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Exploratory analyses for the assessment of climate change impacts on the energy production in an Amazon run-of-river hydropower plant

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ABSTRACT

Study region: The Tapajós Basin is an important Amazon tributary affected by human activities with great potential for water conflicts. The basin, as others within the Amazon region, is receiving a number of hydropower plants, among them the Teles Pires plant, projected to operate in 2015.
Study focus: Hydrological impacts due to climate change affect human activities, such as hydroelectric generation, and should be carefully studied for better planning of water management. In this study, we assess climate change impacts by applying the MHD-INPE hydrological model using several climate models projections as inputs. The impact assessment consisted of statistical shifts of precipitation and discharge. Energy production in a projected hydropower plant was assessed through the development of annual power duration curves for each projection, also considering its design and structural limitations.
New hydrological insights for the region: The high inter-model variability in the climate projections drives a high variability in the projected hydrological impacts. Results indicate an increase of basin's sensitivity to climate change and vulnerability of water exploitation. Uncertainties prevent the identification of a singular optimal solution for impacts assessment. However, exploratory analysis of the plant design robustness for hydropower generation show a reduction in the energy production even under projections of increased discharge, due to plant capacity limitations. This is valuable information for stakeholders to decide about energy production strategies.

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1. Introduction

Brazil is highly dependent on water resources for several economic activities, particularly for hydropower generation and agriculture (Marengo, 2008; Nóbrega et al., 2011). In this context, an increased need for energy to sustain economic growth has boosted governmental plans to expand hydropower in Amazonia. The Growth Acceleration Program – PAC (BRASIL, 2013) is a governmental plan of investments to promote development, including the construction of hydropower plants, and has allocated 45 billion Brazilian Reais (approximately 23 billion dollars) to the Amazon region. The new plants will increase the contribution of the Amazon region to the Brazilian power generation from 10% up to 24% (Empresa de Pesquisa Energética (EPE), 2012).

Water resources availability in the Amazonian region is influenced by climate variability, climate change and human activities (Espinoza-Villar et al., 2009a,b; Rodriguez et al., 2010; Costa et al., 2003). Therefore, understanding the effects of that variability on the hydrological cycle is crucial for private and government development plans and for mitigation of adverse effects (if any) of climate change. Recent studies (Marengo et al., 2011a,c; Joetzjer et al., 2013) have indicated significant potential impacts due to global climate changes until the end of the century in the Amazon region. Most likely, the air temperature will increase, while the annual precipitation over the region will decrease, mainly due to a longer dry season. Those changes will potentially have a profound impact on the basin's hydrological regime (Cox et al., 2004, 2008; Li et al., 2006; Salazar et al., 2007).

In large basins, the impacts on the hydrologic cycle depend not only on the average climate anomalies over the drainage area but also on the geographical distribution of the drivers of such changes combined with the geomorphologic features of the basin (Tomasella et al., 2011). By studying the 2005 Amazon drought, Tomasella et al. (2011) concluded that, if a precipitation deficiency occurs in a geographically restricted region of the drainage area during a critical period of the main channel recession, then the impacts downstream could be more severe than those of a geographically wider drought. In this context, hydrological distributed models should be able to realistically represent the spatial distribution of runoff, evapotranspiration, and soil water storage for a reliable assessment of the impacts due to climate changes or human activities (Cong et al., 2009; Leavesley, 1994).

Climate change impacts on river discharge are generally evaluated through the application of hydrological models using climate model data as input (Demaria et al., 2013; Nóbrega et al., 2011; Cloke et al., 2013; Bravo et al., 2013). Decision-making processes related to climate adaptation demand accurate and detailed information at a wide range of spatial and temporal scales (Dessai et al., 2009). However, there is substantial uncertainty in the assessment of climate change impacts, and this uncertainty is associated with the model chain's propagation of errors (Jones, 2000), which are mainly related to the climate models rather than the hydrologic model (Bates et al., 2008; Nóbrega et al., 2011).

Although climate model projections are affected by irreducible uncertainties (Dessai and Hulme, 2004), impact studies are based on the assumption that projected climate change signals are reliable when obtained from differences in the model "climatology" (model long-term mean values for the simulation period) rather than those in the observed climatology (Wood et al., 2002). Therefore, instead of using absolute values of the predicted scenarios, differences between model climatologies for historical and future periods should be considered (Allen and Ingram, 2002; Bravo et al., 2013) after statistical adjustments to minimize climate model biases (Bates et al., 2008; Bárdossy and Pegram, 2011; Demaria et al., 2013).

Early experience with ensembles of climate models showed significant dispersion among members (Kling et al., 2012; Cloke et al., 2013; Knutti and Sedlacek, 2013); this was also shown in hydrologic model simulations using ensembles or multi-model runs (Nóbrega et al., 2011; Bravo et al., 2013; Siqueira Júnior et al., 2015). Regarding the Amazon basin, published literature showed a lack of agreement about changes in river discharge when different climate model projections were considered (Arora and Boer, 2001; Milly et al., 2005; Salati et al., 2009; Lavado Casimiro et al., 2011; Guimberteau et al., 2013; Siqueira Júnior et al., 2015). These differences were due to inter-model uncertainties in projected precipitation changes, even when those were estimated for the same climate change scenario. Other South American basins studies, such as the upper Paraguay River Basin (Bravo et al., 2013), the Rio Grande River Basin in Brazil (Nóbrega et al., 2011) and a Chilean snow-driven basin (Demaria et al., 2013) presented the same lack of agreement in terms of river discharge changes for different climate scenarios. This behavior emphasizes that uncertainties must be considered with caution because the use of probabilistic climate information does not adequately represent the uncertainties and will lead to maladaptation (Hall, 2007).

Despite the lack of accurate predictions of future impacts, which prevent the use of one optimal performance, the information provided by models could be applied to assess adaptation decision-making processes by analyzing a strategy's robustness (Lempert and Schlesinger, 2000). A suggested approach is to adopt a number of models that provide a range of results for a better assessment of the impacts through an exploratory modeling approach (Bates et al., 2008; Bankes, 1993). This approach identifies potential weaknesses in water management strategies by combining the adopted HPP design with the projected scenarios (Dessai et al., 2009; Nóbrega et al., 2011).

The Tapajós River Basin, one of the Amazon's southern tributaries, is considered an important area for the Brazilian Development Plans. Eleven potential hydropower sites have been identified in the area (EPE, 2011, 2012) and, most importantly, the area has a vital ecological function. In this study, we evaluated the impacts of climate projections on the Tapajós Basin hydrological regime through the 21st century. We also studied the impacts of those changes on the projected run-of-river hydroelectric Teles Pires Hydropower Plant. The robustness of the adopted design for hydropower generation at this plant was analyzed using annual power generation curves and annual power production from the hydrological projections.

