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Integrating climate models into hydrological modelling: What's going on in Brazil?

Integração de modelos de clima na modelagem hidrológica: o que está acontecendo no Brasil?

Pablo Borges de Amorim[1]* and Pedro Luiz Borges Chaffe[1]

[1]Universidade Federal de Santa Catarina, Florianópolis, SC, Brasil
E-mails: borgesdeamorim.pablo@gmail.com (PBA), pedro.chaffe@ufsc.br (PLBC)

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ABSTRACT

Studies integrating climate modelling output into hydrological modelling have grown substantially in the last two decades worldwide; however, there has not been a systematic review about those applications in the Brazilian territory. The aim of this study is to identify how the scientific community has been dealing with the topic in Brazil. The study is based on a systematic review of available peer-reviewed literature. We identify regions and socioeconomic sectors of interest and propose a method to evaluate the methodological consistency of the studies with the current state-of-the-art. The review shows that the topic has grown substantially in this decade, reaching 63 documents until 2018. The sectors under highest concern are the hydropower and the drinking water supply. The Paraná and Atlântico Nordeste Oriental hydrographic regions received great attention; whereas the Atlântico Sudeste did not. In terms of methodology, the use of multi-model ensemble leaves room for improvement. The results suggest a lack of human resources and access to computational infrastructure to handle climate data. Given the current challenges that Brazilian science is facing, we suggest the synchronization of efforts among research institutions. This systematic review provides information to help guiding decision makers to improve the topic in Brazil.

Keywords: Climate models; Hydrological models; Systematic review.

RESUMO

Estudos que integram modelagem climática em modelagem hidrológica têm crescido substancialmente nas últimas duas décadas em todo o mundo; entretanto, pouco se sabe sobre estes no território brasileiro. O objetivo deste estudo é identificar como a comunidade científica tem lidado com o tema no Brasil. O estudo baseia-se numa revisão sistemática da literatura revisada por pares disponível. Identificamos regiões e setores socioeconômicos de interesse e propomos um método para avaliar a consistência metodológica dos estudos com o atual estado-da-arte. A análise mostra que o tema cresceu substancialmente nesta década, abrangendo 63 documentos até 2018. Os setores de maior interesse são o de energia hidrelétrica e de abastecimento de água potável. As regiões hidrográficas do Paraná e do Atlântico Nordeste Oriental receberam grande atenção; enquanto a região Atlântico Sudeste pouca. Em termos de metodologia, o uso do conjunto de multi-modelos deixa espaço para melhorias. Os resultados sugerem limitações em capacidade técnica e em acesso à infraestrutura computacional para lidar com dados climáticos. Diante dos atuais desafios que a ciência brasileira enfrenta, sugerimos a sincronização de esforços entre instituições de pesquisa. Esta revisão sistemática fornece informações que podem ajudar os tomadores de decisão em ações de aprimoramento do tema no Brasil.

Palavras-chave: Modelos de clima; Modelos hidrológicos; Revisão sistemática.

INTRODUCTION

The Brazilian National Plan for Climate Change Adaptation (Plano Nacional de Adaptação à Mudança do Clima - PNA) establishes among its objectives the improvement of the climate projections and the support to incorporate climate change information into adaptation plans (BRASIL, 2016). At the same time, the Projeto Legado (ANA, 2017) foresees the use of climate change scenarios as subsidy for the National Strategic Plan for Water Security. To achieve those goals, the first step is to assess how the scientific community is dealing with the issue in Brazil. Studies integrating climate change information into hydrological modelling have grown substantially in the last two decades worldwide (KUNDZEWICZ et al., 2018); however, there has not been a systematic review about them in the Brazilian territory.

Borges and Chaffe (2019) conducted a synthesis assessment about the impacts of climate change on the Brazilian water resources. They concluded that the recommended use of multi-model ensemble has been rarely applied. Nevertheless, there is a substantial consensus in the literature about potential change in the availability of water resources in Brazil, such as changes into a drier hydrological regime. Here, we extend the work of Borges and Chaffe (2019) with a review of the current state-of-the-practice of the integration of climate model outputs into hydrological models in Brazil. The study is based on a systematic review of all available peer-reviewed literature classified by regions and socioeconomic sectors of interest. We evaluate the methodological consistency of those studies with the current state-of-the-art, identify their strengths and limitations, and discuss how research institutions can improve their practices. Assessing how the scientific community is dealing with the use of climate information in hydrological modelling is a crucial step to understand the challenges and opportunities for the improvement of the topic in Brazil.

MATERIALS AND METHODS

Paper selection and systematic review

A comprehensive literature search was carried out in order to identify peer-reviewed scientific articles that integrate climate model outputs into hydrological modelling in the Brazilian territory. We used three science databases: Scopus, Web of Science and Google Scholar (HARZING; ALAKANGAS, 2016). We also considered the Scientific Electronic Library Online (SciELO) and the following Brazilian scientific journals: Anais da Academia Brasileira de Ciências (AABC), Brazilian Journal of Water Resources, Ciência e Agrotecnologia (CAGRO), Revista Brasileira de Climatologia, Revista Brasileira de Engenharia Agrícola e Ambiental (AGRIAMBI), Revista Brasileira de Meteorologia (RBMet) and Revista Engenharia Agrícola (EAGRI).

The search considered articles published until December 2018. Articles written in English and Portuguese were included. Publications such as book chapters, doctoral dissertations and conference papers were not taken into account. To find the documents, Boolean functions were applied to match the following keywords in the title, abstract or keywords: ['climate model' OR gcm OR aogcm OR oagcm OR 'climate change'] AND [hydrologic OR hydrology OR hydrological OR hydraulic OR 'rainfall-runoff'] AND [Brazil]. Initially the search yielded hundreds of documents, but only 63 were considered relevant for the purpose of this study. The documents are listed in the Table 1, wherein sixteen were published in Brazilian scientific journals.

The systematic review is organized in three major groups that embraces eight aspects for analysis (Figure 1). The year of publication and Impact Factor (IF, Journal Citation Reports of the Institute for Scientific Information) indicate the level of concern of the scientific community. The second group corresponds to the interest, which is divided in hydrographic region, sector and purpose. The third group corresponds to the approach adopted in the studies: i) the quantity and version of the climate models (General Circulation Models – GCM or Earth System Models - ESM), ii) the application of regionalization techniques, and iii) type and quantity of hydrological models.

