Chapter 3
The Impact of Climate Change on Hydroelectric Resources in Brazil

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Abstract In the coming decades, higher temperatures and significantly reduced rainfall are projected for various semi arid regions due to Global Warming. The objective of this study is to estimate the impact of climate change on hydroelectric production in various river basins across South America. Three different downscaled global climate models are used to estimate the percentage changes in rainfall and streamflow by the 2030s and 2080s under a high emission scenario in comparison to baseline data from the end of the twentieth century. While rainfall is projected to increase slightly over the Uruguay River basin, rainfall over the Amazon and Brazil's northeast region is expected to decline. Specifically, it was found that due to climate change, streamflow in the São Francisco River, the Tocantins River and Parnaiba River is projected to decline by 52%, 31% and 32%, respectively, in the coming 3 decades compared to data from 1961–1990. Moreover, one of the three climate models indicated that the São Francisco and Parnaiba rivers' streamflow and hydroelectric production could potentially cease in the second half of the twenty-first century. Despite some inconsistencies amongst the long-term projections from the 3 different climate models, the results of this research are important in the context of regional climate change and energy resource planning.

Introduction

While climate change mitigation will require the use of more renewable energy, renewable resources can be affected by various aspects of regional climate change. As well as impacting air temperature, climate change is already influencing rainfall, wind speeds, storm intensities and drought frequencies as well as various aspects of agriculture and the environment. Climate change projections indicate that there will

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be diminishing precipitation and more severe droughts in Northeast and Northwest Brazil, Southwest Australia, Southwest USA, the Mediterranean (Jenkins and Warren 2015) and various regions in Africa (Gan et al. 2016). In particular, streamflow in semi arid regions is vulnerable to more frequent and intense prolonged droughts due to climate change (de Jong et al. 2018).

Hydrological projections specifically for Brazil's northeast (NE) region and the São Francisco River basin, which are experiencing their worst drought in history, indicate that the water balance and agricultural production will continue to deteriorate in the coming decades (Marengo and Bernasconi 2015; Neto et al. 2016; Marengo et al. 2016). Consequently, hydroelectric generation from the basin could decrease dramatically as a result (de Jong et al. 2018). However, the impact of climate change on other river basins in the South American region requires more in-depth research. The objective of this study is to determine the impact of climate change on the long-term streamflow and natural energy flow projections for the São Francisco River, Tocantins River, Parnaiba River and Uruguay River basins in order to quantify possible changes in each basin's hydroelectricity production.

Originality of This Study Compared to Previous Works

Typically, analysis in previous studies makes use of one climate model with only 3 monthly time series projections (Ruffato-Ferreira et al. 2017), which can give some insight into seasonal rainfall variations, but such studies are dependent on the idiosyncrasies of the specific climate model used. Therefore, in order to overcome this knowledge gap, the present study uses 3 global climate models with a monthly temporal resolution. Additionally, the data is downscaled using a regional climate model with a horizontal resolution of 20 km in order to more precisely estimate future rainfall across specific basins. Previous studies that project future rainfall typically focus on large regions and use models with coarse horizontal resolutions that may not capture climate variations that occur on a local scale. Yet long-term trends in average rainfall can vary substantially from one location to another in the same country.

The majority of electricity in South America is generated from renewable energy, and yet to date there are only a handful of studies that examine the impact of climate change on renewable energy resources (such as wind and solar) in the region (de Jong et al. 2019). To our knowledge, there are only a few previous studies that examine climate change impacts on hydroelectric resources in various basins across the South American region, but these studies only focus on Brazil and are limited to one or two climate models. Given that the large majority (more than 80%) of Brazil's electricity is generated from renewable sources (MME 2018), this study begins to fill the knowledge gaps and is an important step to better enable overall energy resource planning in the region.

Hydroelectricity in the Northeast Region

A recent study by Ruffato-Ferreira et al. (2017) found that the São Francisco, Amazon, Tocantins-Araguaia, and the North and Northeast Atlantic basins are projected to experience a declining water balance under both the RCP4.5 and RCP8.5 emissions scenarios. Moreover, the São Francisco is the most vulnerable basin in the country to water scarcity (Ruffato-Ferreira et al. 2017).[1] However, that study also only used one climate model (the HADGEM2/Eta model).

