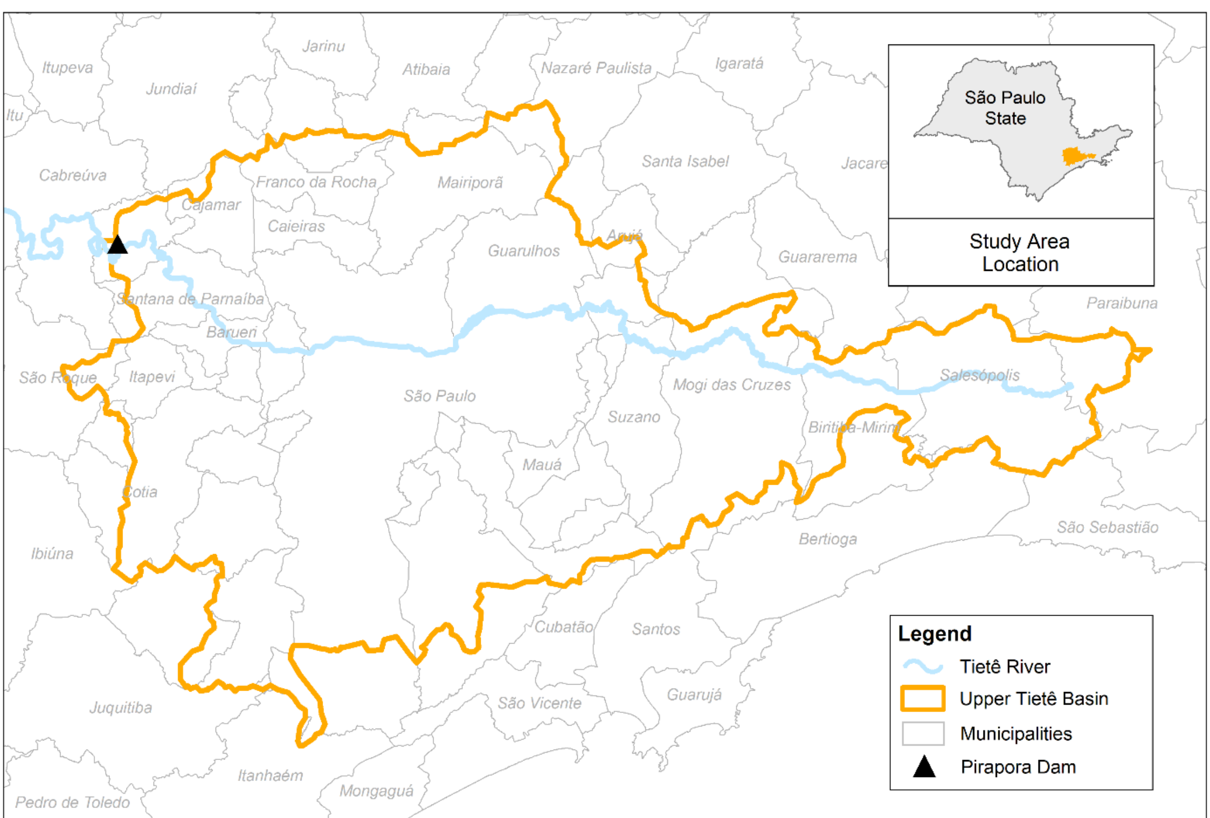


Figure 1 – Study area: Upper Tietê River Basin.

are used as the primary product for setting up RCP scenarios, serving as input information for climate model simulations. RCP consider different levels of radioactive forces, being 8.5, 6, 4.5, and 2.6 W/m^2, covering the period from 1850 to 2100 (VAN VUUREN *et al*., 2011). Two known scenarios in this set are RCP8.5, which considers high concentrations of pollutant emission with radiative force of 8.5 W/m^2, and RCP4.5, which considers radioactive force of 4.5 W/m^2 and mitigation actions to control emissions (TAYLOR; STOUFFER; MEEHL, 2012). The emission scenarios considered in this study for each model are RCP4.5 and RCP8.5 in the 2006-2100 period. Table 1 summarizes the main characteristics of the four models considered in this study. It is worth mentioning that, for the MIROC4h model, there is no data available for the future scenario RCP8.5 and, from the year 2036, for the RCP4.5 scenario. Therefore, when the mean data of all models for precipitation and temperature are calculated, only the missing data of this model are not considered.

The methodology used in this study to obtain data in terms of affluent flow, enabling historical analyses and future scenarios of water availability in BHAT, based on data from the models described in Table 1, is summarized in the diagram in Figure 2.

Table 1 – Main characteristics of the models considered for analysis in this study.

Model	Developer	Coverage	Spatial Resolution (km)	Parameters	Available Period
CMCC-CM	Euro-Mediterranean Center on Climate Change (CMCC), Italia	Global	82.3 × 82.5	Temperature and Precipitation	Historical: 1961–2005 Future Scenarios RCPs: 2006–2100
MIROC4h	Model for Interdisciplinary Research on Climate. Version 4, High Resolution, Japan	Global	61.7 × 61.8	Temperature and Precipitation	Historical: 1961–2005 Future Scenarios RCP4.5: 2006–2039
ETA-MIROC5	CPTEC – SP, Brazil	Regional	20 × 20	Temperature and Precipitation	Historical: 1961–2005 Future Scenarios RCPs: 2006–2100
ETA-HADGEM2-ES	CPTEC – SP, Brazil	Regional	20 × 20	Temperature and Precipitation	Historical: 1961-2005 Future Scenarios RCPs: 2006–2100

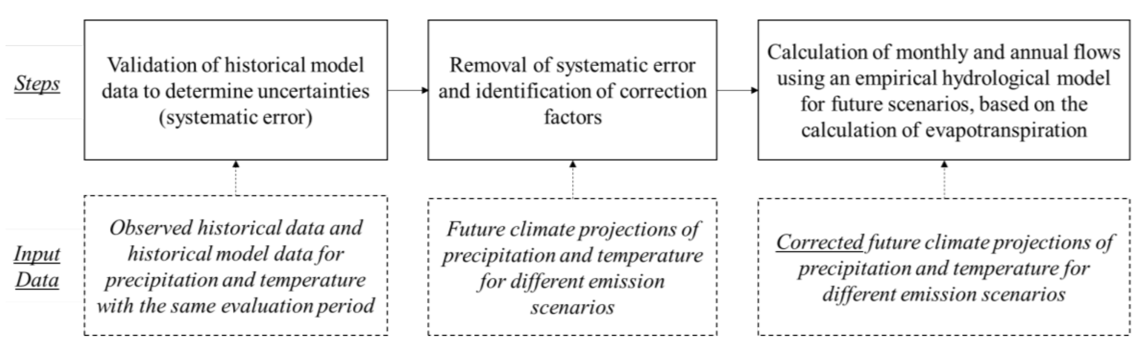


Figure 2 – Methodology applied to obtain monthly and annual affluent flow data for future scenarios of climatological modeling.

Firstly, historical data on precipitation and temperature of each of the models were validated to evaluate their performance in representing the seasonal cycle of precipitation and temperature in BHAT in relation to the historical data. For the validation of the models, data from the Climatic Research Unit (CRU) were used, which were considered as historical data in the analysis (CRU, 2019). The CRU is an institution widely recognized for its studies on natural and anthropogenic climate change, focusing on the development and updating of various data sets from weather stations around the world, widely used in climate research, including the global recording of parameters such as temperature and precipitation. The CRU database is composed of global terrestrial data in a high-resolution grid of 0.5 × 0.5º or thinner (HARRIS *et al.*, 2014). The period of CRU data used in this study comprises the years 1961 to 2005, the same corresponding to the historical simulations of the models, with the spatial resolution of 50 km. The evaluation metrics for the analysis of errors related to the models were BIAS (Equation 1), which represents the systematic error of the model, the Root Mean Square Error (RMSE) (Equation 2) and the Anomaly Correlation Coefficient (AC) (Equation 3). The definition of anomaly for the AC metric is the difference between the simulated and the observed values.

$$BIAS = \frac{1}{n}\sum(F - O) \tag{1}$$

$$RMSE = \sqrt{\frac{1}{n}\sum(F - O)^2} \tag{2}$$

$$AC = \frac{\sum\{[(F-C) - (\overline{F-C})][(O-C) - (\overline{O-C})]\}}{\sqrt{\sum[(F-C) - (\overline{F-C})]^2 \sum[(O-C) - (\overline{O-C})]^2}} \tag{3}$$

In which:

F = the value simulated by the model;

O = the observed value;

C = the climatological value.

