UNIVERSIDADE FEDERAL DE LAVRAS

VINICIUS OLIVEIRA SILVA

EVALUATING AND PROJECTING EXTREME METEOROLOGICAL DROUGHTS OVER TWO BRAZILIAN REGIONS: THE BRAZILIAN PANTANAL AND SOUTHERN MINAS GERAIS

LAVRAS – MG
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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Recursos Hídricos, área de concentração em Hidrologia, para a obtenção do título de Doutor.

Carlos Rogério de Mello
Orientador

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EVALUATING AND PROJECTING EXTREME METEOROLOGICAL DROUGHTS OVER TWO BRAZILIAN REGIONS: THE BRAZILIAN PANTANAL AND SOUTHERN MINAS GERAIS

AVALIAÇÃO E PROJEÇÃO DE SECAS METEOROLÓGICAS SEVERAS SOBRE DUAS REGIÕES DO BRASIL: O PANTANAL E O SUL DE MINAS GERAIS

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Recursos Hídricos, área de concentração em Hidrologia, para a obtenção do título de Doutor.

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RESUMO

O Brasil possui as maiores reservas de água doce do mundo. No entanto, este importante recurso natural está ameaçado pelo aumento da demanda por água e pela degradação de sua qualidade, principalmente como resultado de pressões antrópicas e mudanças climáticas. Como resultado dessas pressões, desastres naturais, como secas, estão se tornando mais comuns. Nos últimos anos, as secas afetaram diversas regiões do Brasil, impactando segurança energética, produção de alimentos e fornecimento de água. Neste estudo, a severidade das secas que atingiram duas importantes regiões do Brasil, Sul de Minas Gerais e o Pantanal brasileiro foram analisadas e projetadas até o final do século XXI. A primeira é conhecida pela produção de cafés de alta qualidade, exportada para o mundo, sendo uma das principais commodities do país e pela geração e potencial hidrelétrica. A segunda, consiste de um dos maiores biomas alagados do mundo e lar de espécies animais e plantas únicos. Para acessar a severidade das secas, o Índice de Precipitação Padronizado e o Índice Padronizado de Precipitação-Evapotranspiração considerando os anos hidrológicos (SPI12 e SPEI12) foram investigados no tempo e no espaço. Dois conjuntos de dados diferentes foram considerados como dados observados neste estudo: dados da Agência Nacional de Águas e Saneamento (ANA) e do Climate Research Unit (CRU). Além disso, secas severas foram projetadas até 2098/2099 usando dados de dois Modelos Regionais Climáticos (RCM), do projeto Eta (BESM, CanESM2, HadGEM2-ES e Eta-MIROC5) e do projeto CORDEX (CSIRO, IPSL-CM5A, GDFL, NorEMS1) sob dois Cenários de Concentrações (RCP), RCP4.5 e RCP8.5. O ano hidrológico 2013/2014 foi o mais seco já registrado no Sul de Minas Gerais. As projeções mostraram que esse evento pode ocorrer novamente no futuro, com vários eventos consecutivos possivelmente acontecendo com mais frequência. No Pantanal, em 80 anos de dados observados, o ano hidrológico de 2019/2020 foi o mais seco observado, sendo a década de 1960 a mais seca. As projeções do SPI mostraram resultados diferentes, com o CORDEX projetando secas extremas até 2040, e os modelos Eta não projetando eventos extremos. As projeções do SPEI, por outro lado, mostraram eventos extremos de seca no final do século XXI, tanto para Eta quanto para CORDEX. Os dados observados e as projeções fornecem informações que ajudarão os tomadores de decisão e os legisladores na detecção de anomalias de seca em curto prazo e para análises de longo prazo, ajudando a reduzir os impactos de secas severas.

Palavras Chaves: Índices de Seca, SPEI, SPI, Áreas alagadas, Minas Gerais

ABSTRACT

Brazil contains the largest volume of freshwater of any country in the world. However, this important natural resource is threatened by increases in water demand and water quality degradation, mainly as a result of anthropogenic pressures. As a result of this pressures, natural hazards, such as droughts are probably becoming more common in the future. In recent years, droughts have affected different regions of Brazil, impacting energy security, food production, and water consumption. In this study, the severity of droughts that hit two strategic regions of Brazil, Southern Minas Gerais and the Brazilian Pantanal were analyzed and were projected up to the end of the XXI century. The first, is well-known by its coffee crop production (more than 30% of country's production) and hydroelectricity generation. The second, it is one of the largest wetland in the world and home for species and unique animals and plants. To access the severity of the droughts, the Standardized Precipitation Index and the Standardized Precipitation Evapotranspiration considering the hydrological years (SPI12) were investigated over time and space. Two different datasets were considered as observaded data in this study: data from the National Water and Sanitation Agency (ANA) and from the Climate Research Unit (CRU). Also, severe droughts were projected up to 2098/2099 using two RCM ensembles, from Eta project (BESM, CanESM2, HadGEM2-ES and Eta-MIROC5) and CORDEX project (CSIRO, IPSL-CM5A, GDFL, NorEMS1) under two Representative Concentration Pathways, RCP4.5 and RCP8.5. The 2013/2014 hydrological year was the driest ever recorded in South of Minas Gerais. Projections have shown that this event might occur again in the future, with several consectuve events possibly happening more often. In Pantanal, in 80 years of observed data, the hydrological year of 2019/2020 was the driest observed in Pantanal, with 1960s decade been the worst. SPI projections have shown different results, with CORDEX projecting extreme droughts until 2040, and Eta models not showing extreme events. SPEI projections, otherwise, have shown extrem drought events in the end of the XXI century, for both, Eta and CORDEX. Observed data and projections give information that will help decision makers and stock holders in the detection of drought anomalies in short terms and for long term analyses.

Keywords: Drought Index, SPEI, SPI, Wetland, Minas Gerais

SUMÁRIO

1 INTRODUCTION

Among all natural hazards, drought is arguably one of the most complex and least-understood of all. The necessity of long-term spatiotemporal monitoring across different locations made it sometimes difficult to be diagnosed, modeled, or projected. Drought can typically be divided into meteorological (negative anomaly of precipitation), agricultural (soil moisture deficiency), hydrological (negative anomaly of runoff and/or groundwater), socioeconomic (social response to water supply and demand), and environmental or ecologic. Droughts are natural phenomena that can affect water availability and water demand, agriculture, human supply, hydroelectricity, and tourism, among other economic activities.

The frequency of extreme weather and climate events, such as floods and severe droughts, has increased in the last decade, with events showing greater intensity and duration. Every year, billions of dollars are spent to mitigate impacts on agriculture, energy production, or water demand. From 2010 to 2020, several drought events are being observed in Brazil. The drought of 2014-2015 in Southeast Brazil, with an emphasis in Sao Paulo, was driven to water restrictions across the metropolitan region of Sao Paulo. In Minas Gerais, in the same event, the Furnas reservoir produced less than 20% of its full capacity. It is also important to highlight the 2011-2012 exceptional drought in Northeast Brazil, the 2014-2015 event over the North of Brazil, and the 2019-2020 exceptional drought event over the Pantanal region.

One of the most difficult challenges in the study of drought is the acquisition of long and good quality datasets. The World Meteorological Organization (WMO) recommends that drought studies should be conducted with at least 30 years of data. In some regions of Brazil, such as the North of Brazil and Pantanal, meteorological and climatological data are very scarce, making it difficult to analyze spatiotemporal drought variability. Finding new approaches for this situation is important and fundamental to conduct drought studies in Brazil. In this context, products like the Climate Research Unit and the ERA-Interim are useful.

Climate influences where the population lives, its growth, and well-being. On this planet, each species of plant and animal has adapted to live and prosper with a climatic niche. Since the last century, water supply is threatened by increasing population growth and climate change. Also, the population of the world has increased more than three times, with the use of nonrenewable energy increasing by more than 30 times. The increase of greenhouse gas emissions is intensifying the temperature of the world, with impacts that are still being studied.

One of the solutions found by scientists to understand the climate changes is the development of Global Climate Models (GCMs). These models simulate the climate using complex numerical simulations of equations of the chemical, physical and biological of the atmosphere to estimate how the greenhouse gas emission may influence the climate of the planet. However, in specific locations, the resolution offered by GCMs are rough and not indicated. The advance in technology allows scientists to develop Regional Climate Models (RCMs), increasing resolutions from ~300 km to 20 km.

In this sense, this thesis aims to advance the knowledge of droughts and their impacts in two different strategic regions of Brazil: a) South of Minas Gerais, one of the main regions of hydroelectricity production for Brazil; b) Pantanal, one of the largest wetlands in the world. The first study was carried out with observed data from the National Water and Sanitation Agency (ANA) and precipitation data downscaled by the Eta model from the National Institute for Space Research (CPTEC/INPE) under two scenarios of the Representative Concentration Pathways, RCP 4.5 and RCP 8.5. The second study was carried out with data from the Center Research Unit and with precipitation and temperature downscaled from by Swedish Meteorological and Hydrological Institute (SMHI) for Atmospheric Regional Climate Model and acquired from the CORDEX project, and by Eta model from the National Institute for Space Research (CPTEC/ INPE) under two scenarios of the Representative Concentration Pathways, RCP 4.5 and RCP 8.5.

2 THEORETICAL FRAMEWORK

2.1 Study Areas

2.1.1 South Of Minas Gerais

Southern Minas Gerais state is located in southeast Brazil. It falls within the latitudes 20° and 23° S and longitudes 44° and 48° W. According to the Brazilian Institute of Geography and Statistics (IBGE; 2019), South of Minas Gerais has an estimated Nominal Gross Domestic Product

(GDP) of US$ 12,684 million dollars, a population of 2,311,547, a GDP per Capita of US$ 5,487 and 142 municipalities

It is an important economic region due to the coffee crop (Coffee arabica) production, and its hydroelectricity potential. In corresponded 2019, the region produced 19,152.2 sacks, which corresponds to over 30% of the total Brazilian production (CONAB 2021). Climate influences directly the coffee production, and it is the major factor in the crop's productive performance and its drinkability (RODRIGUES et al., 2014). Thus, the increase in temperature and the deficits in the water budget may lead to extreme droughts and can potentially affect coffee cultivated areas in southern Minas Gerais (ASSAD et al., 2004).

In addition, the region has significant importance to the Brazilian National Electric System, with the existence of several small hydropower plants and four plants of high power installed capacity. Among such plants, the Furnas Hydropower Plant is the largest reservoir in southeastern Brazil, with an installed capacity of 1216 MW (BUENO et al., 2020).

2.1.2 Pantanal

The Brazilian Pantanal region is one of the largest tropical wetlands in the world with approximately 150 thousands Km². It is located in the center of South America, in western Brazil's Upper Paraguay River Basin (UPRB). Most of its territory is concentered in the Brazilian state of Mato Grosso do Sul, extending towards to the state of Mato Grosso. As a wetland ecosystem, Pantanal is the shelter of thousands of species that are adapted to the shifts between wet and dry season, annually. For its complexity and specificity, a great number of animal and plants can survive with almost no competition (ALHO et al., 2012). Also, the presence of many environments such as open water, ground, perennial and floating vegetation make the Pantanal a unique biome in Brazil and in the world (POTT et al., 2011a).

2.1.2.1 Hydrological Regime

The rainfall patterns in the Upper Paraguay River Basin, where the Pantanal is inserted, is modulated for the South America Summer Monsoon (MARENGO et al, 2011). Trade winds combined with the vapor flux from the equatorial Atlantic Ocean are the main sources to the Amazon Rivers which play an important role as moisture source to the central and southern regions of Brazil (BERGIER et al 2018). Annual average precipitation in Pantanal is 1300 mm, and its rainfall is highly seasonal, occurring, mainly, between October and March. Annual rainfall is less than the potential evaporation and drainage is very slow because of shallow gradients (TUCCI et al., 1999)

The hydrological regime in Pantanal is not only regulated by its rainfall, but also for the rain in the headwaters where the Paraguay river, the main water channel of the Pantanal, slowly conducts water from inside the Pantanal borders (JUNK et al., 2013). Pantanal presents very low and flat relief, with a complex drainage system (PAZ et al., 2011b). This flat morphology of the biome and the slope of the Paraguay river are important for the seasonal lateral inundation (Lazaro et al., 2020).

2.1.2.2 Pantanal Flora

The Pantanal flora is constituting of nearly 2000 species, whereas at least 280 species are aquatic macrophytes (POTT et al., 2011a). The annual cycle of rainfall has a straight impact in the Pantanal Flora. Aquatic plants, for example, respond well to the flood dynamics. Wetland plants have adapted to the water-level season fluctuation, which result in stable or climax communities with shifts in species dominance (CATIAN et al., 2018).

2.1.2.3 Pantanal Fauna

As a wetland system, the Pantanal ecosystem is characterized between the shifts of water and land. This change in the habitats make the Pantanal unique and with high specificity. The Pantanal seasonality in produce food and other resources is unique , and a great number of animals can thrive with no competition (ALHO et al., 2012). Different works have registered the number of mammals in Pantanal. According to Alho et al. (2011), the richness of mammals can be estimated to 174 species.

2.1.2.4 Wetlands And Climate Change

Wetlands cover approximately 6% of planet Earth’s surface. They have an important role in biogeochemical cycles, such as the nitrogen and carbon, and in hydrological cycle. They are also a large part of the world’s biodiversity, and provide multiple services to humankind (JUNK et al, 2013).

Due to its specificity, wetlands are vulnerable to major climate changes. Altering the rainfall patterns and the impacts of rising temperatures can lead to change in its biogeochemistry cycle and to their main functions, leading to direct impacts on its important services (SALIMI et al., 2021). Wetlands are critical environments that provide services earning in billions of dollars (IVORY et al., 2019). From fish production, fruits, and grains, to storage and retention of water, to regulation of greenhouse gases, temperature and precipitation, to groundwater recharge, the wetlands play a significant role in South America (DE GROOT et al., 2006). Only in United States, wetlands have saved $625 Million in direct flood damages during Hurricane Sandy (NARAYAN et al., 2017).

In recent years wetlands have been suffering damages and losses due to their rapid urbanization and agriculture. In China, in the last 20 years, 2,883 Km^2 of wetlands were lost to urban expansion (MAO et al., 2018), while Europe has lost 45% of its wetland (HU et al., 2017). In Ethiopy, where 2% (22,600 Km^2) of the territory is formed of wetlands, wetlands are being lost or altered by unregulated over utilization, which includes agricultural intensification, dam constructions, food shortages and increased drainage and cultivation (BEZABIH; MOSISSA, 2017). According to Hu et al. (2017), by 2017, the world had lost 33% of its wetland in area, including 4.58 million Km^2 of flooded area and 2.64 million Km^2 of water.

2.2 Drought

Drought is a complex phenomenon that impacts natural and urbanized environments and socioeconomic systems in the world (PENG et al., 2020). Generally, is defined as a temporal anomaly from the mean climate for a certain region and represents the lack of water resulting from below-average precipitation, high temperature, or both (CLARK et al., 2016). Drought can typically be divided into meteorological (negative anomaly of precipitation), agricultural (soil moisture deficiency), hydrological (negative anomaly of runoff and/or groundwater), socioeconomic (social response to water supply and demand), and environmental or ecologic (PENG et al., 2020, AGHAKOUCHAK et al., 2015).

Meteorological Drought received its name because of meteorological variables, usually precipitation and temperature (SPINONI et al., 2019). This way, meteorological drought can be defined as a lack of rainfall persisted for a long time (KEYANTASH; DRACUP, 2002), being escalated by high temperatures and, consequently, high evapotranspiration rates (VICENT-SERRANO et al., 2010).

Drought impacts are related to water availability for crop, livestock production, water supply, hydroelectricity, tourism, and industry. Droughts are difficult to be identified and quantified over space and time. Currently, it has caused one of the most significant environmental and economic problems in many countries around the world (VICENTE-SERRANO et al. 2018). Climate variability in a region, whether caused by natural or by anthropogenic forcings, can lead to changes in the climate patterns, and can result in the increase of the frequency of extreme events, such as droughts.

2.2.1 Drought Impacts

Extreme weather has caused losses of billions of dollars every year. Data from the Center for Climate and Energy Solutions (2021) show that since 2000, 132 billions of dollars were lost due to droughts in the USA. Worldwide, the Food and Agriculture Organization (FAO) of the United Nations has reported that drought losses leaded an average USD 170 billion over the past decade, with a peak in 2011 and 2017, when losses reached over USD 300 billion (FAO, 2021). Between 1970 and 2012, in the African continent, 680,000 deaths were caused by droughts and heat waves (WMO, 2014).

In Brazil, some drought years deserve highlights: (i) during the hydrological year of 2000/2001, the water crisis especially in Southeast Brazil collapsed the Brazilian hydroelectricity production (CAVALCANTI; KOUSKY, 2001); (ii) in 2005, the reduction of 16% of the Amazon River runoff along with the increase of 100% of wildfires (ZENG et al., 2005) were observed (MARENGO et al. 2011); (iii) between 2013 and 2015, the worst drought ever observed in Southeast Brazil (COELHO et al., 2016a, b). The latest event caused several losses in Southeast Brazil, with the longest shortage of water supply in the São Paulo metropolitan region; in Belo Horizonte and in Campinas metropolitan regions; the lowest level in the hydropower plants reservoirs in southern Minas Gerais, which put at risk the hydroelectricity generation for the entire Southeast Brazil. The main meteorological causes were the increase of the sea surface temperature (SST) in the Southeastern Brazilian coast, the strong high air pressure values acting in lower levels of the atmosphere, and the subsiding air that prevented the deep rainy cloud formation over Southeast Brazil (COELHO et al., 2016 a, b; MARENGO et al., 2015).

2.2.2 Drought Index

The occurrence and magnitude of the droughts have been evaluated using indexes (WMO, 2014). The Standard Precipitation Index (SPI) and the China-Z Index (CZI) (YANG et al., 1997) are examples of indices that require only precipitation data. The Standard Precipitation-Evapotranspiration Index (SPEI) (VICENTE-SERRANO et al., 2010), the Geographically Independent Integrated Drought Index (GIIDI) (JIAO et al., 2019), and the Global Assessment of the Standardized Evapotranspiration Deficit Index (SEDI) (VICENTE-SERRANO et al., 2018) are other examples. These indices use water balance and remote sensing datasets in their calculations.

2.2.2.1 Standardized Precipitation Index (SPI)

Due to its simplicity and the worldwide application, SPI has been used to model the frequency, duration, and intensity of droughts (SEILER et al., 2002; WORLD METEOROLOGICAL ORGANIZATION, GLOBAL WATER PARTNERSHIP, 2016). Only precipitation data is required for its calculation, which brings the possibility to be used in different time scales and longer historical series (ZARGAR et al., 2011). However, SPI is not always the best assumption for regions vulnerable to climate changes (LI et al., 2015). In addition, problems with the gamma probability distribution may occur since it cannot be fitted if the rainfall is zero, which is common in arid and semi-arid zones (STAGGE; TALLAKSEN 2014).

SPI have been applied in recent studies around the world, such as in Europe (Silva; Mello, 2021; CALOIERO; VELTRI, 2018; COSTA et al., 2011; LIVADA; ASSIMAKOPOULOS, 2006; RUSSO et al., 2017; VERGNI et al. 2017), Asia (ABU HAJAR et al., 2019; LIU et al., 2009; MAHMOUDI et al., 2019; MONDOL et al., 2017), Africa (JEMAI et al., 2018; OKPARA et al., 2017), Australia (HOLMES et al., 2017; RAHMAT et al., 2012), and North America (MALLYA et al., 2013; STRZEPEK et al., 2010). In Brazil, SPI Coelho et al. (2016a, b) assessed the severity of the droughts over Sao Paulo Metropolitan region; Sobral et al. (2019a, b) used SPI to analyze the impact of droughts in the Rio de Janeiro state; Cunha et al. (2019) analyzed the recurrence of extreme drought events from 2011 and 2019; and Silva and Mello (2021) studied the droughts in southeast Brazil in the last 100 years.

SPI is calculated by fitting the two-parameter Gama Probability Density Function (PDF) (equation 1) (COELHO et al., 2016; MCKEE et al. 1993). Afterward, the inverse of Gauss PDF was applied to the non-exceedance probability values estimated by the Gama PDF, defining the SPI. To verify the fitting of the Gama PDF, the Anderson-Darling test was applied (ANDERSON; DARLING, 1952).

$$PDF: f(x) = \frac{1}{\beta^{\alpha} * \Gamma(\alpha)} * x^{\alpha-1} * e^{\frac{-x}{\beta}} \tag{1}$$

Where β e α are the Gama PDF shape and scale parameters, respectively, x is the precipitation in the hydrological year, Γ (α) is the gamma of the α value.

2.2.2.2 Standardized Precipitation-Evapotranspiration Index (SPEI)

The SPEI calculation is based on precipitation accumulated in a given period and air temperature effects by potential evapotranspiration. Thus, the SPEI is calculated based on an atmosphere water budget (P – ET) (VICENTE-SERRANO et al., 2009), which has been relevant when temperature has an anomalous variability.

SPEI has been proved a good indicator to measure the severity of the droughts. Parente et al. (2019) applied it to study the occurrence of large wildfires in Portugal related to the drought regimes and concluded that the droughts play a fundamental role in such events. Comparing the SPI and SPEI to analyze long-term drought severity in Botswana, Byakatonda et al. (2018) demonstrated that the SPEI was a better index to characterize drought in semi-arid regions. Shiru et al. (2019) evaluated the drought events in Nigeria throughout the period of 1901-2010 using the SPEI and they observed a decrease in the return period of moderate droughts, which can lead to losses in agricultural production in the following decades. Gozzo et al. (2019) observed a linear trend of increasing drought events in central and western regions of São Paulo state, and a decreasing tendency in the eastern region.

The Thornthwaite method is suggested by Vicente-Serrano et al. (2009) for potential evapotranspiration estimates as it only considers the average monthly temperatures instead of other meteorological variables. Similar results for SPEI were found when both the Thornthwaite and Penman-Monteith methods were applied, thus, justifying the use of the former method, mainly for regions with minimum monitoring in terms of climate variables (BEGUERIA et al., 2014; MCEVOY et al., 2012).

Monthly potential evapotranspiration series were calculated by equation 2:

$$ETp = 16K * \left(\frac{10T}{I}\right)^{m} \quad (2)$$

where é Ti is the average monthly temperature (°C) i, and I is calculated by the monthly sum of I, according to equation 3:

$$I = \sum_{i=1}^{12} \left(\frac{Ti}{5}\right)^{1,514} \quad (3)$$

where m is a coefficient calculated according to equation 4:

$$m = 6,75 * 10^{-7} * I^3 - 7,71 * 10^{-5} * I^2 + 1,79 * 10^{-2} * I + 0,49239 \quad (4)$$

where k is a coefficient related to latitude and

$$K = \left(\frac{N}{12}\right) * \left(\frac{NDM}{30}\right) \quad (5)$$

where NDM is the number of days for each month and N is the maximum number of sun light, calculated for:

$$N = \left(\frac{24}{\pi}\right) \varpi \quad (6)$$

where ϖ in sun angulation, calculated for:

$$\varpi = arcos(-tan\varphi tang\delta) \quad (7)$$

where φ is a latitude, in radians, and δ is the sun declination, in radians, calculated by:

$$\delta = 0,4093sen\left(\frac{2\pi J}{365} - 1,405\right) \quad (8)$$

where J is the average Julian day of the month.

The monthly differences (P - ET) are grouped into hydrological years and a generalized extreme values (GEV; Equation 9) was fitted to the empirical distribution of the sums. Similar to SPI, an equiprobability transformation is then made from the cumulative probability to the standard normal random, where SPEI takes on the value of z.

$$PDF = \frac{1}{\sigma} * \left[1 - \varepsilon * \left(\frac{x-\mu}{\sigma}\right)\right]^{\left(\frac{1}{\varepsilon - 1}\right)} * exp\left\{-\left[\frac{x-\mu}{\sigma}\right]^{\frac{1}{\varepsilon}}\right\} \quad (9)$$

where ε, σ e μ are the shape, location, and scale are the GEV PDF parameters, and x are P-ET values.

2.3 Climate Research Unit

The Climate Research Unit (CRU) is one of the most popular datasets, frequently used to analyze the historical climate of the world. The CRU dataset is constructed by the Climate Anomaly

Method (CAM) and is subsidized for a combination of many datasets from different sources like the World Meteorological Organization (WMO) and the United States National Oceanographic and Atmospheric Administration (NOAA), and it (HARRIS et al., 2014).The authors also provide a CRU dataset with high spatial resolution of 0.5º x 0.5º that includes precipitation, temperature, wind, solar radiation, among others variables.