2. Materials and methods

2.1. The Tapajós Basin

The Tapajós Basin is an Amazon sub-basin located within Brazilian territory (Fig. 1); it has a drainage area of approximately 493,000 km^2. The Tapajós River accounts for 12.8% of the Amazon drainage area and 10.9% of its average discharge. The main stem of the Tapajós has a length of 1880 km, and its major tributaries are the Juruena and Teles Pires rivers (Agência Nacional de Águas (ANA), 2013).

The basin is mainly covered by Ombrophilous Forest (Instituto Brasileiro de Geografia Estatística (IBGE), 1992). In the upper part of the basin, close to the Juruena and Teles Pires river tributaries, the vegetation is classified as "Cerrado" (Brazilian Savannah). The soils in the basin are mainly composed of red-yellow Acrisols (29%), red-yellow Oxisols (27%) and Arenosols (18%) (Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), 1980).

The Juruena and Teles Pires tributaries drain sedimentary areas, while the Tapajós River flows over the crystalline basement of the Brazilian Shield. The high soil storage capacity of sedimentary areas allows the continuity of large discharges during the entire year; thus, the seasonal amplitude is minimized. The mean average discharge in the basin is approximately 13,500 $m^3\,s^{-1}$ (Ministério do Meio Ambiente (MMA), 2006). The annual rainfall varies between 1800 and 2300 mm; it mainly occurs during the wet season, between October and April.

The upper Tapajós Basin is under intense human pressure due to the expansion of agricultural lands in conjunction with the increased demand of irrigation. Several studies have identified that agricultural lands cover large areas of the Tapajós, indicating a significant demand on water resources with a potential to generate water resource conflicts in the medium and long term (MMA, 2006).

2.2. The distributed hydrological model (MHD-INPE)

The Distributed Hydrological Model of the National Institute for Space Research (MHD-INPE) is a regular grid-cell model that solves a water balance equation (Rodriguez, 2011; Rodriguez and Tomasella, 2014); it was developed from the large-scale hydrological model MGB-IPH (Collischonn et al., 2007). MHD-INPE has been applied in large Amazonian basins for land use and land cover change and climate change studies, where the performance of the model to simulate observed historical conditions were satisfactory (Rodriguez, 2011; Rodriguez and Tomasella, 2014; Siqueira Júnior et al., 2015). The model generates fluxes in each cell using the approach developed by Rodriguez and Tomasella (2014), which combines elements of Topmodel (Beven and Kirkby, 1979) and a storage capacity probabilistic distribution concept that was used in the Xinanjiang model (Zhao, 1992). Evapotranspiration

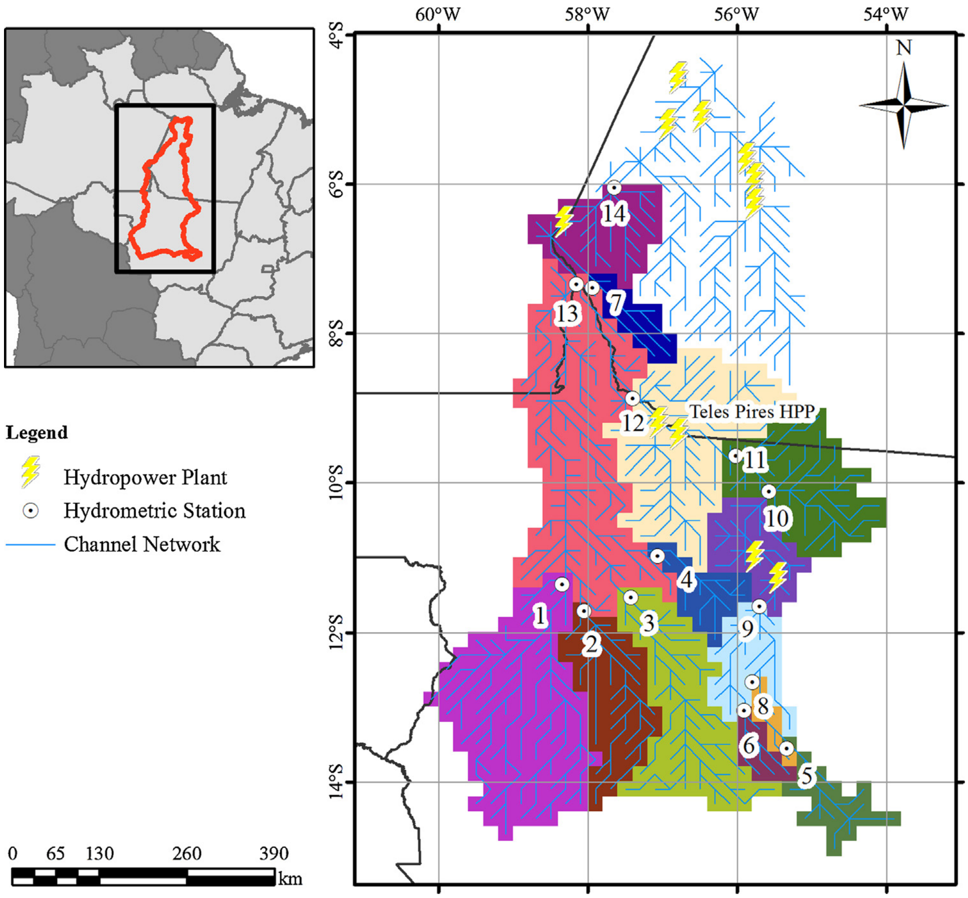

Fig. 1. The Tapajós River basin delimited in regular grid cells and divided into sub-basins. The black points indicate the outlet cell of each sub-basin. The channel network is the simple rectified network created for the model. Only the studied hydropower plant (HPP) is labeled.

is estimated from the Penman–Monteith equation (Monteith, 1965) and is separated into evaporation of canopy interception as estimated with the model proposed by Gash et al. (1995), transpiration of the water taken up by plant roots according to Jarvis' model (Jarvis, 1989), and the evaporation from the soil. Each grid-cell is sub-divided into hydrological response units (HRU), and the water balance is solved for each unit. This tile-type approach is commonly used in large-scale hydrological models (Liang et al., 1994). Routing between grid cells is performed according to the Muskingum–Cunge methodology (Garbrecht and Brunner, 1991).

The model uses meteorological data (air temperature, dew point temperature, wind speed, atmospheric pressure, incoming radiation and precipitation) as input data. The model simulations were carried out in a daily time step. The drainage network is derived from the basin digital elevation model (DEM). The combination of soil types with land use and land cover change maps are used for defining HRU within each grid cell. In Supplementary Material, Section S.1 provides a more detailed explanation on the model together with the list of model parameters (Table S.1).

