REGIONAL CLIMATE PROJECTIONS FOR THE STATE OF SÃO PAULO, BRAZIL, IN THE 2020 – 2050 PERIOD

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ABSTRACT

The objective of this article is to present climate projections for the 2020–2050 period for several climate variables for the State of São Paulo, considering two scenarios RCP 4.5 and RCP 8.5. These projections were based on four climate models (HadGEM2-ES, MIROC5, CanESM2, and BESM) with downscaling of 20 km improved by the CPTEC/INPE Eta Regional Climate Model. Nine variables related to air temperature and rainfall were selected, and the deviation between the observed period (1961–1990) and the projected period (2020–2050) was calculated for the two RCP scenarios for each model and selected variable. Then, the highest and lowest values of the deviations were selected, which represent the maximum and minimum deviations projected for each cell. With this, we obtained the widest range between the possible trends of the four models compared for each variable analyzed in the state of São Paulo. The models used for the two RCP scenarios show the warming of the atmosphere, which tends to be less intense on the shoreline due to the control exerted by the ocean, and greater in the northwest region of the state, furthest from the Atlantic. A reduction in the Cold Spell Duration Index (CSDI) and an increase in the Warm Spell Duration Index (WSDI) is projected, with these trends increasing from south to north of the state. Considering the precipitation, no consensus between the trends of the models used in this study was found, with projections of both increase and decrease in annual total variables and in related extreme indices. Among the different projected trends, the reduction in precipitation is the worst scenario to be faced, given the essential aspect of water. The indicators related to intense precipitation (R95p and RX5day) showed a wide range between the maximum and minimum values projected in the analyzed scenarios, and the increase of these indicators deserves particular attention, since the increase in intense precipitation is a potential trigger of disasters, such as landslides, floods, and accelerated erosion. The results, given their relevance, were applied to the Ecological-Economic Zoning (ZEE) of the State of São Paulo, a technical and political planning instrument that establishes guidelines for land use and management, considering the environmental characteristics and socioeconomic dynamics of different regions of the state.

Keywords: Climate change; Air temperature; Precipitation; Extreme events; Climate projections.

RESUMO

PROJEÇÕES CLIMÁTICAS REGIONALIZADAS PARA O ESTADO DE SÃO PAULO, BRASIL, NO PERÍODO 2020-2050. O objetivo deste artigo é apresentar as projeções climáticas do período 2020-2050 para diversas variáveis climáticas no Estado de São Paulo, considerando os cenários RCP 4.5 e RCP 8.5. Essas projeções foram elaboradas a partir de quatro modelos climáticos (HadGEM2-ES, MIROC5, CanESM2 e BESM) com regionalização de 20 km, aprimorada pelo modelo Regional Eta do CPTEC/INPE. Selecionou-se nove variáveis relacionadas à temperatura do ar e chuva, e calculou-se o desvio entre o período observado (1961-1990) e o projetado (2020-2050) para os dois cenários RCPs 4.5 e RCP 8.5, para cada modelo e variável. Em seguida, foram selecionados os maiores e menores valores dos desvios, que representam o máximo e o mínimo desvios projetados para cada célula. Com isso, obteve-se o maior intervalo entre as tendências possíveis dos quatro modelos comparados para cada variável analisada no estado de São Paulo. Os resultados indicam que do ponto de vista da temperatura do ar, os modelos utilizados para os dois cenários RCP apontam para o aquecimento da atmosfera, que tende a ser menos intenso na fachada litorânea, devido ao controle exercido pelo oceano, e maior no trecho noroeste do estado, mais distante do Atlântico. Projeta-se redução na duração de ondas de frio (CSDI) e de aumento na duração das ondas de calor (WSDI), sendo que essas tendências aumentam de sul para norte do estado. Para a precipitação não há consenso entre as tendências dos modelos empregados no estudo, com projeções tanto de aumento quanto de redução nos totais anuais e índices extremos relacionados. Entre as diferentes tendências projetadas, a redução na precipitação é o pior cenário a ser enfrentado, dado o caráter essencial à vida que a água se reveste. Os indicadores relacionados à precipitação intensa (R95p e RX5day) evidenciaram uma grande amplitude entre os valores máximos e mínimos projetados nos cenários analisados, sendo que o aumento desses indicadores merece especial atenção, visto que o incremento de precipitações intensas são potenciais deflagradores de desastres, como escorregamentos, inundações e erosão acelerada. Os resultados, dada a sua relevância, foram aplicados no Zoneamento Ecológico-Econômico (ZEE) do estado de São Paulo, instrumento técnico e político de planejamento que estabelece diretrizes de ordenamento e de gestão do território, considerando as características ambientais e a dinâmica socioeconômica de diferentes regiões do estado.