Level of comprehensiveness of the studies

The considerable quantity of documents found provides plausible messages of the state-of-the-practice in applying climate scenarios in hydrological impact assessments in Brazil. The methodology used to evaluate the 'level of comprehensiveness' of a certain study was inspired in Mastrandrea et al. (2011) – the same one used in the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5) –, which depends on three aspects: i) theoretical foundation, ii) data used, and iii) sophistication of the modelling procedure. Each aspect is scored from 1 to 5, which are associated with the terms: *very limited*, *limited*, *medium*, *fairly robust* or *robust*. This analysis considered only studies addressing the impacts of climate change on water resources (i.e., 48 articles, see section *Purpose*).

Theoretical foundation

The *theoretical foundation* aspect refers to the regionalization procedure adopted. There are several ways to include projections of climate change in hydrological models. The most plausible and physically consistent representations of climate due to anthropogenic activity are those provided by climate models (WILBY et al., 2009). Due to the coarse resolution, GCMs are often not able to represent spatiotemporal variability of climatic variables (e.g., rainfall) at the scale required for hydrological studies. The application of regionalization techniques is therefore recommended (FOWLER; BLENKINSOP; TEBALDI, 2007; MARAUN et al., 2010). We defined regionalization as downscaling and bias correction (BC). The downscaling is divided into two families, the dynamical (Regional Climate Model - RCM) and the statistical (Empirical Statistical Downscaling - ESD).

The RCMs have the same principles of GCMs in representing the dynamical and physical processes of the terrestrial system but in a much finer resolution and limited domain area. The ESD relies on the principle that local weather is a function of large-scale atmospheric patterns. A statistical function is used to estimate e.g., rainfall based on the large-scale relative humidity and zonal wind data at the 500hPa level. The BC is often mistaken by ESDs since both are based on empirical data. But in BC the

Table 1. List of articles.

Abramopoulos, Rosenzweig and Choudhury (1988)	Pereira, Moraes and Uvo (2014)
Marengo et al. (1994)	Popescu, Brandimarte and Peviani (2014)
Krol et al. (2001)	Ribeiro Neto et al. (2014)
Medeiros (2003)	Silveira et al. (2014)
Tucci et al. (2003)	Adam et al. (2015)
Araújo et al. (2004)	Arroio Junior and Mauad (2015)
Rosenzweig et al. (2004)	Ramos Iensen, Bauer Schultz and Santos (2015)
Coelho et al. (2006)	Mohor et al. (2015)
Krol et al. (2006)	Oliveira, Pedrollo and Castro (2015a)
Krol and Bronstert (2007)	Oliveira, Pedrollo and Castro (2015b)
Mello et al. (2008)	Siqueira Júnior, Tomasella and Rodriguez (2015)
Block et al. (2009)	Valério and Júnior (2015)
Lima and Alves (2009)	Viola et al. (2015)
Montenegro and Ragab (2010)	Alvarenga et al. (2016)
Gondim et al. (2011)	Ho, Thompson and Brierley (2016)
Gosling et al. (2011)	Lamparter et al. (2016)
Nóbrega et al. (2011)	De Queiroz et al. (2016)
Rivarola Sosa et al. (2011)	Ribeiro Júnior, Zuffo and Silva (2016)
Alves, Campos and Servain (2012)	Ribeiro Neto et al. (2016)
Cook, Zeng and Yoon (2012)	Sorribas et al. (2016)
Hirata and Conicelli (2012)	Tejadas et al. (2016)
Kwon et al. (2012)	Fernandes et al. (2017)
Marengo et al. (2012)	Guimberteau et al. (2017)
Montenegro and Ragab (2012)	Melo and Wendland (2017)
Adam and Collischonn (2013)	Mendes, Beluco and Canales (2017)
Braga et al. (2013)	Mohor and Mendiondo (2017)
Kruk, Vendrame and Chou (2013)	De Oliveira et al. (2017)
Perazzoli, Pinheiro and Kaufmann (2013)	Pinheiro, Van Lier and Bezerra (2017)
Pinheiro, Graciano and Kaufmann (2013)	Silveira, Souza Filho and Vasconcelos Júnior (2017)
Bravo et al. (2014)	Gondim et al. (2018)
Fill et al. (2013)	Zaninelli et al. (2018)
Melo, Marin and Wendland (2014)	

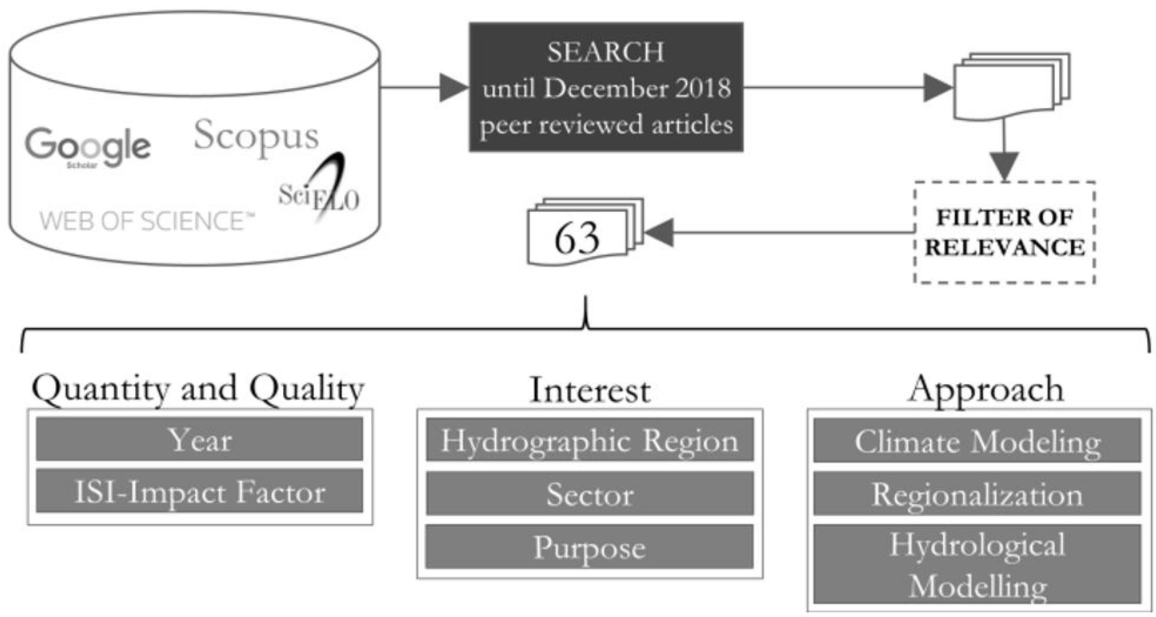

Figure 1. Flowchart of the search and characterization of the systematic review.