2.3. Data

We obtained the vegetation cover from the information about vegetation in RADAM-IBGE (IBGE, 1992) and the PROVEG Project (Sestini et al., 2002), which classify the vegetation map according to SiB classes (Sellers et al., 1986) (Fig. S.1 in Supplementary Material). This static representation of vegetation classes was complemented with yearly information of land use and land cover change from the historical reconstruction by Leite et al. (2011), based on historical census data and contemporary land use classification, considering cultivated areas and both natural and planted pastures in Amazonia. Because historical discharges used in this work are contemporary with land use changes in the basin, the reconstruction of Leite et al. (2011) was an input data for the simulation of discharges during this period. By 1990, the drainage area was 70% covered by "broadleaf evergreen trees", which corresponds to the Amazon Forest; 21% was covered by "broadleaf trees with groundcover", which is the Cerrado biome; the remaining 9% was covered by short vegetation and croplands. We adopted plant functional parameters based on the literature (e.g., Shuttleworth, 1993; Gash et al., 1996; Culf et al., 1995; Chen and Dudhia, 2001).

The soil type distribution was extracted from the soil map of EMBRAPA (1980). The soils of the basin are characterized by low silt content and a wide range of variability between the clay and sand fractions; sandy clay loam soil (37%) and clay soil (19%) are dominant. The hydraulic parameters were obtained from the soil profile information using pedotransfer functions (Tomasella and Hodnett, 2005; Doyle et al., 2013). The distribution of soils is shown in Fig. S.2 in Supplementary Material.

Historical daily flow data from fourteen gauging sites in the basin, available from the Brazilian National Water Agency (ANA, 2013), were used to calibrate the model for each sub-basin and evaluate its performance (Table S.2 in Supplementary material). Geomorphologic information was derived from the Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007). Meteorological data were consulted from the Center for Weather Forecasting and Climate Research's database (Supplementary Fig. 3).

2.4. Climate projections

We used data from a set of global climate models as input for the MHD-INPE model: MIROC-5 (Watanabe et al., 2010); CSIRO-Mk3.6.0 (Rotstayn et al., 2010); IPSL-CM5A-LR (Dufresne et al., 2013); and HadGEM2-ES (Collins et al., 2008). We also used dynamically downscaled data from the Atmospheric Model Eta-INPE over South America (Chou et al., 2002, 2011). The choice of the models was based on their representations of the main characteristics of the present climate over South America (Gulizia and Camilloni, 2014; Chou et al., 2011). All data used from the climate models were extracted in a daily time step, for three time slices: 2011–2040, 2041–2070, 2071–2099. The output time step, spatial resolution and more information on the climate models is presented in the Supplementary Material, Table S.3.

The chosen global climate models are part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). The projections are based on the Representative Concentration Pathways (RCP) 4.5 emission scenarios (Thomson et al., 2011). Eta-INPE downscaling uses four members of a perturbed physical ensemble of the HadC-M3 model as boundary conditions (Gordon et al., 2000; Collins et al., 2001) for the emission scenario SRES (Special Report on Emissions Scenarios) A1B (Nakicenovic et al., 2000). The members were identified as M1 for the unperturbed member and M2 to M4 for the perturbed members.

The application of the meteorological data from the climate models for hydrological applications has spatial and temporal resolution constraints; bias in the variables' distributions is expected (Wood et al., 2004, 2002). For the bias correction, we applied a percentile-to-percentile approach based on Bárdossy and Pegram (2011) to the precipitation data, while the other meteorological data were bias-corrected using the linear scaling (Teutschbein and Seibert, 2013; Lenderink et al., 2007).

2.5. Hydrological model calibration and validation

The basin was discretized in regular cells with a spatial resolution of 20 km. The HRUs in each grid cell were delimited by combining the soil texture and land use classification with a 100 m resolution, summing up 15 HRUs for the whole basin. The basin delineation, drainage network and geomorphologic characteristics were derived using the software TerraView/Hidro (Rosim et al., 2012), which used the approach of Paz and Collischonn (2007, 2008) to derive the river geomorphologic characteristics at the model grid-cell scale. The topographic index was calculated using the Seibert and McGlynn

(2007) methodology, which uses a multiple flow direction algorithm to determine the distribution of the cumulative area and topographic index. Fig. 1 shows the sub-basin delimited. Further details of each sub-basin are shown in Table S.2 in Supplementary Material.

We calibrated the MHD-INPE model using the automatic calibration method of SCE-UA (Duan et al., 1992, 1994) in a daily step, between 1970 and 1990. The performance criteria for the calibration were the sum of three different performance indices: Nash–Sutcliffe efficiency (ENS), the Nash–Sutcliffe efficiency of the logarithmic values of discharge (ENSLog) and the relative volume error (ΔV) (Krause et al., 2005; Moriasi et al., 2007). Additionally, we verified the result by visual inspecting the observed and model estimated hydrographs. Validation was carried out for an independent later period, between 2003 and 2008. However, it should be noted that there is a lack of river discharge information during this period for two of the sub-basins considered. The efficiency criteria specifications are listed in the Supplementary Material Section S.2.

The assessment of climate change impacts relies on the analyses of differences between the historical period and future projections. Due to the biases in the models, changes must be interpreted by the comparison of future projections with the statistical behavior of the model simulation of the historical period instead of the observed data (Wood et al., 2002). Then, historical simulations and future projections must be interpreted in statistical terms that are able to define the climate state and its variability (Demaria et al., 2013; Siqueira Júnior et al., 2015).

The flow duration curves (FDCs) provide holistic information about the flow variability and the assessment of the rain-discharge transformation (Castellarin et al., 2013), and could be used for identifying changes due to global environmental changes (Peña-Arancibia et al., 2012; Rodriguez et al., 2010; Siqueira Júnior et al., 2015). Thus, we evaluated the performance of the model to simulate the present climate conditions when data from climate models are used as input using signatures of the FDCs (Yilmaz et al., 2008; Ley et al., 2011). Therefore, we calculated the FDC signatures resulting from discharge simulations when the hydrological model used observed data as input for the Tapajós Basin, and we compared the results with the same signatures derived from the discharges of the hydrological model driven by the climate model historical simulation outputs.

The signatures of the FDCs used in this paper were the seasonality, the slope of the FDC in the medium range (QSM), the high-flow volume (MWH) and the low-flow volume (MWL) as proposed by Ley et al. (2011):

$$\text{SEASONALITY} = \frac{\text{mean Wet season} - \text{mean Dry season}}{\text{mean Overall}} \quad (1)$$

$$\text{QSM} = \frac{0.8\,\text{quantile} - 0.2\,\text{quantile}}{\text{mean Overall}} \quad (2)$$

$$\text{MWH} = \frac{\sum_{h=1}^{H} Q_h}{H} \quad (3)$$

$$\text{MWL} = \frac{\sum_{l=1}^{L} Q_l}{L} \quad (4)$$

where H is the number of discharges with an exceedance probability <5%, and L is the number of discharges with an exceedance probability between 70% and 90%.

2.6. *Impacts on hydrology*

Change in the hydrologic response of the basin due to climate change was assessed through the comparison of the projected long-term average discharges (LTA) and the simulated LTA for the historical period using the different climate projections. The changes in the magnitude of the annual average discharge were calculated as the difference between the projected values and historical values, which were both simulated using the same climate model data.