Various other studies indicate that rainfall over Brazil's São Francisco river basin and the mostly semi arid NE region as a whole has already declined due to climate change (de Jong et al. 2018; Maisonnave 2018; Jornal da Unicamp 2018). Moreover, annual streamflow in the São Francisco basin has been below its long-term average every year since 1992, and from 2015–2017 streamflow was at least 60% below the long-term average due to the recent drought impacting the basin (de Jong et al. 2018). Based on the IPCC climate models with high emissions scenarios and the historical trend during the last 30 years, it was estimated that there could be a decline in average rainfall over the São Francisco basin of 34% and 47% by 2030 and 2050, respectively, and this could result in a reduction of approximately 60% and 80%, respectively, in the NE's annual average streamflow and resulting hydroelectric generation (de Jong et al. 2018). Similarly, a study by The World Bank (2017) indicated that for the period 2020–2040 the São Francisco's average streamflow could drop by 32% and 57% considering the MIROC5/Eta and HADGEM2/Eta models, respectively. Projections beyond 2040 where not published in the report. According to Neto et al. (2016), the São Francisco's streamflow—simulated with the MIROC5/Eta and HADGEM2/Eta models using the RCP8.5 scenario—is projected to decline by 41% and 63%, respectively, by 2041–2070. Considering the same models, streamflows in the Tocantins, Xingu, Parnaíba, Madeira, Tapajós and Maranhão basins are all projected to decline substantially by 2041–2070 (Neto et al. 2016).

It is worth noting that climate models are subject to cumulative uncertainties, and this is especially true for long-term regional scale hydrological projections. Some models can exhibit large biases when compared to observed data, and the projections from different models can vary significantly. Nevertheless, most models tend to agree in the overall trend direction of a climate variable (e.g. precipitation) in a particular region.

There are also regional impacts on rainfall and streamflow as a consequence of deforestation, removal of riparian vegetation and irrigation farming. As a result of climate feedbacks from land use changes, the continued deforestation of the Amazon and surrounding tropical forests are expected to cause average rainfall reductions and higher temperature extremes over the entire Amazon basin as well as the Brazilian southwest region (Lawrence and Vandecar 2015 and Oliveira et al. 2013). Such rainfall reductions could even reach as far south as Argentina's Rio de la Plata basin

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[1] The study also found that a significant increase in wind speeds is projected for the North, Northeast, Southeast and South regions of Brazil, especially in summer and autumn (Ruffato-Ferreira et al. 2017)

and would negatively impact most Brazilian agricultural regions (Lawrence and Vandecar 2015), as well as affect the hydroelectric potential.

Methodology

Downscaled climate change projection data from 3 different CMIP5 global climate models was obtained from CPTEC-INPE (Centro de Previsão de Tempo e Estudos Climáticos/Weather Forecasting and Climate Studies Centre—Instituto Nacional de Pesquisas Espaciais/National Institute for Space Research) for the Brazilian territory. The 3 global climate models are the Hadley Centre Global Environment Model version 2—Earth System (HADGEM2-ES) developed in the UK, the Model for Interdisciplinary Research on Climate version 5 (MIROC5) developed in Japan, and the Second Generation Canadian Earth System Model (CANESM2). The downscaled projections at higher resolution were carried out by CPTEC-INPE using a South American regional climate model (RCM) known as the Eta Model (Chou et al. 2014a, b; MCTI 2016). The output data (generated by CPTEC-INPE) from the 3 downscaled models known as HADGEM2-ES/Eta, MIROC5/Eta and CANESM2/Eta is available on the PROJETA Platform (CPTEC-INPE 2019). For each of the 3 models there are projections from 2006 until 2100 considering the RCP8.5 (high emissions) scenario and the RCP4.5 (low emissions) scenario. Hindcast data from each model for the historical period from 1961 to 2005 is also available.

The downscaled projection data used in this study has a 20 km spatial resolution and monthly and 3 h temporal resolutions. Projections of precipitation (PREC) and average temperature (TP2M) data with the RCP8.5 (high emissions) scenario will be analyzed. Analysis will focus on the model projections for hydroelectric resources in Brazil considering the 2021–2050 and 2070–2099 climate periods in comparison to the 1961–1990 baseline period.

Rainfall and Streamflow Changes

Climate change impacts on rainfall and streamflow in the São Francisco River, Tocantins River, Parnaiba River, and Uruguay River basins will be estimated. The long-term projections of average rainfall over each of these entire basins from the downscaled HADGEM2-ES/Eta, MIROC5/Eta and CANESM2/Eta models considering the RCP8.5 scenario are calculated using R Core Team (2013) for the periods 2021–2050 and 2070–2099 and compared to the baseline period of 1961–1990. The results from the downscaled models will be compared to observed historical rainfall data from 1961 to 2018, which was provided by CPTEC-INPE.