After determining the uncertainties of the precipitation and temperature simulations of the models, the systematic error was removed using the Direct Approach technique, widely used to correct the outputs of climatic projections on a monthly scale (LENDERINK *et al.*, 2007; OLIVEIRA *et al.*, 2015; SILVA; VALVERDE, 2017). This technique is expressed by the formulation presented in Equation 4.

$$K^{FC}_{(1961-2005)} = K^{F}_{(1961-2005)} \times \left(\frac{K^{O}_{(1961-1991)}}{K^{C}_{(1961-1991)}}\right) \tag{4}$$

In which:

KFC = the corrected value of the climate variable in the evaluation period;

KF = the value without correction of the climatic variable in the evaluation period;

KC = the mean monthly climatic variable of the model in the control period;

KO = the mean monthly climatic variable observed for the control period.

With the application of the Direct Approach technique, the correction factor was found, which was used in the scenarios of RCP4.5 and RCP8.5 emissions to obtain the corrected monthly and annual data precipitation and temperature of each of the climatic models used.

Regarding the methods of application, the objective of the study is the evaluation of water availability for future climatic scenarios based on the behavior of the monthly flow in the basin, and climatic models do not generate flow in their simulations. Thus, this study used a statistical hydrological model that relates precipitation, flow, and evapotranspiration built by Silva (2016) for BHAT. This empirical model was developed based on observed data of precipitation and flow, using the fundamental equation of water balance, which includes the sum of the processes of water inputs and outputs in a basin in the form of a mathematical relationship (SILVA, 2016).

According to Vilela and Mattos (1975), the application of the general equation of water balance is conditioned to the complexity of the study of a basin and some simple mathematical models are important tools for hydrological studies, once they allow establishing a relation between the variables of water balance: evapotranspiration, precipitation, and flow. Thus, Silva (2016) constructed an empirical regression model, determining a dependent variable, in this case, flow, which changes due to independent variables, such as precipitation and evapotranspiration.

The empirical model developed for flow calculation was determined from coefficients derived from the simplified global hydrological equation of a river basin. For this, monthly data of precipitation and potential evapotranspiration (PET) of the sub-basin area and affluent flow of the exutory of the sub-basin were used on the monthly scale. The empirical relation, a fourth-order polynomial equation, is presented in Equation 5. Further details on the development of the empirical model can be found in the study by Silva (2016) and Silva and Valverde (2017).

$$Q = \left(\frac{0{,}0103P^4}{PET^4} - \frac{0{,}0859P^3}{PET^3} + \frac{0{,}289P^2}{PET^2} - \frac{0{,}1406P}{PET} + 0{,}4994\right) \times PET \quad (5)$$

In which:

P = precipitation;

PET = the potential evapotranspiration.

For the calculation of PET, this study used the corrected temperature series and the formulation of Thornthwaite (1948) in Equation 6 (*apud* SILVA, 2016).

$$PET = Fc.16.\left(\frac{10T}{I}\right)^a \quad (6)$$

In which: $I = \sum_{i=1}^{12}\left(\frac{T}{5}\right)^{1,514}$ and $a = 6{,}75.10^{-7}.I^3 - 7{,}71.10^{-5}.I^2 + 1{,}7292.10^{-2} I + 0{,}49239$

In which:

T = the mean monthly temperature of a given month;

Fc = the correlation factor as a function of latitude and month (Table 2);

I = the annual heat index;

a = the function exponent of the annual index.

Thus, based on the calculation of the PET and with the corrected precipitation for future scenarios, Equation 5 was applied for the derivation of the monthly and annual flow data for the historical period and future scenarios of each model.

In the evaluation and analysis of projections in the future period for different time slices (2020-2040, 2041-2070, and 2071-2099), the anomalies metric (Equation 7) was used to assess the increase (excess) or decrease (deficit) of variables (precipitation, temperature, and flow) in relation to the climate simulated by a model in the present (SILVA, 2016).

$$Anomaly = \frac{1}{M_{total}} \sum_{i=1}^{M_{total}} (K_F - K_{Mc}) \quad (7)$$

In which:

KF = the monthly value projected by the model in the future period (times slices);

K_{Mc} = the monthly value estimated by the model for the simulated climate (1961–2005);

M_{total} = the total number of observations.

Table 2 – Thornthwaite monthly evapotranspiration correlation factor (Fc) as a function of the study area (BHAT) — Latitude 23ºS.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fc	1.15	1.00	1.05	0.97	0.95	0.89	0.94	0.98	1.00	1.09	1.10	1.17

Source: Tucci and Beltrame (2001) and Silva and Valverde (2017).

RESULTS

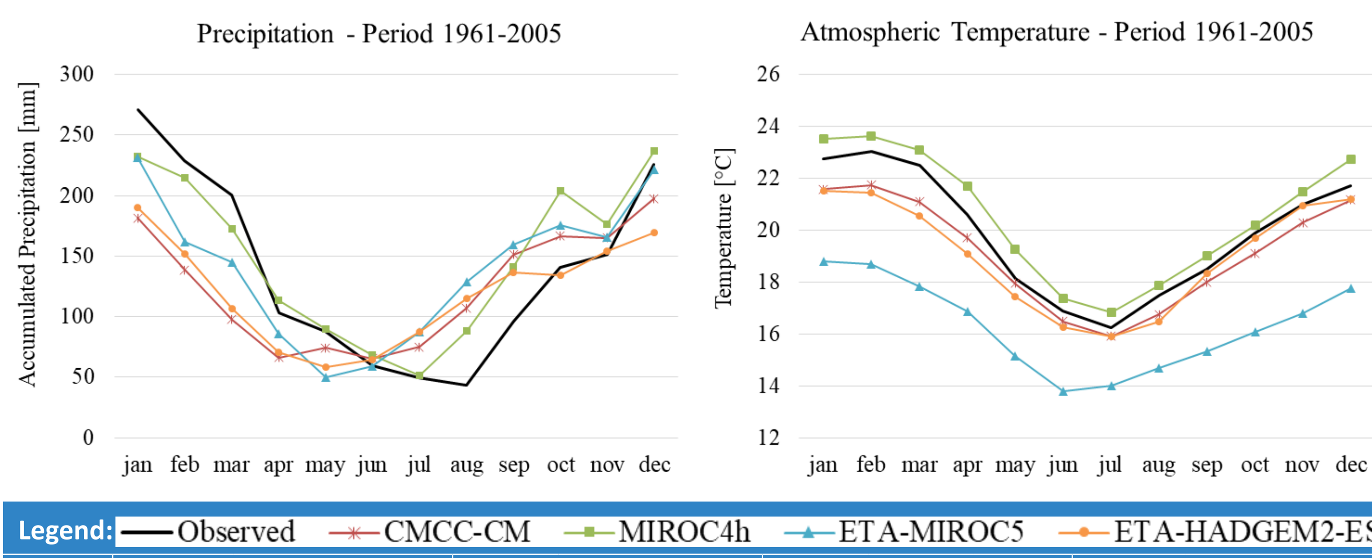
At first, the validation of historical data (1961–2005) of climate models (Table 1) was performed, and it was possible to evaluate their performance in representing the seasonal climatic pattern of precipitation and temperature in BHAT, compared to the historical data derived from CRU. Figure 3 presents the results obtained from the validation, illustrating the mean seasonal cycle in the period between 1961 and 2005 for temperature and precipitation, including the metrics of errors related to each of the models.

From the errors obtained related to the models, it is possible to highlight which models presented the best performance among them in Figure 3, for each parameter and for each of the metrics used in the validation. In green, the best results are highlighted between each metric, and in red, the worst results (high BIAS and RMSE, and low AC).

Figure 3 shows that the dry period in all models is displaced approximately 2 months in relation to the observed data (CRU). CRU data show the wet period between November and March and the dry period between June and March, as already characterized by the literature as the normal behavior of seasonality in BHAT (FUSP, 2009; SILVA; VALVERDE, 2017). Climate models show approximately the dry period between April and June and the wet period from November to January.