Low discharge variability has an important influence on the energy production of the run-of-river (ROR) plants because the plants do not have reservoirs that allow for the storage of water during the wet season or regulation of discharges during the dry season. We assessed low discharge variability using the 95th percentile of the FDC (Q95), which is used for defining critical thresholds for water resources uses, such as hydropower generation. Additionally, changes in the duration of the dry season were assessed based on monthly precipitation by considering that a 100 mm month^{-1} threshold defines the onset and end of the dry season in Amazonia (Sombroek, 2001; Marengo et al., 2011b).

The sensitivity of discharge to climate change was assessed through the climate elasticity, which is defined as the proportional change in discharge divided by the proportional changes in the climatic variables, such as precipitation (Sankarasubramaniam et al., 2001; Fu et al., 2007; Chiew, 2006). To evaluate the change in the discharge sensitivity under future climate conditions, we used the nonparametric estimator of the precipitation elasticity as proposed by Chiew (2006) (Eq. (5)):

$$\varepsilon_p = \text{median}\left(\frac{Q_t - \bar{Q}}{P_t - \bar{P}} * \frac{\bar{P}}{\bar{Q}}\right) \quad (5)$$

where $\bar{P}$ and $\bar{Q}$ are the mean annual precipitation and discharge for each period, respectively, and Q_t and P_t are the annual average discharge and the annual precipitation, respectively.

2.7. Impacts on hydroelectricity

The impacts of potential shifts in the hydrological regime due to global climate change were evaluated for the Teles Pires hydropower plant (HPP). This HPP will be operational in 2015 (EPE, 2012), and it has an expected lifetime of 55 years (MMA, 2010). It is a run-of-river (ROR) plant with an installed capacity of 1820 MW, a maximum plant discharge of 3919 $m^3 s^{-1}$, a head fall of 59 m, a minimum flow (MFD) of 560 $m^3 s^{-1}$ and a reservoir with a 152 km^2 surface area (ANA, 2011). ROR plants are hydropower plants with a weir and a low storage reservoir, with almost no regulation, where the outflow diverted is very similar to the inflow (Basso and Botter, 2012). The Teles Pires plant is located between the outfall of sub-basins "Jusante Foz Peixoto de Azevedo" (sub-basin 11) and "Santa Rosa" (sub-basin 12).

The impacts of climate change on hydropower generation were estimated using the methodology of Vogel and Fenessey (1995), which was developed to study the viability of hydropower ROR plants. A typical (hypothetical) annual FDC was calculated from the median of daily discharge values (Vogel and Fenessey, 1994). For the ROR HPP, this FDC was converted into the power duration curve (PDC) by knowing the hydraulic head and the plant efficiency. This PDC is constrained by the minimum flow (MFD), under which the plant cannot operate, and the plant installed capacity. The integration of the area under this curve represents the typical (hypothetical) annual energy production (Vogel and Fenessey, 1995).

To explore the robustness of the energy production at the Teles Pires HPP, we included the installed plant capacity and the minimum flow required as constraints in the estimation of the PDC (Basso and Botter, 2012; Ministério de Minas e Energia (MME), 2007). Therefore, the energy production was only computed in the range between the MFD and the plant capacity. We also considered evaporation of the reservoir and the plant efficiency based on the net head and the turbine design (Basso and Botter, 2012; MME, 2007). We analyzed the variations in the annual production under the effects of climate change by comparing the simulated PDC for the historical period and the derived PDC from the climate projection of the corresponding climate model. For example, the projected PDC obtained using IPSL data were compared with the simulated PDC for the historical period using IPSL data.

3. Results and discussion

3.1. Calibration and validation results

MHD-INPE performed well in simulating the historic streamflow data at the gauging stations; the ENS and ENSLog were superior to 0.63 and were as high as 0.92; and the relative volumetric errors were lower than 16% in the sub-basins. In most of the gauging stations, the model underestimated the peaks and showed limitations on simulating the lower part of recession curve in few gauging stations. These discrepancies were not very different than those verified in other studies in South America

Table 1
Calibration and validation efficiency on each sub-basin.

Sub-basin	Calibration period (1970–1990)			Validation period (2003–2008)		
	ENS	ENSLog	ΔV (%)	ENS	ENSLog	ΔV (%)
1	0.80	0.80	−2.84	0.86	0.89	−1.00
2	0.69	0.70	6.19	0.31	0.49	−3.00
3	0.67	0.69	9.39	0.75	0.78	11.00
4	0.84	0.83	−1.15	–	–	–
5	0.71	0.84	15.84	0.86	0.90	11.00
6	0.63	0.70	2.70	0.36	0.56	23.00
7	0.79	0.76	−1.29	–	–	–
8	0.83	0.89	4.63	0.85	0.91	10.00
9	0.84	0.88	2.26	0.86	0.92	4.00
10	0.84	0.87	8.95	0.92	0.92	8.00
11	0.84	0.85	11.31	0.93	0.96	−7.00
12	0.90	0.81	14.63	0.79	0.86	−12.00
13	0.90	0.90	4.68	0.93	0.92	−3.00
14	0.90	0.93	−6.98	0.75	0.86	−19.00

ENS: Nash–Sutcliffe efficiency; ENSLog: Nash–Sutcliffe efficiency of the logarithmic values of discharge; ΔV: relative volume error.

(e.g., Collischonn et al., 2007; Bravo et al., 2012; Demaria et al., 2013; Lavado Casimiro et al., 2011; Guimberteau et al., 2012), and are likely to be related to the low density of the raingauge network in several sub-basins. For instance, the density in sub-basin 4 (“Caiabis”) is 1 raingauge every 3600 km^2. The final value of the calibrated parameters is shown in Table S.4 in Supplementary Material.

Efficiency-criteria results (Table 1) and a visual inspection of the hydrographs indicated a good agreement between simulations and the observations, as shown in Fig. S.4 in Supplementary Material. The validation results were in most cases (9 of 14 sub-basins) better than in the calibration period, with ENS and ENSLog superior to 0.7. In two sub-basins, observed discharges were not available for the validation period; while other two sub-basins presented an unsatisfactory though positive Nash-Sutcliffe. Regarding the latter results, it should be noted that both are headwaters sub-basins, with shorter time rainfall runoff response and extremely sensitive to localized rainfall. Considering that the available rainfall data is scarce, there are uncertainties in the interpolated field, particularly in headwater sub-basin with smaller drainage area. In spite of this, a positive ENS is ultimately an indicator that the model gives a minimum representation of seasonality. These results validate the model’s representation of the hydrological behavior of the basin (Moriasi et al., 2007).

Fig. 2a–d shows the correlation between the FDC signatures of the simulations of the historical period using the observed data and the signatures obtained with the bias-corrected climate model data for all sub-basins. In general, the signatures show a close agreement between the experiments. Deviations between the simulated and observed discharges are observed in the signatures associated with higher and lower discharges, mainly when the hydrological model uses IPSL and CSIRO models as input. In this case, the integrations show an overestimation of higher discharges (Fig. 2c) and underestimation of lower discharges (Fig. 2d).