The projected percentage changes in rainfall relative to the baseline are then used to estimate the projected changes in streamflow in each basin based on the precipitation elasticity factor of each basin. The precipitation elasticity is the amplification of streamflow changes in relation to precipitation changes in a particular basin. The precipitation elasticity of streamflow for each basin is calculated using the methodology of de Jong et al. (2018) and Sankarasubramanian et al (2001). Specifically, the "elasticity" factor is calculated using an equation that models streamflow (Q) as a function of precipitation (P) as follows:

$$Q = \alpha P^{\beta};$$

where α and β are constants and the precipitation elasticity $E_p(P, Q) = \beta$. Observed historical streamflow data from 1961 to 2018 from the Operador Nacional do Sistema Elétrico (ONS 2019) for the lower São Francisco River, Tocantins River, Parnaiba River and Uruguay River are used together with historical rainfall data to calculate the elasticity factor, β of each basin by plotting the 12 monthly rolling average of the streamflow and precipitation in a scatterplot and fitting a power curve to the data. The elasticity factor of the São Francisco, Tocantins, Parnaiba and Uruguay basins were estimated to be 1.8, 1.3, 1.2 and 1.6, respectively. It should be noted that these elasticity factors are only estimates and can be influenced by irrigation withdrawals, deforestation and other land use changes.

Results

The changes in average temperature under the RCP 8.5 scenario projected for 2070–2099 compared to the baseline period of 1961–1990 can be observed in Fig. 3.1.

It can be observed in Fig. 3.1 that temperature is expected to increase across all of Brazil. This can also be observed in Fig. 3.2, which shows temperature projections compared to historical observations from 1961 to 2018 at Imperatriz in the state of Maranhão and at Santa Vitoria do Palmar in the state of Rio Grande do Sul. (Imperatriz is located on the most westerly edge of the NE region and Santa Vitoria do Palmar is located in the extreme south of Brazil). The top graph in Fig. 3.2 shows that since 1961–1965, the average temperature measured at Imperatriz has increased by approximately 2 °C, and under the RCP8.5 high emission scenario it is projected to increase an additional 6 °C by 2100.

Rainfall and Streamflow

The percentage change in precipitation in Brazil and over various basins under the RCP 8.5 scenario projected for 2070–2099 compared to the baseline period of 1961–1990 using the MIROC5/Eta, HADGEM2-ES/Eta and CANESM2/Eta models can be observed in Fig. 3.3.

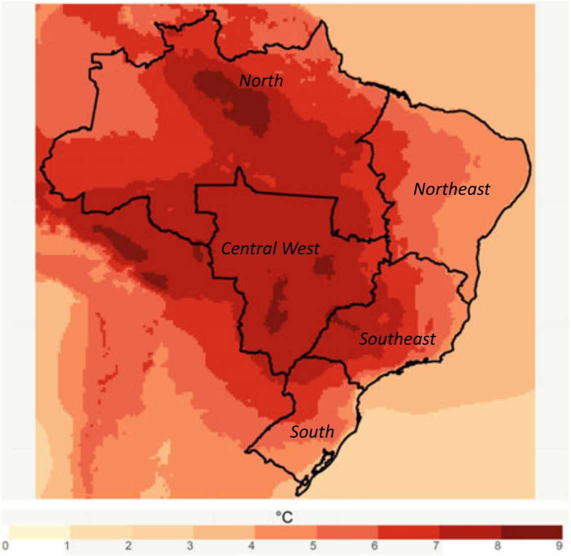

Fig. 3.1 Climate projections under the HADGEM2-ES/Eta RCP8.5 scenario. Changes in average temperature (°C) projected for 2070–2099 compared to the 1961–1990 baseline period in the different regions of Brazil (de Jong et al. 2019)

It can be observed that precipitation is projected to decline dramatically across most of the Brazilian North and semiarid NE regions, especially considering the CANESM2/Eta model. Considering the HADGEM2-ES/Eta model, the largest declines in the percentage of rainfall are mostly over the São Francisco and Tocantins basins as well as most of the semiarid NE region and parts of the east Amazon. The climate change impact on average annual rainfall over the São Francisco, Tocantins, Parnaiba and Uruguay basins are shown in Tables 3.1, 3.2, 3.3 and 3.4 for the 3 different downscaled models (HADGEM2-ES/Eta, MIROC5/Eta and CANESM2/Eta) and their ensemble considering the RCP8.5 emissions scenario. In addition to the hindcast of each model, the Table 3.1 also shows the observed average annual rainfall for 1961–1990.

The Simple Ensemble data shown in Tables 3.1, 3.2, 3.3 and 3.4 is the average of the 3 downscaled climate models (HADGEM2-ES/Eta, MIROC5/Eta and CANESM2/Eta). The ensemble is used in order to overcome idiosyncrasies of one specific climate model. The ensemble rainfall projections over the São Francisco, Tocantins, Parnaiba and Uruguay basins are shown in Figs. 3.4, 3.5, 3.6 and 3.7.

It can be observed from Figs. 3.4, 3.5, 3.6 and 3.7 that rainfall is projected to significantly decline over the São Francisco, Tocantins and Parnaiba basins. Furthermore, the 10-year rolling average and the linear trend-line of the observed annual rainfall of these 3 basins each appear to be declining more rapidly than the respective climate model ensemble data. However, the observed annual rainfall and projected rainfall for the Uruguay basin show a slightly increasing trend over the historical and projected periods.