Palavras-chave: Mudanças climáticas; Temperatura do ar; Precipitação; Eventos extremos; Projeções climáticas.

1 INTRODUCTION

The climate is relevant for environmental and social studies and policies, as its dynamics are responsible for the types and intensity of geomorphological processes, soil formation, evolution and adaptation of biodiversity, distribution of water and energy resources, as well as various socioeconomic impacts. Thus, knowledge of the climate dynamics provides important information about the rhythm of climatic attributes, which includes extreme events, and brings elements to discuss forms of land use and occupancy, both past and present, as well as what is intended for future generations. It is an important aspect to be considered in the planning of human activities.

If, on the one hand, the climate influences society, on the other hand, human actions influence the climate. Society, through its actions, is a modifying agent of the environment, which, by reacting and innovating, is able to create micro and topoclimates, transform local and subregional climates, and indirectly influence regional, zonal and global climates (MONTEIRO 1976).

Climate, whose essence is rhythm, has always been variable on any scale of time and space. Within this variability, climatic risks can generate different degrees of damage or harm to society. Solutions for new forms of economic, social, and political organization must be addressed to mitigate these effects. Based on this statement, it has been observed that in most developing countries, especially those located in the intertropical zone, weather events of small or medium deviation from the usual have their consequences substantially amplified by the prevailing socioeconomic structure (TARIFA & MELLO 1983).

Studies gathered and assessed by the Intergovernmental Panel on Climate Change (IPCC) demonstrate an increase in average air temperature related to the growing concentration of greenhouse gases (GHG) in the atmosphere, caused mainly by human activities, whose impact tends to increase the variability of climatic attributes and produce disasters (ALEXANDER et al. 2005, MEEHL et al. 2005, GRIMM & NATORI 2006, VERA et al. 2006, BOMBARDI & CARVALHO 2008, VALVERDE & MARENGO 2010, RIBEIRO NETO et al. 2012, MARENGO et al. 2013, OBREGON et al. 2014, VIOLA et al. 2014, NATIVIDADE et al. 2017, MACHADO et al. 2021, ZÁKHIA et al. 2021, FERREIRA & VALVERDE 2022, among others). Evidence of human influence on the climate system was considered very likely, with a degree of confidence greater than 90%, in the publication of the Fourth Assessment Report of the IPCC-AR4 (IPCC 2007). However, in the Fifth Assessment Report of the IPCC-AR5 (IPCC 2014), it was indicated that it would be extremely likely that more than half of the observed increase in global mean surface temperature over the last 70 years was caused by the anthropogenic increase in the concentration of greenhouse gases.

Finally, in the Sixth Report (AR6) it was concluded that the climate system is increasingly reaching levels not yet recorded in previous centuries, changing at unprecedented rates in at least the last 2,000 years, and therefore, the human influence on the warming of the atmosphere, ocean, and continents is unequivocal, since the pre-industrial period. It is also worth noting that the increase induced in the global average temperature from 2010 to 2019 was from 0.8 °C to 1.3 °C in relation to the period 1850-1900. The changes induced by the natural forcing of the climate system varied between -0.1 to +0.1°C, in the same period (IPCC 2021). Given this scenario, the issue of climate change is a fundamental aspect of the planning of human activities, whether economic, political or social, in the short, medium and long term.

The objective of this article is to present climate projections for the 2020-2050 period for several climate variables for the State of São Paulo, considering two scenarios RCP 4.5 and 8.5. These projections were based on four climate models (HadGEM2-ES, MIROC5, CanESM2, and BESM) with downscaling improved by CPTEC/INPE Eta Regional Climate Model. The final resolution of the products presented is 20 km.

Such results, given their relevance, were applied to the Ecological-Economic Zoning (ZEE) of the state of São Paulo, a technical and political planning instrument that establishes guidelines for land use and management, considering the environmental characteristics and socioeconomic dynamics of different regions of the state. In this instrument, efforts made to incorporate the issue “Climate Change” in the articulation between the different policies that operate in the state territory culminated in a guideline focused exclusively on this theme, defined as “resilient region to climate change”, aiming to identify and reduce vulnerabilities social and environmental, as well as preparing the state of São Paulo for risk situations. The economic exploitation of the territory of São Paulo, as well as Brazil, was historically conducted to the detriment of geoecological conditions. In the current context, in which greater and faster economic development is always sought, awareness of environmental problems arising from human actions is, therefore, increasingly important.