3.2. Hydrological effects of climate change

Climate change impacts on the long-term average discharge at the Fortaleza gauge station show high variability among the models (Fig. 3). In Fig. 3, for simplicity, the baseline used as a reference corresponds to the average of the simulations over the historical period using all climate models. It is worth noting that the largest variations occur during the period of higher discharges (JANUARY–MAY). In general, Eta-INPE members show more variability and broader seasonal amplitudes. However, the IPSL projections produced an increase in the discharge during the wet season.

Fig. 4 shows the relationship between precipitation and discharge changes simulated by the hydrological model for all climate models and time-slices at the Fortaleza gauging station, while Fig. 5 shows

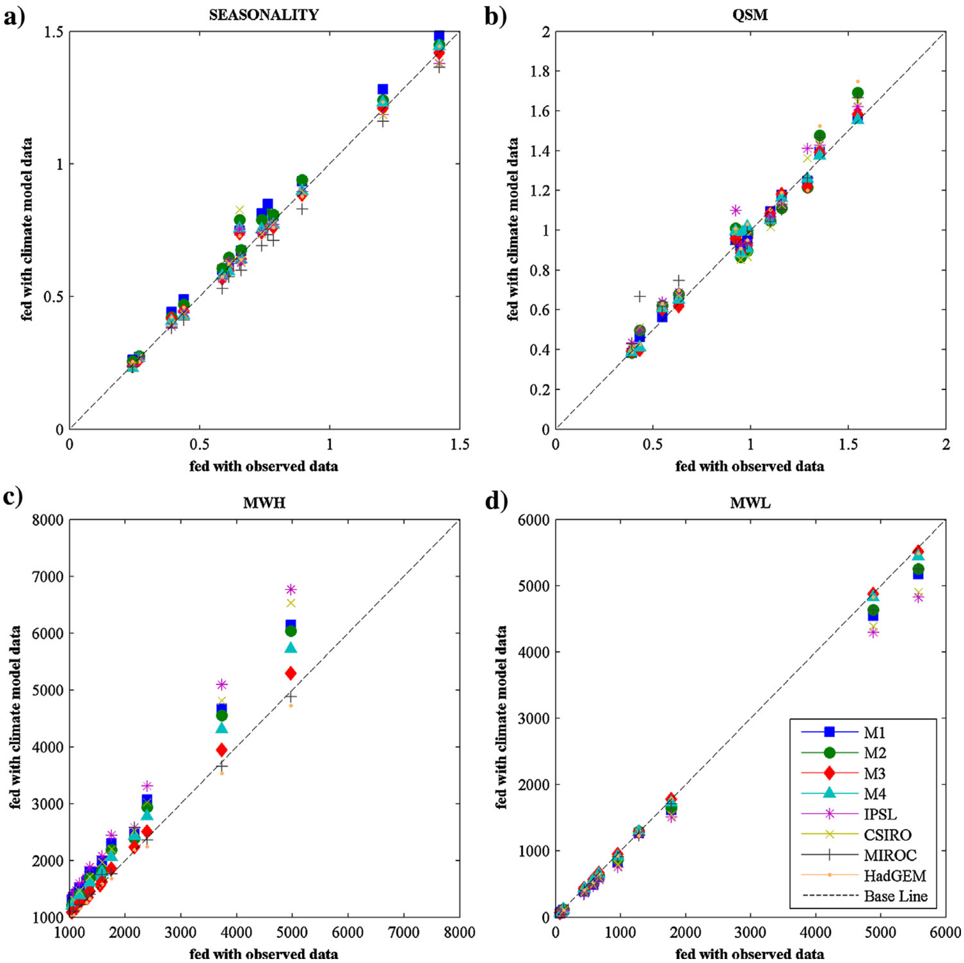

Fig. 2. Comparison of catchment behavior indices obtained with observed data and with climate models data for each sub-basin. (a) Seasonality; (b) slope of medium range (QSM); (c) high-flow segment volume of FDC (MWH); (d) low-flow segment volume of FDC (MWL).

the results for all sub-basins, highlighting only differences among sub-basins. These results represent the new hydrological condition, or state, for a given climate scenario, indicated by the relationship between ΔP and ΔQ at the Tapajós Basin, and illustrate how dispersion of climate models projections affect the hydrologic response. In terms of precipitation, the climate projections show a high inter-model variability in which the Eta-INPE members indicate the most severe reduction while the IPSL model shows an increase until the end of the century (Fig. 4).

Climatologically, the relationship between discharge and precipitation is a function of the relationship between evaporation and precipitation. Then, dispersion of discharge changes is explained by the dispersion of the precipitation simulated by the climate models, as also showed in previous studies in a Brazilian large basin (Bravo et al., 2013). When changes in precipitation are small, there is a greater influence of evaporation changes on the discharges (Fig. 5b), resulting in opposite sign between precipitation and discharge changes. In general, simulations show that, for similar changes in precipitation, the changes in the discharge are greater in larger basins (Fig. 5a). However, for the small sub-basins 6 and 7, $\Delta Q/\Delta P$ is as high as that in the larger sub-basins.