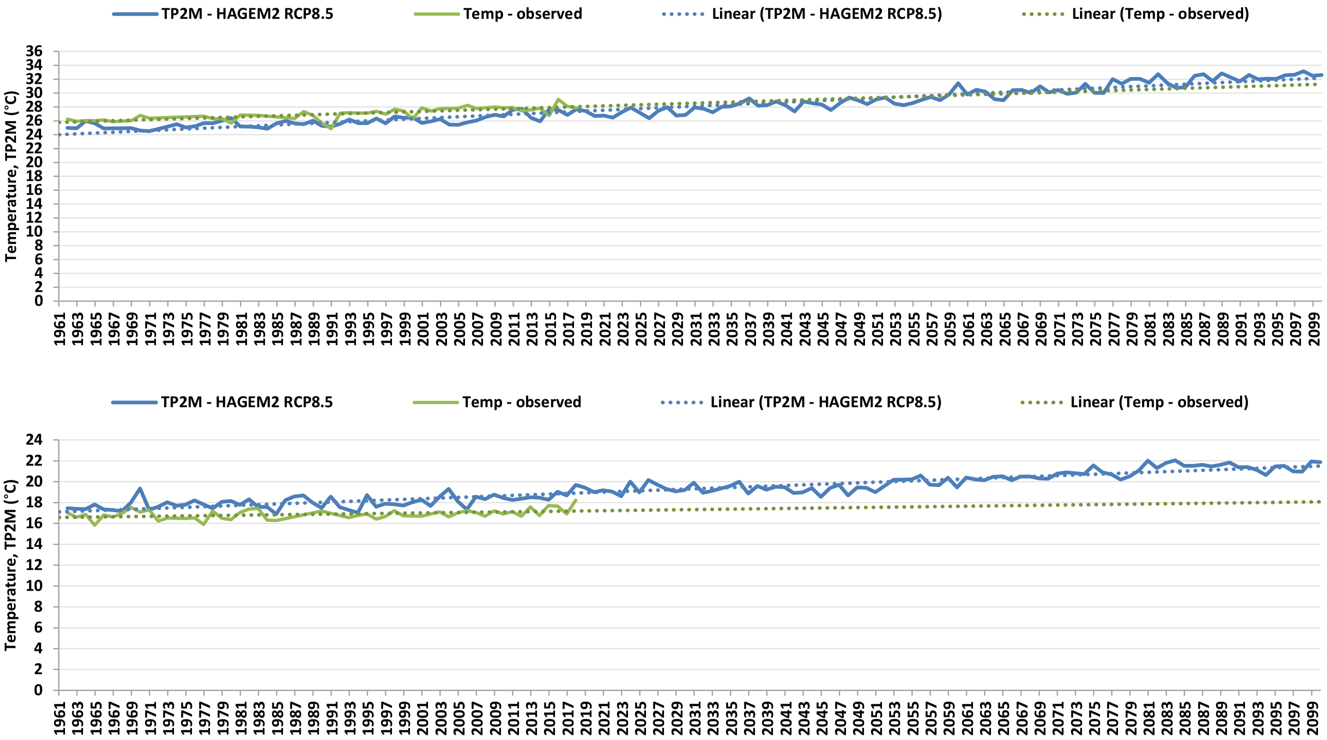

Fig. 3.2 Temperature–TP2M (°C) projections (using the HADGEM2-ES/Eta RCP8.5 scenario) compared to historical observations (BDMEP 2018) of temperature (°C) at Imperatriz in the state of Maranhão (top) and at Santa Vitoria do Palmar in the state of Rio Grande do Sul (bottom)

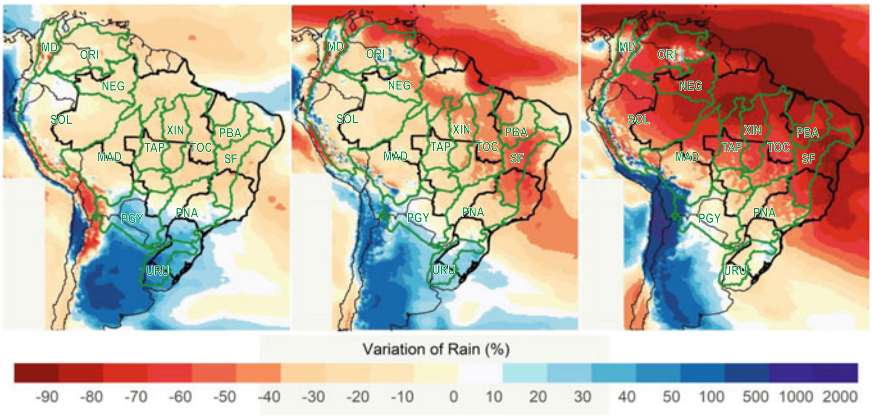

Fig. 3.3 Percentage change in precipitation projected for 2070–2099 compared to the baseline period of 1961–1990 under the RCP8.5 scenario (LHS: MIROC5/Eta; middle: HADGEM2-ES/Eta; RHS: CANESM2/Eta). Note, the boundary of various basins is shown with green lines. Key to basin names: **SF—São Francisco**; **TOC—Tocantins**; **PBA—Parnaiba**; XIN—Xingu; TAP—Tapajós; MAD—Madeira; PNA—Parana; PGY—Paraguay; **URU—Uruguay**; NEG—Negro; SOL—Solimões; ORI—Orinoco; MD—Magdalena