As a result, most models underestimated precipitation in summer and autumn, and overestimated it in winter and spring. The MIROC4h model is the closest to that observed in summer, autumn and winter, which is reflected in performance metrics. For temperature, it is observed that climate models follow the same seasonality as observed data (CRU), demonstrating hot and cold periods that coincide seasonally. However, the MIROC4h model overestimates the mean monthly temperature by almost 0.5°C compared to the observed data, while the other models underestimate the same data, presenting mean monthly temperatures of almost 1°C below, reaching a variation of more than 2.5°C for ETA-MIROC5.

Regarding the metrics for both the RMSE and AC, the model that presented the best performance



Model	CMCC-CM			MIROC4h			ETA-MIROC5			ETA-HADGEM2-ES		
Metric	BIAS	RMSE	AC	BIAS	RMSE	AC	BIAS	RMSE	AC	BIAS	RMSE	AC
Temp.	-0.746	1.651	0.814	**0.663**	**1.494**	**0.860**	**-3.583**	**3.875**	0.806	-0.832	1.930	**0.749**
Prec.	-14.220	**104.098**	**0.333**	10.805	**91.136**	**0.524**	**1.145**	97.984	0.418	**-18.308**	102.150	0.366

Figure 3 – Results from the validation of seasonal cycles of precipitation and temperature.

for the two parameters (precipitation and temperature) was MIROC4h, since it presented values close to those observed, as described above. Being that, only for temperature, BIAS was the one that presented the lowest value also for the MIROC4h model. For BIAS, the ETA-MIROC5 model presented the lowest value for precipitation. The ETA-HADGEM2-ES model presented the worst AC results for temperature and BIAS for precipitation.

Thus, it was necessary to remove systematic errors related to the models. Therefore, the direct approach formulation was applied and the correction factor for the monthly values of each model was found. This factor was applied month by month for the entire historical period. The results of the corrected seasonal precipitation and temperature cycles confirm the removal of the mean monthly errors for the seasonal cycle for the 1961–2005 period, since the mean monthly values of the series coincide with the mean monthly values of the observed CRU data, both for precipitation and temperature.

The correction factors found for the historical data were applied to the data of the future scenarios of all the models evaluated, for the scenarios of RCP4.5 and RCP8.5 emissions in the 2006–2100 period, thus minimizing the uncertainties related to the systematic error generated in the historical simulation and propagated to the projections of the climate models.

Figure 4 shows the annual variability of historical precipitation and temperature for the results of simulations with each model after correction, in the 1961–2005 period, and in future scenarios. The greatest discrepancy in data variability in the future scenario is noted for the ETA-HADGEM2-ES model, which deviates from the results simulated by the other models, generally presenting lower precipitations (Figures 4A and 4B) and higher temperature (Figures 4C and 4D). From the corrected data of precipitation and temperature for future emission scenarios, it was possible to obtain the historical values and flow projections for BHAT, according to the methodology of this study (Figure 2). Figures 4E and 4F show the annual flow variability calculated for each simulated model in the 1961–2005 period, as well as in future scenarios. It is observed that, for both RCP4.5 and RCP8.5 emission scenarios, all models present annual flow variability and most values are in the approximate range of 40 to 80 m^3/s. The CMCC-CM model stands out when presenting some mean annual flow peaks over the studied period, indicating that the occurrence of extreme flow values will be more frequent for this model. These anomalies can be better evaluated based on the analysis of annual seasonality and identification of anomalies in the monthly flow means, presented in Figures 4E and 4F.

Table 3 presents the monthly flow anomalies expressed as a percentage for future RCP4.5 and RCP8.5 scenarios. By separating the analysis period by time slices (2020–2040, 2041–2070, and 2071–2100), anomalies in relation to the historical period simulated by each model are more clearly observed. It is noted that for the wet period, in the months of January, February and March, anomalies with decreased flow rates are evidenced for all models in the future scenarios of RCP4.5 and RCP8.5, with the exception of the CMMC-CM model, which presents only positive anomalies in almost every month throughout the period studied. This behavior is mainly verified for the 2020–2040 time slice, which characterizes a short-term anomaly prediction.

For long-term time slices, both negative and positive anomalies are presented in the wet period of the study area for simulated models, however, with less marked variations than in the short term. In the period characterized by little precipitation in the study area (also called dry period), between June, July, and August, it is inferred, based on Table 3, that there will be an increase in the mean monthly flows in all time slices of the simulated models, except for the ETA-HADGEM2-ES model, which presents small negative anomalies in the dry period, only in the short term.

The results of the CMCC-CM model stand out, which presented the greatest positive anomalies in the dry period for all the time slices, reaching an increase of 61% in relation to the historical period for the mean monthly flow in June, in the 2071–2100 slice of the RCP8.5 scenario. The results of the ETA-HADGEM2-ES model are also noteworthy, showing the greatest negative anomalies in the wet period for all the time slices. The anomalies for this model reached a decrease of 28% in relation to the historical period of the mean monthly flow in January, in the 2020–2040 time slice of the RCP4.5 scenario, which also considers the adoption of mitigation measures to control environmental impacts.

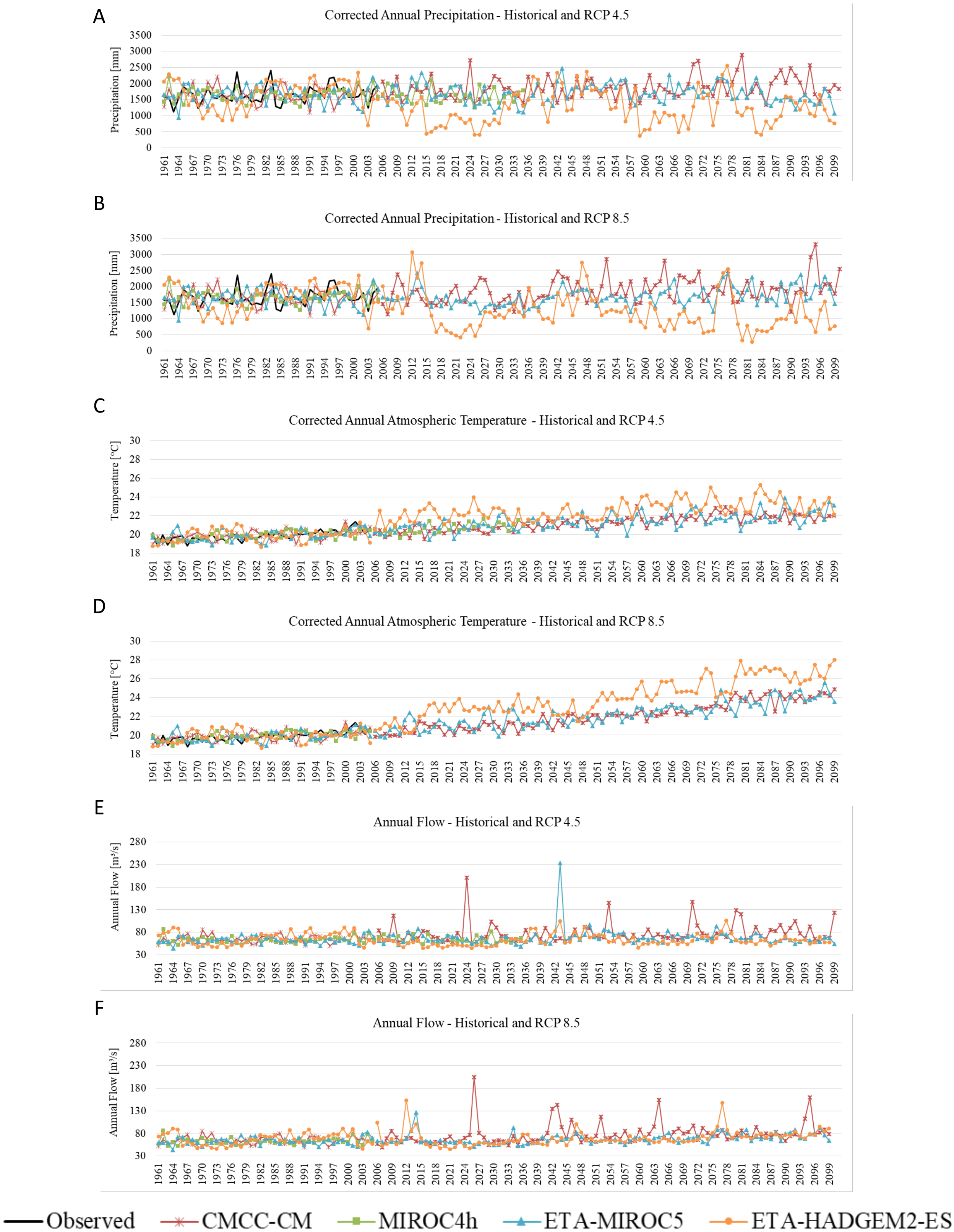


Figure 4 – (A, B) Annual variability of precipitation, (C, D) temperature, (E, F) and flow rate in the historical period (1961–2005) and future scenarios (2006–2100) for each corrected model.