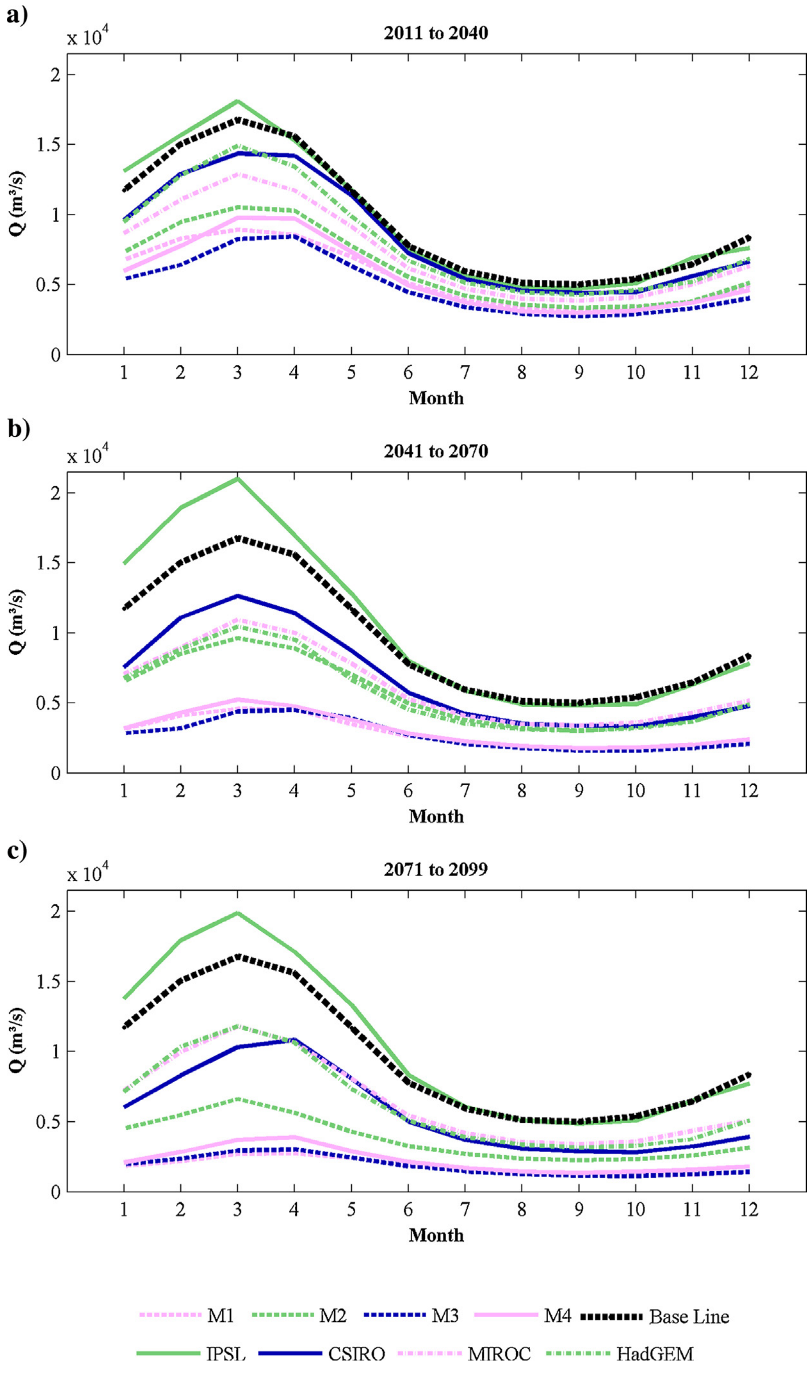

Fig. 3. Projections of monthly long-term discharges at the Fortaleza gauging station for the periods between (a) 2011 and 2040, (b) 2041 and 2070, and (c) 2071 and 2099. The baseline is the average of the simulations using climate model data for the historical period (1970–1990).

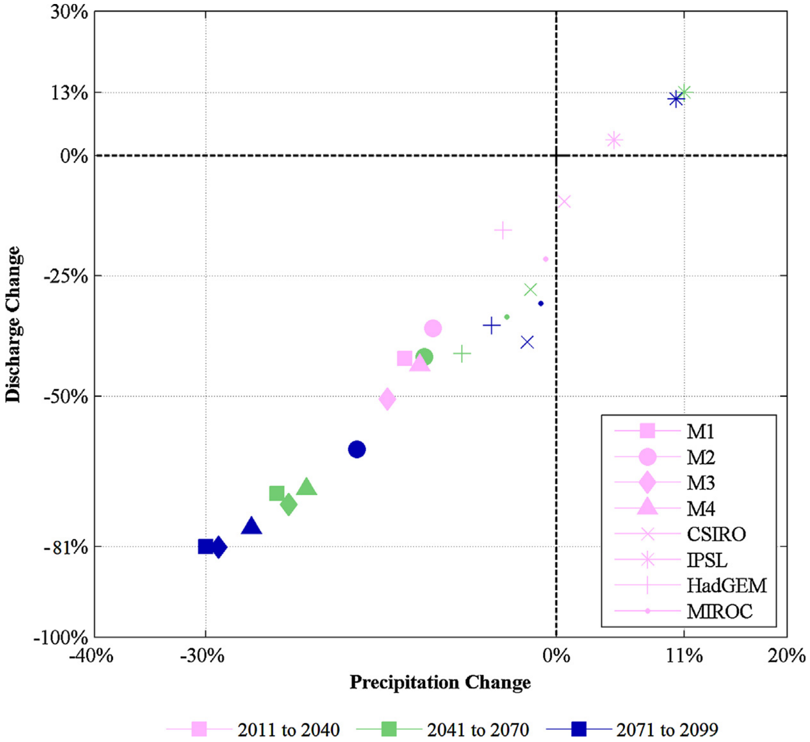

Fig. 4. Mean precipitation and discharge changes in the sub-basin of Fortaleza from 2011 to 2040 (blue), 2041 to 2070 (green) and 2071 to 2099 (red). Changes were calculated over the historical period daily average (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

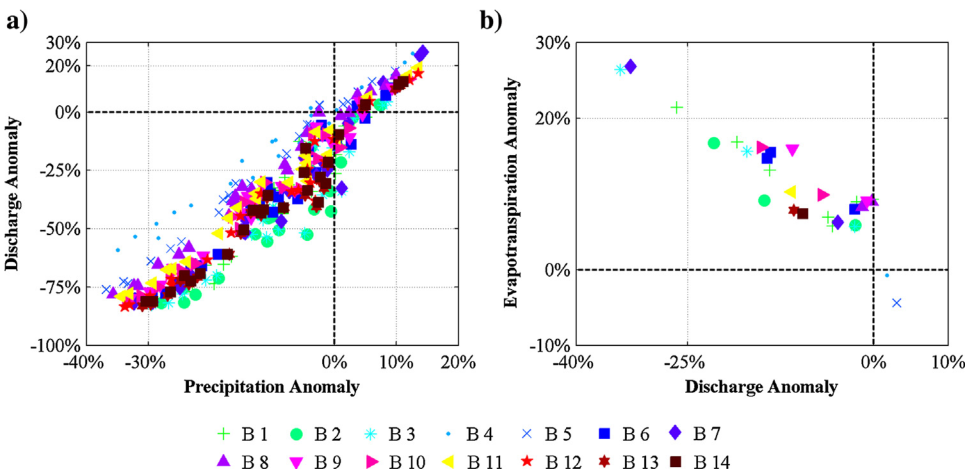

Fig. 5. (a) Precipitation and discharge changes for all 14 sub-basins; (b) discharge and evapotranspiration changes for the cases in (a) located in the second and fourth quadrants (when precipitation and discharge impacts have opposite signs).