The Case of the São Francisco Basin

Applying the rainfall elasticity factor of 1.8 calculated for the São Francisco River signifies that, for a given decrease in rainfall, the decrease in streamflow would be amplified 1.8 times. Therefore, the projected decline in the São Francisco River's streamflow by the 2080s, considering the downscaled HADGEM2-ES and MIROC5 models, would be 91% and 54%, respectively. These results concur with the finding of Neto et al. (2016). However, considering the rainfall decline of 70% projected by the CANESM2 downscaled model it is possible that the São Francisco River could virtually dry up by 2070–2099. Moreover, it should be noted that of the 3 different models used in this study, it is the downscaled CANESM2 model that appears to most accurately model the decline in observed rainfall from 1961 to 2018, as can be seen in Fig. 3.8.

In comparison to observed average rainfall over the São Francisco basin, the HADGEM2-ES/Eta model simulation has a negative bias (that is, it underestimates rainfall). Furthermore, the simulation of annual rainfall (considering a 10-year rolling average) from 1961 to 2018 has a correlation of only 0.075 with the observed annual rainfall due to an anomaly in the simulated rainfall data from 1964 to 1980. However, the simulation does show a declining trend for the entire period from 1961 to 2099, although the gradient is less steep than the decline in observed annual rainfall from 1961 to 2018.

The MIROC5/Eta model simulation has a positive bias (that is, it overestimates rainfall) in comparison to observed average rainfall over the São Francisco, (as well as for the Tocantins and Parnaiba basins). Furthermore, the simulation of annual rainfall

Table 3.1 Changes in average annual rainfall over the São Francisco (SF) basin compared to the 1961–1990 baseline for 3 different climate models and their ensemble with the RCP8.5 emissions scenario. Observed average rainfall and streamflow changes are shown in bold

Basin	Climate model	Annual rainfall 1961–1990 (mm)	Avg rainfall 2011–2018 (mm)	Annual rainfall 2021–2050 (mm)	Rainfall % change	Streamflow % change	Annual rainfall 2070–2099 (mm)	Rainfall % change	Streamflow % change
SF	HADGEM2-ES RCP8.5/Eta	671	543	456	−32%	−57%	331	−51%	−91%
SF	MIROC5 RCP8.5/Eta	1283	1355.1	932	−27%	−49%	899	−30%	−54%
SF	CANESM2 RCP8.5/Eta	969	904	697	−28%	−51%	291	−70%	−126%
SF	*Simple ensemble*	*974*	*934*	*695*	*−29%*	*−52%*	*507*	*−48%*	*−86%*
SF	**Observed avg rainfall/flow**	**1083**	**720**	**% change: −33%**		**−60%**			

Table 3.2 Changes in average annual rainfall over the Tocantins (TOC) basin compared to the 1961–1990 baseline for 3 different climate models and their ensemble with the RCP8.5 emissions scenario. Observed average rainfall and streamflow changes are shown in bold

Basin	Climate model	Annual rainfall 1961–1990 (mm)	Avg rainfall 2011–2018 (mm)	Annual rainfall 2021–205 (mm)0	Rainfall % change	Streamflow % change	Annual rainfall 2070–2099 (mm)	Rainfall % change	Streamflow % change
TOC	HADGEM2-ES RCP8.5/Eta	1335	1166	1055	−21%	−27%	791	−41%	−53%
TOC	MIROC5 RCP8.5/Eta	1823	1826	1324	−27%	−36%	1259	−31%	−40%
TOC	CANESM2 RCP8.5/Eta	1346	1298	1057	−22%	−28%	494	−63%	−82%
TOC	*Simple ensemble*	*1502*	*1430*	*1145*	*−24%*	*−31%*	*848*	*−44%*	*−57%*
TOC	**Observed avg rainfall/flow**	**1609**	**1200**	**% change: −25%**		**−33%**			

Table 3.3 Changes in average annual rainfall over the Parnaiba (PBA) basin compared to the 1961–1990 baseline for 3 different climate models and their ensemble with the RCP8.5 emissions scenario. Observed average rainfall and streamflow changes are shown in bold