2.4 Climate Change Projections

To understand how climate change can affect the planet, climate projections have been made by the Global Climate Models (GCM). These models simulate the climate using complex numerical simulations of equations of the chemical, physical, and biological atmosphere to estimate how greenhouse gas emissions influence the planet's climate (CHOU et al., 2014). However, the GCMs outputs cover a coarse resolution (~300 Km). Thus, their applicability to basins or specific regions with compatible resolutions (5 km; 20 km; 40 km) is not recommended (SILVA; MELLO, 2021). In this context, downscaling techniques are having been applied to GCMs to generate Regional Climate Models with better resolutions.

2.4.1 Eta Model

The eta model adopts in its calculation the eta vertical coordinate (MESINGER, 1984), which stays approximately horizontal in mountain areas, and which makes the coordinate suitable for studies in regions of steep topography. The model was set up at 20-km resolution and 38 vertical levels, and covers most of South America and Central America (CHOU et al., 2014).

2.4.2 CORDEX

The Coordinated Regional Climate Downscaling Experiment (CORDEX) is a program sponsored by the World Climate Research Program that aims to assess and to compare Regional Climate Models around the world. With regional problems like water demand and consumption, droughts and floods becoming more common, Regional Climate information is more than needed for decision-making, to diagnose vulnerabilities and to adapt to climate with weather extremes been more common (LLOPART et al., 2020).

The CORDEX Goals are to better understand relevant regional/local climate phenomena, their variability and changes, through downscaling, to evaluate and improve regional climate downscaling models and techniques, to produce coordinated sets of regional downscaled projections worldwide, and to foster communication and knowledge exchange with users of regional climate information (SOLMAN; BLÁZQUEZ, 2019).

2.4.3 BESM

The Brazilian Earth System Model was developed in the National Institute for Space Research (INPE) (NOBRE et al., 2013). The atmosphere model is coupled to the MOM4 ocean model with 50 levels in the ocean and resolution varying from 0.25 degree between 10˚N and 10˚S, 1 degree between 10˚N/S and 45˚N/S, up to 2 degree between 45˚N/S and 90˚N/S latitudes. In the longitude, the resolution is constant, 1 degree (CHOU et al., 2014)

The model can capture general mean climate state, however some substantial biases appeared in the simulation associated with a double Intertropical Convergence Zone (ITCZ) over the Pacific and Atlantic oceans and regional biases in the precipitation over the Amazon and Indian regions (VEIGA et al., 2019; CAPISTRANO et al., 2020).

2.4.4 CanESM2

CanESM2 has evolved from the first generation Canadian earth system model (CanESM1) (ARORA et al., 2009; CHRISTIAN et al., 2010) of the Canadian Centre for Climate Modelling and Analysis (CCCma). The atmospheric component of CanESM2 (CanAM4) has evolved from the third generation atmospheric general circulation model (CanAM3). It is a spectral model employing T63 triangular truncation with physical tendencies calculated on a 128 × 64 (~2.81°) horizontal linear grid. The physical ocean component of CanESM2 differs from that of CanESM1 in that it has higher resolution and improved physical parameterization.

2.4.5 HadGEM2-ES

The Hadley Centre Global Environmental Model is a grid-point model, with a resolution of approximately 1.875 degrees in longitude and 1.275 degrees in latitude, with 38 levels in the atmosphere (CHOU et al., 2014). For oceans, eta model has 40 levels vertical resolution, while in the horizontal, the resolution varies from 1/3 degree in the tropics to 1 degree in latitudes higher than 30˚. The model includes atmospheric chemistry and aerosol model with organic carbon and dust representation (MARTINS et al., 2011; COLLINS et al, 2011).

2.4.6 MIROC5

MIROC5 is a Japanese cooperatively developed model known as Model for Interdisciplinary Research on Climate (MIROC), version 5 (Watanabe et al., 2010).The model has a horizontal resolution of 150 Km, with 40 vertical atmospheric levels. It is coupled to COCO 4.5 ocean with 50 levels in depth and 1˚ of horizontal resolution.

2.4.7 CSIRO

The climate model provided for the Commonwealth Scientific and Industrial Research Organisation (CSIRO) was developed in Australia. Climate change simulations from CSIRO Mk3.6.0 (hereafter referred to simply as CSIRO) (GORDON et al., 2010) are used to derive the initial and lateral boundary conditions needed to drive RegCM4. The horizontal resolution of the atmospheric component of CSIRO is T63 (~1.875° longitude × 1.875° latitude).

2.4.8 IPSL-CM5A

Climate is a complex system. In this context, the Global Circulation Model IPSL-CM5 was developed to simulate the response of this system to natural and anthropogenic forces under the 5th Phase of the Coupled Model Intercomparison Project (CMIP5). The carbon cycle, a characterization of tropospheric and stratospheric chemistry, and a comprehensive representation of aerosols are included in this model. As it represents the principal dynamical, physical, and bio-geochemical processes relevant to the climate system, it may be referred to as an Earth System Model (DUFRESNE et al., 2013).

2.4.9 GFDL CM3- NOAA-ESM

The National Oceanic and Atmospheric Administration (NOAA) Earth System Models (ESMs) (BENTSEN et al, 2013) is a Global Climate model that seeks to understand how the Earth's biogeochemical cycles, including human actions, interact with the climate system.

The main components of the ESMs were developed under the Geophysical Fluid Dynamics Laboratory (GFDL; DUNNE et al., 2012) and can be separated among atmospheric (aerosols, cloud physics, and precipitation), land components (evaporation, streams, lakes, rivers, and runoff), and oceanic (free surface to capture wave processes; water fluxes, or flow; currents; sea ice dynamics).

2.4.10 NorESM

The Norwegian Earth System Model (NorESM) is based on version 4 of the Community Climate System Model (CCSM4) developed at the US National Center for Atmospheric Research (NCAR) (GENT et al., 2011). The Norwegian Earth System Model version 2 (NorESM2) is the second generation of the coupled Earth system model (ESM) developed by the Norwegian Climate Center, and is the successor of NorESM1 (BENTSEN et al., 2013; IVERSEN et al., 2013; KIRKEVÅG et al., 2013; TJIPUTRA et al., 2013) which was used in the fifth phase of the Coupled Model Intercomparison Project (CMIP5; TAYLOR et al., 2012) and for the evaluation of potential climate impacts between the 1.5 and 2 ◦C warming targets of "the 21st Conference of Parties" (COP21). NorESM2 is based on the Community Earth System Model (CESM2.1).

REFERENCES

ABU HAJAR, H. et al. Drought assessment and monitoring in Jordan using the standardized precipitation index. **Arabic Journal of Geoscience,** vol. 12, n. 417, 2019. doi. org/10.1007/s12517- 019- 4590-y

AGHAKOUCHAK, A. et al. Remote sensing of drought: Progress, challenges and opportunities, **Reviews Geophysics**, vol. 53, p. 452–480, 2015. doi.org/10.1002/2014RG000456

ALHO C. AND SILVA J. Effects of Severe Floods and Droughts on Wildlife of the Pantanal Wetland (Brazil)—A Review. **Animals**, vol. 2, n. 4, p. 591–610, 2012. doi:10.3390/ani2040591

ALHO, C. J. R.; CAMARGO G.; FISCHER E. Terrestrial and aquatic mammals of the Pantanal. Brazilian **Journal of Biology**. vol. 1, n. 1, p. 297-310, 2011. doi.org/10.1590/S1519-69842011000200009

ANDERSON, T. W.; DARLING, D. A. A test of goodness of fit. **Journal of American Statistics Association**. vol. 49, p. 756–769, 1954

ARORA, V. K.; MATTHEWS, H. D. Characterizing uncertainty in modeling primary terrestrial ecosystem processes. **Global Biogeochemical Cycles**, vol. 23, e-GB2016, 2009 doi:10.1029/2008GB003398

ASSAD E.; PINTO H.; ZULLO JUNIOR, J.;, ÁVILA, A. Impacto das mudanças climáticas no zoneamento agroclimático do café no Brasil (Portuguese). **Pesquisa Agropecuária Brasileira** vol. 39, n.11, p. 1057–1064, 2004. doi.org/ 10. 1590/s0100- 204x2 00400 11000 01

ASSOCIAÇÃO COMERCIAL E EMPRESARIAL DE MINAS GERAIS. Minas Gerais Business Guide 2020/2021. **Governo de Minas Gerais e Ministério de Relações Exteriores**. 44p, 2021

BEGUERIA, S.; VICENTE-SERRANO, S.M.; REIG, F. & LATORRE, B. Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. **International Journal of Climatology**, v. 34, p. 3001-3023, 2014. doi.org/10.1002/joc.3887

BENTSEN, M. et al. The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation of the physical climate, **Geoscientific Model Development**, vol. 6, p. 687–720, 2013 doi.org/10.5194/gmd-6-687-2013

BERGIER, I. et al. Amazon rainforest modulation of water security in the Pantanal wetland, **Science of The Total Environment**, v. 619-620, p. 1116-1125, 2018 doi.org/10.1016/j.scitotenv.2017.11.163

BEZABIH, B. AND MOSISSA, T. Review on distribution, importance, threats and consequences of wetland degradation in Ethiopia. **International Journal of Water Resources and Environmental Engineering**, vol. 9, n. 3, p. 64-71, 2017 doi:10.5897/IJWREE2016.0697.

BLACK, T. L. The New NMC Mesoscale Eta Model: Description and Forecast Examples. Weather and Forecasting, v. 9, n. 2, p. 265–278, 1994

BUENO, E.; MELLO, C.; ALVES, G. Evaporation from Camargos hydropower plant reservoir: water footprint characterization. **Revista Brasileira De Recursos Hídricos**, vol. 21, n. 3, 570–575, 2016 doi.org/10. 1590/ 2318- 0331. 01161 6021

BYAKATONDA, J.; PARIDA, B. P.; MOALAFHI, D. B.; KENABATHO, P. K. Analysis of long-term drought severity characteristics and trends across semiarid Botswana using two drought indices. **Atmosphere Research**, vol. 213, p. 492-508, 2018

CALOIERO, T.; VELTRI, S. Drought assessment in the Sardinia region (Italy) during 1922–2011 using the standardized precipitation index. **Pure Applied Geophysics**, vol 176, n. 2, p. 925–935, 2018 doi. org/ 10.1007/ s00024- 018- 2008-5

CAPISTRANO, V. B. et al.. Assessing the performance of climate change simulation results from BESM-OA2. 5 compared with a CMIP5 model ensemble. **Geoscientific Model Development**, vol. 13, n. 5, p. 2277-2296, 2020. doi:10.5194/gmd-13-2277-2020

CATIAN, G. et al.. Effects of Flood Pulse Dynamics on Functional Diversity of Macrophyte Communities in the Pantanal Wetland. **Wetlands**. 38, 975-991, 2018 https://doi.org/10.1007/s13157-018-1050-5

CAVALCANTI, I.; KOUSKY, V. Drought in brazil during summer and fall 2001 and associated atmospheric circulation features. **Climanálise**, vol. 1, p. 1–10, 2001

CENTER FOR CLIMATE AND ENERGY SOLUTIONS. **Drought and climate change**. 2021 Access in: https://www.c2es.org/content/drought-and-climate-change/

CHOU, S.C. et al. Evaluation of the Eta Simulations Nested in Three Global Climate Models. **American Journal of Climate Change**, vol. 3, n.12, p. 438–454, 2014a

CHOU, S. C. et al. Assessment of Climate Change over South America under RCP 4.5 and 8.5 Downscaling Scenarios. **American Journal of Climate Change**, vol. 3, n. 5, p. 512–527, 2014b. doi.org/10.4236/ajcc.2014.35043

CHRISTIAN, J. R. et al. The global carbon cycle in the Canadian Earth system model (CanESM1): Preindustrial control simulation, **Journal of Geophysics Research**, vol. 115, e-G03014, 2010 doi:10.1029/2008JG000920

CLARK, J. S. et al. The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. **Global Change Biology**, vol. 22, n. 7, p. 2329–2352, 2016 doi:10.1111/gcb.13160

COELHO, C.; CARDOSO, D.; FIRPO, M. Precipitation diagnostics of an exceptionally dry event. **Theoretical Applied Climatology,** vol. 125, p. 769–784, 2016. doi.org/10.1007/s00704- 015-1540-9

COELHO, C. et al. The 2014 southeast Brazil austral summer drought: regional scale mechanisms and teleconnections. **Climate Dynamics**, vol. 46, n. 11–12, p.3737–3752, 2016 doi. org/10.1007/s00382- 015- 2800-1

COLLINS, W. J. et al. Development and evaluation of an Earth-System model – HadGEM2, **Geoscience Modeling Development**, v. 4, p. 1051–1075, 2011 doi.org/10.5194/gmd-4-1051-2011.

CONAB - COMPANHIA NACIONAL DE ABASTECIMENTO (2021) **Acompanhamento da safra brasileira de café**, Brasília, DF, v.8 - Safra 2020/21, n. 3, p.1-58, 2021

COSTA, A. et al. Local patterns and trends of the standard precipitation index in southern Portugal (1940–1999). **Advanced Geosciences** vol. 30, n. 11–16, 2011. doi. org/10.5194/ adgeo- 30- 11-2011

CUNHA, A.P. et al. Extreme Drought Events over Brazil from 2011 to 2019. **Atmosphere** vol. 10, n.11, p. 642, 2019 doi. org/ 10. 3390/ atmos 10110 642

DE GROOT, R.S.; STUIP, M. A. M.; FINLAYSON ,C.M.; DAVIDSON, N. Valuing wet-lands: guidance for valuing the benefits derived from wetland ecosystem services. **Ramsar Technical Report No. 3/CBD Technical Series No. 27** (Montreal: Ramsar Convention Secretariat, Gland, Switzerland & Secretariat of the Convention on Biological Diversity), 2006

DONNER, L.J. et al. The Dynamical Core, Physical Parameterizations, and Basic Simulation Characteristics of the Atmospheric Component AM3 of the GFDL Global Coupled Model CM3, Journal of Climate, v. 24, n. 13, p. 3484-3519, 2011 doi.org/10.1175/2011JCLI3955.1

DUFRESNE, J. L. et al. Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. **Climate Dynamics** v. 40, p. 2123–2165, 2013 doi.org/10.1007/s00382-012-1636-1

DUNNE, J. P. et al.GFDL's ESM2 Global Coupled Climate–Carbon Earth System Models. Part I: Physical Formulation and Baseline Simulation Characteristics, **Journal of Climate**, v. 25, n. 19, p. 6646-6665, 2012 doi.org/10.1175/JCLI-D-11-00560.1

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO). Damage and Loss. 2021. https://www.fao.org/resources/digital-reports/disasters-in-agriculture/en/

GENT, P. R., et al. The CSIRO Mk3.5 Climate Model. **Technical report No. 21**, CSIRO Marine and Atmospheric Research. Aspendale, Victoria, Australia, 2010

GOZZO, L.; PALMA, D.; CUSTODIO, M.; MACHADO, J. Climatology and Trend of Severe Drought Events in the State of Sao Paulo, Brazil, during the 20th Century. **Atmosphere**, vol. 10, n. 4, p. 190-206, 2019

HARRIS, I.; JONES, P.; OSBORN, T.; LISTER, D. Updated high-resolution grids of monthly climatic observations–the CRU TS3. 10 dataset. **International Journal of Climatology**, n. 34, p. 623–642, 2014

HOLMES A, RÜDIGER C, MUELLER B, HIRSCHI M, TAPPER N (2017) Variability of soil moisture proxies and hot days across the climate regimes of Australia. **Geophysics Research Letter**. Vol 44, n.14, p. 7265–7275. doi.org/10.1002/2017g l0737 93

HU, S.; NIU, Z.; CHEN, Y.; LI, L.; ZHANG, H. Global wetlands: Potential distribution, wetland loss, and status. **Science of The Total Environment**, n. 586, 319–327, 2017, doi:10.1016/j.scitotenv.2017.02.001

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (2019). Cidades do Sul de Minas Gerais. Governo do Brasil. Access in https://cidades.ibge.gov.br/brasil/mg/bandeira-do-sul/panorama

IVERSEN, T. et al. The Norwegian Earth System Model, NorESM1-M – Part 2: Climate response and scenario projections, **Geoscionsce. Modelling Devolepment**, vol 6, pp. 389–415, 2013 https://doi.org/10.5194/gmd-6-389-2013

IVORY, S et al. Vegetation, rainfall, and pulsing hydrology in the Pantanal, the world's largest tropical wetland. **Environmental Research Letters**, vol. 14, n. 12, e-124017 2019 doi:10.1088/1748-9326/ab4ffe

JEMAI, S.; KALLEL, A.; ABIDA, H. Drought distribution using the standardized precipitation index: case of Gabes Basin, South Tunisia. **Arabian Journal of Geosciences** vol. 11, n. 23, p. 737, 2018. doi.org/ 10. 1007/ s12517- 018- 4053-x

JIAO, W. et al. A new multisensor integrated index for drought monitoring. **Agricultural for Meteorology** vol. 268, pp. 74–85, 2019. doi. org/ 10. 1016/j. agrfo rmet. 2019. 01. 008

JUNK, W. J. et al. Current state of knowledge regarding the world's wetlands and their future under global climate change: a synthesis. **Aquatic Science** vol. 75, pp. 151–167, 2013. doi.org/10.1007/s00027-012-0278-z

KEYANTASH, J. AND DRACUP, J. A. The Quantification of Drought: An Evaluation of Drought Indices. **Bulletin of the American Meteorological Society**, vol. 83, n. 8, pp. 1167-1180. 2002 doi.org/10.1175/1520-0477-83.8.1167

KIRKEVÅG, A. et al. Aerosol–climate interactions in the Norwegian Earth System Model – NorESM1-M, **Geoscience Modelling Development**, vol. 6, pp. 207–244, 2013, doi.org/10.5194/gmd-6- 207-2013, 2013.

LÁZARO W. L. et. al. Climate change reflected in one of the largest wetlands in the world: an overview of the Northern Pantanal water regime. **Acta Limnologica Brasiliensia**, vol. 32, e104, 2020 doi.org/10.1590/S2179-975X7619

LI, J.; WANG, Y., LI, S.; HU, R. Nonstationary Standardized Precipitation Index incorporating climate indices as covariates. **Journal of Geophysics Research**, vol. 120, n. 12, pp. 82–95, 2015. https:// doi. org/ 10. 1002/ 2015j d0239 20

LIU X, XU Z, LIU B Spatio-temporal characteristics of standardized precipitation index in the Taihu basin during 1951–2000. **Wuhan University Journal Natural Science**, vol. 14, n. 6, pp. 518–524, 2009. doi. org/ 10. 1007/s11859- 009- 0611-0

LIVADA, I.; AND ASSIMAKOPOULOS, V. Spatial and temporal analysis of drought in Greece using the Standardized Precipitation Index (SPI). Theoretical and Applied Climatology vol. 89, n.3, pp. 43–215, 2006 doi.org/ 10.1007/ s00704- 005- 0227-z

LLOPART, M; SIMÕES REBOITA, M.; PORFÍRIO DA ROCHA, R. Assessment of multi-model climate projections of water resources over South America CORDEX domain. **Climate Dynamics** vol. 54, pp. 99–116, 2020 doi.org/10.1007/s00382-019-04990-z

MAHMOUDI, P.; RIGI, A.; MIRI KAMAK, M. A comparative study of precipitation-based drought indices with the aim of selecting the best index for drought monitoring in Iran. **Theoretic and Applied Climatology** vol. 137, pp. 3123–3138, 2019 https:// doi. org/ 10. 1007/ s00704- 019- 02778-z

MALLYA, G. et al. 2012 Midwest drought in the United States. **Jounal of Hydrology Engineering** vol. 18, n.7, pp.737–745, 2013. doi.org/10.1061/(asce)he.1943- 5584. 00007 86

MAO, D. et al. China’s wetlands loss to urban expansion. **Land Degradation & Development**, vol. 29, n.8 , 2644–2657, 2018. doi:10.1002/ldr.2939

MARENGO J. et al A seca e a crise hídrica de 2014–2015 em São Paulo. **Revista USP** n. 106, pp. 31–44, 2015. doi.org/10. 11606/issn.2316- 9036. v0i106p31- 44

MARENGO J et al. The drought of 2010 in the context of historical droughts in the Amazon region. **Geophysical Research Letter** vol. 38, n. 12, pp. 1–5, 2011. doi.org/ 10. 1029/2011g l0474 36

MARTINS, G.M. et al. The HadGEM2 family of met office unified model climate configurations. **Geoscientific Model Development**, vol. 4, n.3, pp. 723-757, 2011

MCEVOY, D.J.; HUNTINGTON, J.L.; ABATZOGLOU, J.T.; EDWARDS, L.M. An evaluation of multiscalar drought indices in Nevada and Eastern California. **Earth Interact** v.16, n.18, p. 1-18, 2012 doi.org/10.1175/2012EI000447.1

MCKEE T.B.; DOESKEN N.J.; KLIEST J. The relationship of drought frequency and duration to time scales. **American Meteorological Society**, pp 179–184, 1993

MESINGER, F. A Blocking Technique for Representation of Mountains in Atmospheric Models. **Rivista di Meteorologia Aeronautica**, vol. 44, pp. 195-202, 1984

MONDOL, M.; ARA I.; DAS, S. Meteorological drought index mapping in Bangladesh using standardized precipitation index during 1981–2010. **Advances in Meteorology**, pp. 1–17, 2017. doi. org/10.1155/2017/ 46420 60

NARAYAN, S. et al. The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA. **Scientific Reports**, vol. 7, n. 1, 2017 doi:10.1038/s41598-017-09269-z

NOBRE, P. et al. Climate Simulation and Change in the Brazilian Climate Model, **Journal of Climate**, vol.26, n.17, pp. 6716-6732, 2013. doi.org/10.1175/JCLI-D-12-00580.1

OKPARA, J. et al. The applicability of Standardized Precipitation Index: drought characterization for early warning system and weather index insurance in West Africa. **Natural Hazards** vol. 89, n. 2, pp. 555–583, 2017. doi.org/10.1007/s11069-017-2980-6

PARENTE, J.; Amraoui M.; Menezes, I; Pereira, M. G. Drought in Portugal: Current regime, comparison of indices and impacts on extreme wildfires. **Science Total Environment** vol. 685, pp. 150-173, 2019

PAZ, A. R.; Collischonn W.; Tucci C. E. M.; Padovani C. R. Large-Scale modelling of channel flow and floodplain inundation dynamics and its application to the Pantanal (Brazil). **Hydrological Processes**. vol. 25, pp. 1498-1516, 2011. doi.org/10.1002/hyp.7926

PENG, J. et al. A pan-African high-resolution drought index dataset. **Earth System Science Data**. Vol. 12, pp. 753-769, 2020 doi.org/10.5194/essd-12-753-2020

POTT, A.; OLIVEIRA, A.; DAMASCENO-JUNIOR, G.; SILVA, J. Plant diversity of the Pantanal wetland. **Brazilian Journal of Biology**, vol. 71, pp. 265–273, 2011a doi:10.1590/s1519-69842011000200005

POTT, V.; POTT, A.; LIMA, L.; MOREIRA, S.; OLIVEIRA, A. Aquatic macrophyte diversity of the Pantanal wetland and upper basin. **Brazilian Journal of Biology**, vol. 71, n. 1, pp. 255–263, 2011b doi:10.1590/s1519-69842011000200004

RAHMAT, S.; JAYASURIYA, N.; BHUIYAN, M. Trend analysis of drought using Standardised Precipitation Index (SPI) in Victoria, Australia. **34th Hydrology & Water Resources Symposium**. Australia, Sydney, pp 19–22, 2012

RODRIGUES N, REIS E, TAVARES M Influências dos fatores climáticos no custo de produção do café arábica. Custos e Agronegócio Online vol. 10, n 13, pp. 216–255, 2014

RUSSO, A. et al. Assessing the role of drought events on wildfires in the Iberian Peninsula. **Agricultural for Meteorology** vol. 237–238, pp. 50–59, 2017. doi.org/ 10.1016/j. agrfo rmet. 2017. 01. 021

SALIMI, S.; ALMUKTAR S. A. N.; SCHOLZ, M. Impact of climate change on wetland ecosystems: A critical review of experimental wetlands. **Journal of Environmental Management**, vol, 286, e-112160, 2021. doi:10.1016/j.jenvman.2021.112160

SEILER, R. A.; HAYES, M.; BRESSAN, L. Using the standardized precipitation index for flood risk monitoring. **International Journal of Climatology** vol.22, pp. 1365– 1376, 2002 doi. org/ 10. 5194/ hess- 21- 6307- 2017

SHIRU, M.S.; SHAHID, S.; CHUNG, E. S.; ALIAS N. Changing characteristics of meteorological droughts in Nigeria during 1901-2010. **Atmosphere Research** vol. 223, pp. 60-73, 2019

SILVA V.; MELLO C. R. Meteorological droughts in part of southeastern Brazil: Understanding the last 100 years. **Acadeemia Brasileira de Cienciências**. Vol. 93, e20201130, 2021 doi. org/ 10. 1590/ 0001- 3765202120 201130

SOBRAL, B. S. et al.. Drought characterization for the state of Rio de Janeiro based on the annual SPI index: trends, statistical tests and its relation with ENSO. **Atmosphere Research** vol. 220, pp. 141–154, 2019b

SOLMAN ,S.A.; BLÁZQUEZ J. Multiscale precipitation variability over South America: Analysis of the added value of CORDEX RCM simulations. **Climate Dynamics** vol. 53, pp. 1547–1565, 2019 https://doi.org/10.1007/s00382-019-04689-1

SPINONI, J. et al. A new global database of meteorological drought events from 1951 to 2016. **Journal of Hydrology: Regional Studies**. Vol. 22, e-100593, 2019 doi.org/10.1016/j.ejrh.2019.100593

STAGGE J.; TALLAKSEN L. Standardized precipitation-evapotranspiration index (SPEI): Sensitivity to potential evapotranspiration model and parameters. **International Association Hydrology Science (IAHS)** vol.10:, pp. 67–373, 2014

STRZEPEK, K. et al. Characterizing changes in drought risk for the United States from climate change. **Environmental Research Letter** vol. 5, n.4, pp.1–9, 2010. doi. org/ 10. 1088/ 1748-9326/5/4/ 044012

TAYLOR K. E.; STOUFFER R. J.; MEEHL G. A. An Overview of CMIP5 and the Experiment Design, B. **American Meteorologic Society**, vol. 93, pp. 485–498, 2012 https://doi.org/10.1175/BAMS-D-11-00094.1

TJIPUTRA J. F. et al. Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM), Geoscience Modellling Development, vol. 6, pp. 301–325, 2013, https://doi.org/10.5194/gmd-6-301-2013.