The results presented for anomalies, in general, show an increase in the mean monthly flows during the dry period (Jun-Jul-Aug) in the BHAT region for the seasonal cycle of the future projections simulated by the models, as well as a decrease in the mean monthly flows in the wet period (Nov-Dec-Jan). This behavior shows a different pattern from the anomalies found in the study on the future scenario of water availability at BHAT carried out by Silva and Valverde (2017), who analyzed the simulations of the Japanese MRI-JMA model for the A2 emissions scenario. The study results presented an increase in the mean monthly flows during the wet period and a decrease in the dry one.

Since the flow is strongly influenced by precipitation and indirectly by temperature, Figure 5 presents the annual climatic projections of precipitation and temperature in the BHAT for the emission scenarios RCP4.5 and RCP8.5, which were estimated by calculating the mean of the annual values of all analyzed models (CMCC-CM, MIROC4h, ETA-MIROC5, and ETA-HADGEM2-ES) from 2006 to 2100. The trend lines by emission scenario are also presented, divided by time slice.

For precipitation (Figure 5A), it is not possible to observe a clear and unique trend along the whole period, either of increase or decrease in the future scenarios evaluated in RCP4.5 and RCP8.5. Analyzing by periods,

Table 3 – Monthly flow anomalies for the emission scenarios RCP4.5 and RCP8.5, in relation to the historical period simulated by each model (in %)

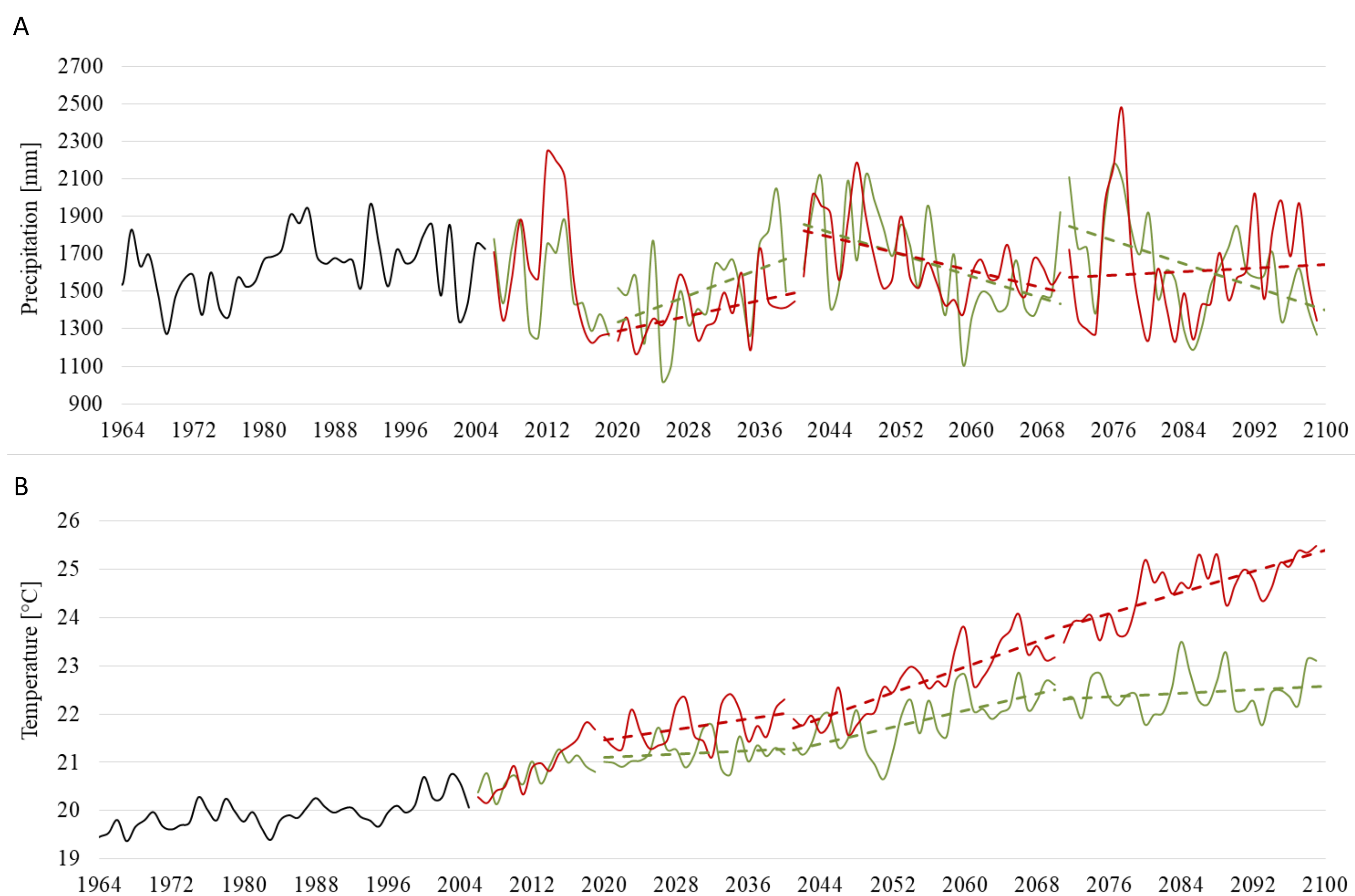
Scenario	Model	*Time Slices*	Monthly Anomaly [%]											
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP4.5	CMCC-CM	2020-2040	4	5	16	-5	26	23	22	10	10	16	6	-1
		2041-2070	5	15	0	8	21	38	12	8	7	14	14	1
		2071-2100	12	20	26	19	26	60	37	24	15	21	18	-2
	ETA-MIROC5	2020-2040	-18	-8	-17	-12	2	12	3	3	12	29	12	0
		2041-2070	-1	-1	-1	-7	18	48	4	2	20	28	26	15
		2071-2100	-7	8	-10	-7	13	12	7	6	20	18	21	-1
	ETA-HADGEM2-ES	2020-2040	-28	-18	-20	0	-12	-8	-5	8	-9	9	-14	-29
		2041-2070	-1	-1	-1	-7	18	48	4	2	20	28	26	15
		2071-2100	-25	-17	-5	3	11	25	14	20	5	18	-2	-19
	MIROC4h	2020-2035	-4	-4	10	12	-5	2	3	1	-3	-2	3	0
RCP8.5	CMCC-CM	2020-2040	1	-13	15	10	3	42	18	7	3	-6	5	-1
		2041-2070	5	15	0	8	21	38	12	8	7	14	14	1
		2071-2100	23	28	15	44	26	61	17	32	17	35	34	-3
	ETA-MIROC5	2020-2040	-14	-5	-15	-12	-9	-9	-2	3	2	21	0	-5
		2041-2070	-1	-1	-1	-7	18	48	4	2	20	28	26	15
		2071-2100	9	1	4	10	31	38	12	21	36	48	42	15
	ETA-HADGEM2-ES	2020-2040	-27	-21	-17	5	-3	4	18	7	-6	-10	-17	-28
		2041-2070	-1	-1	-1	-7	18	48	4	2	20	28	26	15
		2071-2100	-10	-4	1	33	23	44	47	50	20	31	14	-1

in the short term (time slice of the 2020–2040 period), there is a slight tendency to increase the accumulated precipitation in both emission scenarios, being this more accentuated for the RCP4.5 scenario, which considers mitigation measures to control environmental impacts. However, in the long term (time slices in periods 2041–2070 and 2071–2100), the RCP8.5 scenario presents an inter-annual variability with the occurrence of more intense events in some periods in relation to the RCP4.5 scenario.