predictor variable is the same as the target variable. That is, a transfer function is used to generate e.g., local rainfall from the precipitation simulated by a GCM. BC does not consider physical arguments and is thus less plausible than downscaling techniques. We found numerous studies in Brazil applying BC in combination with RCM outputs or even as a means of replacing downscaling. Although the application of BC is controversial in hydrological impact assessments (EHRET et al., 2012), we cannot neglect this step (TEUTSCHBEIN; SEIBERT, 2012) and thus we assume BC as a simple form of regionalization. The pattern scaling technique is also often applied in hydrological impact studies (FOWLER; BLENKINSOP; TEBALDI, 2007), for instance in Brazil (i.e., BRAVO et al., 2014; NÓBREGA et al., 2011; PERAZZOLI; PINHEIRO; KAUFMANN, 2013). Due to the degree of sophistication, the pattern scaling is classified as ESD. For more details on the definitions adopted here see Maraun et al. (2010).

Table 2 describes the scoring criteria adopted to classify the articles. The study that uses only GCM outputs without any regionalization is considered less theoretically sound and is given a score of 1. GCM combined with a very simple BC (e.g., Delta Change Factor - DCF), counts 2. When more sophisticated BC is applied (e.g., Quantile Mapping - QM), the study is given a score of 3. Studies integrating a GCM with either a RCM or a ESD gets 4 scores. A maximum scoring study should consider: i) the GCM outputs integrated with RCM followed by a BC, or ii) GCM with RCM in addition to GCM with ESD.

Data used

A common approach in sampling all aspects of model uncertainties in climate impact assessments is the multi-model ensemble (MME). The MME is based on the assertion that no model performs better than another. The combination of several climate models has the potential to increase the skill, reliability and consistency of projections. The application of MME in impact assessments does not only benefit from error compensation and quantification of uncertainties, but also from its greater consistency and reliability (TEBALDI; KNUTTI, 2007). The MME approach is strongly recommended in hydrological impact assessments (KUNDZEWICZ et al., 2018). This category is dedicated to the quantity of GCM members used. Studies using a single GCM receive 1 score. Two GCMs obtain 2 scores. From three to nine GCMs, the study counts 3. From ten to nineteen GCMs, 4 scores. From twenty GCMs, the score is 5.

Sophistication of the modelling procedure

The criteria adopted was the version of the GCMs and the level of sophistication, and the quantity of the regionalization methods (REG) and hydrological models (HM). This group was thus divided into five sub-aspects: GCM, RCM, ESD, BC e HM. GCMs belonging to the Coupled Model Intercomparison Project Phase 3 (CMIP3) receive 4 scores, while the last version (i.e., CMIP5) gets 5. GCM versions prior to CMIP3 receive 2 scores. The CMIP3's GCMs show a significant progress from previous versions. The version used in most studies of the Fourth Assessment Report (AR4) of the IPCC embraces the dynamics of important physical components of the climate system. The most relevant advances are: i) improvement of dynamical core; ii) increase of vertical and horizontal resolutions; iii) incorporation of process such as land surface and sea-ice, and iv) improvement of parametrizations (RANDALL; WOOD, 2007). The CMIP5 includes the representation of various biogeochemical cycles

Table 2. Aspects and scores for rating the level of comprehensiveness of the studies.

Aspect	Sub-aspect	Condition	Score
Theoretical foundation		raw GCM	1
		GCM->DCF	2
		GCM->QM	3
		GCM->RCM or GCM->ESD	4
		GCM->RCM->BC or GCM->RCM + GCM->ESD	5
Data Used		1 GCM	1
		2 GCMs	2
		3-9 GCMs	3
		10-19 GCMs	4
		≥20 GCMs	5
Sophistication of the modelling procedure	GCM	Before CMIP3	3
		CMIP3	4
		CMIP5	5
	REG	DCF or DA	1*
		QM	2*
		RCM or ESD	3*
	HM	SEE	2*
		Physically-based models	3*

GCM: General Circulation Model; DCF: Delta Change Factor; DA: Direct approach; QM: Quantile-Mapping; RCM: Regional Climate Model; ESD: Empirical Statistical Downscaling; BC: Bias Correction; CMIP: Coupled Model Intercomparison Project; REG: Regionalization; HM: Hydrological Modelling; SEE: simple empirical estimations. *If more than one model is used, than add 1 score per extra model.

(FLATO; MAROTZKE, 2013) which are key for better representing e.g., the carbon cycle (TAYLOR; STOUFFER; MEEHL, 2012). Although the last version includes more comprehensive models, the enhancement in estimating precipitation over South America is questionable (BLÁZQUEZ; NUÑEZ, 2013; GULIZIA; CAMILLONI, 2015; TORRES; MARENGO, 2014). The difference between both CMIP versions is thus only 1 score.

We did not consider any differentiation among the types of RCM. Any study that adopts one RCM get 3 scores no matter the model. If the study adopted more than one, then 1 score is added per RCM. For instance, studies considering three RCMs get 5 scores (3 + 1 + 1 = 5). The same criterion is valid for ESD, BC e HM. Exceptions are studies considering less sophisticated methods: i) the DCF for BC receives 1 score and, ii) simple empirical estimations (SEE) for HM (i.e., simple water budget, Thornthwaite-Mather and Artificial Neural Network) receives 2 scores, when adopted alone. The final score of the '*sophistication of modelling procedure'* aspect is the arithmetic mean of the scores obtained among the sub-aspects (GCM, RCM, ESD, BC e HM). If the study did not apply any regionalization technique, the respective sub-aspect is not counted in the calculation. In case of an arithmetic mean resulting in a decimal number, the value is rounded to the nearest integer. All data regarding the articles and respective scoring are included as a spreadsheet file in the Supplementary Material (Table S1).