TUCCI, C. E. M.; GENZ, F.; CLARKE, R. T. Hydrology of the upper Paraguay basin. In Management of Latin American River Basins: Amazon, Plata and São Francisco, Biswas K, Cordeiro N, Braga B, Tortajada C (eds). United Nations University Press: Tokyo; 103–122, 1999

VEIGA, S. F.; et al..The Brazilian Earth System Model ocean–atmosphere (BESM-OA) version 2.5: evaluation of its CMIP5 historical simulation. **Geoscientific Model Development**, vol. 12, n. 4, pp. 1613–1642, 2019 doi:10.5194/gmd-12-1613-2019

VERGNI, L.; DI LENA, B; TODISCO, F; MANNOCCHI, F. Uncertainty in drought monitoring by the Standardized Precipitation Index: the case study of the Abruzzo region (central Italy). **Theoretical and Applied Climatology** vol. 128, n.1–2, pp. 13–26, 2017. doi.org/ 10. 1007/s00704- 015- 1685-6

VICENTE-SERRANO, S. M.; BEGUERÍA S.; LÓPEZ-MORENO, J. I. A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. **Journal of Climatology** vol. 23, n. pp.1696-1718, 2010 doi.org/10.1175/2009JCLI2909.1

VICENTE-SERRANO S. M. et al Global assessment of the standardized evapotranspiration deficit index (SEDI) for drought analysis and monitoring. **Journal of Climate** vol. 31, n. 14, pp. 5371–5393, 2018. doi. org/ 10. 1175/ JCLI-D- 17- 0775.1

WATANABE M et al. Improved Climate Simulation by MIROC5: Mean States, Variability, and Climate Sensitivity. **Journal of Climate**, vol. 23, n.23, pp. 6312–6335, 2010 doi:10.1175/2010jcli3679.1

WORLD METEOROLOGICAL ORGANIZATION. Atlas of mortality and economic losses from weather, Climate and Water Extremes. **World Meteorological Organization (WMO)**, Geneva 2, Switzerland, 2014

WORLD METEOROLOGICAL ORGANIZATION, GLOBAL WATER PARTNERSHIP. **Handbook of drought indicators and indices**. Switzerland, Geneva, 2014

YANG, J. X.; LIJUAN X. C.; YOUMIN W Research on determination of station indexes and division of regional flood/ drought grades in china. **Quartely Journal of Applied Meteorology** vol. 8, n. 1, pp. 26–33, 1997

ZARGAR A, SADIQ R, NASER B, KHAN F A review of drought indices. **Environmental Review**, vol. 19, n. 1, pp. 333–349, 2011. https:// doi. org/ 10. 1139/ a11- 013

ZENG N et al Causes and impacts of the 2005 Amazon drought. Environ Research Letters vol.3; n.1, pp. 1–17, 2005. doi. org/ 10.1088/ 1748- 9326/3/ 1/ 014002

ARTICLE1- PROJECTIONS OF SEVERE DROUGHTS IN FUTURE CLIMATE IN SOUTHEAST BRAZIL: A CASE STUDY IN SOUTHERN MINAS GERAIS STATE, BRAZIL

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Abstract

South of Minas Gerais state, in Southeast Brazil, is known for the coffee crop production (more than 30% of country's production) and hydroelectricity generation (1216 MW installed power). Droughts are natural climate phenomena that may strongly affect a region during a certain period. In this study, the severity of the droughts that hit southern Minas Gerais state was analyzed in the period from 1970 to 2020 and was projected up to 2098/2099 using four global circulation models (HadGEM2-ES, MIROC5, BESM, CanESM2), downscaled by Eta model to 20-km resolution, under two Representative Concentration Pathways (RCP4.5 and RCP8.5). To access the severity of the droughts, the Standard Precipitation Index considering the hydrological year (SPI12) was investigated over time and space. The results demonstrated that the 2013–2014 hydrological year was the driest in southern Minas Gerais, followed by 2014/2015, which led to water shortage, reduction of the hydroelectricity and reduction of coffee crop production. Future projections indicate that extreme droughts will continue occurring, but with similar rarity. However, the RCM downscaling pointed out the possible occurrence of several dry consecutive years, which can collapse the hydrology and put at risk the economy of the region. Except from the Eta-MIROC under RCP 8.5, that simulated most of the droughts in middle to the end of XXI century, the other RCMs projected recurrent droughts for the next two decades, supporting the detection drought anomalies and helping in adoption actions to anticipate and mitigate drought effects in the future.

Keywords: regional climate change, meteorological droughts projection; Regional Climate Models, climate change impacts.

1. Introduction

Drought is a natural climate phenomenon caused by the rainfall amount below the average over a region for a long period. It impacts the water availability for crop, livestock production, water supply, hydroelectricity, tourism, and industry. Droughts are difficult to be identified and quantified over space and time. Currently, it has caused one of the most significant environmental and economic problems in many countries around the world (Vicente-serrano et al. 2018). Climate variability in a region, whether caused by natural or by anthropogenic forcings, can lead to changes in the climate patterns, and can result in the increase of the frequency of extreme events, such as droughts, heavy rains, heat waves, and strong cyclones. To understand the past events and to predict the future ones may help stakeholders, government, engineers, and scientists to identify the causes and effects of droughts, and how to adapt to their impacts.

Extreme weather has caused losses of billions of dollars every year. Data from the Center for Climate and Energy Solutions (2019) show that since 2000, 132 billions of dollars were lost due to droughts in the USA. Worldwide, the Food and Agriculture Organization (FAO) of the United Nations has reported that drought losses leaded an average USD 170 billion over the past decade, with a peak in 2011 and 2017, when losses reached over USD 300 billion (FAO 2021). Between 1970 and 2012, in the African continent, 680,000 deaths were caused by droughts and heat waves (WMO 2014). In Brazil, some drought years deserve highlights: (i) in 2005, the reduction of 16% of the Amazon River runoff along with the increase of 100% of wildfires (Zeng et al. 2005) were observed (Marengo et al. 2011); (ii) during the hydrological year of 2000/2001, the water crisis especially in Southeast Brazil collapsed the Brazilian hydroelectricity production (Cavalcanti and Kousky 2001); (iii) between 2013 and 2015, the worst drought ever observed in

Southeast Brazil (Coelho et al. 2016a, b). The latest event caused several losses in Southeast Brazil, with the longest shortage of water supply in the São Paulo metropolitan region; in Belo Horizonte and in Campinas metropolitan regions; the lowest level in the hydropower plants reservoirs in southern Minas Gerais, which put at risk the hydroelectricity generation for the entire Southeast Brazil. The main meteorological causes were the increase of the sea surface temperature (SST) in the Southeastern Brazilian coast, the strong high air pressure values acting in lower levels of the atmosphere, and the subsiding air that prevented the deep rainy cloud formation over Southeast Brazil (Coelho et al. 2016a, b; Marengo et al. 2015).

The occurrence and magnitude of the droughts have been evaluated using indexes (WMO 2016). The Standard Precipitation Index (SPI) and the China-Z Index (CZI) (Yang et al. 1997) are examples of indices that require only precipitation data. The Standard Precipitation-Evapotranspiration Index (SPEI) (Vicente-serrano et al. 2010), the Geographically Independent Integrated Drought Index (GIIDI) (Jiao et al. 2019), and the Global Assessment of the Standardized Evapotranspiration Deficit Index (SEDI) (Vicente-serrano et al. 2018) are other examples. These indices use water balance and remote sensing datasets in their calculations.

Due to its simplicity and the worldwide application, SPI has been used to model the frequency, duration, and intensity of droughts (Seiler et al. 2002; World Meteorological Organization, Global Water Partnership 2016. Only precipitation data is required for its calculation, which brings the possibility to be used in different time scales and longer historical series (Zargar et al. 2011). However, SPI is not always the best assumption for regions vulnerable to climate changes (Li et al. 2015). In addition, problems with the gamma probability distribution may occur since it cannot be fitted if the rainfall is zero, which is common in arid and semi-arid zones (Stagge and Tallaksen 2014).

SPI have been applied in recent studies around the world, such as in Europe (Silva and Mello 2021; Caloiero and Veltri 2018; Costa 2011; Livada and Assimakopoulos 2006; Russo et al. 2017, Vergni et al. 2017), Asia (Abu Hajar et al. 2019; Liu et al. 2009; Mahmoudi et al. 2019; Mondol et al. 2017; Yusof et al. 2014), Africa (Jemai et al. 2018; Okpara et al. 2017), Australia (Holmes et al. 2017; Rahmat et al. 2012), and North America (Mallya et al. 2013; Strzepek et al. 2010). In Brazil, SPI Coelho et al. (2016a, b) assessed the severity of the droughts over Sao Paulo Metropolitan region; Sobral et al. (2019a, b) used SPI to analyze the impact of droughts in the Rio de Janeiro state; Cunha et al. (2019) analyzed the recurrence of extreme drought events from 2011 and 2019; and Silva and Mello (2021) studied the droughts in southeast Brazil in the last 100 years.

To provide policymakers with scientific assessments and to develop adaptation and mitigation options for climate change extreme events, many global meteorological products have been developed in recent years (Xu et al. 2021). However, the global climate model (GCM) outputs have generally coarse resolutions (~ 300 km). Thus, their applicability to catchments or smaller areas are not suitable (Silva et al. 2014). Therefore, the downscaling is needed to reduce the scale of the GCM outputs. The Eta model (Mesinger et al. 2012) has been modified to run long-term integrations (Pesquero et al. 2010; Chou et al. 2012) and has produced simulations and projections over South America (Chou et al. 2014a,b; Blazquez and Silvina 2020) at 20-km resolution; over Central America (Imbach et al. 2018) at 8-km resolution, and over the small islands of Sao Tome and Principe (Chou et al. 2020) at 4-km resolution.

Minas Gerais state accounts for 10% of the 210 million inhabitants in Brazil, of which 2.5 million are in its southern region. Well known for the mild climate and high altitudes, southern Minas Gerais suffered the drought of 2013/2014 period, with impacts its economy, water supply, and hydroelectric generation. According to Silva and Mello (2021), the hydrological year of 2013/2014 was the driest ever recorded in 100 years for the city of Lavras, in the eastern border of southern Minas Gerais.

The present study has two parts. The first one aimed at analyzing the severity of the droughts in southern Minas Gerais state from the hydrologic year (October to September) of 1970–2020 until 2019/2020, and to assess their recurrences and impacts using the SPI index (SPI12: from October until September). The second part aimed at analyzing the projections of droughts for this region under the RCP4.5 and RCP8.5 using four downscaling of GCMs produced by the Eta model, based on the SPI index.

2. Material and methods

2.1. Study Area

Southern Minas Gerais state is located in southeast Brazil. It is an important economic region due to the coffee crop (Coffee arabica) production, and its hydroelectricity potential. In corresponded 2019, the region produced 19,152.2 sacks, which to over 30% of the total Brazilian production (CONAB 2021). Climate influences directly the coffee production, and it is the major factor for the crop productive performance and its drinkability (Rodrigues et al. 2014). Thus, the increase in temperature and the deficits in water budget may lead to extreme droughts and can potentially affect coffee cultivated areas in southern Minas Gerais (Assad et al. 2004).

In addition, the region has a significant importance to the Brazilian National Electric System, with the existence of several small hydropower plants and four plants of high power installed capacity. Among such plants, the Furnas Hydropower Plant is the largest reservoir in southeastern Brazil, with a installed capacity of 1216 MW (Bueno et al. 2020). Figure 1 locates the southern Minas Gerais region and the weather stations used in this study.

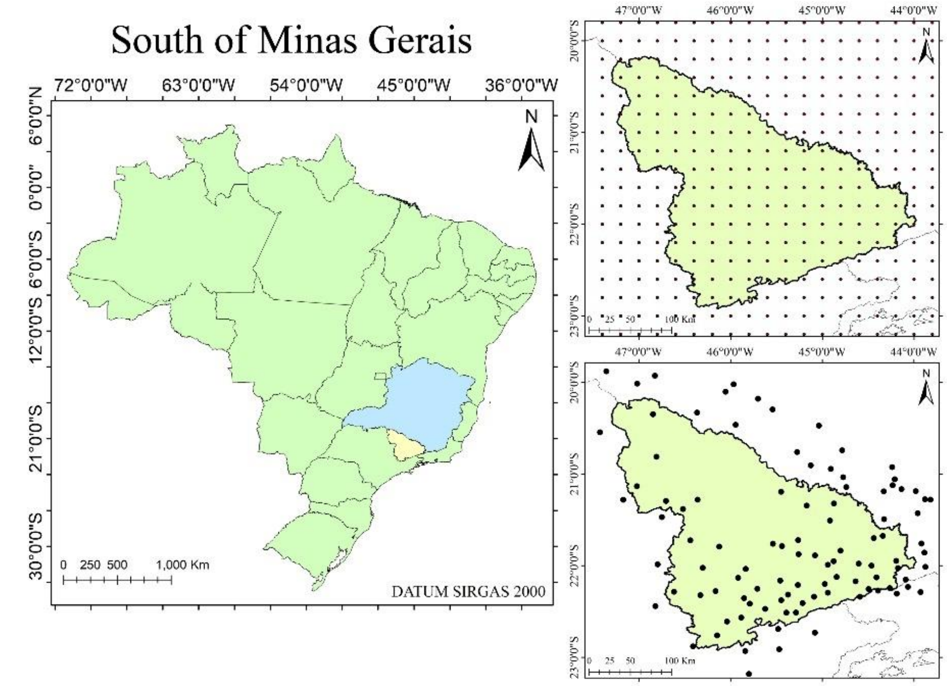

Figure 1. Location of Minas Gerais state and South of Minas Gerais in Brasil, the location of weather stations used in this study and the Eta RCM grid point.

2.2. Database

For the present study, 102 weather stations from the Brazilian National Water Agency (ANA) were used, of which 87 in southern Minas Gerais and surroundings, 10 in Sao Paulo, and 5 in Rio de Janeiro states (Fig. 1). These rain gauges were selected because they contain at least 50 years of daily precipitation data (1970–2020).

To fill the existing gaps, a spatial consistence analysis was carried out to verify the homogeneity with the closest rain gauges. Linear regressions were fitted between the precipitation data of stations with gaps and the data of neighbor stations to fill the gaps in the precipitation time series.

2.3 Projections of Climate change for the southern Minas Gerais state

Projections of drought occurrences throughout the twentyfirst century are based on the daily rainfall produced from the downscaling by the Eta model of the BESM, CanESM2, HadGEM2-ES, and MIROC5, GCM runs. The RCMs, hereforth referred to as Eta-BESM, Eta-CanESM2, Eta-HadGEM2-ES, and Eta-MIROC5, project the daily rainfall at 20-km resolution, under the two scenarios of the RepresentativeConcentration Pathways, RCP4.5 and 8.5 Wm^{-2}. The RCP4.5 is an intermediate scenario, with produces warming from to 1.1 to 2.6 °C by the end of twenty-first century, with stabilization of the emission gases. RCP8.5 is the most pessimist scenario and forces the continuous increase of the temperature of approximately 5.0 °C by the end the twenty-first century. The dataset are provided by the PROJETA Web address (Holbig et al. 2018).

The model grid boxes (Fig. 1) were taken for the analysis of the projection of the droughts. The daily rainfall data were grouped into monthly datasets and then into the total of the hydrological years. Systematic errors in the Eta RCM precipitation simulations and projections were removed according to the Bárdossy and Pegram (2011) methodology.

2.4 Standard Precipitation Index (SPI)

According to the World Meteorological Organization (WMO 2012), the SPI can be used for identifying and monitoring droughts. In this study, the SPI was defined based on the total precipitation during the hydrological year, from October to September of the following year. Thus, historical series of such period were organized for SPI calculation (SPI12).

SPI12 was calculated by fitting the two-parameter Gama Probability Density Function (PDF) (equation 1) (Coelho et al., 2016; Mckee et al. 1993). Afterward, the inverse of Gauss PDF was applied to the non-exceedance probability values estimated by the Gama PDF, defining the SPI. To verify the fitting of the Gama PDF, the Anderson-Darling test was applied (Anderson and Darling, 1952).

$$PDF: f(x) = \frac{1}{\beta^{\alpha} * \Gamma(\alpha)} * x^{\alpha-1} * e^{\frac{-x}{\beta}} \qquad (1)$$

Where β e α are the Gama PDF parameters, x is the precipitation in the hydrological year, Γ (α) is the gamma of the α value.

According to the Standard Precipitation Index User Guide (WMO, 2012), SPI values are classified as: Extremely Wet: > 2.0; Very Wet: 1.5 to 2.0; Moderately Wet: 1.0 to 1.5; Near Normal: -1.0 to 1.0; Moderately Dry: -1.0 to -1.5; Severely Dry: -1.5 to -2.0; Extremely Dry: < -2.0.

To assess the spatial associations between the drought episodes, ordinary kriging was applied to generate annual maps of the SPI12 for the observed data (2019-2020) and for the Eta RCM downscaling (2010-2099).

3. Results and Discussion

3.1. Extreme Droughts in southern Minas Gerais between 1970 and 2020

We identified the main extreme drought events in the last 5 decades over the southern region of Minas Gerais using SPI12. In this assessment, only drought events with SPI12 < − -1 were selected to be further projection and discussion. From − 1 to 0, the drought is considered abnormally.

Figure 2 illustrates the annual maps of SPI12 using the observed precipitation from 1970/1971 to 2019/2020 hydrologic years (only the driest years). The average annual precipitation in the region in the studied period was 1511.1 ± 150.7 mm. The three driest years recorded were 2000/2001, 1970/1971, and 2013/2014, showing average precipitations of 1210.3 ± 77.1 mm, 1171.90 ± 226.86 mm, and 1011.2 ± 244.1 mm, respectively. These values correspond to a reduction of 21.1%, 30.6%, and 34.1%, respectively, in relation to the average.

Drought events have been recorded in southern of Minas Gerais (Silva and Mello, 2021); however, only in 2013–2014, an extremely drought event was observed in entire the region. This event (SPI12 < -2) was observed in 52.9% of the region, while severe and moderate droughts were observed in 44.4% and 2.7%, respectively. This extreme climatological condition was linked to a strong atmospheric subsidence, which prevented the formation of convective rainfall over the area. In addition, the South Atlantic Subtropical Anticyclone acted strongly over the region, blocking frontal systems and South Atlantic Convergence Zone formation that usually occur during summer in the region (Coelho et al. 2016a, b).

The hydrological years of 2014/2015 and 2016/2017 were also very dry. Consecutive dry years caused direct impacts on the hydroelectricity generation in the region. In January2014, the Grande River, one of the most important of Brazil, reduced to less than 20% of its regular flow; consequently, the downstream Furnas hydropower plant reservoir produced less than 20% of its full installed capacity in this period (Bueno et al. 2016). According to the Bueno et al. (2020), the losses of Furnas Lake economy were over 6.8 million dollars in tourism and over 9 million dollars in fishery.

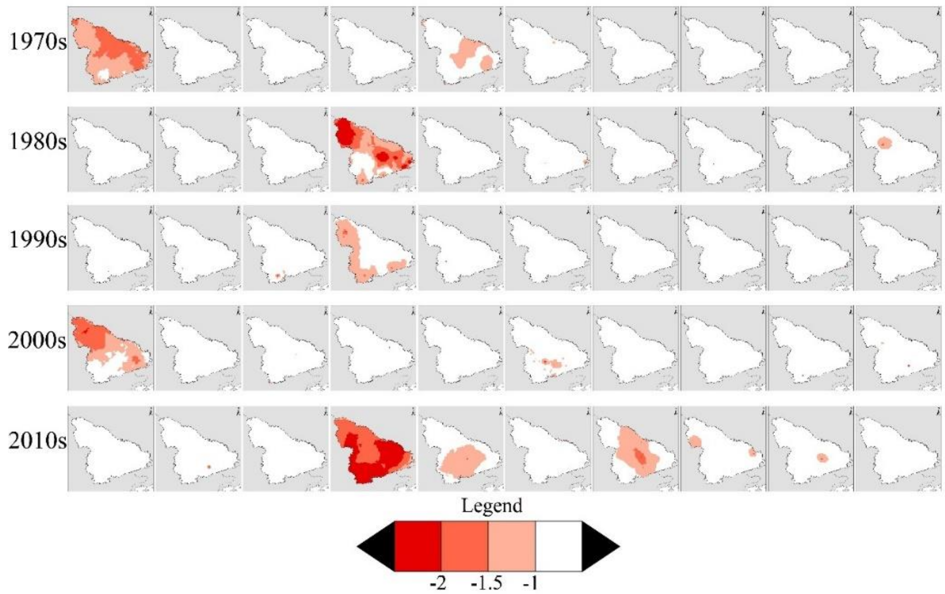

Figure 2. Annual observed SPI12 (from 1970/2020 to 2019/2020) for southern Minas Gerais state, Brazil.

In the drought of 2000/2001 hydrological year, the Brazilian Electric Energy System faced a critical water level in the hydropower plants reservoirs that led to reduction in hydroelectricity production. The upper-tropospheric vortices, which moved from the Atlantic Ocean into the continent in Northeast Brazil, blocked the passage of frontal systems and the formation of the South Atlantic Convergence Zone. The study of 118 years of precipitation, between 1890 and 2007, in the city of Campinas, Sao Paulo, by Blain and Kayano (2011) also found a SPI12 of almost − 3.0 for the 2000/2001 hydrological year, which was one of the dryest recorded at the time. In the city of Sao Paulo, Vicenteserrano et al. (2010) also pointed out the impacts of the 2000/2001 drought in the city.

The coffee productivity has a biannual cycle, as floweryng is limited by the higher production of the previous year (DaMatta 2004). Because of that, the 2013/2014 productivity was supposed to be higher than 2012/2013 hydrological year. However, extensive effects of the drought in 2013/2014 hydrological year resulted in the decrease of the productivity in 15.88% when compared to the Brazilian.were ever more severe. In 2014/2015 hydrological year, the energy generation reached its lowest value (1.7 GW), which represents a reduction of 26.1% of the period average. As a result of the 2013/2014 drought, reservoir levels were reduced by almost 80% of the normal value.