Basin	Climate model	Annual rainfall 1961–1990 (mm)	Avg rainfall 2011–2018 (mm)	Annual rainfall 2021–2050 (mm)	Rainfall % change	Streamflow % change	Annual rainfall 2070–2099 (mm)	Rainfall % change	Streamflow % change
PBA	HADGEM2-ES RCP8.5/Eta	841	689	665	−21%	−25%	507	−40%	−48%
PBA	MIROC5 RCP8.5/Eta	1174	1221	924	−21%	−26%	879	−25%	−30%
PBA	CANESM2 RCP8.5/Eta	788	767	614	−22%	−26%	167	−79%	−95%
PBA	*Simple ensemble*	*934*	*892*	*735*	*−21%*	*−26%*	*518*	*−45%*	*−54%*
PBA	**Observed avg rainfall/flow**	**1140**	**692**	**% change: −39%**		**−47%**			

Table 3.4 Changes in average annual rainfall over the Uruguay (URU) basin compared to the 1961–1990 baseline for 3 different climate models and their ensemble with the RCP8.5 emissions scenario. Observed average rainfall and streamflow changes are shown in bold

Basin	Climate model	Annual rainfall 1961–1990 (mm)	Avg rainfall 2011–2018 (mm)	Annual rainfall 2021–2050 (mm)	Rainfall % change	Streamflow % change	Annual rainfall 2070–2099 (mm)	Rainfall % change	Streamflow % change
URU	HADGEM2-ES RCP8.5/Eta	1466	1445	1530	4%	7%	1697	16%	25%
URU	MIROC5 RCP8.5/Eta	937	1024	1045	12%	18%	1244	33%	52%
URU	CANESM2 RCP8.5/Eta	1765	1898	2011	14%	22%	1652	−6%	−10%
URU	*Simple ensemble*	*1389*	*1456*	*1528*	*10%*	*16%*	*1531*	*10%*	*16%*
URU	**Observed avg rainfall/flow**	**1714**	**1664**	**% change: −3%**		**−5%**			

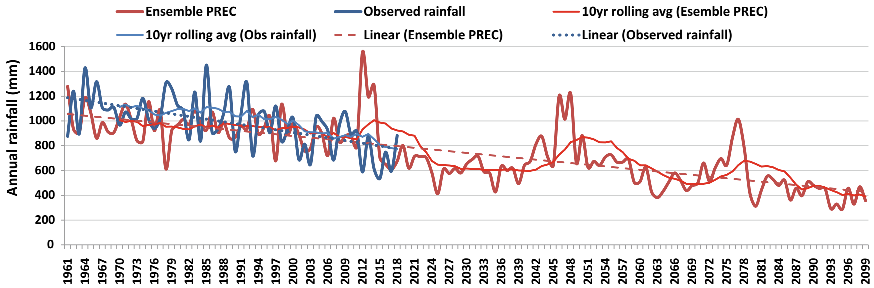

Fig. 3.4 Simple ensemble projection of annual precipitation with the RCP8.5 scenario and observed average annual rainfall over the São Francisco basin from 1961 to 2018

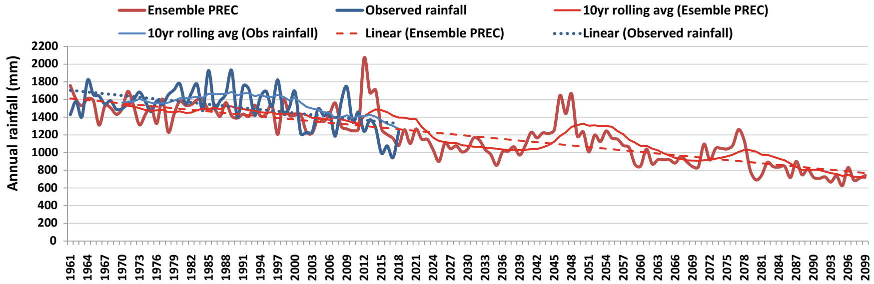

Fig. 3.5 Simple ensemble projection of annual precipitation with the RCP8.5 scenario and observed average annual rainfall over the Tocantins basin from 1961 to 2018

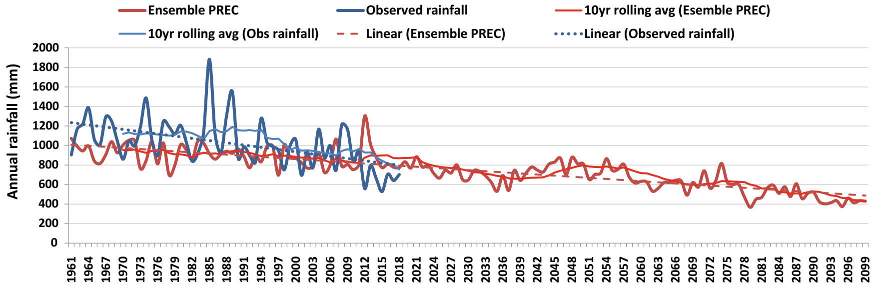

Fig. 3.6 Simple ensemble projection of annual precipitation with the RCP8.5 scenario and observed average annual rainfall over the Parnaiba basin from 1961 to 2018