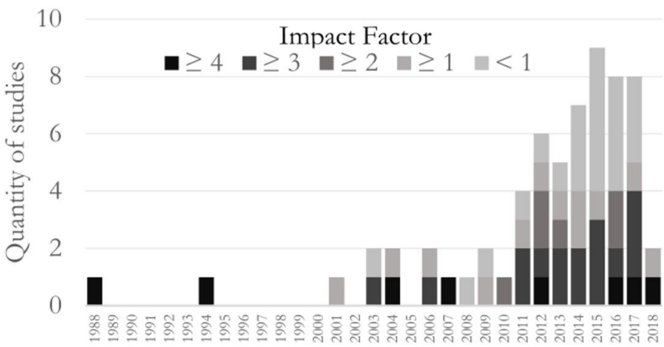

Figure 2. Quantity of articles per year and respective IF.

RESULTS AND DISCUSSION

Quantity and quality of the publications

The first scientific article about the subject in Brazil was published at the end of the 80s by Abramopoulos et al. (1988). At that time, the subject was novel and studies constituted mainly of evaluation of model coupling between land-surface and atmosphere at the global scale, such as Marengo et al. (1994). More than one decade later, Krol et al. (2001) starts the era of regional studies addressing the impact of climate change on water resources in Brazil. Since 2011, substantial increase in the quantity of publications per year is observed (Figure 2). The year of 2015 is the most productive with nine publications. The first articles are associated with high IF (≥ 4) due to the originality at that time. The increasing amount of publications with significant IF (≥ 2) shows the great interest on the subject in the current decade. Surprisingly, in 2018 only two articles were published.

Interest

Hydrographic regions

Figure 3 illustrates the hydrographic regions and respective quantity of studies by sector. It is important to note that in some cases more than one hydrographic region and/or sector is considered

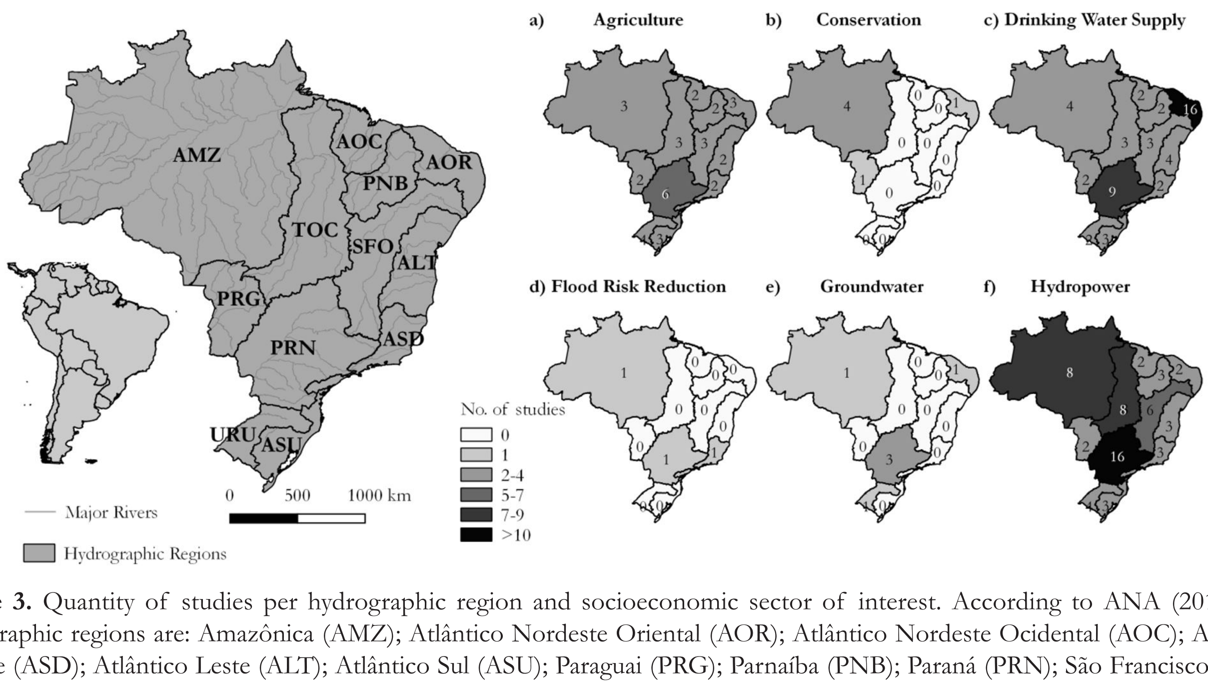

Figure 3. Quantity of studies per hydrographic region and socioeconomic sector of interest. According to ANA (2017), the hydrographic regions are: Amazônica (AMZ); Atlântico Nordeste Oriental (AOR); Atlântico Nordeste Ocidental (AOC); Atlântico Sudeste (ASD); Atlântico Leste (ALT); Atlântico Sul (ASU); Paraguai (PRG); Parnaíba (PNB); Paraná (PRN); São Francisco (SFO); Tocantins-Araguaia (TOC); Uruguai (URU).

in the same study. Most of the papers (i.e., twenty-eight studies) focused on the Paraná (PRN) hydrographic region. The main interest is the hydropower sector (sixteen studies) followed by the drinking water supply (nine studies) and the agriculture (six studies). The PRN region has the greatest economic development of Brazil and is strongly dependent on energy supply from hydropower plants. The growth of urban areas, such as São Paulo, has generated great pressure on water resources and increased water use conflicts. With the highest energy and water demand in the country (BRASIL, 2006a), it is not a surprise that most of the studies addressed the PRN.

The second region of highest interest is the Atlântico Nordeste Oriental (AOR), with eighteen studies. This region includes the Brazilian semi-arid and has the drinking water supply as the sector under highest concern (sixteen studies). The drinking water supply in the semi-arid is strongly dependent on artificial reservoirs, which are highly vulnerable to alterations in the climatic conditions (BRASIL, 2006b)

Worldwide known for its water availability and biodiversity, the Amazônica (AMZ) region tends to be the focus when it comes to climate change (NOBRE et al., 2016). We found fifteen studies about the AMZ. The most relevant sectors in this region are hydropower (eight studies), drinking water supply and conservation (both with four studies). The studies available are in accordance with the current issues in the AMZ region. The largest and most biodiverse tropical rainforest in the world is under great concern. Recent socioeconomic growth in the region has brought about discussions on the traditional development models based on agriculture/pasture expansion and large inundated areas for hydropower production. Understanding the impacts of land cover and climate change on the water availability is crucial to guide proper adaptation strategies (BRASIL, 2006c).