Furnas hidropower plant is one of the most important plants in Brazil. In the hydrological year of 2001/2002, it was responsible for 9.17GW of energy production. However, the impacts of the droughts between 2013 and 2015

Southern Minas Gerais has 155 cities. In Fig. 3, one can assess the driest period in each city through two different perspectives: (a) dividing the period in 5 years and (b) dividing the period in 10 years. Importantly, the 1970–1974 spam was the driest observed in the region for 52.9% of the cities, while 2010–2014 and 2015–2019 were the driest for 37.4 and 9.7% of the cities, respectively. However, assessing a 10-year period span, the 2010–2019 was the driest for 94.5% of the cities (Fig. 3b). Thus, this behavior may indicate a shift in the climate of the region, which is becoming more susceptible to severe droughts.

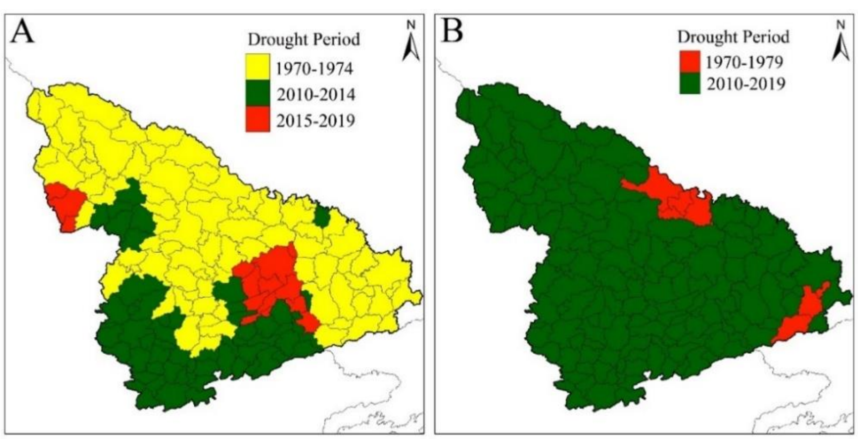

Figure 3. Spatial pattern of occurrence driest periods: a) 5 years spam; b) 10 years spam

3.2.RCM simulation performance

Figure 4 shows the average precipitation of the hydrological years between 1970/1971 and 2004/2005 hydrological years from the observed data and the RCMs. The “baseline” (or present time) represents the period when the models are run without the greenhouse gases increment.

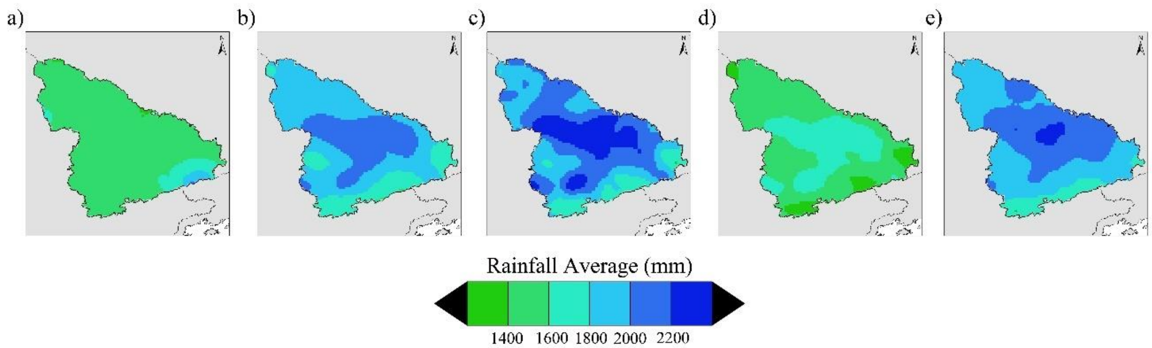

Figure 4. Mean annual precipitation (mm/year) of the hydrological years in southern Minas Gerais from 1970 to 2005 (a); and simulated by the RCMs Eta-BESM (b) Eta-CanESM2 (c), Eta-HadGEM2-ES (d) and Eta-MIROC5 (e).

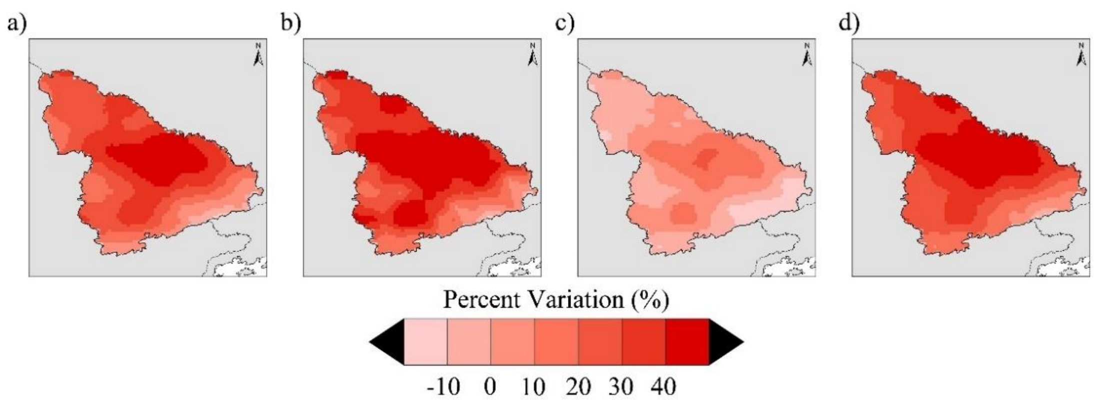

Figure 5. Differences between the observed and simulated precipitation for the hydrological years in the period of 1970/2005: a) Eta-BESM b) Eta-CanESM2; b) Eta-HadGEM2-ES; c) Eta-MIROC5.

Figure 5 shows the percentage of variation between the estimated and the observed average precipitation data. The annual average observed precipitation in the present period is 1522.1 ± 150.7 mm, and the simulated values were 1914.5 ± 133.7 mm, 2034.8 ± 174.1 mm, 1536.4 ± 101.2 mm, and 1982.7 ± 125.4 mm, by the Eta-BESM, Eta-CanESM2, Eta-HadGEM2-ES, and Eta-MIROC5, respectively.

The comparison between the Baselines and observed data have shown that, in general, the models tends to overestimate precipitation from 1970 to 2005. The Eta-HadGEM2-ES, however, produced values closer to the observed ones, and the lowest variability in the precipitation spatial distribution. Evaluating the performance of Eta-BESM, Eta-HadGEM2-ES and Eta-MIROC with observed precipitation between 1961 and 1990, Chou et al. (2014a) observed a higher spatial correlation with Eta-HadGEM2-ES when compared to other RCMs. The authors also observed that Eta-MIROC can simulate precipitation in the wettest months (December to February), but overestimate it in the dryest months (June to August), which might justify the high variability observed in Fig. 3.

Futhermore, Alemseged and Tom (2015), evaluating the performance of the climate models between 1981 and 2000 in the Upper Blue Nile basin, found that CanESM2 simulations showed the least accuracy relative to HadGEM2-ES and MIROC5, with differences up to 50%, similar to this study. These finding agree with Blazquez and Silvina (2020) for South America.

3.3. Projections of extreme droughts in southern Minas Gerais state, Brazil

Table 1 shows the average precipitation of the hydrological years projected by the RCMs divided into four different periods: baseline, 2011–2040, 2041–2070, and 2071–2099 (Chou et al 2014a, b a,b). Comparing the future periods with the baseline, Eta-HadGEM2-ES simulates a precipitation decrease in both RCPs and in all time slices. In the Eta-CanESM2 and Eta-BESM, the reduction of precipitation is stronger in the RCP 8.5, reaching 43.1% and 34.6%, respectively. For the Eta-MIROC5, however, precipitation increases 9.3% in RCP8.5 in the end of the century, suggesting a future climate different from the other models. Since Eta-HadGEM2-ES performed better than the other RCMs (Figs. 4 and 5), its projections should be considered more reliable for southern Minas Gerais state.

Regional Model	Baseline	RCP	2011 - 2040	2041 - 2070	2071 - 2099
Eta-BESM	1914.5 ± 133.7	4.5	1508.3 ± 86.3	1515.9 ± 83.3	1547.1 ± 87.6
		8.5	1655.9 ± 87.1	1488.3.8 ± 78.9	1251.5 ± 63.3
Eta-CanESM2	2034.8 ± 174.1	4.5	1920.8 ± 199.3	1729.6 ± 172.7	1770.4 ± 185.3
		8.5	1893.3 ± 200.6	1601.0 ± 159.0	1156.8 ± 122.7
Eta-HadGEM2-ES	1536.4 ± 101.2	4.5	1034.7 ± 87.6	1243.9 ± 108.0	1243.3 ± 106.7
		8.5	984.9 ± 191.6	1169.0 ± 114.2	1020.4 ± 95.1
Eta-MIROC5	1982.7 ± 125.4	4.5	1916.6 ± 149.3	1729.6 ± 172.7	1770.4 ± 185.3
		8.5	1788.0 ± 128.7	2047.9 ± 194.1	1880.3 ± 141.2

Table 1. Average precipitation for the hydrological years (mm/year) projected by the RCMs for southern Minas Gerais state, Brazil.

Figure 6 shows the projected droughts in southern Minas Gerais under Eta-HadGEM2-ES simulations. In 90 years of simulations under RCP 4.5 (Fig. 6a), three extremely dry events (SPI < -2) can be highlighted (2016/2017, 2059/2060, and 2067/2068). The first two decades of simulation should be evaluated. Several and consecutive events were simulated, making the 2010s and 2020s the driest decades in the simulation. Furthermore, moderate droughts ($-1.0 < SPI < -1.5$) should occur once every 10 years; however, projections show that its recurrence may increase with at least 8 events up to 2030. Thus, this scenario can indicate a possible repetion of the 2013–2017 period observed in southern Minas Gerais. After 2050, the number of drought events based on RCP4.5 are drastically reduced.

Figure 6b shows the SPI12 for RCP8.5 projected by Eta-HadGEM2-ES. In this scenario, greenhouse gases increments are simulated from the begining of the XXI century until the end, while in RCP 4.5 the gases increment goes until 2050. These differences between the scenarios, however, are not so well observed. As noted in RCP4.5 (Fig. 6a), the severe droughts are projected in consecutive years in the first two decades with random intense drought events in the rest of the century. The absence of intense droughts between 2040 and 2060s may be explained observing Table 1, where both scenarios simulate an increase in the average precipitation in the period. According to Chou et al. (2014a, b), the Eta-HadGEM2 projects severe reduction of precipitation in the center-south of Brazil in the end of the century, which includes southern Minas Gerais. In this work, however, this reduction did not reflect in the severity of the droughts, which was more common in the beginning of the projections.

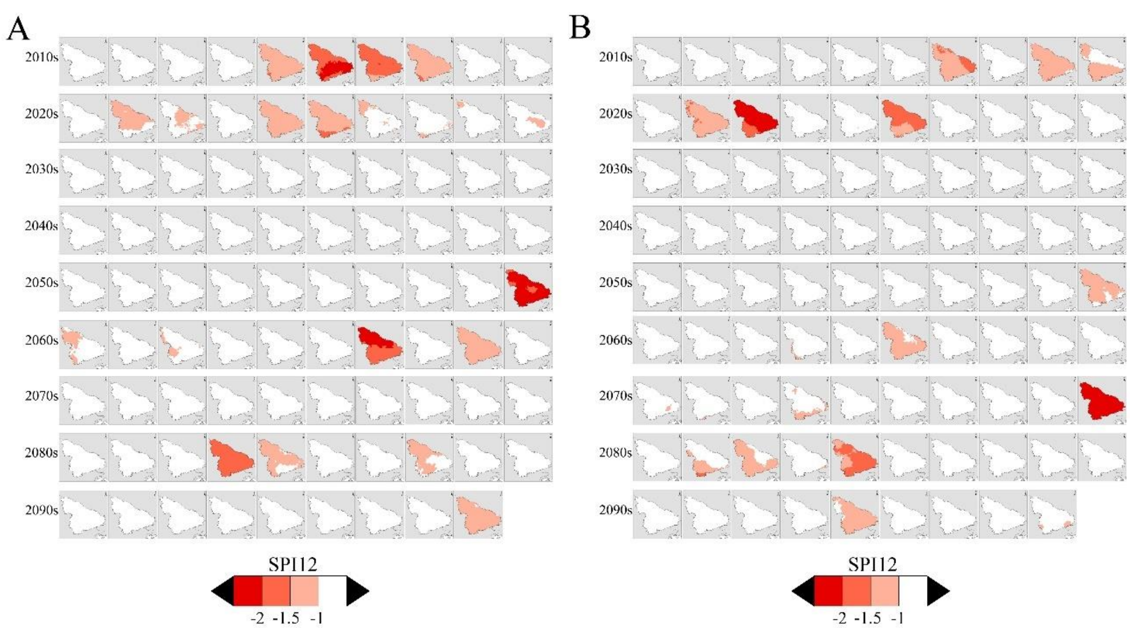

Figure 6. Annual maps of the SPI12 projected by the Eta-HadGEM2-ES for RCP4.5 (A) and RCP8.5 (B).

Differently from Eta-HADGEM2-ES, Eta-MIROC5 (Fig. 7) shows different SPI12 behaviors between RCP4.5 and RCP 8.5. Observing the simulated droughts in Fig. 6b, three decades can be highlighted, 2020s, 2030s, and 2040s. In these periods, consecutive and sequencial events were simulated. Extremely dry events are scarcely observed in 2027/2028, 2032/2033, and 2092/2093, and in almost all region in 2098/2099.

For Eta-MIROC5 droughts projection in RCP8.5 (Fig. 7b), it is possible to observe a concentration of the droughts before 2040. Besides, no extremely dry events were simulated. This find may be explained for the increase in the precipitation amount due to the intensification of the SACZ in the region (Chou et al 2014b). These authors also observed an intenfication of precipitation between December and February, indicating that the wet season may become even wetter.

To assess the possible impacts on streamflow and hydropower potential in the upper Grande River Basin under climate change scenarios, Oliveira et al. (2017) found similar results for Eta-HadGEM2-ES and for Eta-MIROC5. The latest projected precipitation increase, which led to less drought events or less severe events in the future. Otherwise, the reduction of precipitation followed by the increase of drought events can lead to the reduction in hydroelectricity production by up to 58.6% in the end of the twenty-first century.

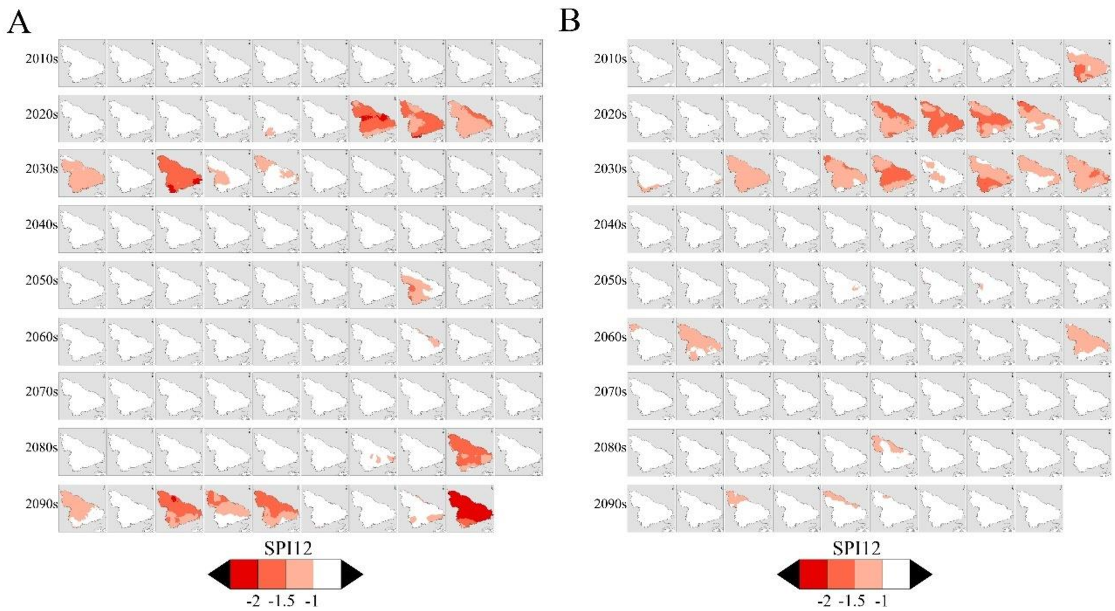

Figure 7. Annual maps of the SPI12 projected by the Eta-MIROC5 for the RCP4.5 (A) and RCP8.5 (B).

Figure 8a depicts the SPI12 projected by Eta-CanESM2-ES RCP4.5. In the 90 years of simulations, only 1 year had an extremely drought in almost all the region (2070/2071). Different from Eta-MIROC5 and Eta-HadGEM2-ES RCP4.5, several consecutive dry years were not projected until the second half of the twenty-first century. A study of the change of land use using CanESM2 projected a decrease of Leaf Area Index (LAI) until 2100 for southern Minas Gerais (Hua et al. 2015), which could contribute to the increase of 0.2 °C in the region. Changes in land use associated with deforestation and increase of greenhouse emissions can lead to consecutive droughts as simulated during the 2060s and early 2070s.

Figure 8b shows the SPI12 projected by Eta-CanESM2, under RCP8.5. Until the 2050s, scarcely drought evens were simulated. After this point, and specially, in the 2080s and 2090s, all the years were dry, indicating a possible megadrought (Cook et al. 2007; Garreaud et al., 2017), which might lead to a decrease in runoff, a decrease in crop production, a decrease in hydroelectricity generation, and several social-economic problems for the region.

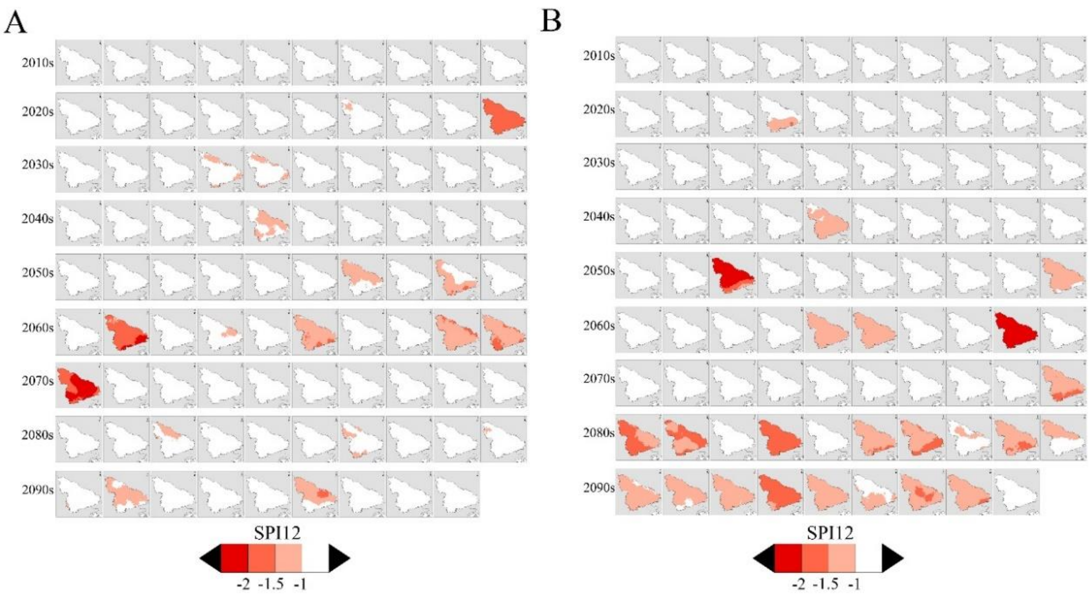

Figure 8. Annual maps of the SPI12 projected by the Eta-CanESM2 for RCP4.5 (A) and RCP8.5 (B).

Based on the Eta-BESM simulations, severe droughts events were identified for RCP4.5 (Fig. 9a) and for RCP8.5 (Fig. 9b). In RCP4.5, three extremely droughts were simulated, being concentrated in 2020s and 2030s. For these events, two were observed in consecutive years (2027/2028 and 2028/2029). The potencial damage of consecutive droughts have been discussed in Kizeková et al. (2013) and Dorman et al. (2013). According to them, long drought periods interfere in the dynamic of forests, in the soil microorganisms, and in phsysiological processes of the plants.

Differentely from RCP4.5, under RCP8.5 (Fig. 9b), few drought events were observed until the hydrological year of 2070/2071. However, the last decade is highlighted for consecutive dry years. Although the episodes are not as long as observed in Eta-CanESM2 RCP8.5 (Fig. 7b), the consequences associated with this megadroughts may potentially impact in all over the region.

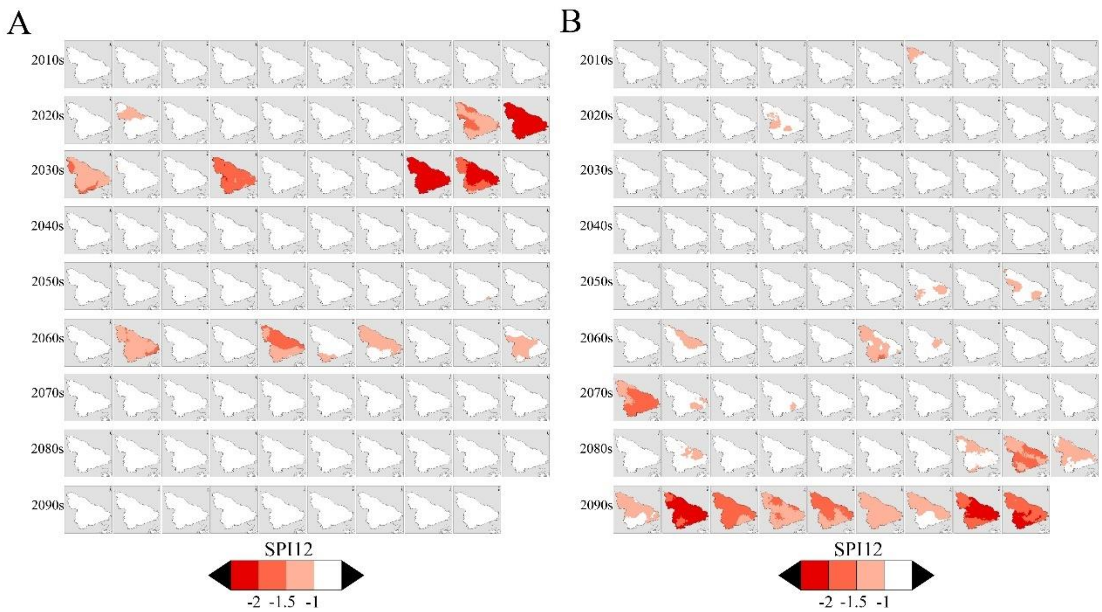

Figure 9. Annual maps of the SPI12 projected by the Eta-BESM for RCP4.5 (A) and RCP8.5 (B).

Figure 10 shows the average SPI12 for south of Minas Gerais, considering the RCMs and RCPs. The projections pointed out consecutive years of low volumes of precipitation in all runs (SPI12 < 0), which should impact the economy of the region, mainly in the hydroelectricity and coffee crop production. The reduction of approximately 20 to 23% on precipitation during three consecutive years was enough to cause the one of the worst water crisis in the southeast Brazil from 2013 to 2015 (Nobre et al. 2016). The impacts of more than 10 consecutive years with low volumes of precipitation as projected by the RCMs might cause impacts even worse than observed in recent years, impoverishing the region at an unprecedented level.