(considering a 10-year rolling average) from 1961 to 2018 has a correlation of only 0.187 with the observed annual rainfall and also shows a declining trend for the entire period from 1961 to 2099. Again, the gradient is less steep than the decline in observed annual rainfall over the São Francisco basin from 1961 to 2018. Moreover, the projected average rainfall decline of 27% for 2021–2050 is only marginally lower than the projected decline for the 2070–2099 period. However, according to the linear

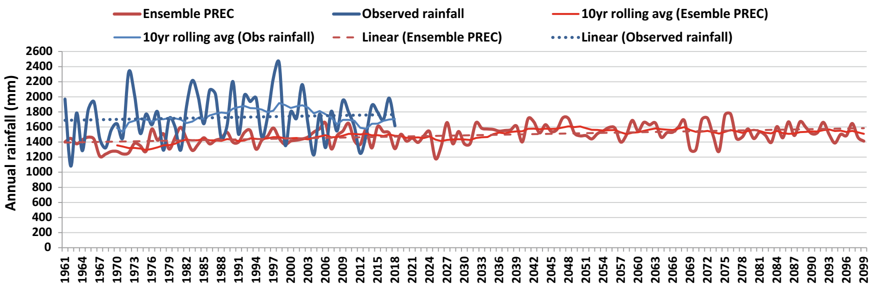

Fig. 3.7 Simple ensemble projection of annual precipitation with the RCP8.5 scenario and observed average annual rainfall over the Uruguay basin from 1961 to 2018

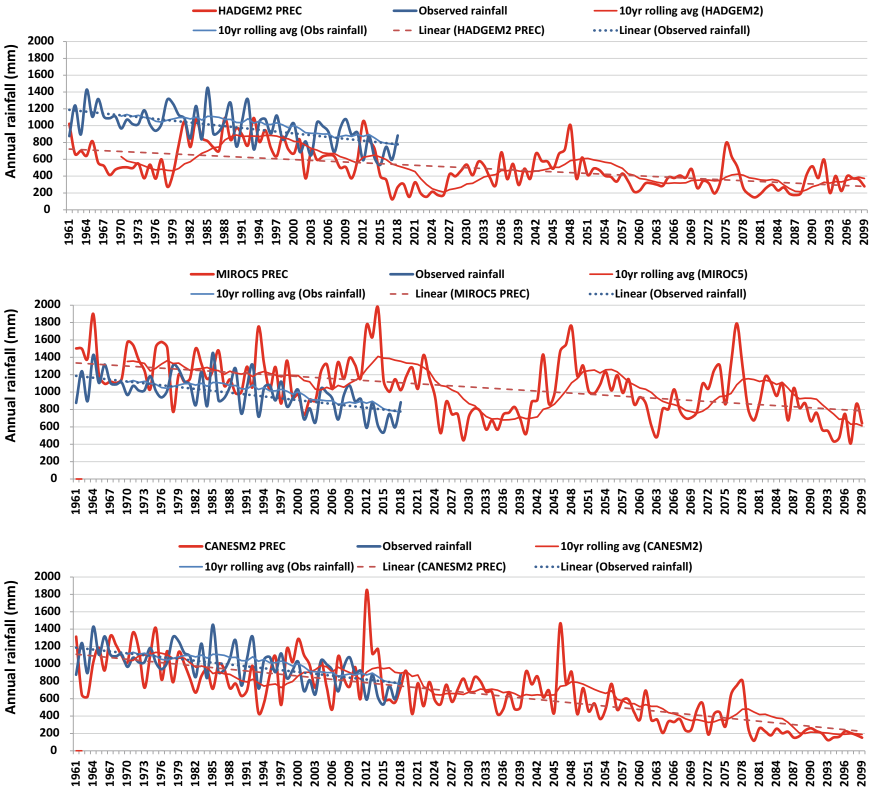

Fig. 3.8 Annual precipitation projections for 3 different downscaled climate models (from top to bottom: HADGEM2-ES/Eta, MIROC5/Eta and CANESM2/Eta) with the RCP8.5 scenario and observed average annual rainfall over the São Francisco basin from 1961 to 2018

observed rainfall trend-line (see Fig. 3.8), rainfall over the São Francisco basin has already declined by more than 25% from the 1961–1990 baseline average (de Jong et al. 2018) and the annual rainfall since 2011 has actually declined by an average of 33%. Furthermore, it was noted that the standard deviation of rainfall projected by the MIROC5/Eta model was substantially higher than the projections from the other models for both the 2021–2050 and 2070–2099 periods. Therefore, it appears that the MIROC5/Eta model does not satisfactorily simulate observed rainfall data in the region. It should be noted that some reanalysis data products of rainfall do not reproduce the decline in rainfall over the São Francisco basin that has occurred since 1995 (de Jong et al. 2018) and this might be one reason for the poor performance of some climate models on a regional scale.