As for the temperature (Figure 5B), it is possible to observe a clear tendency of annual mean increase in the two future scenarios presented. For the RCP8.5 scenario, the growth is more accentuated in all the time slices presented, with an mean annual increase of 0.5°C between the years 2006 and 2099, being the total annual mean temperature variation of 5.2°C between these two years. In addition, the RCP8.5 scenario even showed a difference in the annual mean temperature of 3.4°C compared to the RCP4.5 scenario in the year 2080.

Figure 6 presents the annual flow climate projections for the BHAT, calculated based on the mean of the annual values obtained from each model evaluated, for the RCP4.5 and RCP8.5 scenarios. There is a slight trend of flow growth in the study area for the two scenarios, of significance proven by the p-value statistical test, considering the mean annual flows in the study area, with greater variability and intensification of anomalies in the future scenario (period from 2006 to 2099).

In Figure 7, it is possible to evaluate in more detail the differences between the mean and the variance of the results for the two simulated emission scenarios, by presenting the curve of the normal distribution of the annual mean flow values in the two simulations.



*The projections for the future scenarios in this table were estimated by averaging the annual values of all analyzed models (CMCC-CM, MIROC4h, ETA-MIROC5, and ETA-HADGEM2-ES).

Figure 5 – Annual climate projections of precipitation and temperature for BHAT obtained through the mean of the analyzed models*.

This evaluation considered a sample space with a minimum flow value equivalent to the mean minus 4 standard deviations of the flow series of the future scenario, and a maximum flow value equivalent to the mean plus 4 standard deviations of the flow series. It can be observed that there is an increase in the mean and variance of the projected annual mean flow of the emission scenario RCP8.5 in relation to RCP4.5.

Figure 8 shows the mean monthly pattern in the historical period (1964–2005) and in the future scenario (2006–2100) for CPR4.5 and CPR8.5, illustrating the mean annual seasonality in the study area for these periods.

Table 4 presents the mean monthly flow anomalies for the RCP4.5 and RCP8.4 emission scenarios, in relation to the mean historical period simulated by the four models.

Regarding seasonality conditions, as shown in Figure 8 and Table 4, once more there is an increase of mean monthly flows during the dry period (Jun-Jul-Aug) in the BHAT region. In addition, it is possible to observe a downward trend in mean monthly flows in the wet period (Nov-Dec-Jan), and for the RCP8.5 emission scenario the decrease in flow is more accentuated in the 2020–2040 time slice, reaching a value 13% lower than the mean monthly flow in the month of January, in comparison with the simulated historical mean. In the drought period, the increase in mean monthly flows is more pronounced both in the RCP4.5 emission scenario, reaching an increase of 48% in the mean monthly flow for June for the 2041–2070 time slice, and in the RCP8.5 emission scenario, which also shows an increase of 48% in the mean monthly flow for June, but for the 2071–2100 time slice.

Table 4 shows that for the average situation, as well as the anomalies presented for each of the models in Table 3, there are more intense negative anomalies in the short-term forecast time slices (2020–2040), while for long-term scenarios, there are less pronounced positive anomalies.

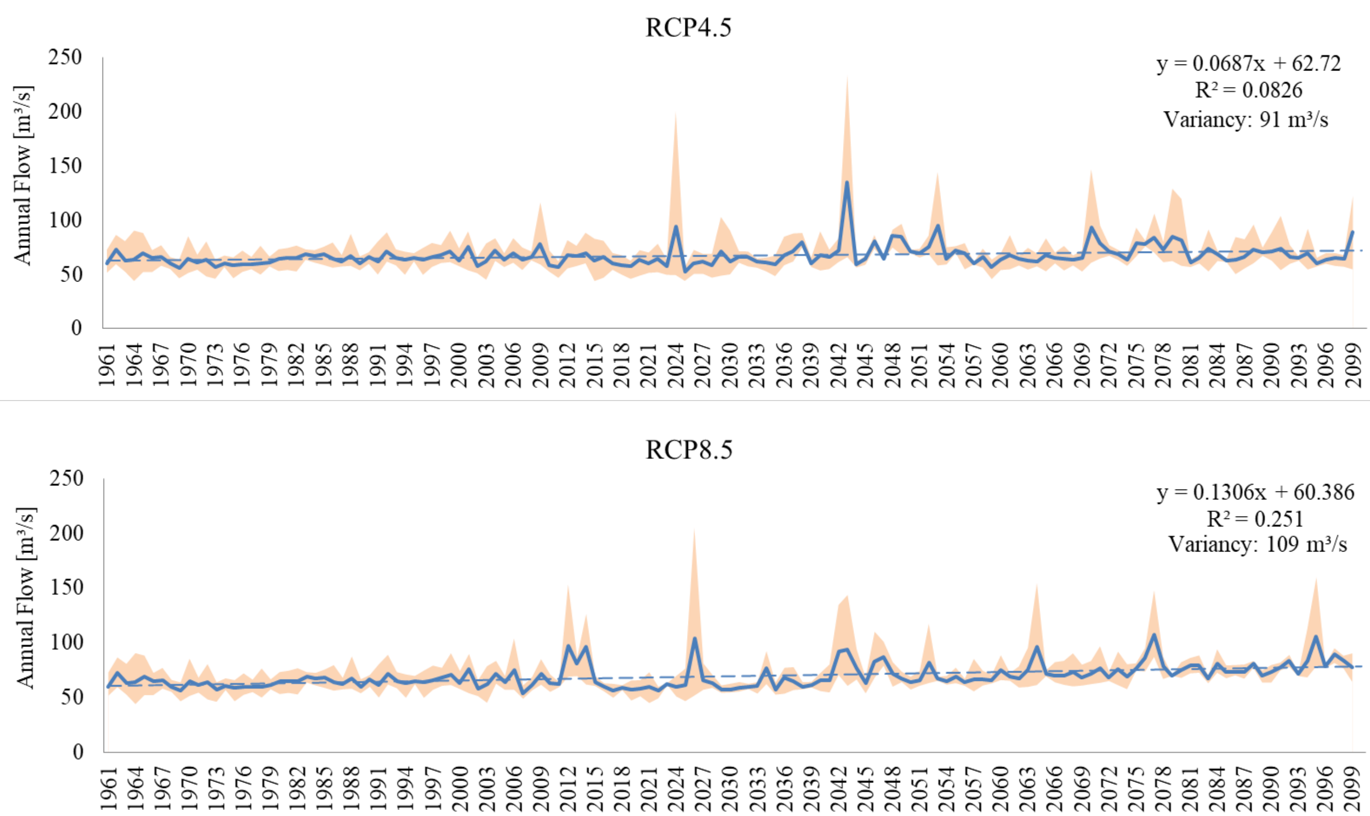
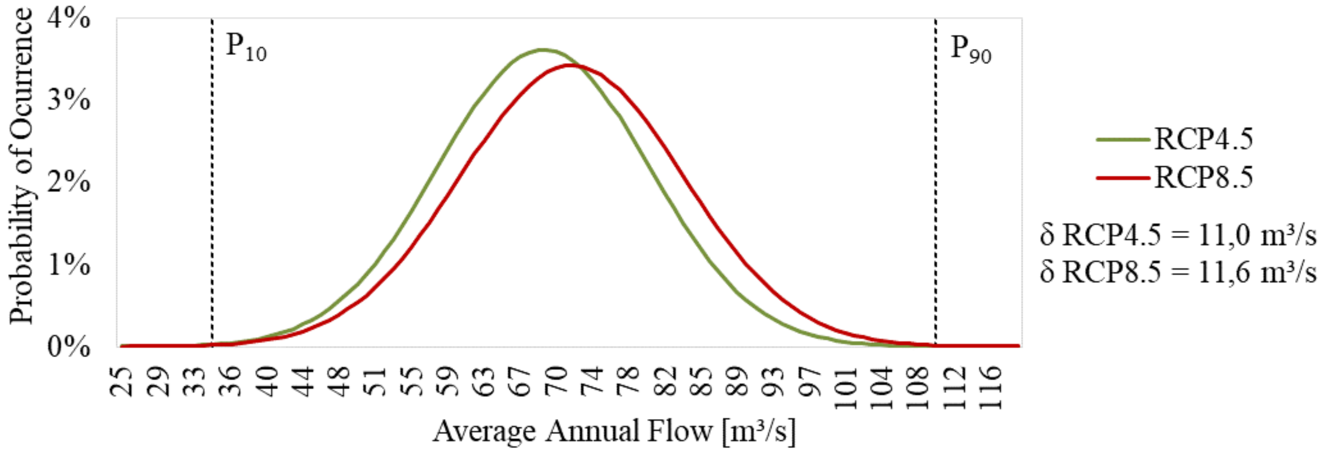


Figure 6 – Mean annual flow projections for BHAT in the RCP4.5 and RCP8.5 emission scenarios.