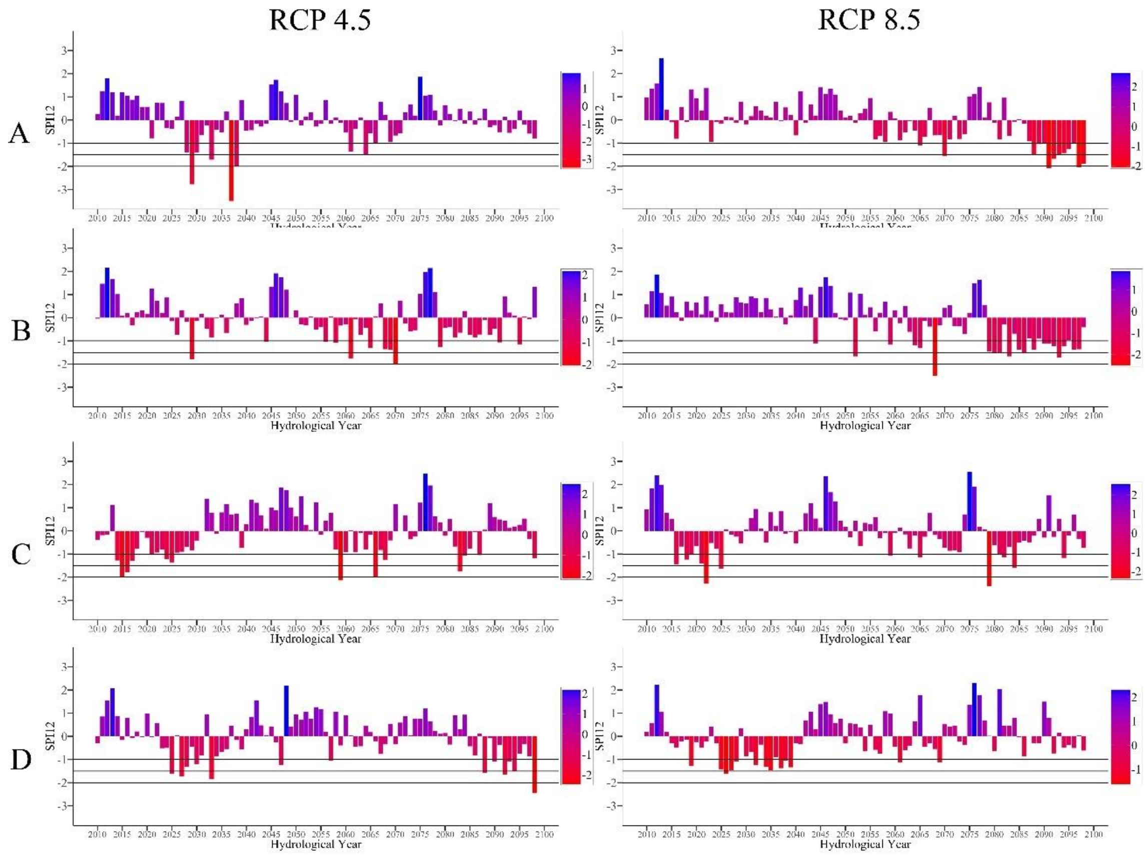

Figure 10. Mean SPI for southern Minas Gerais from 2011/2012 to 2098/2099: a) Eta-BESM b) Eta-CanESM2; c) Eta-HadGEM2-ES; d) Eta-MIROC5;

It is possible to distinguish the patterns of RCP4.5 and RCP8.5 in the Eta-BESM and Eta-CanESM2 projections. In these scenarios, most of the simulated dry events are positioned in the first half of the XXI century for RCP4.5, while for RCP8.5, they are in the second half of the century, specially in the last two decades. For Eta-MIROC5, the opposite was projected. In this case, the increase of the projected greenhouses emissions until the end of the century do not have the same impacts. The simulations under RCP4.5 concentrate the driest years in the 2020s and the 2090s, while in the RCP8.5, the dry decades were 2020s and 2030s, followed by continuous wet years. For Eta-HadGEM2-ES, the similarities in severe droughts between RCP4.5 and RCP8.5 were simulated.

Eta-CanESM2 and Eta-BESM show different pattern from the other RCMs, the most significant droughts are projected in the 2060s and 2070s for RCP4.5, and in the 2080s and 2090s for RCP8.5. In a study of effects of the climate change on hydrology and sediments in the Paranaiba River Basin, in southeast Brazil, Oliveira et al. (2019) calculated precipitation reduction of 28.1, 13.5 and 21.5% up to the end of the twenty-first century for Eta-HadGEM2-ES, Eta-MIROC5, and Eta-CanESM2, respectively, under RCP4.5 scenario. For the RCP8.5, the changes in precipitation were − 37.2, − 14.5, and 33.3%. These results may indicate drier hydrological years predicted by Eta-HadGEM2-ES. In agreement with Oliveira et al. (2017), the Eta-MIROC5 projected wetter years, showing that even when the greenhouse gases are supposed to increase (RCP8.5), such dry years tend to become more frequent in the second half of the century.

Consecutive dry years were projected by all the Eta RCM downscalings and both RCPs. The development of plans to adapt to the impacts of droughts on the regional economy are necessary. These plans are related to the water resources management, such as a threshould for groundwater explotation, a consistent policy to preserve the Atlantic Forest, and a well-controlled policy for the water allocation for the users can help prevent the impacts of continuos years of drought.

4. Conclusions

This work discusses severe meteorological droughts in southern Minas Gerais, an important economic area located in Southeast Brazil, based on the SPI index considering the hydrological year and from observational and modelling perspectives. The main conclusions are:

a) The assessment of droughts between the years 1970 and 2020 showed that the 2013/2014 hydrological year was the driest in the period. Two consecutive years with negative SPIs intensified the negative consequences of the drought over the region. This sequence of dry years caused critical volume of the main reservoirs of the region, consequently reducing the energy generation in the plants of the region and coffee crop production.

b) A 5 years spam analyze indicate that 1970-1975 was the driest period for most of South of Minas Gerais. However, a 10 years spam showed that 2011-2020 was the driest in almost all region. This shift might indicate that the region is becoming more susceptible to extreme dry events.

c) Evaluation of downscaling of four regional climate model showed that the Eta RCM driven by HadGEM2-ES simulated better the amounts and variability of the drought SPI index.

d) The future scenarios indicate that an extremely severe drought will continue to occur, however, they will be rare, with similar frequency as in observations. From all the simulations, it is expected the occurrence of two events with this intensity, indicating a similar pattern of the present. However, an increase of consecutive drought events was projected by all GCM downscaling, which can lead to serious impact on the environment, agriculture, and hydroelectricity.

e) Comparing the downscaling, the Eta-CanESM2 projected the most severe drought projections, mainly in the second half of the XXI century, with several consecutive drought years, whereas Eta-MIROC5 under RCP8.5 projected precipitation increase in southern Minas Gerais.

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References

Abu Hajar H, Murad Y, Shatanawi K, Al-Smadi B, Abu Hajar Y (2019) Drought assessment and monitoring in Jordan using the standardized precipitation index. Arabian Journal of Geosciences 12:417. doi:10.1007/s12517-019-4590-y

Alemseged T, Tom R (2015) Evaluation of regional climate model simulations of rainfall over the Upper Blue Nile basin. Atmospheric Research, 161–162: 57–64. doi:10.1016/j.atmosres.2015.03.013

Assad E, Pinto H, Zullo Junior J, Ávila A (2004) Impacto das mudanças climáticas no zoneamento agroclimático do café no Brasil. Pesquisa Agropecuária Brasileira, 39(11):1057–1064. doi:10.1590/s0100-204x2004001100001

Bárdossy A, Pegram G (2011) Downscaling precipitation using regional climate models and circulation patterns toward hydrology. Water Resources Research, 47(4):1-15. doi:10.1029/2010wr009689

Blain GC, Kayano M (2011) 118 anos de dados mensais do índice padronizado de precipitação : série meteorológica de Campinas, estado de São Paulo. Revista Brasileira de Meteorologia 26(1):137-148 doi: 10.1590/S0102-77862011000100012

Blázquez J, Silvina A (2020) Multiscale precipitation variability and extremes over South America: analysis of future changes from a set of CORDEX regional climate model simulations. Climate Dynamics https://doi.org/10.1007/s00382-020-05370-8

Bueno E, Mello C, Alves G (2016) Evaporation from Camargos hydropower plant reservoir: water footprint characterization. Revista Brasileira de Recursos Hídricos 21(3):570–575 doi:10.1590/2318-0331.011616021.

Caloiero T, Veltri S (2018) Drought assessment in the Sardinia region (Italy) during 1922–2011 using the standardized precipitation index. Pure and Applied Geophysics 176(2):925–935 doi:10.1007/s00024-018-2008-5

Cavalcanti I, Kousky V (2001) Drought in brazil during summer and fall 2001 and associated atmospheric circulation features. Climanálise 1:1-10.

Chou S, Lyra A, Gomes J, Rodriguez D, Martins M et al. 2020. Downscaling projections of climate change in Sao Tome and Principe Islands. Africa. Clim Dyn doi: 10.1007/s00382-020-05212-7

Chou S, Lyra A, Mourão C, Dereczynski C, Pilotto I (2014a) Evaluation of the eta simulations nested in three global climate models. American Journal of Climate Change 3:438–454 doi:10.4236/ajcc.2014.35039.

Chou S, Lyra A, Mourão C, Dereczynski C, Pilotto I (2014b) Assessment of climate change over South America under rcp 4.5 and 8.5 downscaling scenarios. American Journal of Climate Change 3(5):512–527 doi:10.4236/ajcc.2014.35043

Chou S, Marengo J, Lyra A, Medeiros G, Pesquero J et al (2012) Downscaling of South America present climate driven by 4-member HadCM3 runs. Climate Dynamics 38(3):635–653 doi: 10.1007/s00382-011-1002-8

Chou SC, Bustamante JF, Gomes JL. (2005). Evaluation of Eta Model seasonal precipitation forecasts over South America. Nonlinear Processes in Geophysics, 12:537–555

Coelho C., Cardoso D, Firpo M (2016) Precipitation diagnostics of an exceptionally dry event. Theoretical and Applied Climatology 125:769-784. doi: 10.1007/s00704-015-1540-9

Coelho C, Oliveira C, Ambrizzi T, Reboita M, Carpenedo C et al. (2016) The 2014 southeast Brazil austral summer drought: regional scale mechanisms and teleconnections. Climate Dynamics 46(11-12): 3737–3752. doi:10.1007/s00382-015-2800-1

CONAB (2022). Acompanhamento da Safa Brasileira: Café, Safra 2021. 8(4):1-56. ISSN: 2318-7913

CONAB (2015). Acompanhamento da Safa Brasileira: Café, Safra 2014. 8(4):1-56. ISSN: 2318-7913

Cook ER, Seager R, Cane MA, Stahle, DW. (2007). North American drought: Reconstructions, causes, and consequences. Earth-Science Reviews, 81(1-2): 93–134. doi:10.1016/j.earscirev.2006.12.002

Costa A (2011) Local patterns and trends of the standard precipitation index in southern Portugal (1940-1999). Advances in Geosciences 30:11-16. doi: 10.5194/adgeo-30-11-2011

DaMatta F (2004). Ecophysiological constraints on the production of shaded and unshaded coffee: a review. Field Crops Research 86(2-3):99–114. doi:10.1016/j.fcr.2003.09.001

Dorman M, Svoray T, Perevolotsky A, Sarris D. (2013). Forest performance during two consecutive drought periods: Diverging long-term trends and short-term responses along a climatic gradient. Forest Ecology and Management, 310:1–9. doi:10.1016/j.foreco.2013.08.009

Cunha AP, Zeri M, Leal KD, Costa L, Cuartas LA, Marengo JA, Tomasella J, Vieira RM, Barbosa AA, Cunningham C, Garcia JVC, Broedel E, Alvalá R, Ribeiro-Neto, G. 2019. Extreme Drought Events over Brazil from 2011 to 2019. Atmosphere 10(11): 642. doi:10.3390/atmos10110642

FAO. 2021. The impact of disasters and crises on agriculture and food security: 2021.

Rome. Doi:10.4060/cb3673en

Flato G, Marotzke J, Abiodun B, Braconnot P, Chou S et al. (2013) Evaluation of climate models. In: T, Qin D, Plattner G, Tignor M, Allen S et al. (eds.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 741-866. doi:10.1017/CBO9781107415324.020 ISBN: 978-1-107-66182-0

Furnas Lake Area Watershed Committee (2014) Water Crisis in Furnas Lake. http://cbhfurnas.org.br/blog.asp. Accessed 20 May 2020

FURNAS. 2021. Geração de Energia no Sistema Furnas. https://www.furnas.com.br/subsecao/120/usina-de-furnas---1216-mw?culture=pt

Garreaud RD, Alvarez-Garreton C, Barichivich J, Boisier JP, Christie D, Galleguillos M, LeQuesne C, McPhee J, Zambrano-Bigiarini M. The 2010–2015 megadrought in central Chile: impacts on regional hydroclimate and vegetation. Hydrology and Earth System Sciences, 21(12):307–6327. doi:10.5194/hess-21-6307-2017

Golnaraghi M, Etienne C, Sapir D, Below R (2014) Atlas of mortality and economic losses from weather, Climate and Water Extremes. World Meteorological Organization (WMO), Geneva 2, Switzerland

Hayes M. Drought Indices (2002). International Journal of Climatology, 23:18 doi:10.1002/joc.931.

Hölbig C, Mazzonetto A, Borella F, Pavan W, Fernandes J et al. (2018) PROJETA platform: accessing high resolution climate change projections over Central and South America using the Eta model. Agrometeoros 26(1):71-81.

Holmes A, Rüdiger C, Mueller B, Hirschi M, Tapper N (2017) Variability of soil moisture proxies and hot days across the climate regimes of Australia. Geophysical Research Letters 44(14):7265–7275. doi: doi:10.1002/2017gl073793

Hua W, Chen H, Sun S, Zhou L (2015). Assessing climatic impacts of future land use and land cover change projected with the CanESM2 model. International Journal of Climatology, 35(12):3661–3675. doi 10.1002/joc.4240

Imbach P, Chou S, Lyra A, Rodriguez D , Rodrigues D et al. (2018) Future climate change scenarios in Central America at high spatial resolution. PLOS ONE 13(4) doi:10.1371/journal.pone.0193570

Jemai S, Kallel A, Abida H (2018) Drought distribution using the standardized precipitation index: case of Gabes Basin, South Tunisia. Arabian Journal of Geosciences 11(23):737. doi:10.1007/s12517-018-4053-x

Jiao W, Tian C, Chang Q, Novick K, Wang L. (2019) A new multi-sensor integrated index for drought monitoring. Agricultural and Forest Meteorology 268:74-85. doi: 10.1016/j.agrformet.2019.01.008

Kendall M (1975) Rank Correlation Methods. Oxford University Press, New York

Kizeková M, Tomaškin J, Čunderlík J, Jančová L, Martincová J. (2013) The yield stability and quality of legumes during two consecutive, extremely dry years. Agriculture (Pol'nohospodárstvo) 59.4 (2013): 167-177. doi: 10.2478/agri-2013-0015

Li J, Wang Y, Li S, Hu R (2015) Nonstationary Standardized Precipitation Index incorporating climate indices as covariates. Journal of geophysical research, 120(12):82–95. doi:10.1002/2015jd023920

Liu X, Xu Z, Liu B (2009) Spatio-temporal characteristics of standardized precipitation index in the Taihu basin during 1951-2000. Wuhan University Journal of Natural Sciences, 14(6):518–524. doi:10.1007/s11859-009-0611-0

Livada I, Assimakopoulos V (2006) Spatial and temporal analysis of drought in Greece using the Standardized Precipitation Index (SPI). Theoretical and Applied Climatology, 89(3):143–15. doi: 10.1007/s00704-005-0227-z

Lyra A, Tavares P, Chou S, Sueiro G, Dereczynski C, et al. Climate change projections over three metropolitan regions in Southeast Brazil using the non-hydrostatic Eta regional climate model at 5-km resolution. Theoretical and Applied Climatology, 132(1-2):663–682. doi:10.1007/s00704-017-2067-z

Mahmoudi P, Rigi A, Miri kamak M (2019) A comparative study of precipitation-based drought indices with the aim of selecting the best index for drought monitoring in Iran. Theoretical and Applied Climatology, 137:3123–3138. doi:10.1007/s00704-019-02778-z

Mallya G, Zhao L, Song X, Niyogi D, Govindaraju R (2013) 2012 Midwest drought in the United States. Journal of Hydrologic Engineering, 18(7):737–745. doi:10.1061/(asce)he.1943-5584.0000786

Mann, S (1945) Nonparametric Tests Against Trend. Econometrica, 13(3): 245–259

Marengo J, Nobre C, Seluchi M, Obregón G; Sampaio G et al. (2015). A seca e a crise hídrica de 2014-2015 em São Paulo. Revista USP, 106:31–44, 2015. Doi: 10.11606/issn.2316-9036.v0i106p31-44

Marengo J, Tomasella J, Alves L, Soares W, Rodriguez D (2011) The drought of 2010 in the context of historical droughts in the Amazon region. Geophysical Research Letters, 38(12):1-5. doi:10.1029/2011gl047436

Mckee B, Doesken N, Kleist J (1993) The relationship of drought frequency and duration to time scales. Eighth Conference on Applied Climatology, 17–22

Mesinger F, Chou SC, Gomes JL, Jovic D, Bastos P, Bustamante JF, Lazic L, Lyra AA, Morelli S, Ristic I, Veljovic K. (2012) An upgraded version of the Eta model. Meteorology and Atmospheric Physics. Vol 116 (3), 63-79. DOI: 10.1007/s00703-012-0182-z

Mesinger F, Veljovic K, Chou S, Gomes J, Lyra A (2016) The Eta Model: Design, Use, and Added Value. Topics in Climate Modeling, 2016. InTech doi:10.5772/64956

Ministry of Science, Technology and Inovation (2016) Executive Summary: Third national communication of Brazil to the united nations framework convention on climate change. Brasilia, DF

Mondol M, Ara I, Das S (2017) Meteorological Drought Index Mapping in Bangladesh Using Standardized Precipitation Index during 1981-2010. Advances in Meteorology 2017:1-17. doi: 10.1155/2017/4642060

Nobre C, Marengo J, Seluchi, M, Cuartas A, Alves L (2016) Some Characteristics and Impacts of the Drought and Water Crisis in Southeastern Brazil during 2014 and 2015. Journal of Water Resource and Protection, 8(2):252–262. doi: 10.4236/jwarp.2016.82022

Okpara J, Afiesimama E, Anuforom A, Owino A, OgunjobI K (2017) The applicability of Standardized Precipitation Index: drought characterization for early warning system and weather index insurance in West Africa. Natural Hazards, 89(2):555–583. doi: 10.1007/s11069-017-2980-6

Oliveira V, Mello C, Beskow S, Viola M, Srinivasa R. (2019). Modeling the effects of climate change on hydrology and sediment load in a headwater basin in the Brazilian Cerrado biome. Ecological Engineering, 133:20–31. doi: 10.1016/j.ecoleng.2019.04.021

Oliveira V, Mello C, Viola M, Srinivasan R (2017) Assessment of climate change impacts on streamflow and hydropower potential in the headwater region of the Grande river basin, Southeastern Brazil. International Journal of Climatology, 37(15):5005–5023.

Pesquero J, Chou S, Nobre C, Marengo J (2010) Climate downscaling over South America for 1961-1970 using the Eta Model. Theoretical and Applied Climatology. 99(1-2):75-93. doi: 10.1007/s00704-009-0123-z

Rahmat S, Jayasuriya N, Bhuiyan M (2012) Trend analysis of drought using Standardised Precipitation Index (SPI) in Victoria, Australia. In: 34th Hydrology & Water Resources Symposium. 19-22 Sydney, Australia.

Rodrigues N, Reis E, Tavares M (2014) Influências dos fatores climáticos no custo de produção do café arábica. Custos e Agronegócio online, 10(3):216–255

Russo A, Gouveia C, Páscoa P, Dacamara C, Sousa P et al (2017) Assessing the role of drought events on wildfires in the Iberian Peninsula. Agricultural and Forest Meteorology, (237-238):50–59. doi: 10.1016/j.agrformet.2017.01.021

Silva V, Mello C (2021) Meteorological droughts in part of southeastern Brazil: Understanding the last 100 years. Annals of the Brazilian Academy of Sciences. 93(4). Doi:10.1590/0001-3765202120201130

Silva W, Dereczynski C, Chou S, Cavalcanti I (2014) Future Changes in Temperature and Precipitation Extremes in the State of Rio de Janeiro (Brazil). American Journal of Climate Change, 3(4):353–365. doi: 10.4236/ajcc.2014.34031.

Skansi M, Brunet M, Sigró J, Aguilar E, Groening J et al. (2013) Warming and wetting signals emerging from analysis of changes in climate extreme indices over South America. Global and Planetary Change, 100:295–307. doi: 10.1016/j.gloplacha.2012.11.004

Sobral B, Oliveira-Júnior J, Gois G, Pereira-Junior E, Terassi P, et al. (2019) Drought characterization for the state of Rio de Janeiro based on the annual SPI index: trends, statistical tests and its relation with ENSO. Atmospheric Research, 220:141–154. doi: 10.1016/j.atmosres.2019.01.003

Stagge J, Tallaksen L (2014) Standardized precipitation-evapotranspiration index (SPEI): Sensitivity to potential evapotranspiration model and parameters. International Association of Hydrological Sciences (IAHS), 10:367–373

Sobral BS, Oliveira-júnior JF, Gois G, Pereira-júnior ER, Terassi P MB, Muniz-júnior JGR, Lyra GB & Zeri M. 2019. Drought characterization for the state of Rio de Janeiro based on the annual SPI index: trends, statistical tests and its relation with ENSO. Atmosphere Research (220): 141-154.

Strzepek K, Yohe G, Neumann J, Boehlert B (2010) Characterizing changes in drought risk for the United States from climate change. Environmental Research Letters, 5(4):1-9 doi:10.1088/1748-9326/5/4/044012

Vergni L, Di Lena B, Todisco F, Mannocchi F (2017) Uncertainty in drought monitoring by the Standardized Precipitation Index: the case study of the Abruzzo region (central Italy). Theoretical and Applied Climatology, 128(1-2):13–26. doi:10.1007/s00704-015-1685-6

Vicente-serrano, S, Beguería S, López-Moreno J (2010) A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. Journal of Climate, 23(7):1696–1718. American Meteorological Society. doi:10.1175/2009JCLI2909.1

Vicente-Serrano S, Miralles D, Domínguez-Castro F, et al. Global Assessment of the Standardized Evapotranspiration Deficit Index (SEDI) for Drought Analysis and Monitoring. Journal of Climate 31(14):5371–5393 https://doi.org/10.1175/JCLI-D-17-0775.1

World Meteorological Organization, Global Water Partnership (2016). Handbook of drought indicators and indices. Geneva, Switzerland

World Meteorological Organization (2012) Standardized Precipitation Index User Guide. Geneva, Switzerland, 2012.

Wu J, Chen X, Yao H, Gao L, Chen Y, Liu M (2017) Non-linear relationship of hydrological drought responding to meteorological drought and impact of a large reservoir. Journal of Hydrology 551:495-507. doi: 10.1016/j.jhydrol.2017.06.029

Xu Y, Zhang X, Hao Z, Hao F, Li C. (2021). Projections of future meteorological droughts in China under CMIP6 from a three-dimensional perspective. Agricultural Water Management, 252-106849. doi:10.1016/j.agwat.2021.106849

Yang JX.; Lijuan XC, Youmin W (1997) Research on determination of station indexes and division of regional flood/ drought grades in china. Quartely Journal of Applied Meteorlogy, 8(1):26–33.

Yusof F, Hui-Mean F, Suhaila J, Yusop Z, Ching-Yee K (2014) Rainfall characterisation by application of standardised precipitation index (SPI) in Peninsular Malaysia. Theoretical and Applied Climatology, 115(3-4):503–516. doi:10.1007/s00704-013-0918-9

Zargar A, Sadiq R, Naser B, Khan F (2011) A review of drought indices. Environmental Reviews 19(1):333-349. doi:10.1139/a11-013

Zeng N, Yoon J, Marengo J, et al. Causes and impacts of the 2005 Amazon drought. Environmental Research Letters, 3(1)1-17. doi: 10.1088/1748-9326/3/1/014002

ARTICLE2- EVALUATING EXTREME METEOROLOGICAL DROUGHTS CHARACTERISTICS OVER THE PANTANAL BIOME USING CRU AND RCM PRODUCTS

Os autores submeterão o artigo na revista Ecological Indicators, sendo apresentado segundo normas de publicação do mesmo.