The Tocantins-Araguaia (TOC) has great vocation for irrigated agriculture and hydropower production (BRASIL, 2006d). Ten studies considered the TOC region. The hydropower sector is of interest in eight studies. Agriculture and drinking water supply were addressed in three studies each.

The São Francisco (SFO) is known for the growth of agriculture, the intended revitalization of navigation, the increase in energy demand and the interbasin water transfer projects. The multiple uses of water resources in this region can induce to conflicts among the different sectors (BRASIL, 2006e). Out of the eight studies about the region, six of them addressed hydropower production. Agriculture and drinking water supply were considered in three studies each.

As part of the La Plata basin, the Uruguai (URU) has great importance for the country due to its agroindustry and hydropower potential (BRASIL, 2006f). The number of studies in the region (eight articles) corroborates that, agriculture and hydropower sectors are under concern in four studies each.

The Atlântico Leste (ALT) is characterized by high population density. Economic activities are mainly related to petrol-chemical industry, tourism and sugarcane and cacao production (BRASIL, 2006g). Five studies were found. The drinking water supply sector is under concern in four of them.

The Atlântico Sul (ASU) is notable for its significant population contingent, for economic development and for its importance for tourism (BRASIL, 2006h). We found five studies in the region. Agriculture and drinking water supply were addressed in three studies each.

The Paraguai (PRG) includes one of the largest wetlands on the planet, the Pantanal. Conservation of biodiversity is under high concern in the region, especially due to the recent expansion of pasture and agriculture (BRASIL, 2006i). Four studies addressed the PRG region. The sectors of interest are agriculture and drinking water supply (three studies each). Conservation was considered in one study.

Even with the high population and economic importance, the Atlântico Sudeste (ASD) presented only four studies. The region has serious problems with water supply (BRASIL, 2006j). Two articles regarded the water supply sector. Also known for flood-related disasters (CEPED UFSC, 2013), one study tackled the flood risk reduction sector in the region.

The main issues in the Parnaíba (PNB) are droughts, urban water supply, irrigation and conflicts of use (BRASIL, 2006k). The region was contemplated in three studies, wherein the agriculture and drinking water supply sectors were addressed in two studies each.

The Atlântico Nordeste Ocidental (AOC), where water criticality and deforestation are the main issues (BRASIL, 2006l), was contemplated in two studies only. The agriculture and drinking water supply sectors were addressed in two studies each.

Socioeconomic Sectors

One of the main economic activities of Brazil, the agriculture was addressed in thirteen studies (Figure 3a). The agriculture sector is responsible for most of the water use in the country and there is a great potential for expansion through irrigation (ANA, 2013). Despite the territorial extension and favorable physical factors, alterations on climatic conditions can significantly affect the water availability for this sector.

The conservation sector was considered in six studies (Figure 3b). Understanding the impacts of vegetation replacement on the water cycle is crucial to establish best practices for land and water conservation (STERLING; DUCHARNE; POLCHER, 2012). Land use and cover change (LUCC) directly affects the water availability and quality of river basins. Runoff changes are often attributed to LUCC rather than rainfall variability (CHAGAS; CHAFFE, 2018). Besides the direct influence on the water cycle, climate determines natural land cover as well (SALAZAR; NOBRE; OYAMA, 2007). Assessing the vulnerability of water resources to non-climatic drivers, such as LUCC, and related feedback effects with regional climate is crucial to determine effective adaptation strategies (JIMÉNEZ CISNEROS et al., 2014).

The drinking water supply sector is of the highest interest (twenty-seven studies, Figure 3c). Issues on water supply in Brazil are mainly related to the quantity in the semi-arid region and quality in urban areas. Recent climatic conditions have significantly affected the water supply in metropolitan regions such as São Paulo and Rio de Janeiro (ANA, 2014). Although COELHO et al., (2016) attributed recent rainfall deficits to natural climate variability, the impacts of anthropogenic-induced climate change is still little known.

Floods are under high concern worldwide (IPCC, 2012). In the last two decades, nearly 9 thousand disasters related to extreme hydrological events were registered in Brazil. Direct and indirect damages were estimated in R$72 billion (~US$22 billion, CEPED UFSC; WORLD BANK, 2016). Despite the great importance in terms of socioeconomic impacts, the flood risk reduction sector - in the context of climate change - was addressed in three studies only (Figure 3d).

The groundwater sector is of great importance in Brazil. According to (ANA, 2010), 39% of the municipalities depend exclusively on this water resource. Groundwater can be strategic in terms of adaptation to surface water scarcity, therefore understanding its vulnerability to climate change is crucial (JIMÉNEZ CISNEROS et al., 2014). There were only six studies that considered the impacts of climate change on the groundwater (Figure 3e).

The hydropower sector was the main focus of twenty-nine studies (Figure 3f). Hydroelectricity is approximately 61% of the total installed capacity in the country (ANEEL, 2017). The recent water crisis has raised the concern about the impacts of climate change in the Brazilian hydropower sector (ANA, 2014). The operation of all power plants in the country is centralized in the National System Operator (Operador Nacional do Sistema - ONS). The distinct climatic regions across the country and conflicts among multiple-uses represents an enormous challenge for the establishment of robust operational plans under climate change (SILVEIRA; SOUZA FILHO; VASCONCELOS JÚNIOR, 2017)

Purpose

Forty-eight articles focused on the application of models to assess the impacts of climate change (Figure 4). The evaluation of methods was the main focus in eleven studies, whereas four aimed at model development. The disparity of purpose is consistent with the scientific context. In general, most scientific studies tend to address the application of consolidated methods in different locations and/or circumstances. The evaluation of methods is primordial for the development of robust and consistent impact studies (FLATO; MAROTZKE, 2013), but requires more refined investigations. The low number of studies focusing on model development is likely associated with technical and financial limitations. Those model development studies are usually more sophisticated, requiring highly qualified human resources and appropriate infrastructure, e.g., a supercomputer (SHUKLA et al., 2010).