*P10 is the 10th percentile, P90 is the 90th percentile, and δ is the standard deviation.

Figure 7 – Normal distribution curves of the annual mean flow for the mean values calculated for the future emission scenarios RCP4.5 and RCP8.5, considering the period 2006 to 2100*.

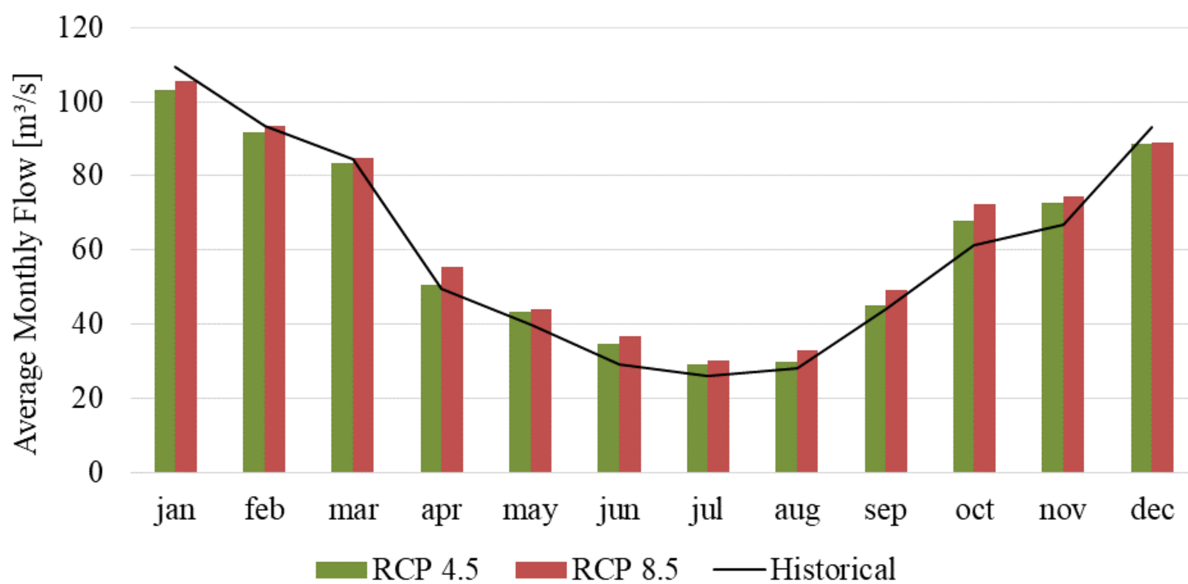


Figure 8 – Mean monthly flow pattern in the historical period (1964–2005) and future scenario (2006–2100) for RCP4.5 and RCP8.5.

Table 4 – Mean monthly flow anomalies for the emission scenarios RCP4.5 and RCP8.4, in relation to the mean historical period simulated by the four models (in %).

Scenarios	*Time Slices*	Monthly Anomaly [%]											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP4.5	2020-2040	-11	-6	-3	-1	3	8	6	5	2	13	2	-7
	2041-2070	-1	-1	-1	-7	18	48	4	2	20	28	26	15
	2071-2100	-6	4	4	5	17	32	19	17	13	19	12	-7
RCP8.5	2020-2040	-13	-13	-6	1	-3	12	11	6	-1	2	-4	-11
	2041-2070	-11	1	7	-11	8	8	3	10	23	34	26	10
	2071-2100	7	8	7	29	27	48	25	34	25	38	30	4

The study by Lyra *et al*. (2018) evaluated the influence of climate change on the annual seasonality of temperature and precipitation in SPMR using the ETA-HADGEM2-ES model, which was also evaluated in this study. For spatial resolutions of 5 × 5 and 20 × 20 km, the study by Lyra *et al*. (2018) reinforces that it is difficult to identify patterns in rainfall behavior in southeastern Brazil, since it underestimates the rainfall events associated with the South Atlantic Convergence Zone, and neither model captures the heaviest rainfall (above 150 mm/d). However, the authors found that the ETA-HADGEM2-ES model shows more pronounced warming projections in the SPMR, with maximum temperatures increasing by 9°C by the end of the century in the RCP8.5 scenario. Precipitation volume decreased and the mean annual precipitation reached a reduction of more than 50% in the state of Rio de Janeiro and between 40 and 45% in São Paulo. In the present study, the analysis with the same model also presented reduced precipitation (Figures 4A and 4B) and accentuated temperatures (Figures 4C and 4D) throughout the evaluated future period (2006–2100).

The present study also found a reduction in precipitation volume for the BHAT region more evident in the ETA-HADGEM2-ES model projection, when compared with the other models analyzed (CMCC, ETA-MIROC5, and MIROC4h), which showed an upward trend. For this reason, the models (Figure 4A) showed a lot of variability in their mean until 2099. However, the analysis for smaller periods (time slices) showed a decrease in precipitation from the historical period to the beginning of the year 2020, and that there would still be an increase until 2040, to soon present a new reduction.

Previous works in the SPMR and BHAT region, such as those of Marengo *et al*. (2012), Silva *et al*. (2017), and Silva and Valverde (2017), which used Special Report on Emissions Scenarios (SRES) from IPCC (NAKICENOVIC *et al*., 2000), identified increased precipitation and flow, respectively, mainly in summer. However, with the new RCP4.5 and RCP8.5 scenarios, and specifically for the ETA-HadGEM2-ES model, a reduction in precipitation was identified until the end of the 21st century. This result influenced the calculated mean flow that presented a significant reduction, mainly for the near future 2020–2040, in the summer. Other studies that evaluated water availability for future climate scenarios in river basins that feed producing systems that supply the BHAT were developed by Gesualdo *et al*. (2019) and Pontes *et al*. (2019) for the JRB. The JRB is the main tributary of the Cantareira System, which is responsible for the water supply of 4.5 million inhabitants of the SPMR.

Pontes *et al*. (2019) used the SWAT hydrological model and four climate models (GFDL, HadGEM, IPSL, and MIROC) in three emission scenarios (RCP2.6, RCP6.0, and RCP8.5) to determine the tributary flow of the JRB. The results did not show a consensus among the climate models in the simulation of rainfall until the 21st century. While the GFDL model simulated a substantial decrease in precipitation, especially in the RCP8.5 scenario, similar to the results obtained by this study, the other models showed increasing precipitation. Under these conditions, the calculated flow rate was reduced (maximum, mean, and minimum flow) in the case of the GFDL model, while for the other models the maximum discharges increased.

The study by Gesualdo *et al*. (2019) also worked with the JRB to analyze climate change scenarios that may impact the flow. Using the ensemble of 17 climate models from CMIP5 for the RCP4.5 and RCP8.5 emission scenarios and a hydrological model. The authors found that the flow rate showed greater annual variability, with significant increases between January and March and a 2-month extension of the dry hydrological season (June to September) through November. Also, according to the model simulations, there will be a reduction of more than 35% in the flow from September to November, with a reduction of more than 50% in October. These data portray a condition contrary to the results obtained in this study for BHAT, a region close to JRB, which verified a trend of decreasing mean monthly flows in the wet period for a characteristic that extends from November to March, and an increase in mean monthly flows in the dry period.

Although the above-mentioned studies have not been addressed for the area of BHAT, they are related to the study area of the present work, since JRB is part of the Cantareira System, one of the main water supply systems of the BHAT. If there is a decrease or increase in water availability, as simulated by the hydrological models that used the climate model simulations, it will directly affect the water supply in the SPMR.