Evaluating extreme meteorological droughts characteristics over the Pantanal Biome using CRU and RCMs products

Abstract

The Brazilian Pantanal is one of the most important ecosystems in the world. Being a shelter for thousands of animals and plants, its complexity and specificity made him unique. In 2019 and 2020, Pantanal has suffered a long and severe drought that has spread disaster in the region. The negative anomaly of the rainfall associated with high temperatures has brought many fires responsible for destruction of thousands hectares. This study compares two drought indexes, the Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI) and evaluates their performance to identify historic droughts in the Pantanal region through the Climate Research Unit datasets. Also, the severity of droughts was projected up to 2098/2099 using two RCM ensembles, from "Projeta" project (BESM, CanESM2, HadGEM2-ES, and Eta-MIROC5) and the CORDEX project (CSIRO, IPSL-CM5A, GDFL, NorEMS1) under two Representative Concentration Pathways, RCP4.5 and RCP8.5. The results demonstrated that in 80 years of observed data, the hydrological year of 2019/2020 was the driest observed in Pantanal. However, the 1960s decade proved to be the worst. Future projections indicate different results from SPI and SPEI. Eta ensemble did not project extreme events both RCPs, while for the CORDEX ensemble, most of the extreme drought events are concentrated until the 2040s in both scenarios. For SPEI, the results are similar for both ensembles, with a concentration of extreme dry events towards the end of the XXI century. The increments of greenhouses, and consequently, the increase of the temperature, had an impact on SPEI and the concentration of extreme drought events. We recommend the use of simulated SPI to help decision-makers and stockholders in detection of drought anomalies in short term and SPEI for long-term analyses.

1. Introduction

The Brazilian Pantanal region is one of the largest tropical wetlands in the world with approximately 150 thousand Km². It is located in the center of South America, in western Brazil's Upper Paraguay River Basin (UPRB). Most of its territory is in the Mato Grosso do Sul state, extending to the Mato Grosso state. As a wetland ecosystem, Pantanal is the shelter of thousands of species that are adapted to the annual shifts between wet and dry seasons. Due to its complexity and specificity, a great number of animals and plants can survive with almost no competition (Alho et al., 2012). Also, the presence of many environments such as open water, ground, perennial, and floating vegetation make the Pantanal a unique biome in Brazil and in the world (Pott et al., 2011).

The rainfall patterns in the Upper Paraguay River Basin, where the Pantanal is inserted, are modulated for the South America Summer Monsoon (Marengo et al, 2010). Trade winds combined with the vapor flux from the equatorial Atlantic Ocean are the main sources of the Amazon basin rivers, which play an important role for the climate of South America (Bergier et al 2018). The annual average precipitation in Pantanal is approximately 1300 mm, and the rainfall is highly seasonal, occurring, mainly, between October and March.

Wetlands are critical environments that provide services earning billions of dollars (Ivory et al., 2019). From fish production, fruits, and grains to storage water, to regulate greenhouse gases, temperature, and precipitation, to groundwater recharge, the wetlands play a significant role in South America (De Groot et al., 2006). Only in the United States, wetlands have saved $625 Million in direct flood damages during Hurricane Sandy (Narayan et al., 2017). However, in recent years wetlands have been suffering damage and losses due to their rapid urbanization and agriculture. In China, in the last 20 years, 2,883 Km² of wetlands were lost to urban expansion (Mao et. al, 2018), while Europe has lost 45% of its wetland (Hu et al., 2017).

The Pantanal flora is constituting nearly 2000 species, whereas at least 280 species are aquatic macrophytes (Pott et al., 2011). The annual cycle of rainfall has a straight impact in the Pantanal Flora. Aquatic plants, for example, respond well to the flood dynamics. Wetland plants have adapted to the water-level season fluctuation, which results in stable or climax communities with shifts in species dominance (Catian et al., 2018).

Drought is a complex phenomenon that impacts natural and urbanized environments and socioeconomic systems in the world (Peng et al., 2020). Generally, is defined as a temporal anomaly from the mean climate for a certain region and represents a shortage of water resulting from below-average precipitation, high temperature, or both (Clark et al., 2016). Drought can typically be divided into meteorological (negative anomaly of precipitation), agricultural (soil moisture deficiency), hydrological (negative anomaly of runoff and/or groundwater), socioeconomic (social response to water supply and demand), and environmental or ecologic (Peng et al., 2020, AghaKouchak et al., 2015)

Due to its complexity, there is not a best drought index for all types of droughts. Every index is designed for a specific drought type, thus every index changes in its complexity and objective (Van Loon, 2015). The Standardized Precipitation Index has been capable of modeling the frequency of droughts, as well as their duration and occurrences throughout the time (WMO, GWP, 2016). This index is suggested by the World Meteorological Organization as the main statistical indicator because of its simplicity and wide range of applications to study drought and wet events (Hayes, 2002). The main SPI features are: (i) only precipitation data is required, becoming it wider than other indexes that require further detailed meteorological data; (ii) is adapted to several time scales (monthly, wet and dry summer periods, winters, etc.); (iii) can be used to understand the hydrology, the weather and their impacts; (iv) allow to compare droughts in different regions, regardless the climate pattern (Zargar et al., 2011).

For only accounting precipitation in its calculations, SPI accuracy can be smaller when compared to other indexes. Adding the atmospheric evaporative demand (Precipitation – Evapotranspiration), Vicente-Serrano et al. (2010), proposed an alternative drought index for SPI, which is called Standardized Precipitation-Evapotranspiration Index (SPEI). For its calculations, high quality and long-term observations of precipitation and temperature are necessary. The Thornthwaite method is suggested by Vicente-Serrano et al. (2012) for potential evapotranspiration estimates as it only considers the average monthly temperatures instead of other meteorological variables. Similar results for SPEI were found when both the Thornthwaite and Penman-Monteith methods were applied, thus, justifying the use of the former method, mainly for regions with minimum monitoring in terms of climate variables (Begueria et al. 2014, McEvoy et al. 2012).

To understand how climate change can affect the planet, climate projections have been made by the Global Climate Models (GCM). These models simulate the climate using complex numerical simulations of equations of the chemical, physical, and biological atmosphere to estimate how greenhouse gas emissions influence the planet's climate (Chou et al., 2014). However, the GCMs outputs cover a coarse resolution (~300 Km). Thus, their applicability to basins or specific regions with compatible resolutions (5 km; 20 km; 40 km) is not recommended (Silva and Mello, 2021). Therefore, a downscaling technique is needed to regionalize the GCMs outputs. In this context, the Eta model (Black, 1994; Chou et al., 2014; Mesinger, 1984; Mesinger et al., 2016), improved by the National Institute for Space Research (INPE) and nested to the GCMs to run future climate projections over almost all South America in horizontal resolutions of 20 km (Chou et al.

2014), and the Coordinated Regional Climate Downscaling Experiment (CORDEX - https://cordex.org/) models are being used to drought-related studies.

Due to the severity of the event observed in Pantanal through the 2019/2020 hydrological year, it is indispensable to detail how the droughts behaved in the past, which can be relevant to subsidize climate change studies. Thus, our goal is to answer the following questions: (i) was the drought observed in 2019/2020, the worst observed in the last 80 years? (ii) is it possible that an event with that magnitude happens again in the future? (iii) how relevant are RCMs data for decision-makers in Brazil? These questions are relevant to understanding the climatology of droughts, which will allow improving the comprehension of this phenomenon in tropical regions, as well as support the prediction of the behavior of droughts in Pantanal throughout the XXI Century

1. **Materials and Methodology**

2.1 Study Area

This study focused on the Pantanal biome (Figure 1). Pantanal falls within the latitudes 15^o and 23^o S and longitudes 54^o and 60^o W. In Brazil, it is located in the states of Mato Grosso do Sul (MS; 65%) and Mato Grosso (MT; 35%). Based on CRU datasets, Annual Average Precipitation was calculated in 1300 mm, ranging from 1023 mm in the East to 1481 mm in the Southwest. Also, the annual temperature ranges from 21.2^o C in July to 28^o C in December with annual average evapotranspiration of 1623 mm, which ranges from 1371 mm in the south to 1736 mm in the north. The Pantanal has two well-defined seasons, a rainy and a dry one. However, from a hydrological perspective, four seasons can be identified Flooding (January-March), limb recession (April-June), drought (July-September), and rising water (October-March) (Almeida et al., 2015). The first one takes place when Pantanal's area progressively get flooded; the second one happens when the rainy season is ended and the flows start reduced; the third represents the time of the year when the rainfall is almost absent, and the vegetation is dry; the fourth indicates that the rainfall is returning, and the wetland is preparing to get flooded again.

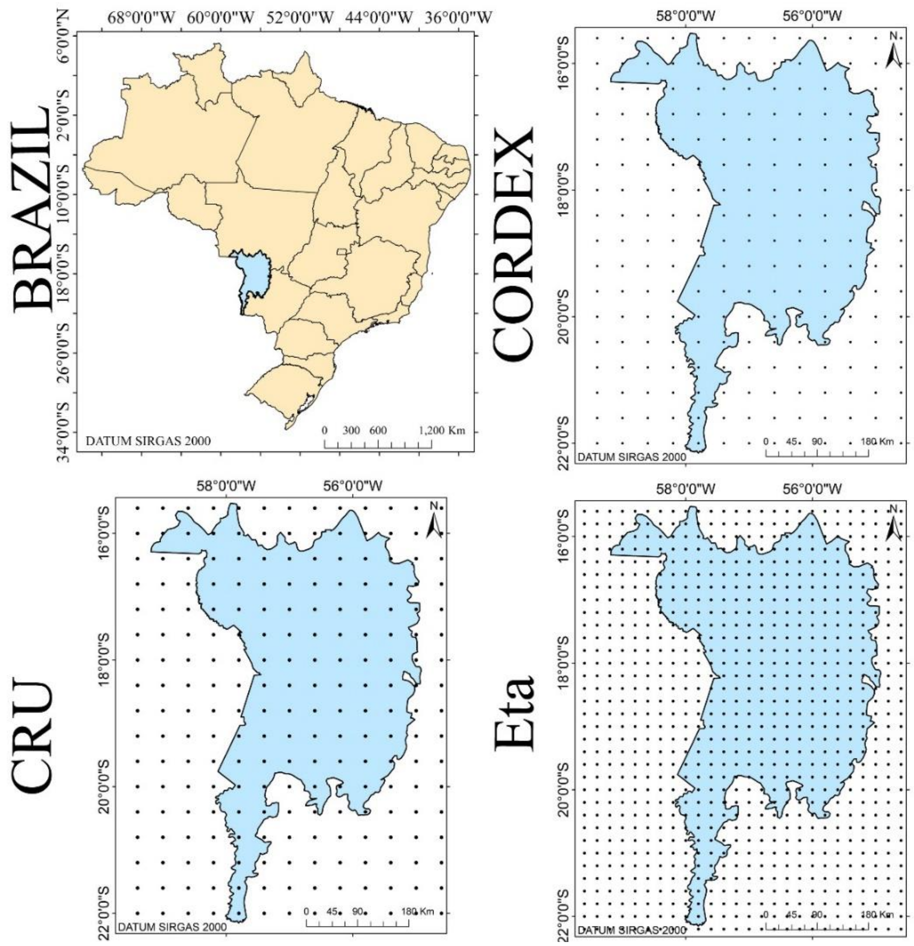

Fig 1. Geographical location of Pantanal biome in Brazil, and CRU, CORDEX, and Eta grid points

2.2 Observed Dataset

Observed and simulated datasets were used in this study. During the summer rainy season, the rivers overflow Pantanal banks and flood their low lands, inundating as much as 70% of the floodplain (Marengo et al., 2015). Thus, the local meteorological monitoring is scarce and, when available, presents gaps that don't allow using it. For this reason, the observation dataset used in this study was retrieved from the global gridded climatology of the Climate Research Unit (CRU TSv.4.06; https://www.uea.ac.uk/groups-and-centres/climatic-research-unit; Harris et al., 2014). The latest version of CRU (Fig 1) datasets covers the entire land surface from 1901 to 2020 with a monthly temporal resolution and lateral resolution of 0.5º x 0.5º. To minimize uncertainties resulting from the low numbers of weather stations, in this study, the period of evaluation was constrained between 1940 and 2020. Monthly rainfall and temperature datasets were grouped in hydrological years, i.e., the former was summed up and the latter was averaged.

To provide a data validation between CRU and observational data, four INMET meteorological stations inside or near the biome were used. The closest data point from the meteorological station was chosen from the CRU grid point. No observational data were observed beyond 1970, thus the validation was made comparing data from this year until 2020.

2.3 Projections of climate change for Pantanal biome

For the purposes of this study, we used simulated datasets downscaled by Swedish Meteorological and Hydrological Institute (SMHI) for Atmospheric Regional Climate Model (RCA4-RCM; Popke et al. 2013) and by Eta/CPTEC model (Pesquero et al. 2010, Chou et al. 2012, Marengo et al. 2012). RCA4 data were obtained from the CORDEX project (https://cordex.org/) at a horizontal resolution of 0.44º x 0.44º over Pantanal. Eta model outputs were obtained from the "Projeta" project from CPTEC/INPE (projeta.cptec.inpe.br) at a horizontal resolution of approximately 0.2º x 0.2º (20 Km). The models' outputs used in this study consist of monthly temperature and precipitation over the historical period (1961-2005) and projection period (2011-

2100) under two different emission scenarios of RCP 4.5 and RCP 8.5. In Table 1, it is listed four ensemble members of the CORDEX project and four members of the Eta model.

Table 1. List of GCMs and RCMs considered in this study. (Annex)

GCM Run	GCM Institute	Reference	RCM Institute	Institute	Historical	RCP 4.5	RCP 8.5
BESM[1]	National Institute for Space Research (INPE)	Nobre et al., 2013	Eta	INPE	1961 -2005	2006-2099	2006-2099
CanESM2[2]	CCCma (Canadian Centre for Climate Modeling and Analysis, Victoria, BC, Canada)	Chylek et al., 2011; Arora et al., 2009	Eta	INPE	1961 -2005	2006-2099	2006-2099
MIROC5[3]	Centre for Climate System Research (Kashiwa, Japan) Atmosphere and Ocean Research Institute, The University of Tokyo, (Kashiwa, Japan)	Watanabe et al., 2010	Eta	INPE	1961 -2005	2006-2099	2006-2099
HadGEM2-ES[4]	MOHC(Met Office Hadley Centre for Climate Science and Services, Exeter, United Kingdom)	Collins et al., 2011	Eta	INPE	1961 -2005	2006-2099	2006-2099
CSIRO-Mk3.6.0	CSIRO (Commonwealth Scientific and Industrial Research Organization; Australia)	Jeffrey et al., 2013	RCA4_v3	SMHI	1951 -2005	2006-2100	2006-2100
IPSL-CM5A-MR	IPSL (Institut Pierre-Simon-Laplace, France) Universitè Pierre et Marie Curie (Paris, France)	Dufresne et al., 2013	RCA4_v3	SMHI	1951 -2005	2006-2100	2006-2100
GFDL CM3	NOAA (National Oceanic and Atmospheric Administration, United States)	Donner et al., 2011; Dunne et al., 2012	RCA4_v3	SMHI	1951 -2005	2006-2100	2006-2100
NorESM1-M	NCC(Norwegian Climate Center and University of Bergen, Norway)	Bentsen et al., 2013	RCA4_v3	SMHI	1951 -2005	2006-2100	2006-2100

2.3 SPI and SPEI calculation

Recommended by the World Meteorological Organization, and being one of the most popular meteorological drought indexes (Meresa et al., 2016), the Standardized Precipitation Index was developed for drought monitoring and characterization by McKee et al. (1993). The index is based on a statistical analysis of local precipitation summed at a given time scale. In this study, monthly datasets were grouped into the hydrological year (P12; Oct – Sep), and then used to develop a cumulative probability of these time series. The Gamma two parameters probability density distribution (PDF) was fitted using the maximum likelihood approach (McKee et al., 1993; Coelho et al., 2016) and, additionally, tested by the Anderson-Darling hypothesis test (Anderson and Darling, 1952) to verify its adherence. An equiprobability transformation is then made from the cumulative non-exceedance probability to the standard normal PDF (mean = 0; variance = 1). The SPI12 is then calculated as the Z value.

In order to increase the sensibility of this index, Vicente-Serrano et al. (2010a, b) developed the Standardized Precipitation Evapotranspiration Index (SPEI) including the atmosphere demand in its calculation. Similar to SPI, this index uses a normalization approach, but it takes into account both precipitation (P) and potential evapotranspiration (ETp), i.e., it is based on the P -ETp values. Therefore, the inclusion of the potential atmospheric evaporative demand in SPEI computation made it better for drought identification (Vicente-Serrano et al., 2010; Silva and Mello, 2021). ETp was calculated by the Thornthwaite method, requiring only air temperature as input. According to Begueria et al. (2014) and McEvoy et al. (2012), similar results were found when both Thornwaite and Penman-Monteith methods are applied for SPEI calculation, which justify the use of the former method, especially for regions with minimum monitoring of climate variables.

The monthly P-ETp values were grouped into hydrological years and the generalized extreme value PDF (GEV) was fitted to the empirical non-exceedance frequencies. Anderson-Darling test (Anderson and Darling, 1952) was also applied to test the adherence of the PDF. Thus, an equiprobability transformation is made from the cumulative probability to the standard normal random, where SPEI12 assumes the z values.

According to the WMO (WMO 2012), SPI and SPEI values are considered severe drought events when they are < -1. Here, we use the follow categories i) moderately dry: − 1.0 to − 1.5; ii) severely dry: − 1.5 to − 2.0; iii) extremely dry: < − 2.0. To assess the spatial behavior of the drought episodes, ordinary kriging was applied to generate SPI12 and SPEI12 maps for the observed data (1940–2020) and for the Eta and CORDEX RCM downscaling (2010–2099).

3 Results and Discussion

3.1 Drought Episodes from 1940-2020 in Pantanal biome

To provide a comparison between CRU and observed datas, a validation was shown in Fig 2. Due to the lack of meterological stations over the biome, it was not possible to compare the CRU data with more observational datasets. Only the station of Nhumirim is inside of the study Area. However, through the comparison, is possible to observe that CRU is capable to reproduce either the temperature or the precipitation behaviour in Pantanal area.

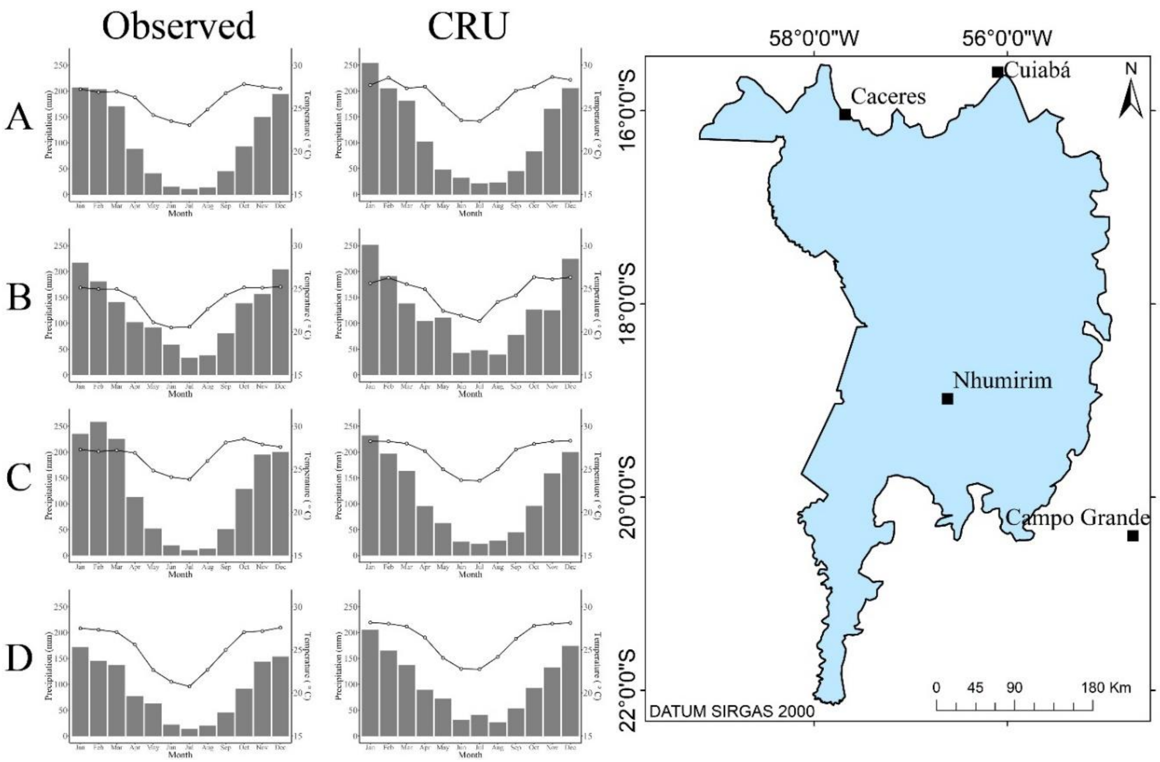

Fig 2. CRU validation from four different meteorological stations A) Cáceres; B) Cuiabá; C) Campo Grande; D) Nhumirim

The annual maps of SPI12 and SPEI12 from 1940/1941 to 2019/2020 hydrological years are presented in Figure 3. A study carried out in the hydrological station at Ladario (near the city of Corumba) analyzed the level of Paraguay river in the Pantanal from 1900 to 2012 (Alho and Silva, 2012). The authors pointed out some unusually dry periods, such as the 1960-1970 decade, where no floodings were recorded at the station, except for one event in 1965/1966. SPI12 and SPEI12 were capable to identify the intensity of these drought events. The hydrological years of 1961/1962 (SPI12 = -1.72; SPEI12= -1.50), 1963/1964 (SPI12= -1.67; SPEI12= -1.29), 1966/1967 (SPI12= -1.76; SPEI12= -1.32), and 1968/1968 (SPI12= -0.95; SPEI12= -1.36) showed to be drier, agreeing with Alho and Silva (2012). Besides, the authors still observed that from 1973/1974 to 1988/1989 the Pantanal experienced several inundations, demonstrating that droughts do not hit the region in this period.

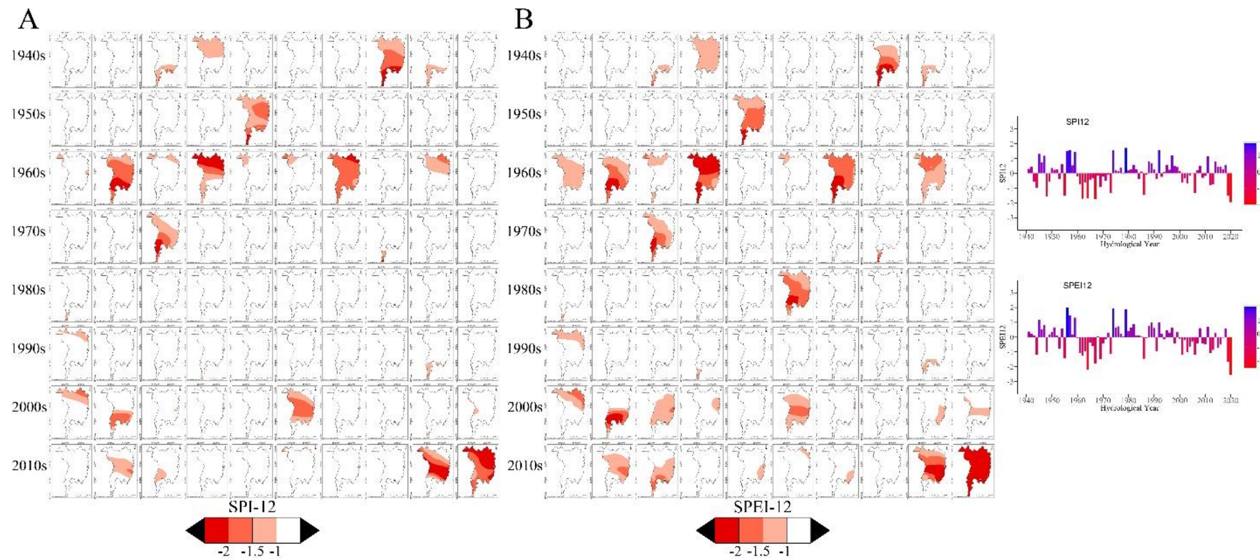

Fig 3. Drought episodes in Pantanal in the historical period using A) SPI12 B) SPEI12

There is not agreement in the literature about the influence of global-scale phenomena such as El Niño and La Niña over Pantanal. Marengo et al. (2015) highlighted that the large interannual variability of the hydrometeorological conditions of the Pantanal may indicate that the biome is independent of El Niño/La Niña. On other hand, Alho e Silva (2012) showed that from 1900 to 2012, in all 30 years that El Niño had occurred, no severe floods were registered at the Ladario gauge station (Paraguay River). Marengo et al (2021), however, observed that some droughts hit the region in El Niño years and some during La Niña years, thus, no conclusion regarding the influence of these events on droughts can be inferred.