Approach applied by the studies

Climate modelling

The MME approach is under limited application in Brazil. Nearly half of the studies (twenty-nine) considered a single GCM (Figure 5). Twelve articles made use of the outputs from 2 GCMs, ten studies considered from 3 to 9 GCMs and four studies adopted from 10 to 19 GCMs. The use of nearly all GCMs available (more than 20) were found in nine studies. The use of several GCM outputs combined with regionalization techniques requires specialized human resources and, in the case of RCMs, a considerable computational infrastructure (WILBY et al., 2009). The higher the quantity of GCMs used, the lower the amount of studies applying RCMs. For large sets of GCM, the most applied techniques are the ESD and the BC. Additionally, RCMs are prone to systematic biases and BC is often applied (CHRISTENSEN et al., 2008). In the case of Brazil, this approach was considered in fifteen studies.

The higher the variety of regionalization techniques, the more robust the study. Multiple regionalization methods (GCM+RCM+ESD and GCM+RCM+BC+ESD) were found in two studies, but their limitation comes from the low number of GCM outputs used.

The results suggest limitations in the acquisition of GCM data as well as in the access to computational infrastructure to run sophisticated models. We recognize that the acquisition of large amounts of GCM data is not a trivial task. It requires specialized technical support and considerable computational resources. In addition, we noticed gaps in the communication of scientific information. The definition of regionalization techniques is often inaccurate. We also detected differences in the terminology used by climatologists and hydrologists.

We found that different types of climate model products were applied (Figure 6). The CMIP3 GCMs were first launched in 2005 (MEEHL et al., 2007), but the first application in Brazil is dated from 2008. The increase in the use of CMIP3 was observed only from 2011. The use of the fifth version (CMIP5) was first published three years after its launching in 2012. Since 2015, there has been a replacement of the previous version to the newest

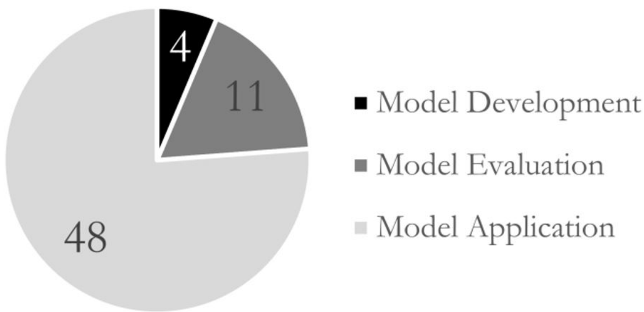

Figure 4. Quantity of studies by purpose.

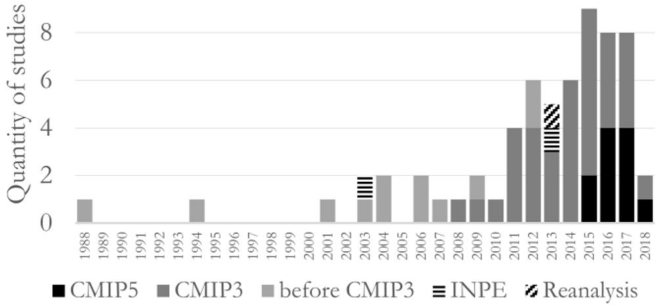

Figure 5. Quantity of articles by amount of GCMs and regionalization techniques applied. All studies are included.

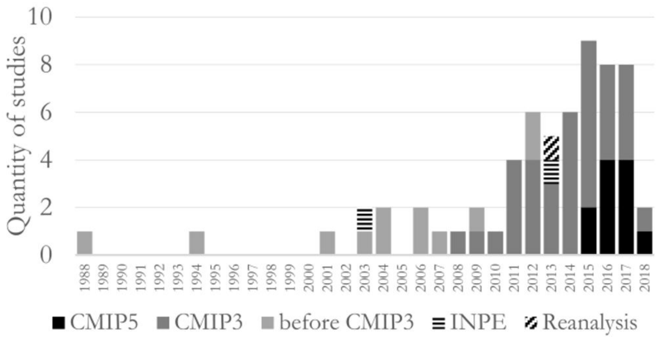

Figure 6. Quantity of articles by climate model products per year. All studies are included.

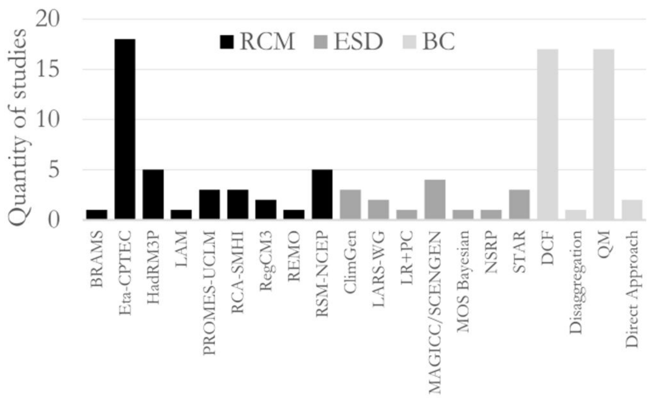

Figure 7. Quantity of studies by regionalization models and techniques. All studies are included.

one. Some studies considered a Brazilian model developed by the Instituto Nacional de Pesquisas Espaciais (INPE) and the NCEP Reanalysis, but their aim was for model evaluation purposes, not for model application in impact assessments.

Typology of regionalization techniques

Figure 7 shows that the most applied RCM was the Eta-CPTEC (CHOU et al., 2012). Its popularity is attributed to the successful collaboration of the Centro de Previsão do Tempo e Estudos Climáticos (CPTEC/INPE) with other research groups. Seven out of eighteen studies included CPTEC researchers as co-authors. The HadRM3P (MARENGO et al., 2009) and RSM-NCEP (JUANG; KANAMITSU, 1994) were applied in five studies each. The HadRM3P together with PROMES-UCLM (CASTRO; FERNÁNDEZ; GAERTNER, 1993), RCA-SMHI (SAMUELSSON et al., 2011) and RegCM3 (GIORGI; MARINUCCI; BATES, 1993), are part of the Coordinated Regional Climate Downscaling Experiment (CORDEX, JACOB et al., 2007). The initiative aims to provide outputs of downscaling models for impact studies at the regional scale. However, it is not clear whether the application of RCMs is associated with the CORDEX South America's efforts.