FINAL CONSIDERATIONS

For a successful integrated and preventive management of water resources, especially in large metropolitan regions such as the SPMR, it is necessary to prepare studies to assess the region's resilience to the impacts of climate change, ensuring a condition of water security. A potential tool to provide inputs for the elaboration of these studies is the use of climate models as a complement to hydrological ones for the study of water availability. The results of this study complement the results of previous studies already elaborated for the assessment of water availability in BHAT with the use of climate models for the assessment and comparison of climate variability among several future scenarios. It reaffirms that the water demand for the subsistence of the population in the region of the BHAT can be affected by extreme climate variability in the context of global climate change.

The main conclusions of this study show that, when the mean between the four models (ensemble) evaluated is calculated, there is a small tendency to increase the mean annual flow in the future projections analyzed in the period 2006–2100 with statistical significance, for the RCP4.5 and RCP8.5 emission scenarios. The mean and variance of the annual flow in the period analyzed, as well as the positive tendency, are slightly more accentuated for the RCP8.5 scenario, considered as the most extreme.

Another result verified through this study covers the seasonality of the mean monthly flow pattern identified in the BHAT, both calculated based on the monthly means of the future analyzed period (2006–2100) and for each time slice. The results showed there will be a decrease in the mean monthly flows in the wet period for the study region of up to 13% in the 2020–2040 time slice, while in the dry period there is an increase in these means (9.7%) for the RCP8.5 emissions scenario, compared with the simulated historical data.

This seasonal behavior for the future scenarios differs from those already observed in studies already conducted for Tietê River Basin, such as the study by Silva and Valverde (2017), which presents a pattern of increased mean monthly flows during the wet period, and a decrease in the dry one. In the study by Lyra *et al*. (2018), for future projections in the Southeast region of Brazil using the ETA-HADGEM2-ES model, seasonal rainfall patterns similar to those verified for the seasonality of the mean monthly flows presented in this study for BHAT were verified.

It should be noted that the studies mentioned above used only one climate model for analysis, the regional ETA-HADGEM2-ES (RCP emission scenarios) (LYRA *et al*., 2018) and the global high-resolution MRI model (SRES scenario – A2) (SILVA; VALVERDE, 2017). However, in analyses of climate projections of emissions scenarios, the use of more than one model is recommended in order to reflect the range of uncertainties and qualities that each of the climate models may present. Even when working with a set of models, the mean results (ensembles) can offer better performance than any individual model (DHAKAL; KAKANI; LINDE, 2018; GLECKLER; TAYLOR; DOUTRIAUX, 2008). For this reason, in addition to showing the individual simulation of each model, in this work, the mean of the simulations of each analyzed variable was calculated.

Regarding the mean annual temperature, there was a consensus of the models for a progressive increase until 2099, which did not occur for precipitation. Although the temperature increase causes greater evapotranspiration, it is the change in the rainfall regime that is determinant for the water balance, especially in the flow.

Considering the critical situation of BHAT in the state of São Paulo, the importance of analyzing seasonal climatology is emphasized, and the decrease in flow during the rainy season in the near future (2020–2040) is considered as a warning that reaffirms the need for more alternative sources of water supply in the region.

The results of Gesualdo *et al*. (2019), which show an 89% increase in the mean flow in the Jaguari basin in the summer, a result of the ensemble of 17 climate models (RCP4.5) for the near future (2010–2040), may seem optimistic, since this basin supplies water for the BHAT and would partially compensate for the deficit found in the results of this work. However, Gesualdo *et al*. (2019) warn in their study about the problem of the extension of the dry season until November (currently June to September) in the Jaguari basin, which completely alters the hydrological cycle of the basin, with an increased risk of floods and droughts and an extension of its critical period.

Thus, it is recommended that future work be carried out to evaluate the availability of water in the BHAT region based on other high-resolution climatic models, with different resolutions and emission scenarios. This word could reinforce whether there is a recurrent pattern for the Southeast region of Brazil, since some results of the models used by other studies presented here showed results both contrary and similar to those verified in this study.

The recommendation is to use at least two models for analyzing climate projections. It is also important to emphasize that there are divergences between different climate models that simulate climate projections, since they depend on several factors (spatial resolution, parameterization, emission scenarios, whether it is regional or global, etc.). For this reason, it is recommended to evaluate more than one model and to analyze the consensus in addition to uncertainties. The simulation of a model, in the context of climate change, is not considered a forecast, but rather a projection of a potential scenario.

Moreover, it is suggested the development of water availability studies, based on simulations of future projections using global and regional models, also for other regions of the SPMR supply systems besides BHAT, such as the Cantareira System and the São Lourenço System, in order to provide subsidies for the management and operation of these systems. This initiative could verify the need to include alternative water sources to supply the SPMR. It is also recommended that, in future works, conceptual hydrological models be used in the methodology, including variables such as infiltration rate, base flow, recharge flow, and surface humidity in the calculations.

However, the results obtained in this work and in the other studies cited are not yet sufficient to guide public policies aimed at minimizing future risks involving variability and climate change in a context of water security in the SPMR, but they serve as subsidies to guide the development of new studies.

REFERENCES

BORK, C. K.; CASTRO, A. S.; LEANDRO, D.; CORRÊA, L. B.; SIQUEIRA, T. M. Índices de precipitação extrema para os períodos atual (1961-1990) e futuro (2011-2100) na bacia do rio Taquari-Antes, RS. *Revista Brasileira de Ciências Ambientais*, n. 46, p. 29-45, 2017. https://doi.org/10.5327/Z2176-947820170233

CABRERA, V. E.; SOLÍS, D.; BAIGORRIA, A.; LETSON, D. Managing climate variability in agricultural analysis. *In*: LONG, J. A.; WELLS, D. S. (orgs.). *Ocean circulation and El Niño:* new research. Hauppauge: Nova Science Publishers, 2019. p. 163-179.

CALADO, G. G.; VALVERDE, M. C.; BAIGORRIA, G. A. Use of teleconnection indices for water management in the Cantareira System, São Paulo, Brazil. *Environmental Processes*, v. 6, p. 413-431, 2019. https://doi.org/10.1007/s40710-019-00368-9

CHOU, S. C.; LYRA, A.; MOURÃO, C.; DERECZYNSKI, C.; PILOTTO, I.; GOMES, J.; BUSTAMANTE, J.; TAVARES, P.; SILVA, A.; RODRIGUES, D.; CAMPOS, D.; CHAGAS, D.; SUEIRO, G.; SIQUEIRA, G.; MARENGO, J. Assessment of climate change over South America under RCP4.5 and 8.5 downscaling scenarios. *American Journal of Climate Change*, v. 3, n. 5, p. 512-527, 2014a. https://doi.org/10.4236/ajcc.2014.35043

CHOU, S. C.; LYRA, A.; MOURÃO, C.; DERECZYNSKI, C.; PILOTTO, I.; GOMES, J.; BUSTAMANTE, J.; TAVARES, P.; SILVA, A.; RODRIGUES, D.; CAMPOS, D.; CHAGAS, D.; SUEIRO, G.; SIQUEIRA, G.; NOBRE, P.; MARENGO, J. Evaluation of the Eta simulations nested in three global climate models. *American Journal of Climate Change*, v. 3, n. 5, p. 438-454, 2014b. https://doi.org/10.4236/ajcc.2014.35039

CLIMATIC RESEARCH UNIT (CRU). *Data*. CRU, 2019. Available at: <http://www.cru.uea.ac.uk/data>. Accessed on: Oct. 21, 2019.

FUSP. *Plano da Bacia do Alto Tietê:* Relatório Final. Comitê da Bacia Hidrográfica do Alto Tietê. São Paulo: FUSP, 2009. 201 p.

DHAKAL, K.; KAKANI, V. G.; LINDE, E. Climate change impact onwheat production in the southern great plains of the US using downscaled climate data. *Atmospheric and Climate Sciences*, v. 8, n. 2, p. 143-162, 2018. https://doi.org/10.4236/acs.2018.82011

FISCH, G.; SANTOS, T. A.; SILVA, R. C. Water security in the Vale do Paraiba's basin: future scenarios. *Ambiente e Água*, v. 12, n. 6, 2017. http://dx.doi.org/10.4136/ambi-agua.2156

FUNDAÇÃO AGÊNCIA DA BACIA HIDROGRÁFICA DO ALTO TIETÊ (FABHAT). *Relatório de Situação dos Recursos Hídricos:* Bacia Hidrográfica do Alto Tietê - UGRHI 06 - Ano Base 2013. São Paulo: FABHAT, 2014. 162 p.