The hydrological year 2019/2020 (SPI12= -1.95; SPEI12= -2.65) was the driest for this study. Extremely drought events as observed in this year are rarely observed through the time series. The hydrological year 1964/1965 (SPI12=-1.68, SPEI12= -2.07) was the second driest, characterized by a severe drought and an extreme drought were observed in almost all Brazilian biomes. In both years, the magnitude of SPEI was bigger than SPI, possibly indicating that the combination of rainfall associated with high temperatures, and consequently high atmosphere water demand, resulted in a dry year.

Possible explanations for the 2019/2020 extreme drought event were detailed by Marengo et al. (2021). Relevant changes in upper, middle, and lower-level circulation and moisture in South America were observed during the summer of 2019 and 2020. Specifically, between December 2019 and February 2020, a blocking system in the Pacific Ocean associated with an anticyclonic anomaly over subtropical altitudes prevailed, preventing that convection storms, typical of this time of the year in Pantanal, to occur. Thus, a strong anomalously anticyclonic circulation over the entire continent at 500 and 200 hPA explain the negative anomaly of precipitation observed.

The Amazon Forest has an important role in redistributing the moisture in South America (Nobre, 2014). The vapor that emerges from Amazon brings essential rainfall to Pantanal (Bergier et al., 2018). This strip of moisture is called out South Atlantic Convergence Zone (SACZ) and plays a fundamental role in the hydrology of Center-South Brazil. However, during the 2019-2020 hydrological year, Pantanal was located over an anticyclonic influence, which inhibited the formation of the SACZ, and thus, on the occurrence of precipitation.

Impacts of the 2019/2020 drought in Pantanal are still being documented in the literature. Data from the monitoring system of the National Institute of Spatial Research (INPE) observed 6244 fire spots in Pantanal through the 2018/2019 hydrological year. This number escalated to 10693 in 2019/2020, an increase of 71.3 %. Data from the ALARMES system (Pinto et al., 2020) from the Laboratory for Environmental Satellite Applications (LASA-UFRJ) showed that 26% of the Pantanal suffered from wildfire caused by the drought, totalizing an area of approximately 3.9 million hectares (Filho et al., 2021).

The combination of fire and drought in Pantanal can be dangerous for Brazil. According to Libonati et al (2022), fire's impact was felt nationwide, with smoke being spread to other states like Sao Paulo, Rio de Janeiro, and Parana, decreasing the air quality in major cities and causing rare phenomenon as the black rain. Also, it is important to point out the impacts of fires on human health. According to the Oswald Cruz Foundation (2020), extreme wildfires drop the resources for the surviving species which may force them to dislocate to unburned areas, such as those occupied by humans, facilitating the appearance of new diseases.

Extreme inter-annual events of drought in Pantanal can impact the biome ecosystem and, in consequence, affect local ecological communities (Alho & Filho, 2012). Through the 2019/2020 drought and wildfires, Jaguars (Panthera onca), hyacinth macaws (Anodorhynchus hyacinthinus), and other iconic wildlife have been directly affected (died, suffered severe injuries, or starved) (Garcia et al., 2021). The event experienced in Pantanal was similar to the one in Australia at the end of 2019, where fires spread all over the country and devastated thousands of houses and wildlife (Wintle et al., 2020).

3.2 RCMs performance in simulating precipitation and evapotranspiration of the hydrological years in the Pantanal region

Figure 4 shows the average precipitation and evapotranspiration of the hydrological years between 1961/1972 and 2004/2005 hydrological years from the observed data and the Eta and CORDEX ensemble models. The baseline (or historical period) represents the period without greenhouse gases increment added to the model (Chou et al., 2014). The average observed precipitation in the studied period (1961-2005) is 1280.2 ± 85.6 mm, and the RCMs simulated 1101.7 ± 71.2 mm, 1609.4 ± 8.0 mm, respectively, from Eta Ensemble, and CORDEX ensemble.

The average evapotranspiration for the 1961-2005 period is 1623.2 mm ± 64.9, and the RCMs simulated 1779.6 ± 6.1 mm, 1506.4 ± 86.6 mm, respectively, from Eta Ensemble, and CORDEX ensemble.

A pixel to pixel variation of precipitation and evapotranspiration is provided in Fig. 5. Precipitation is overestimated in the CORDEX ensemble, reaching more than 30% in the southern Pantanal. On the other hand, it is underestimated in almost all Pantanal's area for the Eta ensemble. However, the variation is smaller than observed in the CORDEX. For evapotranspiration, the opposite is observed, with CORDEX underestimating variations close to 0, whereas Eta ensemble overestimated it.

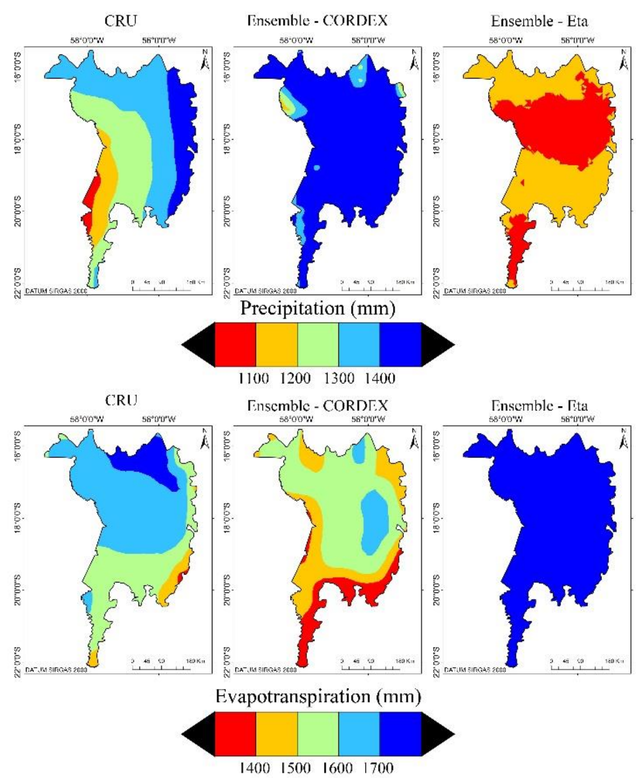

Fig 4. Mean annual precipitation (mm/year) of Pantanal from 1961/1962 to 2004/2005 for CORDEX and Eta ensembles.

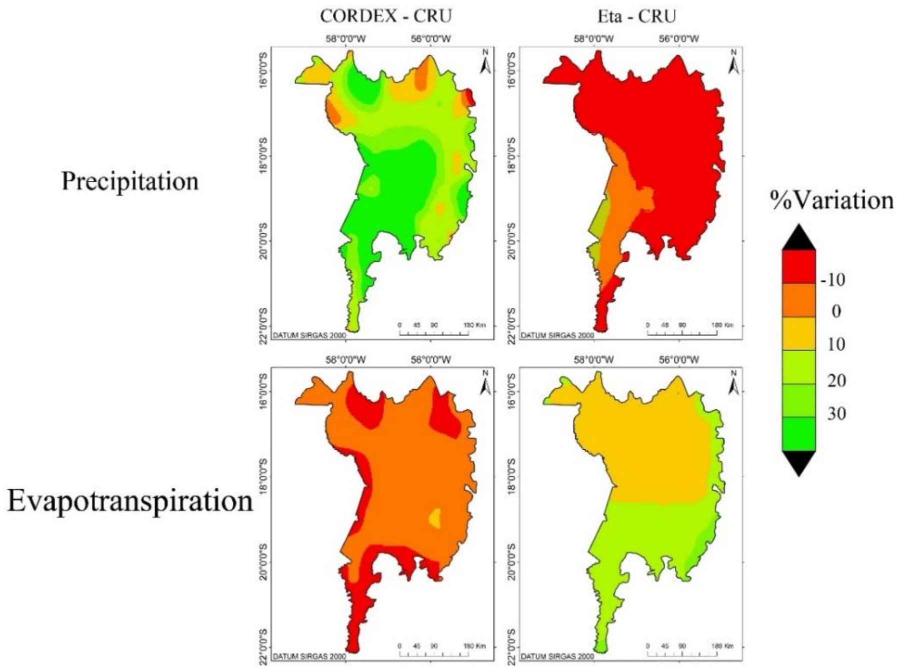

Fig. 5 Differences between the observed and simulated precipitation for the hydrological years in the period of 1961 to 2005 for CORDEX and Eta Ensembles.

3.3 Projections of extreme droughts in Pantanal

Figure 6 shows the projected droughts in Pantanal under the Eta RCM models ensemble. In 90 years of simulations under RCP 4.5 (Fig. 6a), there are no projected extremely droughts (SPI < -2). Eta ensemble has been successfully applied in different climate change studies in South America. Chou et al. (2014) evaluated the assessments of climate change projections in the region using Eta-BESM, Eta-HadGEM2-ES, Eta-MIROC5 and their ensemble and some information can be extracted to Pantanal. Eta-MIROC simulates an increase in precipitation due to the intensification of the South Atlantic Convergence Zone in the region. Also, the authors observed a concentration of rain between December and February, making the summer months wetter. In contrast, Eta-BESM simulates less precipitation through the wet season. Eta-HadGEM2-ES simulations tend to distribute the rain throughout year, making the wet season less rainy and the dry season, less dry. Silva et al. (2022) studying projections of droughts in Minas Gerais observed that Eta-CanESM tends to simulate a decrease in precipitation towards the end of the Century in the Center of Brazil.

Figure 6a also provides the compilation of the average SPI12 for each model and the ensemble in Pantanal. Eta-HadGEM concentrates several concecutive dry years in the 2020s and 2030s, which resulted in several drought years over the ensemble. Eta-BESM, Eta-CanESM, Eta-MIROC simulatated dry years intercalated with wet years. Thus, the ensemble is not able to fully identify extreme events of drought throughout the 21st century.

Under the RCP 8.5 (Fig. 6b), extreme droughts were not projected (SPI < -2). Differently from the RCP 4.5, the severe drought events are concentrated in the 2090s. This concentration is might be explained by the behavior of the Eta-BESM and Eta-CANESM to decrease the amount of rainfall in the end of the century and concentrating the extremes drought events after 2080s (Chou et al., 2014; Silva et al., 2022).

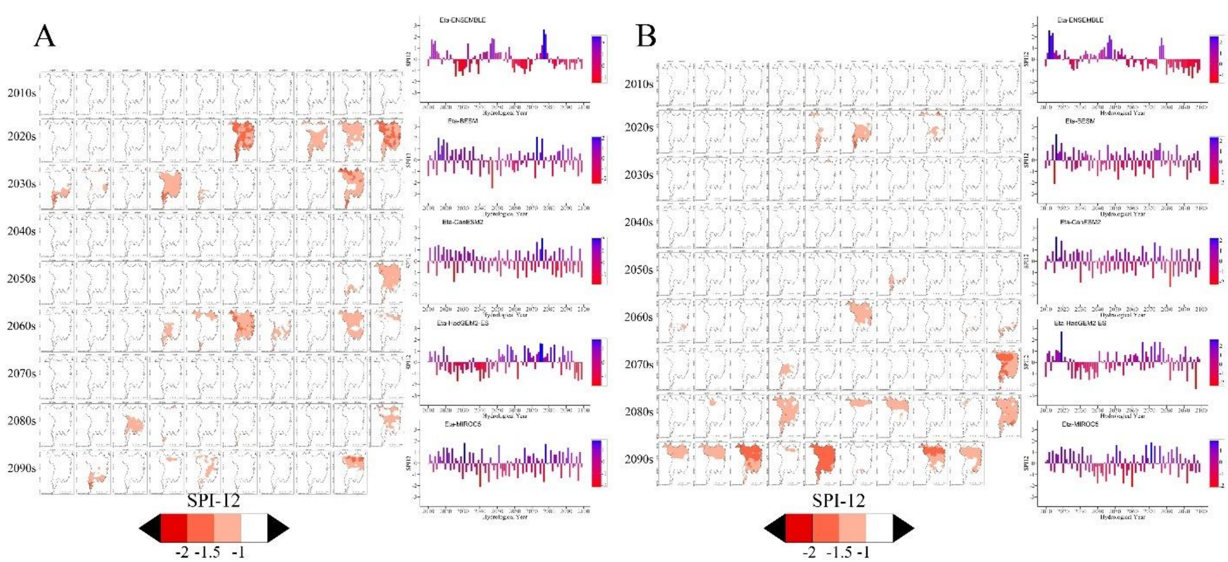

Fig. 6 Annual maps of the SPI12 projected by Eta models ensemble for RCP4.5 (A) and RCP8.5 (B)

Based on the CORDEX simulations, some extreme drought events were identified (Fig. 7). In RCP 4.5 (Fig 7a), the simulations of severe droughts are sparsed up to the end of the XXI century with an extremely event being observed extensively over the biome in 2010/2011 (SPI12= -2.87), and in some of its areas in 2019/2020, 2034/2035, 2052/2053, 2081/2082 (SPI12=-063; SPI12=-1.82, SPI12=-1.45, SPI12=-1.22).

In RCP 8.5, the severe droughts are concentrated between 2010 and 2040. An extreme event was projected in 2035/2036 (SPI=-2.55), and in some areas of the biome, in 2012/2013, 2016/2017, 2033/2034 (SPI12=-1.75, SPI12=-1.53, SPI12=-1.42). CORDEX-IPSL and CORDEX-GFDL simulations were fundamental to understand the Ensemble behaviour, eother for RCP4.5 or RCP8.5, once they concentrate several drought events until 2040s and wet events in the second half of the XXI century

Few studies have been conducted with CORDEX RCM ensemble models in South America to evaluate climate change projections (Solman et al., 2019; Llopart et al., 2020; Falco et al., 2019). As observed in Eta ensemble, CORDEX ensemble (CSIRO, IPSL, GFDL-CM3, and NorESM1) presents high variability among them. However, Falco et al (2019) showed that even with a high variability, an increase in precipitation is expected for RCP4.5 and RCP8.5 toward the end of the XXI century, justifying the concentration of droughts in the first three decades.

Comparing CORDEX and Eta models, it is possible to observe that the results are different. CORDEX is able to simulate events with the magnitude of 2019/2020 in Pantanal and Eta wasn’t. The high variability of the models in the Eta ensemble balanced the precipitation projections, which might result in understimated magnitude of the droughts. In CORDEX, the models trend to project similar events like those observed in the 1960s and in the 2010s since there is no such variability found in Eta models.

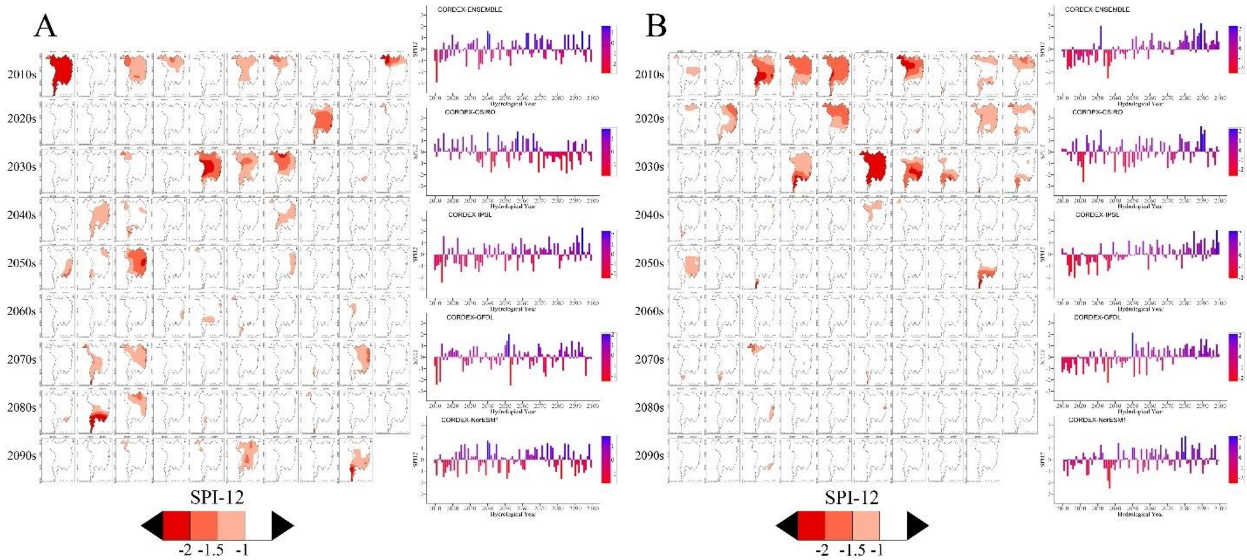

Fig. 7 Annual maps of the SPI12 projected by CORDEX models for RCP4.5 (A) and RCP8.5 (B)

The addition of atmosphere demand enhanced the Eta ensemble, become it able to simulate extreme droughts (Fig. 8). Severe drought events were projected between 1940 and 2100 for RCP4.5. Events like that observed in the 2019/2020 hydrological year could be projected in 2045/2046, 2095/2096, and 2097/2098 (SPEI12= -1.87, SPEI12= -2.66, SPEI= -2.36). For RCP8.5, most of the severe drought events are concentrated between the 2080s and 2090s, with three extreme droughts in 2092/2093, 2095/2096, 2097/2098 (SPEI12=-2.83, SPEI12=-2.04, and SPEI12=-2.85). Differently for SPI12, Eta-BESM, Eta-CanESM2, Eta-HadGEM2-ES, Eta-MIROC5 haven't shown up differences in their behaviors, concentrating most of the severe drought events in the second half of XXI century, either for RCP4.5 or RCP8.5 (Fig. 8a and Fig.8b).

A study of the land use change with CanESM2 projected a decrease in Leaf Area Index (LAI) until 2100 for the central region of Brazil, where Pantanal is located (Hua et al. 2015), which could contribute to the increase of 0.2 °C in the region. During the austral summer (DJF), Eta-HadGEM2-ES and Eta-MIROC5 have different sensibilities to the greenhouse increments. In RCP

4.5, Eta-MIROC projects an increment up to 2^{o}C, while for Eta-HadGEM2-ES the temperature anomalies can reach 4^{o}C. For RCP8.5, towards the end of the century, Eta-HadGEM2-ES simulates an increase that can reach 5-7^{o}C. Thus, towards the end of the century, potential evapotranspiration can reach values even greater than precipitation, justifying the concentration of extreme drought events at the end of the century.

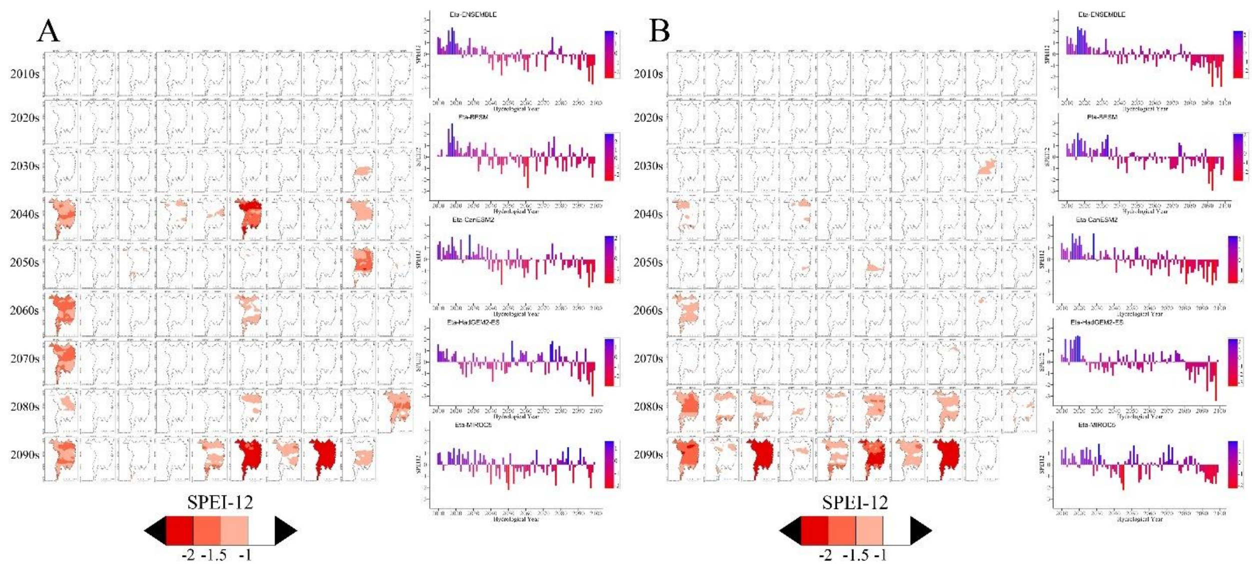

Fig. 8 Annual maps of the SPEI12 projected by Eta models for RCP4.5 (A) and RCP8.5 (B).

Figure 9 shows the SPEI12 projected by the CORDEX ensemble, under RCP4.5 and RCP8.5. Until the 2050s, no drought events were projected. Under RCP4.5, the hydrological years of 2072/2073, 2081/2082, 2095/2096 (SPEI12=-1.77. SPEI12=-1.85, SPEI12=-2.07) were the driest projected. Considering the RCP8.5 scenarios, the most severe droughts are concentrated in the last decade of the 2090s, highlighting 2092/2093, 2096/2097 (SPEI12=-2.92, SPEI12=-1.93). Similar to Eta models, CORDEX RCM models (CSIRO, IPSL, GFDL, NorESM1), haven’t shown up big differences among them, simulating most of the severe drought events in the last three decades of the XXI century.

The concentration of drought events in the 2080s and 2090s can indicate a shift in the climate of Pantanal to a semi-arid climate and a possible megadrought (Garreaud et al., 2019), which might lead to a decrease in the runoff, a decrease in crop production, a decrease in hydroelectricity generation, and several social-economic problems for the region. Furthermore, recurrent extremely dry events can lead to an increase of wildfires in Pantanal, to ecosystem losses and to direct impacts on human health.

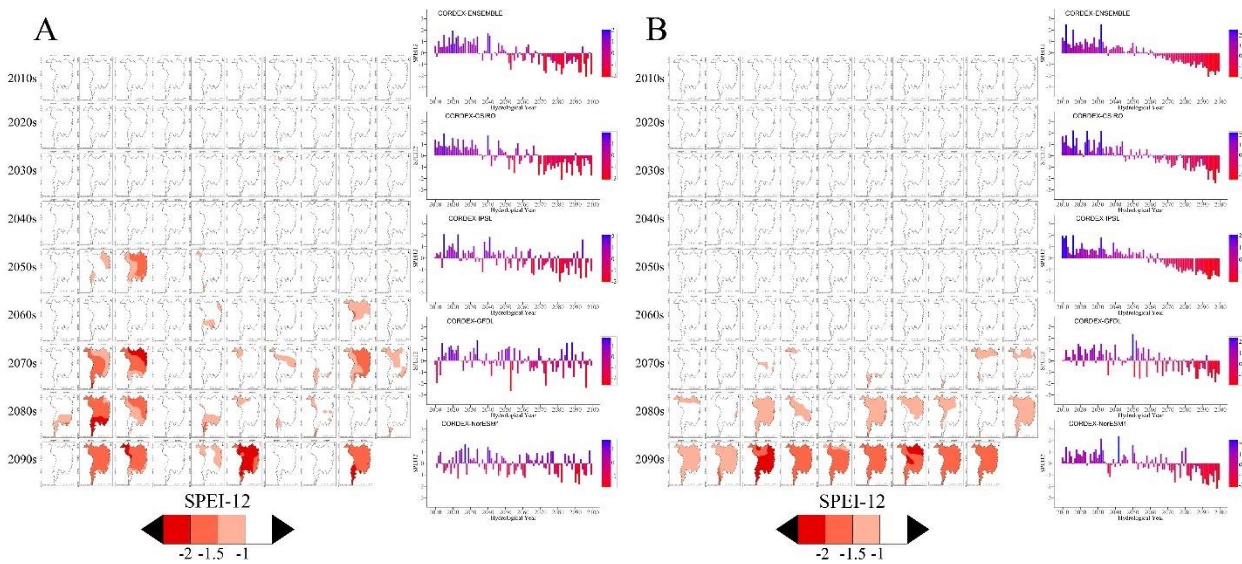

Fig. 9 Annual maps of the SPEI12 projected by CORDEX models for RCP4.5 (A) and RCP8.5 (B)

4 Conclusions

This work discusses meteorological droughts in Pantanal, an important ecological area in the central-western region of Brazil, based on the SPI12 and SPEI12 indexes considering the CRU datasets and two RCM ensembles (Eta and CORDEX). The main conclusions are:

a. The Climate Research Unit (CRU) datasets proved capable of representing the meteorological droughts in Pantanal. The region is well known for its lack of meteorological and climate stations due to the adversities of a wetland.

b. The evaluation of drought episodes from 1940 to 2020 showed that the 2019/2020 hydrological year was the driest in the period. The consequences of this episode have still been reviewed, but its impacts on wildlife, vegetation, and population in the surroundings are enormous. The association of negative anomalies of precipitation, positive anomalies of temperature, deforestation, and wildfires harm the Biome existence.
c. The SPI12 and SPEI12 showed similar results in the observed period of time. It maybe indicates that the absence of precipitation is the main factor of droughts in the biome. However, in extreme drought events, the combination of little precipitation and high atmosphere water demand can lead to catastrophic events.
d. Eta ensemble was not capable of simulating extremely dry events in Pantanal considering the SPI12. For SPEI12, however, most of the extreme drought events are located in the last two decades of simulations. The increase of greenhouse gas emissions impacts straight in the temperature levels and, following, the potential evapotranspiration. For future analysis and decision makings, the authors recommend the use of the SPEI to analyze projections of droughts using the Eta ensemble.
e. The CORDEX project ensemble was capable to simulate extreme dry events over Pantanal. A clear difference is observed between RCP4.5 and RCP 8.5 for SPI12 and SPEI12. SPI12 projects a concentration of dry events in the first three decades for RCP4.5 and spread through the 90 years of simulation for RCP8.5. For SPEI12, under both RCP4.5 and RCP8.5, severe droughts were projected in the last two decades of the XXI century, indicating the increment of greenhouse gases and, consequently, the temperature, is key factor for drought identification.