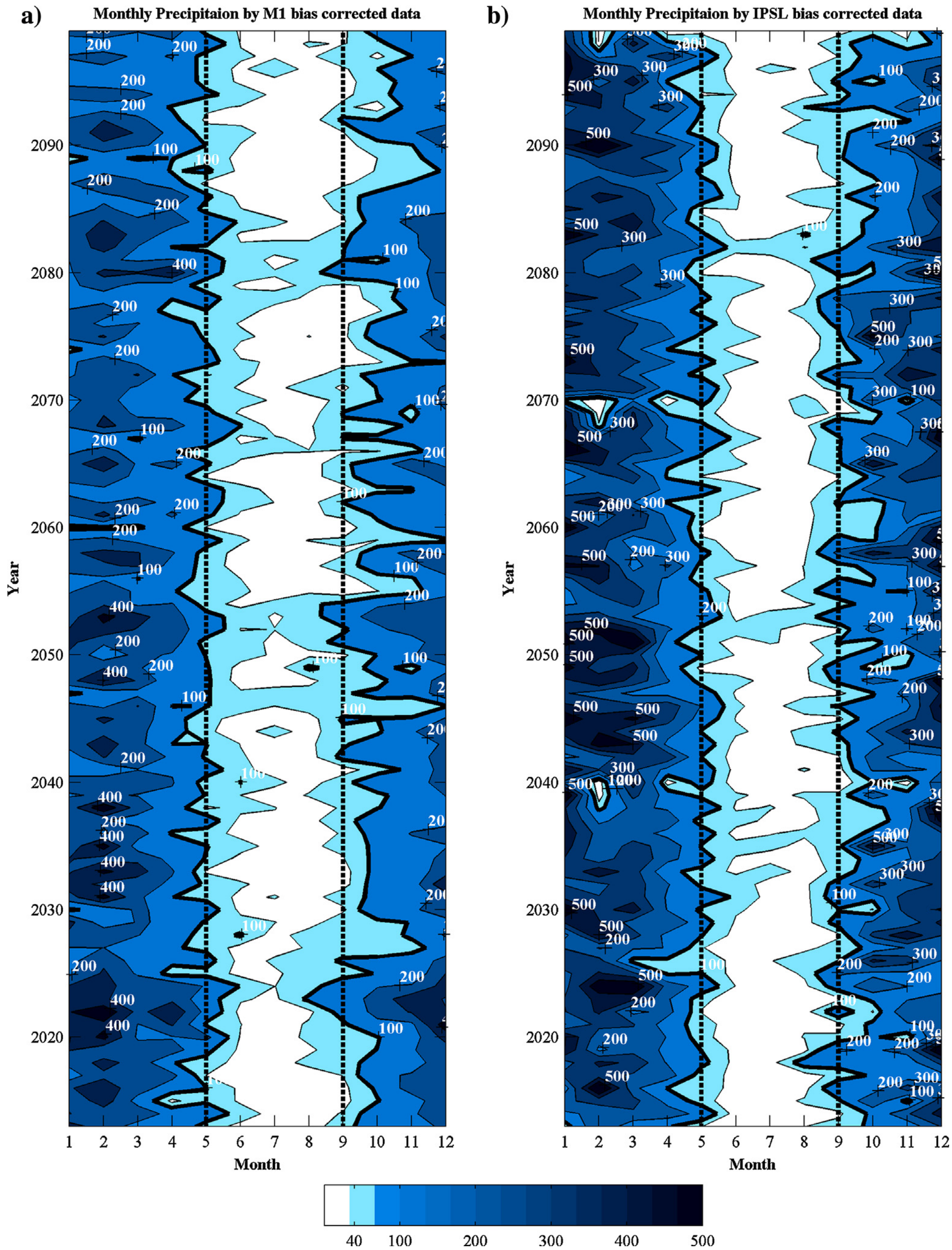

Fig. 6. Projected monthly precipitation over the Tapajós Basin using (a) M1 data (the model with the most negative precipitation impact) and (b) IPSL data (the model with a positive precipitation impact). The dashed lines indicate the boundary of the average dry season, which is delimited by 100 mm/month isohyets, observed in the historical period of 1970–1990.

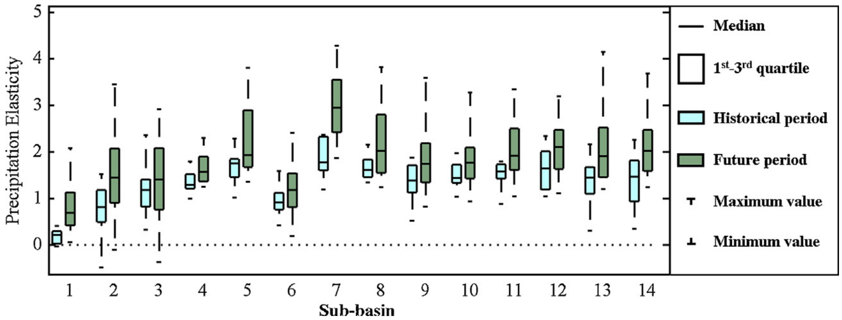

Fig. 7. Variability among the model integrations of precipitation elasticity per sub-basin. The box-plots at left represent data from the simulations of the historical period, and the box-plots at right represent data from the projections of future periods.

The changes in Q95 at the Fortaleza gauge station by the end of the century (2071–2099) are +5% in the IPSL projections, while the remaining models range from −30% to −91%; the M4 member projection has the lowest value. Alternatively, we checked the exceedance probability in the future projections that equals the average simulated Q95 for the historical period at the Fortaleza station (4897 $m^3 s^{-1}$). The discharge value is associated with lower than 95% exceedance probabilities until the end of the century, i.e., 61%, 46% and 41% average exceedance probabilities for 2011–2040, 2041–2070 and 2071–2099, respectively. This indicates that low discharges last longer due to climate change and have implications for the water resources management in the basin.

It is important to mention that strong impacts on the dry-season discharges have also been verified in the observed discharges in the Amazon basin; they are related to the late demise of the dry season associated with the warming in the tropical North Atlantic (Tomasella et al., 2011; Marengo et al., 2011b). Fig. 6 shows the dry season length in the Tapajós Basin for the most extreme scenarios in terms of changes in precipitation, i.e., the M1 member and the IPSL. Both models project temperature rises of at least 3 °C over the entire basin by the end of the century; however, IPSL indicates an average annual precipitation increase over the basin, while the M1 member and the other climate models indicate a decrease. Following Marengo et al. (2011b), dry months were identified by the period when the monthly rainfall was lower than 100 mm. Fig. 6 indicates that the dry season length, which extends from May to September in the historical period, gradually increases during the future period for both simulations, even when wet season rainfall increases. These results are in agreement with the trends noted by Marengo et al. (2011b) in the southern Amazonia dry season.

Fig. 7 compares climate elasticity box-plots derived from all simulations for the historical period and for the future projections in each of the 14 sub-basins of the Tapajós River to identify the variation of the sensitivity of the models for both the historical simulations and future projections. The inter-model variability increases for the future projections (i.e., produce higher uncertainties). Additionally, the median values of elasticity for each sub-basin increase for the entire basin from the historical simulations compared with the future projections under climate change (Fig. 7). The results from the non-parametric Wilcoxon test (Supplementary Material, Table S.5) reject the null hypothesis of equal medians between the present and future periods with a statistical significance of 95%. Similar to the $\Delta Q/\Delta P$ rate, negative values of elasticity are found in some basins, showing that small increases in precipitation combined with increases in temperature may lead to a decrease in streamflow (Fu et al., 2009).