The CANESM2/Eta model simulation appears to have almost no bias in comparison to observed average rainfall over the basin, although it slightly underestimated rainfall during the 1961–1990 baseline period. Furthermore, the simulation of annual rainfall (considering a 10-year rolling average) from 1961 to 2018 has a correlation of 0.221 with the observed annual rainfall. The simulation also shows a declining trend for the entire period from 1961 to 2099 with a gradient that matches the decline in observed annual rainfall from 1961 to 2017.

The Simple Ensemble model simulation (shown in Fig. 3.4) appears to have almost no bias in comparison to observed average rainfall over the basin, although it also slightly underestimated rainfall during the 1961–1990 baseline period. Furthermore, the Simple Ensemble simulation of annual rainfall (considering a 10-year rolling average) from 1961 to 2018 has the best correlation of 0.475 with the observed annual rainfall. The simulation also shows a declining trend for the entire period from 1961 to 2099 with a gradient that is a little less steep than the decline in observed annual rainfall from 1961 to 2017.

These results illustrate that projections from different models can vary significantly. Moreover, while the CANESM2/Eta model appears to have reasonably simulated the historical trend in annual rainfall, there is still uncertainty that rainfall over the basin will continue to follow the CANESM2/Eta model. Nevertheless, all 3 models projected very similar declines in annual rainfall of 27–32% over the semi arid São Francisco basin for the 2021–2050 period compared to the baseline period. Consequently, streamflow and hydroelectric potential in the São Francisco River could decline by 49–57% by the 2030s compared to the baseline period. Moreover, considering the projected rainfall reductions in combination with inter-annual rainfall variations, it could mean that the São Francisco basin and agriculture in the semi arid NE region will be increasingly vulnerable to severe droughts in the coming decades, which is consistent with the findings of Marengo and Bernasconi (2015), Neto et al. (2016), Marengo et al. (2016) and de Jong et al. (2018).

As a consequence, irrigation in the São Francisco basin and other basins in the region is likely to increase to compensate for lost rainfall. Therefore, in accordance with the findings of Neto et al. (2016), de Jong et al. (2018) and by The World Bank (2017), hydroelectric generation from the São Francisco River could continue to decline in the coming decades. On the other hand, wind power in the NE region is complementary to hydroelectric generation and will improve energy security by saving water in the São Francisco basin (de Jong et al. 2017).

Conclusions

Climate change is predicted to cause significantly reduced rainfall and higher temperatures in most regions of Brazil compared to the end of the twentieth century. Specifically, streamflow in the São Francisco River is projected to decline dramatically according to all 3 climate models used in this study. However, there were substantial differences between the model projections, particularly for the 3rd climate period from 2070–2099. The CANESM2/Eta model and the Simple Ensemble best approximated the historical decline in rainfall over the São Francisco basin. The projected reduction in streamflow, considering both the CANESM2/Eta and HADGEM2-ES/Eta models, together with inter-annual weather variations and an expected increase in irrigation could cause the São Francisco's hydroelectric production to virtually cease in the second half of the twenty-first century. This is consistent with the findings of de Jong et al. (2018) who concluded that streamflow in the semi arid São Francisco basin is particularly vulnerable to climate change.

In general, the CANESM2/Eta model projected the biggest decreases in rainfall across most of Brazil and the other tropical regions of South America. However, projected rainfall changes across Brazil's southern region demonstrated only marginal reductions, and in some areas of the southern region slight increases in rainfall were projected, while a large increase in rainfall is projected for northern Argentina and especially across northern Chile. In comparison, the HADGEM2-ES/Eta model typically showed intermediate decreases in rainfall, with the exception of Brazil's southern region and northern Chile and Argentina which showed increased rainfall, while the MIROC5/Eta model demonstrated smaller decreases in rainfall across the north and NE regions and a substantial increase in rainfall over Brazil's southern region and northern Argentina and most of northern Chile. However, the MIROC5/Eta model appeared to be the least reliable model of the three for simulating past climate data in Brazil (such as historical wind and rainfall data). This result is consistent with the findings of McSweeney et al. (2015) who showed that the MIROC global climate models exhibited significant shortcomings in reproducing historical observations.

However, given the differing results amongst the 3 climate models, this study also demonstrates the large uncertainties and variations between different downscaled climate models, particularly when estimating long-term rainfall. In order to more accurately estimate changes in hydrology, an ensemble of the 3 climate models together with basin elasticity factors were used to estimate basin rainfall and streamflow changes, respectively.

Future work could also compare historical rainfall and streamflow data to climate model projections for other vulnerable river basins in South America such as the

Xingu, Madeira, Tapajós and Parana basins in Brazil, as well as the Orinoco river basin in Venezuela and the Magdalena river basin in Colombia.

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