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6 References

AghaKouchak A, Farahmand A, Melton FS, Teixeira J, Anderson MC, Wardlow BD and Hain C R (2015) Remote sensing of drought: Progress, challenges and opportunities, Reviews Geophysics, 53, 452–480. doi.org/10.1002/2014RG000456

Alho C, Silva J (2012). Effects of Severe Floods and Droughts on Wildlife of the Pantanal Wetland (Brazil)—A Review. Animals, 2(4), 591–610. doi:10.3390/ani2040591

Alho CJ, Silva JS. (2012) Effects of Severe Floods and Droughts on Wildlife of the Pantanal Wetland (Brazil)-A Review. Animals (Basel).2(4), 591-610. doi:10.3390/ani2040591

Almeida TIR, Penatti NC, Ferreira LG, Arantes AE, Amaral CH. (2015). Principal component analysis applied to a time series of MODIS images: the spatio-temporal variability of the Pantanal wetland, Brazil. Wetlands Ecology and Management, 23(4), 737–748. doi:10.1007/s11273-015-9416-4

Anderson, TW, Darling DA. (1954) A test of goodness of fit. Journal of American Statistics Association. 49, 756–769.

Arora VK, Matthews HD (2009), Characterizing uncertainty in modeling primary terrestrial ecosystem processes, Global Biogeochemic. Cycles, 23, GB2016, doi:10.1029/2008GB003398

Begueria S, Vicente-Serrano SM, Reig F & Latorre B. (2014). Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. International Journal of Climatology 34: 3001-3023. doi.org/10.1002/joc.3887

Bentsen M, Bethke I, Debernard JB, Iversen T, Kirkevåg A, Seland Ø, Drange H, Roelandt C, Seierstad IA, Hoose C, Kristjánsson JE. (2013) The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation of the physical climate, Geoscientific Model Development, 6, 687–720, doi.org/10.5194/gmd-6-687-2013.

Bergier I (2010) River level sensitivity to SOI and NAO in Pantanal and Amazonia. In III Simpósio de Geotecnologias no Pantanal, Cáceres-MT, October 2010. Embrapa Informática Agropecuária/INPE, 25–34

Bergier I, Assine ML, McGlue, MM, Alho CJR, Silva A, Guerreiro RL, Carvalho JC (2018). Amazon rainforest modulation of water security in the Pantanal wetland. Science of The Total Environment, 619-620. doi.org/10.1016/j.scitotenv.2017.11.163

Black, T. L. The New NMC Mesoscale Eta Model: Description and Forecast Examples. Weather and Forecasting, v. 9, n. 2, p. 265–278, 1994

Catian G, Silva DM, Súarez YR, Scremin-Dias E (2018). Effects of Flood Pulse Dynamics on Functional Diversity of Macrophyte Communities in the Pantanal Wetland. Wetlands. 38, 975-991 https://doi.org/10.1007/s13157-018-1050-5

Chou SC, Lyra A, Mourão C, Dereczynski C, Pilotto I, Gomes J, Bustamante J, Tavares P, Silva A, Rodrigues D, Campos D, Chagas D, Sueiro G, Siqueira G, Nobre P (2014) Evaluation of the Eta Simulations Nested in Three Global Climate Models. American Journal of Climate Change. 3(12), 438–454

Chou SC, Lyra A, Mourão C, Dereczynski C, Pilotto I, Gomes J, Bustamante J, Tavares P, Silva A, Rodrigues D, Campos D, Chagas D, Sueiro G, Siqueira G, Marengo J (2014) Assessment of Climate Change over South America under RCP 4.5 and 8.5 Downscaling Scenarios. American Journal of Climate Change, 03(05), 512–527, 2014a. doi.org/10.4236/ajcc.2014.35043

Chou SC, Marengo JA, Lyra AA, Sueiro G, Pesquero JF, Alves LM, Kay, G, Betts R, Chagas JL, Bustamante JF, Tavares P (2012) Downscaling of South America present climate driven by 4-member HadCM3 runs. Climate Dynamics 38: 635−653. doi.org/10.1007/s00382-011-1002-8

Chylek P, Li J, Dubey MK, Wang M Lesins G. (2011) Observed and model simulated 20th century Arctic temperature variability: Canadian Earth System Model CanESM2. Atmospheric Chemistry Physics Discussion, 11(22), 893–915 , doi.org/10.5194/acpd-11-22893-2011.

Clark JS, Iverson L, Woodall CW, Allen CD, Bell DM, Bragg DC, D’Amato AW, Davis FW, Hersh MH, Ibanez I, Jackson ST, Matthews S, Pederson N, Peters M, Schwartz MW, Waring KM, Zimmermann NE (2016). The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. Global Change Biology, 22(7), 2329–2352. doi:10.1111/gcb.13160

Coelho CAS, Cardoso DHF, Firpo MAF. Precipitation diagnostics of an exceptionally dry event. Theoretical and Applied Climatology, 125, 769–784, doi.org/10.1007/s00704-015-1540-9

Collins WJ, Bellouin N, Doutriaux-Boucher M, Gedney N, Halloran P, Hinton T, Hughes J, Jones CD, Joshi M, Liddicoat S, Martin G, O'Connor F, Rae J, Senior C, Sitch S, Totterdell I, Wiltshire A Woodward S. (2011) Development and evaluation of an Earth-System model – HadGEM2, Geosci. Model Dev., 4, 1051–1075, doi.org/10.5194/gmd-4-1051-2011.

De Groot RS, Stuip MAM, Finlayson CM, Davidson N (2006). Valuing wet-lands: guidance for valuing the benefits derived from wetland ecosystem services. Ramsar Technical Report No.

3/CBD Technical Series No. 27 Technical Series No. 27(Montreal: Ramsar Convention Secretariat, Gland, Switzerland & Secretariat of the Convention on Biological Diversity)

Donner LJ, Wyman BL, Hemler RS, Horowitz LW, Ming Y, Zhao M, Golaz J, Ginoux P, Lin SJ, Schwarzkopf MD, Austin J, Alaka G, Cooke WF, Delworth TL, Freidenreich SM, Gordon CT, Griffies SM, Held IM, Hurlin WJ, Klein SA, Knutson TR, Langenhorst AR, Lee H, LinmY, Magi BI, Malyshev SL, Milly PCD, Naik V, Nath MJ, Pincus R, Ploshay JJ, Ramaswamy V, Seman C J, Shevliakova E, Sirutis JJ, Stern WF, Stouffer RJ, Wilson RJ, Winton M, Wittenberg AT, Zeng F. (2011). The Dynamical Core, Physical Parameterizations, and Basic Simulation Characteristics of the Atmospheric Component AM3 of the GFDL Global Coupled Model CM3, Journal of Climate, 24(13), 3484-3519. doi.org/10.1175/2011JCLI3955.1

Dufresne JL, Foujols MA, Denvil S, Caubel A, Marti O, Aumont O, Balkanski Y, Bekki S, Bellenger H, Benshila R, Bony S, Bopp L, Braconnot P, Brockmann P, Cadule P, Cheruy F, Codron F, Cozic A, Cugnet D, Noblet N, Duvel JP, Ethé C, Fairhead L, Fichefet T, Flavoni S, Friedlingstein P, Grandpeix JY, Guez L, Guilyardi E, Hauglustaine D, Hourdin F, Idelkadi A, Ghattas J, Joussaume S, Kageyama M, Krinner G, Labetoulle S, Lahellec A, Lefebvre MP, Lefevre F, Levy C, Li ZX, Lloyd J, Lott F, Madec G, Mancip M, Marchand M, Masson S, Meurdesoif Y, Mignot J, Musat I, Parouty S, Polcher J, Rio C, Schulz M, Swingedouw D, S. Szopa, Talandier C, Terray P, Viovy N, Vuichard N (2013). Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. Climate Dynamics 40, 2123–2165 doi.org/10.1007/s00382-012-1636-1

Dunne JP, John JG, Adcroft AJ, Griffies SM, Hallberg RW, Shevliakova E, Stouffer RJ, Cooke W, Dunne KA, Harrison MJ, Krasting JP, Malyshev SL, Milly PCD, Phillipps PJ, Sentman LT, Samuels BL, Spelman MJ, Winton M, Wittenberg AT, Zadeh N. (2012). GFDL's ESM2

Global Coupled Climate–Carbon Earth System Models. Part I: Physical Formulation and Baseline Simulation Characteristics, Journal of Climate, 25(19), 6646-6665. Retrieved May 11, doi.org/10.1175/JCLI-D-11-00560.1

Falco M, Carril AF, Menéndez CG., Zaninelli PG, LI Laurent ZX. (2019). Assessment of CORDEX simulations over South America: added value on seasonal climatology and resolution considerations. Climate Dynamics 52, 4771–4786 doi.org/10.1007/s00382-018-4412-z

Leal Filho W, Azeiteiro UM, Salvia AL, Fritzen B, Libonati R. (2022). Fire in Paradise: Why the Pantanal is burning. Environmental Science & Policy, 123, 31-34, https://doi.org/10.1016/j.envsci.2021.05.005

Garcia LC, Szabo JK, Roque FO, Martins Pereira AM, Cunha CN, Damasceno-Júnior GA, Morato RG, Tomas WM, Libonati R, Ribeiro DB. (2021). Record-breaking wildfires in the world's largest continuous tropical wetland: Integrative fire management is urgently needed for both biodiversity and humans. Journal of Environmental Management, 293, 112870. doi:10.1016/j.jenvman.2021.112870

Garreaud RD, Boisier JP, Rondanelli R, Montecinos A, Sepúlveda H, Veloso-Äguila D. (2019). The Central Chile Mega Drought (2010-2018): A Climate dynamics perspective. International Journal of Climatology. doi:10.1002/joc.6219

Harris I, Jone PD, Osborn TJ, Lister DH (2014) Updated high-resolution grids of monthly climatic observations—the CRUTS3.10 Dataset. International Journal of Climatology 34:623–642. doi.org/10.1002/ joc.3711

Hayes M. 2002. Drought Indices. International Journal of Climatology 23: 1335-1357

Hu S, Niu Z, Chen Y, Li L, Zhang H. (2017). Global wetlands: Potential distribution, wetland loss, and status. Science of The Total Environment, 586,

Hua W, Chen H, Sun S, Zhou L (2015) Assessing climatic impacts of future land use and land cover change projected with the CanESM2 model. Int J Climatol 35(12):3661–3675. doi.org/ 10. 1002/ joc. 4240

index datasets based on the Palmer Drought Severity Index. Journal of Hydrometeoroly 11:1033–1043 doi.org/10.1175/2010JHM1224.1

Ivory S, McGlue M, Spera S, Silva A, Bergier I (2019). Vegetation, rainfall, and pulsing hydrology in the Pantanal, the world’s largest tropical wetland. Environmental Research Letters. doi:10.1088/1748-9326/ab4ffe

Jeffrey S, Rotstayn L, Collier M, Dravitzki S, Hamalainen C, Moeseneder C, Wong K, Syktus J. (2013) Australia's CMIP5 submission using the CSIRO-Mk3.6 model. Australian Meteorological and Oceanographic Journal 63 1–13 doi.org/10.22499/2.6301.001

Libonati R, Geirinhas JL, Silva PS, Russo A, Rodrigues JA, Belem LBC, Nogueira J, Roque FO, DaCamara CC, Nunes AMB, Marengo JA, Trigo RM. 2022. Assessing the role of compound drought and heatwave events on unprecedented 2020 wildfires in the Pantanal. Environmental Research Letters. 17-015005. https://doi.org/10.1088/1748-9326/ac462e

Llopart M, Simões Reboita M, Porfírio da Rocha R. (2020). Assessment of multi-model climate projections of water resources over South America CORDEX domain. Climate Dynamics 54, 99–116 doi.org/10.1007/s00382-019-04990-z

Mao D, Wang Z, Wu J, Wu B, Zeng Y, Song K, Yi K, Luo L. (2018). China’s wetlands loss to urban expansion. Land Degradation & Development, 29(8), 2644–2657. doi:10.1002/ldr.2939

Marengo J, Liebmann B, Grimm A, Misra, V, Silva Dias PL, Cavalcanti IFA., Carvalho LMV, Berbery EH, Ambrizzi T. Vera CS, Saulo AC, Nogues-Paegle J, Zipser E, Seth A, Alves LM (2010). Recent developments on the South American monsoon system. International Journal of Climatology, 32(1), 1–21. doi:10.1002/joc.2254

Marengo JA, Chou SC, Kay G, Alves LM, Pesquero JF, Soares WR, Santos DC, Lyra AA, Sueiro G, Betts R, Chagas DJ, Gomes JL, Bustamante JF, Tavares P. (2012) Development of regional future climate change scenarios in South America using the Eta CPTEC/HadCM3 climate change projections: climatology and regional analyses for the Amazon, São Francisco and the Paraná River basins. Clim Dyn 38, 1829–1848. doi.org/10.1007/s00382-011-1155-5

Marengo JA, Cunha AP, Cuartas LA, Deusdara Leal KR, Broedel E, Seluchi ME, Michelin CM, Praga Baião CF, Ângulo EC, Almeida EK, Kazmierczak ML, Mateus NPA, Silva RC, Bender F (2021) Extreme Drought in the Brazilian Pantanal in 2019–2020: Characterization, Causes, and Impacts. Frontiers in Water. 3: 639204. doi.org/10.3389/frwa.2021.639204

Marengo JA, Oliveira GS, Alves LM (2015). Climate Change Scenarios in the Pantanal. Dynamics of the Pantanal Wetland in South America, 227–238. doi:10.1007/698_2015_357

Marengo JA, Oliveira GS, Alves LM. (2015). Climate Change Scenarios in the Pantanal. In: Bergier, I., Assine, M. (eds) Dynamics of the Pantanal Wetland in South America. The Handbook of Environmental Chemistry, vol 37. Springer, Cham. https://doi.org/10.1007/698_2015_357

McEvoy DJ, Huntington JL, Abatzoglou JT, Edwards LM. (2012) An evaluation of multiscalar drought indices in Nevada and Eastern California. Earth Interact 16(18): 1-18. doi.org/10.1175/2012EI000447.1

McKee TB, Doesken NJ, Kliest J (1993) The relationship of drought frequency and duration to time scales. American Meteorological Society, Boston, pp 179–184

Meresa HK, Osuch M, Romanowicz R. (2016). Hydro-meteorological drought projections into the 21-st century for selected Polish catchments. Water, 8(5), 206. doi.org/10.3390/w8050206

Mesinger F, Veljovic K, Chou SC, Gomes J, Lyra A. (2016). The Eta Model: Design, Use, and Added Value. Topics in Climate Modeling.

Mesinger F, Veljovic K, Chou SC, Lyra JG. (2016). The Eta Model: Design, Use, and Added Value. In Hromadka T, Rao P. (Eds.), Topics in Climate Modeling. Intech Open. doi.org/10.5772/64956

Mesinger, F. A blocking technique for representation of mountains in atmospheric models. Rivista di Meteorologia Aeronautica, v. 44, n. 1, p. 195–202, 1984.

Narayan S, Beck MW, Wilson P, Thomas CJ, Guerrero A, Shepard CC, Reguero BG, Franco G, Ingram JC, Trespalacios D. (2017). The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA. Scientific Reports, 7(1). doi:10.1038/s41598-017-09269-z

National Institute for Space Research. (2021) Queimadas e Sistemas de Monitoramento. Brasil. Access in https://queimadas.dgi.inpe.br/queimadas/portal

Nobre AD (2014) The Future Climate of Amazonia, Scientific Assessment Report. CCST-INPE, INPA, ARA. São José dos Campos, Brazil, 42p

Nobre P, Siqueira LSP, Almeida RAF, Malagutti M, Giarolla E, Castelão GP, Bottino MJ, Kubota P, Figueroa SN, Costa MC, Baptista MJr, Irber LJr, Marcondes GG. (2013). Climate Simulation and Change in the Brazilian Climate Model, Journal of Climate, 26(17), 6716-6732. doi.org/10.1175/JCLI-D-12-00580.1

Oswaldo Cruz Fundation. 2020. Fiocruz assesses the impact of Pantanal fires on human health. Ministério da Saúde do Brasil, Governo Federal, Brasil. Access in https://portal.fiocruz.br/en/print/81214

Peng J, Dadson S, Hirpa F, Dyer E, Lees T, Miralles DG, Vicente-Serrano S, Funk C. (2020) A pan-African high-resolution drought index dataset. Earth System Science Data. 12, 753-769. doi.org/10.5194/essd-12-753-2020

Pesquero JF, Chou SC, Nobre CA, Marengo JA (2010) Climate downscaling over South America for 1961–1970 using the Eta model. Theoretical and Applied Climatology 99, 75–93. doi.org/10.1007/s00704-009-0123-z

Pinto MM, Libonati R, Trigo RM, Trigo IF, DaCamara CC. (2020). A deep learning approach for mapping and dating burned areas using temporal sequences of satellite images. ISPRS Journal of Photogrammetry and Remote Sensing, 160, 260–274. doi:10.1016/j.isprsjprs.2019.12.014

Popke D, Stevens B, Voigt A (2013) Climate and climate change in a radiative-convective equilibrium version of ECHAM6. Journal of Advances in Modeling Earth Systems 5(1):1–14. https ://doi.org/10.1029/2012M S000191

Pott A, Oliveira A, Damasceno-Junior G, Silva J (2011). Plant diversity of the Pantanal wetland. Brazilian Journal of Biology, 71(1 suppl 1), 265–273. doi:10.1590/s1519-69842011000200005

Pott V, Pott A, Lima L, Moreira S, Oliveira A. (2011). Aquatic macrophyte diversity of the Pantanal wetland and upper basin. Brazilian Journal of Biology, 71(1), 255–263. doi:10.1590/s1519-69842011000200004

Libonati

Silva MVM, Silveira CS, Silva GK, Pedrosa WHV, Marcos Junior AD, Souza Filho FA. (2020) Projections of climate change in streamflow and affluent natural energy in the Brazilian hydroelectric sector of CORDEX models. Revista Brasileira de Recursos Hídricos 25, e34, doi.org/10.1590/2318-0331.252020200020

Silva VO, Mello CR. (2020) Meteorological droughts in part of southeastern Brazik: Understanding the last 100 years. Engineering Science of Annals of the Brazilian Academy of Sciences.93(4) e20201130 doi.org/10.1590/0001-3765202120201130

Solman SA, Blázquez J. (2019) Multiscale precipitation variability over South America: Analysis of the added value of CORDEX RCM simulations. Climate Dynamics 53, 1547–1565 doi.org/10.1007/s00382-019-04689-1

Tomas WM, Oliveira Roque F, Morato RG, Medici PE, Chiaravalloti RM, Tortato FR, et al. (2020). Sustainability agenda for the pantanal wetland: perspectives on a collaborative interface for science, policy, and decision-making. Trop. Conserv. Sci. 12, 1–30. doi: 10.1177/1940082919872634

Van Loon, AF (2015) Hydrological drought explained, Wiley Interdisciplinary Reviews: Water, 2, 359–392. doi.org/10.1002/wat2.1085

Vicente-Serrano SM, Beguería S, López-Moreno JI, Angulo M, El Kenawy A (2010) A new global 0.5 gridded dataset (1901–2006) of a multiscalar drought index: comparison with current drought

Vicente-serrano SM, Beguería S, López-Moreno JI. (2010) A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. Journal of Climatology 23(7): 1696-1718. doi.org/10.1175/2009JCLI2909.1

Vicente-Serrano SM, Beguería S, Lorenzo-Lacruz J, Camarero JJ, López-Moreno JI, Azorin-Molina C, Revuelto J, Morán-Tejeda E, Sanchez-Lorenzo A (2012). Performance of Drought Indices for Ecological, Agricultural, and Hydrological Applications, Earth Interaction, 16, 1–27, 2012. doi.org/10.1175/2012EI000434.1

Watanabe M, Suzuki T, O'ishi R, Komuro Y, Watanabe S, Emori S, Takemura T, Chikira M, Ogura T, Sekiguchi M, Takata K, Yamazaki D, Yokohata T, Nozawa T, Hasumi H, Tatebe H, Kimoto M. (2010). Improved Climate Simulation by MIROC5: Mean States, Variability, and Climate Sensitivity. Journal of Climate, 23(23), 6312–6335. doi:10.1175/2010jcli3679.1

Wintle BA, Legge S, Woinarski JCZ. (2020). After the Megafires: What Next for Australian Wildlife? Trends in Ecology & Evolution. doi:10.1016/j.tree.2020.06.009

World Meteorological Organization (WMO) & Global Water Partnership (GWP). 2016. Handbook of Drought Indicators and Indices. (Eds. Svoboda M & Fuchs B). Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2. Geneva.

Zargar A, Sadiq R, Naser B, Khan F (2011) A review of drought indices. Environmental Review 19(1):333–349. doi.org/10.1139/a11-013

3 FINAL REMARKS

This work discusses severe meteorological droughts in southern Minas Gerais, an important economic area located in Southeast Brazil, and Pantanal, one of the largest wetlands in the world. Drought is a natural climate phenomenon caused by the rainfall amount below the average over a region for a long period. Its study should be more recurrent and more common in the future, helping decision-makers and stakeholders to avoid and to mitigate its impacts.

The assessment of droughts between the years 1970 and 2020 showed that the 2013/2014 hydrological year was the driest in the period. Two consecutive years with negative SPIs intensified the negative consequences of the drought over the region. This sequence of dry years caused the critical volume of the main reservoirs of the region, consequently reducing the energy generation in the plants of the region and coffee crop production. Furthermore, future scenarios indicate that extreme drought events will continue to occur. However, they will be rare, with similar frequency as in observations. From all the simulations, it is expected the occurrence of two events with this intensity, indicates the similar pattern of the present. An increase of consecutive drought events was projected by all GCM downscaling, which can lead to a serious impact on the environment, agriculture, and hydroelectricity

In Pantanal, in 80 years of observed data, the hydrological year of 2019/2020 was the driest observed in Pantanal, with the 1960s decade being the worst. SPI projections have shown different results, with CORDEX projecting extreme droughts until 2040, and Eta models not showing extreme events. SPEI projections, otherwise, have shown extreme drought events at the end of the XXI century, for both, Eta and CORDEX. The concentration of drought events in the 2080s and 2090s can indicate a shift in the climate of Pantanal to a semi-arid climate and a possible megadrought which might lead to a decrease in the runoff, a decrease in crop production, a decrease in hydroelectricity generation, and several social-economic problems for the region. Furthermore, recurrent extremely dry events can lead to an increase of wildfires in Pantanal, ecosystem losses, and direct impacts on human health.