GESUALDO, G. C.; OLIVEIRA, P. T. S.; RODRIGUES, D. B. B.; GUPTA, H. V. Assessing Water Security in the Sao Paulo Metropolitan Region Under Projected Climate Change. *Hydrology and Earth System Sciences*, 2019. https://doi.org/10.5194/hess-2019-134

GLECKLER, P. J.; TAYLOR, K. E.; DOUTRIAUX, C. Performance metrics for climate models. Journal of Geophysics Research Atmospheres, v. 113, n. D06, p. 104, 2008. https://doi.org/10.1029/2007JD008972

LENDERINK, G.; BUISHAND, A.; DEURSEN, W. Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach. *Hydrology and Earth System Science*, v. 11, n. 3, p. 1145-1159, 2007.

HARRIS, I.; JONES, P. D.; OSBORN, T. J.; LISTER, D. H. Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *International Journal of Climatology*, v. 34, n. 3, p. 623-642, 2014. https://doi.org/10.1002/joc.3711

LIRA, F. A.; CARDOSO, A. O. Estudo de tendência de vazões de rios das principais bacias hidrográficas brasileiras. *Revista Brasileira de Ciências Ambientais*, n. 48, p. 21-37, 2018. https://doi.org/10.5327/Z2176-947820180273

LYRA, A.; TAVARES, P.; CHOU, S. C.; SUEIRO, G.; DERECZYNSKI, C. P.; SONDERMANN, M.; SILVA, A.; MARENGO, J.; GIAROLLA, A. Climate change projections over three metropolitan regions in Southeast Brazil using the non-hydrostatic Eta regional climate model at 5-km resolution. *Theoretical and Applied Climatology*, v. 132, p. 663-682, 2018. https://doi.org/10.1007/s00704-017-2067-z

MARENGO, J. A.; ALVES, L. N.; ALVALA, R. C. S.; CUNHA, A. P.; BRITO, S.; MORAES, O. L. L. Climatic characteristics of the 2010-2016 drought in semiarid Northeast Brazil region. *Anais da Academia Brasileira de Ciências*, v. 90, n. 2, suppl. 1, p. 1973-1985, 2018. https://doi.org/10.1590/0001-3765201720170206

MARENGO, J. A.; BERNASCONI, M. Regional differences in aridity/drought conditions over Northeast Brazil: present state and future projections. *Climate Change*, v. 129, n. 1-2, p. 103-115, 2015. https://doi.org/10.1007/s10584-014-1310-1

MARENGO, J. A.; CHOU, S. C.; KAY, G.; ALVES, L. M.; PESQUERO, J. F.; SOARES, W. R.; SANTOS, D. C.; LYRA, A. A.; SUEIRO, G.; BETTS, R.; CHAGAS, D. J.; GOMES, J. L.; BUSTAMANTE, J. F.; TAVARES, P. Development of regional future climate change scenarios in South America using the Eta CPTEC/HadCM3 climate change projections: climatology and regional analyses for the Amazon, São Francisco, and the Paraná River basins. *Climate Dynamics*, v. 38, p. 1829-1848, 2012. https://doi.org/10.1007/s00382-011-1155-5

NAKICENOVIC, N.; ALCAMO, J.; DAVIS, G.; DE VRIES, B.; FENHANN, J.; GAFFIN, S. *Special report on emissions scenarios:* A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2000. 570 p.

NOBRE, C. A.; MARENGO, J. A.; SELUCHI, M. E.; CUARTAS, L. A.; ALVES, L. M. Some characteristics and impacts of the drought and water crisis in southeastern Brazil during 2014 and 2015. *Journal of Water Resource and Protection*, v. 8, n. 2, p. 252-262, 2016. https://doi.org/10.4236/jwarp.2016.82022

OLIVEIRA, G. G.; PEDROLLO, O. C.; CASTRO, N. M. R. As incertezas associadas às condições climáticas obtidas pelo modelo ETA CPTEC/HADCM3: avaliação comparativa entre os dados simulados e observados de precipitação, evapotranspiração e vazão na bacia hidrográfica do Rio Ijuí, Brasil. *Revista Brasileira de Meteorologia*, São Paulo, v. 30, n. 1, p. 101-121, mar. 2015.

OTTO, F. E. L.; COELHO, C. A. S.; KING, A.; PEREZ, E. C.; WADA, Y.; OLDENBORGH, G. J. V.; HAARSMA, R.; HAUSTEIN, K.; UHE, P.; AALST, M. V.; ARAVEQUIA, J. A.; ALMEIDA, W.; CULLEN, H. Factors other than climate change, main drivers of 2014/15 water shortage in Southeast Brazil [in Bexplaining extremes of 2014 from a climate perspective]. *Bulletin of America Meteor Society*, v. 96, n. 12, p. S35-S40, 2015. http://dx.doi.org/10.1175/BAMS-EEE_2014_ch8.1

PEREIRA, A. J.; MASSAMBANI, O.; KARAM, H. A.; HALLAK, R.; HAAS, R.; VEMADO, F. Sistema de previsão hidrometeorológica para a Bacia do Alto Tietê. *Boletim da Sociedade Brasileira de Meteorologia*, v. 32, p. 42-60, 2008.

PONTES, L. M.; DOMINGUES, L. M.; FIRPO, M. A. F.; ROCHA, H. R. A Vazão do rio Jaguari no século 21 estipulada com projeções climáticas regionalizadas. *In*: SIMPÓSIO BRASILEIRO DE RECURSOS HIDRÍCOS, 23., 2019. *Annals*... Foz do Iguaçu: ABRH, 2019.

SILVA, M. C. O. Cenário futuro da disponibilidade hídrica na Bacia do Alto Tietê. Dissertação (Mestrado) – Pós-Graduação em Ciência e Tecnologia Ambiental, Universidade Federal do ABC. Santo André, p. 116. 2016.

SILVA, M. C. O.; VALVERDE, M. C. Cenário futuro da disponibilidade hídrica na Bacia do Alto Tietê. *Revista Brasileira de Ciências Ambientais*, n. 43, p. 114-130, 2017. http://doi.org/10.5327/Z2176-947820170185

SILVEIRA, C. S.; SOUZA FILHO, F. A.; VASCONCELOS JUNIOR, F. C.; ARAUJO JUNIOR, L. M.; CABRAL, S. L. Mudanças climáticas e o setor hidroelétrico brasileiro: uma análise com base em modelos do IPCC-AR5. *Revista Brasileira de Ciências Ambientais*, n. 47, p. 46-60, 2018. https://doi.org/10.5327/Z2176-947820180210

TAYLOR, K. E.; STOUFFER, R. J.; MEEHL, G. A. A summary of the CMIP5 experiment design. *PCDMI Report*, 2009.

TAYLOR, K. E.; STOUFFER, R. J.; MEEHL, G. A. An overview of CMIP5 and the experiment design. *Bulletin of American Meteorology Society*, v. 93, n. 4, p. 485-498, 2012. https://doi.org/10.1175/BAMS-D-11-00094.1

TUCCI, C. E. M.; BELTRAME, F. S. Evaporação e evapotranspiração. Hidrologia: ciência e aplicação. 2. ed. Porto Alegre: *UFRGS, ABRH*, 2001. p. 253-287.

VAN VUUREN, D. P.; EDMONDS, J.; KAINUMA, M.; RIAHI, K.; THOMSON, A.; HIBBARD, K.; HURTT, G. C.; KRAM, T.; KREY, V.; LAMARQUE, J.-F.; MASUI, T.; MEINSHAUSEN, M.; NAKICENOVIC, N.; SMITH, S. J.; ROSE, S. K. The representative concentration pathways: An overview. *Climate Change*, v. 109, p. 5-31, 2011. https://doi.org/10.1007/s10584-011-0148-z

VILLELA, S. M.; MATTOS, A. Hidrologia aplicada. São Paulo: *McGraw-Hill*, 1975. 245p.