In terms of ESD, the most adopted method was the Model for the Assessment of Greenhouse-Gas Induced Climate Change/Scenario Generator (MAGICC/SCENGEN; WIGLEY, 2008). The projections of global-mean temperature produced by the MAGICC drives the regional climate change scenario generator SCENGEN. This pattern scaling method appears in IPCC reports since 1990 (JEGANATHAN; ANDIMUTHU, 2013) and was applied in four studies in Brazil. The ClimGen (TODD et al., 2011), also a pattern scaling technique, was considered in three studies. Intended for impact assessments in the agriculture, ClimGen was used in Brazil for hydropower, drinking water supply and conservation purposes. The STatistical Analogue Resampling Scheme (STARS, WERNER; GERSTENGARBE, 1997) was applied in three studies as well.

The most applied BC techniques were the DCF and the QM, both in seventeen studies. The DCF is widely applied in hydrological impact assessments (JIMÉNEZ CISNEROS et al., 2014). The method can rapidly provide a broad set of bias adjusted projections, but its simplicity implies to critical limitations, e.g., changes in temporal variability are neglected (FOWLER; BLENKINSOP; TEBALDI, 2007). The QM is more sophisticated and has demonstrated a considerable added value in providing corrected projections. When the aim is to adjust the statistical distribution of the data, that is the recommended method. However, the tail of the distribution is often distorted by QM and extreme events can be misrepresented (MARAUN et al., 2010). Additionally, QM does not directly consider time-dependent statistics such as consecutive dry days (ADDOR; SEIBERT, 2014). The majority of the studies in Brazil using QM are not related to extreme events or time-dependent indices, showing a coherence in the application of the technique. It is important to highlight that most studies used a distinct definition for QM (i.e., 'transformation of the frequency distribution', 'percentile-to-percentile', 'correction of probability density function', 'correction of probability density function', 'adjustment of cumulative distribution functions' and 'probability mapping').

Hydrological Modelling

The Instituto de Pesquisas Hidráulicas (IPH) is the institution in Brazil leading the topic of modelling in water resources. Figure 8 shoes that the Modelo de Grandes Bacias (MGB-IPH, COLLISCHONN et al., 2007) was the most applied hydrological model (ten studies). The Soil Moisture Accounting Procedure (SMAP, LOPES; BRAGA JUNIOR; CONEJO, 1981) was applied in nine studies and the very popular Soil and Water Assessment Tool (SWAT, SANTHI et al., 2006) was used in seven studies. Three studies made use of the Modelo Hidrológico Distribuído (MHD-INPE, TOMASELLA et al., 2011). Many other models were applied in one or two studies. It is important to highlight the efforts of Pereira, Moraes and Uvo (2014), who implemented a two-way coupling, or inline hydrological-atmospheric system, for regional scale modelling. In this case, the Brazilian Regional Atmospheric Modeling System (BRAMS, FREITAS et al., 2009) was coupled to the MGB-IPH. Most studies adopt offline modelling approaches, even though feedback effects can play a substantial role. The coupled regional modelling is physically more consistent than the offline version, but it demands enormous computational capacity and technical knowledge. In addition, crucial aspects leave

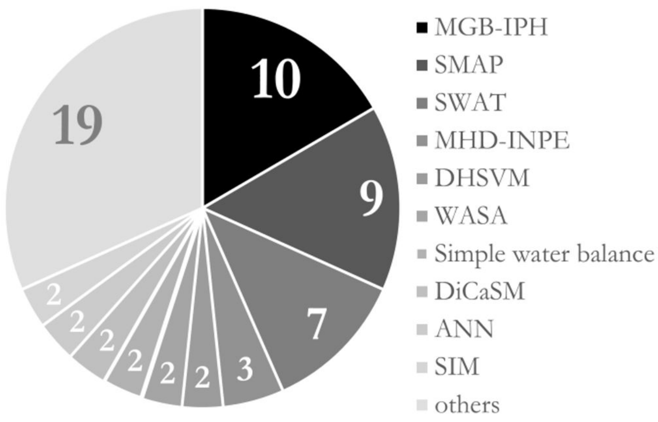

Figure 8. Type of hydrological models used. All studies are included.

room for improvement, especially regarding the parameterization schemes. These models are in development phase rather than being applied in impact assessments. Robust and reliable estimates are still unlikely to be obtained (BUTTS et al., 2014). Therefore, the study of PEREIRA; MORAES; UVO (2014) deserves merit by pioneering the development of a two-way coupling approach in Brazil.

Studies addressing 'model evaluation'

Several studies demonstrated that RCMs significantly improve rainfall estimates (ALVES; CAMPOS; SERVAIN, 2012; BLOCK et al., 2009; BRAGA et al., 2013; KRUK; VENDRAME; CHOU, 2013; KWON et al., 2012; LIMA; ALVES, 2009; OLIVEIRA; PEDROLLO; CASTRO, 2015a, 2015b; PEREIRA; MORAES; UVO, 2014). That's also valid when RCM is coupled inline with a hydrological model (PEREIRA; MORAES; UVO, 2014). The added value of ESDs was confirmed by Coelho et al. (2006) and Block et al., (2009), who used Bayesian Approach and Linear Regression with Principal Components respectively. The QM is very useful for adjusting the statistical distribution of the data (ALVES; CAMPOS; SERVAIN, 2012; LIMA; ALVES, 2009; TUCCI et al., 2003), while the DCF is questionable. When combined with RCM outputs, Braga et al. (2013) and Oliveira, Pedrollo and Castro (2015a) demonstrated advantages in applying DCF for monthly scale. On the other hand, when intended for high resolution studies, Kruk, Vendrame and Chou (2013) concluded that the technique is useless. Oliveira, Pedrollo and Castro (2015a) shows no evidence of the superiority of one bias correction technique over the others.

Some authors (BRAGA et al., 2013; TUCCI et al., 2003) suggest that the information extracted from GCMs without regionalization may be useful for impact assessments. The superiority of the MME approach is unquestionable. Block et al. (2009) demonstrated the benefits of MME, not only in the quantification of uncertainties, but also in error compensation. Another important aspect is the propagation of uncertainties along the modelling chain. Block et al. (2009) states that uncertainty analysis *"remains a formidable challenge"*. The uncertainties associated with climate modelling and regionalization are usually thought to be greater than that of hydrological modelling (KWON et al., 2012). Block et al. (2009) highlight the application of weighting methods to generate probabilistic estimates of GCM outputs. Kwon et al. (2012) and Tucci et al. (2003) emphasize the need for a super-ensemble approach in order to quantify the uncertainties related to the structure of all model types in the modelling chain.