3.3. Hydroelectric generation impacts

We analyzed the expected changes of a run-of-river plant in terms of the typical annual energy production. Fig. 8b depicts the typical power duration curves for hydroelectric generation at the Teles Pires HPP considering the median values during 2041–2070 by the end of the HPP lifetime. The baseline in the figure represents the average of the climate models' PDCs over the historical period (Fig. 8a). It should be noted that, even with deviations in the extreme values, the duration curves of the typical

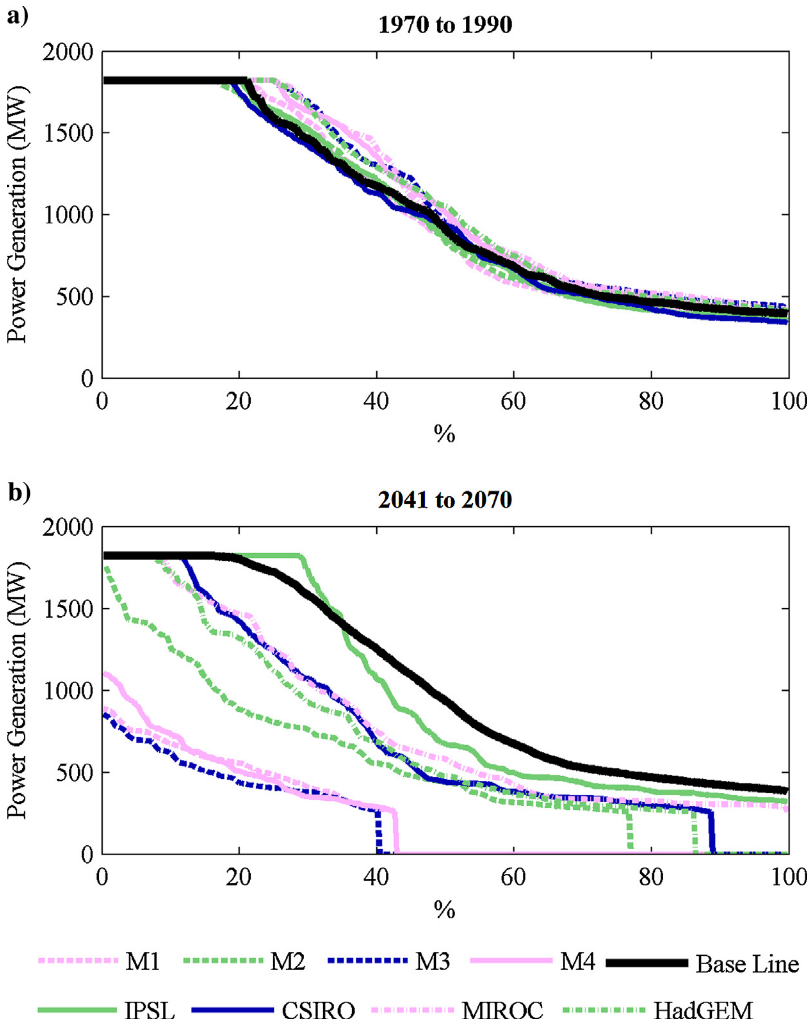

Fig. 8. Annual processed power duration curves based on median daily values at the Teles Pires HPP site between (a) 1970 and 1990 and (b) 2041 and 2070. The plant's installed capacity is 1820 MW. The baseline in (a) is the PDC of the historical period (1970–1990) obtained using the observed data as input. The baseline in (b) is the average of the PDCs obtained using the climate model data as input for the hydrological model integrations.

energy production are consistent between experiments due to the use of median discharge values in the calculation.

Provided the MFD does not change until 2070, the most critical projection/scenario indicates that between 2041 and 2070 the plant should not be operating 59% of the time because the MFD should not be reached. Considering that these results do not include scenarios for water consumption, it follows that this scenario could be further aggravated. Due to the increase of human pressure on the basin, the water demand for irrigation is very likely to increase (MMA, 2006).

As the most critical projection, Eta-INPE member M3 indicates a production of 1.7×10^6 MWh/year between 2041 and 2070, which is 82% lower than the hypothetical production of 9.6×10^6 MWh/year simulated for the historical period (Fig. 8). M3 projects that, by the end of the century, the HPP may reach 292 days/year (80%) of idle time and the annual production may fall by 92%. However, the IPSL model projection, which indicates an increase in precipitation, results in a reduction of 3% in the annual production for the period of 2041–2070 and an idle time of 16 days/year (Fig. 8). Despite the high variability among the model simulations, the annual energy production is likely to decrease until the end of the century for the analyzed projections under the current HPP design. Although the IPSL scenario points to an increase in rainfall, this is not reflected in the annual production because the constraint is given in terms of plant capacity.

4. Conclusions

We applied the MHD-INPE over the Tapajós Basin using meteorological data from several climate projections to assess the impacts on the hydrologic regime and its consequences for hydroelectric generation due to climate change.

By calibrating the model using the observed meteorological and hydrological data for 1970–1990, the MHD-INPE performed well at fourteen gauging stations. Additionally, hydrological simulations of the historical period using bias-corrected data from the climate models were able to reproduce the main FDC signatures, although differences are identified in the extreme values for some of the simulations. An independent validation was also carried out between 2003 and 2008, showing good agreement to observed data in most sub-basins. These results highlight the confidence of using MHD-INPE for climate change studies in the basin.

Most of the projections result in a decreasing discharge in the basin in response to changes in precipitation. On average, changes in the annual hydrological cycle indicate a longer duration of low discharges in most of the projected scenarios. These results are associated with a longer dry season length as projected by the climate models.

Discharge sensitivity, as evidenced by precipitation elasticity, increases under the impacts of climate change. This result agrees with what is expected from the analyses of Budyko curve (Teng et al., 2012). Moreover, the elasticity shows a higher dispersion among the model projections than that in the historical period, driven by the larger dispersion of the bias-corrected climate data in future projections. These results highlight that projected hydrological changes in the basin have higher uncertainties than simulations of the historical period.

Because it is not possible to conclude which projected climate scenario is the most appropriate, this work is suggesting to assess climate change impacts on energy production through an exploratory analyses, evaluating the robustness of the plant design. Unlikely most previous work (for instance Zhang et al., 2014; Zhao et al., 2013; Coe et al., 2009) that analyze the impacts in terms of mean monthly or even annual discharge, this paper implicitly includes seasonality in the analysis of the impact changes in the hydrological regime: by including the hydropower plant characteristics it is possible to simulate the annual power duration curves changes under a series of different scenarios.

An adopted HPP design for hydropower generation was tested under several plausible scenarios of climate change to identify potential impacts on hydroelectricity. The results show that the climate change projections lead to a decreasing annual energy production and an increasing idle time at the Teles Pires HPP, in spite of the differences in the climate projections. Seasonal changes in precipitation, together with the limitation of the maximum installed capacity, explain the decreasing energy production, even when the annual average precipitation increases.

In 2012, hydroelectric power accounted for 76.9% of Brazil's Electricity Matrix (EPE, 2013), which is the largest electricity source in the country. In addition to the well-known advantages of hydroelectricity, this scenario confirms that the hydrological regime is very sensitive to environmental changes. The variability in the results among the projections complicates the choice of an optimal response to the changes. However, when the HPP design performance is analyzed under several feasible projections, it is possible to evaluate its robustness, and to provide valuable information to stakeholders.

Conflict of interest

None declared.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:10.1016/j.ejrh.2015.04.003.

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