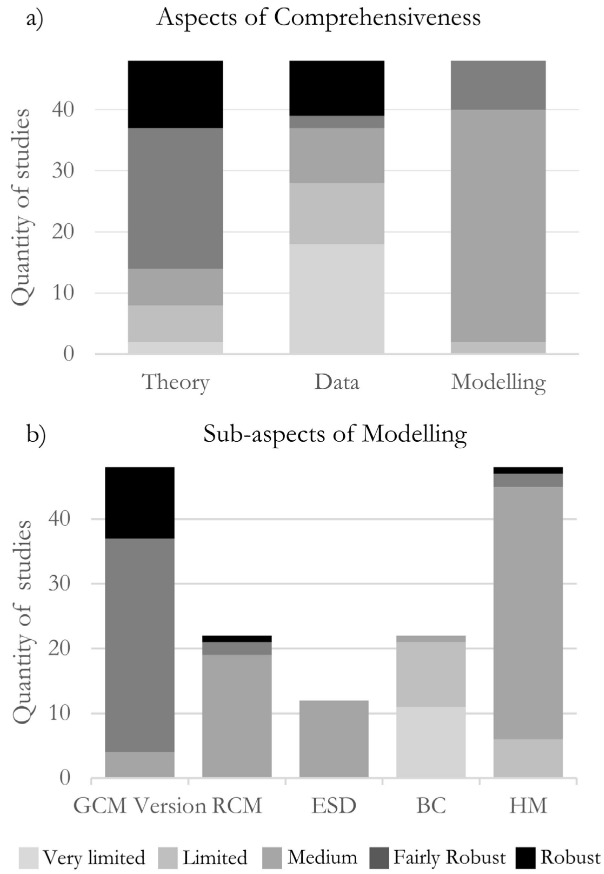

Figure 9. Classification of: a) aspects of comprehensiveness and b) the sub-aspects of modelling. Only 'model application' studies are included.

Studies addressing 'model application'

Studies addressing 'model application' in the context of impacts assessments were evaluated considering their level of comprehensiveness (see section 'Level of comprehensiveness of the studies'). Under this framework, the theoretical foundation is usually *fairly robust* or *robust*, with thirty-four studies adopting the regionalization procedure consistent with the state-of-the-art (Figure 9a). Drawbacks are clear when comes to data. More than a half of the articles (twenty-seven studies) adopted up to two GCMs. Only eleven studies made use of a considerable quantity of GCM outputs ($\geq$ 10 members). In terms of modelling, the great majority of the studies (thirty-eight articles) are at *medium* level of comprehensiveness; whereas two studies are classified as *limited*. The GCM versions used in the studies are consistent with the available datasets. Thirty-three studies used outputs from the CMIP3 database and eleven studies applied the last version (Figure 9b). Concerning the RCM, ESD and HM, the majority of the studies used models that are consistent with the recommendations of the scientific community. Eight studies are classified as *fairly robust* in terms of modelling procedure, mainly due to the application of more than one model in the regionalization and/or hydrologic modelling procedure. In terms of BC, eleven documents are considered *very limited* due to the application of DCF, a technique which is under low reliability (MARAUN; WIDMANN, 2018). Ten studies are *limited* due the application of QM and one study is at *medium* level due to the application of two BC methods combined. The aspects of comprehensiveness reveal important scientific issues in dealing with the impacts of climate change on the Brazilian water resources. Although strongly recommended, the MME approach is under limited application.

CONCLUSIONS

With 63 scientific articles, we identified that great attention was given to the integration of climate models into hydrological models in Brazil in this decade. The majority of the studies are about the Paraná hydrographic region and focus on hydropower and drinking water supply sectors. The second region of greatest interest is the Atlântico Nordeste Oriental, which has the drinking water supply as the most relevant sector. Despite the high population density and economic importance, the Atlântico Sudeste region is under represented.

The hydropower sector is of highest interest. Nearly two thirds of the electricity production in the country depends on the water resources. Including information about the potential impacts of climate change represents an enormous challenge for the establishment of robust operational plans and resilient designs. The second sector under highest interest is the drinking water supply. Issues are mainly related to the quantity of water in the semi-arid region and in urban areas. Despite the great socioeconomic relevance, the flood risk reduction was addressed in very few studies.

The theoretical basis and the modelling procedure adopted in the studies are usually consistent with the state-of-the-art. Drawbacks are clear when it comes to the application of a large ensemble of GCMs. A realistic reason for that is the lack of technical capacity and limited access to computational infrastructure to assimilate and postprocess GCM data. There is also a demand to equalize the understanding of the concepts and terms used among climatologists, hydrologists and stakeholders. General lexicon and guidelines are recommended to match the understanding of the concepts and the terms used in the integration of climate models into hydrological models.

The comprehensiveness of studies can be improved by adding more models and, perhaps, using more sophisticated BC techniques. However, we strongly recommend that the modelling procedure adopted should be user-tailored. In other words, the evaluation and the application of models should be based on the needs of the end-users and process-informed rather than looking for e.g., the highest resolution (MARAUN et al., 2017). The evaluation of the degree of comprehensiveness proved to be a valuable analysis to guide actions to improve the subject in Brazil. We suggest to increase accessibility to GCM databases and enhance capacity on postprocessing of data. One way to bridge this gap is to build capacity across research institutions and universities. Given the challenges that Brazilian science is facing, we recommend the synchronization of efforts among research institutions. Research should prioritize regions and sectors according to e.g., their level of vulnerability and observed ongoing changes. That represents an outstanding opportunity for initiatives such as the Brazilian Network on Global Climate Change Research (Rede Clima) and, consequently, for a more effective use of climate change impacts information by decision-makers in Brazil.

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SUPPLEMENTARY MATERIAL

Supplementary material accompanies this paper.
Table S1. Articles list database.
This material is available as part of the online article from http://www.scielo.br/rbrh.

Author contributions

Pablo Borges de Amorim: Article's search and gathering, selection of articles, conceptualization of the approach, translation of the article's information to the matrix, analysis, preparation of the figures, discussion and manuscript preparation.

Pedro Luiz Borges Chaffe: Article's search and gathering, selection of articles, conceptualization of the approach, double-check of the matrix, discussion and revision of the manuscript