2 THE CLIMATIC CHARACTERISTICS OF THE STATE OF SÃO PAULO

The state of São Paulo is located mostly in the intertropical zone, and a smaller part in the subtropical. It is influenced by the Atlantic Ocean, where the Brazil Ocean Current is predominant.

Its climate is intrinsically associated to its position in South American Continent. The shape of the continent and the thermal variations of the ocean surface constitute the basis of climate macrocontrols. The continental surface of South America, wider in the intertropical portion, with the Amazon plain occupying a large part of this area, allows the formation of what is conventionally called “Continental Equatorial Mass” (mEC). In the center of the continent, the Platina plain, combined with summer warming and dynamic subsidence, promotes the genesis of the “Tropical Continental Mass” (mTC). In the extratropical portion, the continent becomes even narrower and does not offer conditions for the formation of a “Continental Polar Mass” (mPC). Polar migratory anticyclones develop in subpolar latitudes over the oceans and, depending on their routes, can turn into maritime or continental polar masses.

The configuration and morphology of the Andes Mountains, North-South oriented and with high altitudes, practically separate the atmospheric circulation from the low and medium levels of the Pacific and Atlantic slopes, with the exception of the extreme south, where the altitudes are lower and it becomes discontinuous, allowing the leakage of polar air from west to east, which promotes the accumulation of cold air on the eastern slope. The maritime polar mass, generated in the Atlantic at the height of the Patagonian plateau, over relatively cold waters (Falklands Current) finds it easier to advance to lower latitudes because the interior lowlands and relatively low altitudes of the Brazilian Plateau, moduled by the action of the polar front, make possible large invasions of extratropical air over the Atlantic slope of the continent. The warm waters of the Brazil Current contribute to changes in the properties of the polar masses, diversifying their properties as a function of their routes, either along the coast or in the interior of the continent.

The interaction zone between the intertropical and extratropical systems was generically designated as the polar front. In South America, the Atlantic Polar Front (FPA) that operates on the eastern portion of South America has great southern mobility, with a high degree of penetration over the central and eastern strip of the South American continent. The highest frequency of FPA passages occurs between the Rio de la Plata and the Tropic of Capricorn. In this way, the territory of São Paulo receives the influence of the direct action of polar fronts precisely because it is an area of interaction of the tropical maritime currents of E-NE, the polar currents of the south, and the currents of W-NW of the interior of the continent. The state of São Paulo is located at the site of interaction between different atmospheric systems, together with the presence of the zonal boundary between two climates: the one from Southern Brazil, classified as permanently humid Subtropical, and the other one from Central Brazil, classified as Tropical with periods well-defined alternating from dry and wet. This zonal boundary was defined by MONTEIRO (1973), as it can be seen in figure 1. This climatic classification was carried out from the dynamics of atmospheric systems at the continental level to assess their genetic participation in the territory of São Paulo.

The distribution of rainfall in the state of São Paulo reflects, at the same time, the major features of the São Paulo relief, the position in relation to the coast or the interior, and the frequency of atmospheric systems in the different parts of the state. In the south of the zonal boundary (Figure 1) the frequency of extratropical systems is significantly higher than in the north.

The extratropical systems, including the frontal systems and the polar migratory anticyclones, act in the state for about 50% to 25% of the year, alternating with the maritime tropical system (from 50% to 25%), responsible for the tendency to stabilize the weather in the state. Often, intercalated between the extratropical and the maritime tropical, the systems coming from the interior of the continent, linked to the NW and W winds, dominate for about 10 to 15% of a year. The last one, associated with polar fronts, are responsible for prefrontal warming, with high levels of instability that promote high intensity rainfall events.

Among the Brazilian states, São Paulo is the one with the highest occupancy rate of the territory, the largest population contingent and the greatest economic development, directly associated with the performance of its agriculture, industry, and services. Due to these reasons, it is the part of the Brazilian territory with the greatest rate of modification of the natural environment.

The interest of the “productive systems” in the state of São Paulo almost eliminated all native vegetation. Currently, the state has about 22.9% of native forest vegetation (SÃO PAULO 2020), mostly restricted to conservation areas.

The population of the state of São Paulo in 2021 was estimated at 46.6 million people (IBGE 2022), which represents about 20% of the Brazilian population. The state has the highest Brazilian industrial production, and the highest Gross Domestic Product (GDP) among the Brazilian states, which represented R$2.120 trillion in 2017 (SÃO PAULO 2020). This economic result comes from a diversified economy: the tertiary sector (services) is the main responsible for the economic greatness, representing 76.7% of GDP, while industry (secondary sector) represents approximately 21.2%, and the agricultural sector (primary) around 2% (SÃO PAULO 2020).

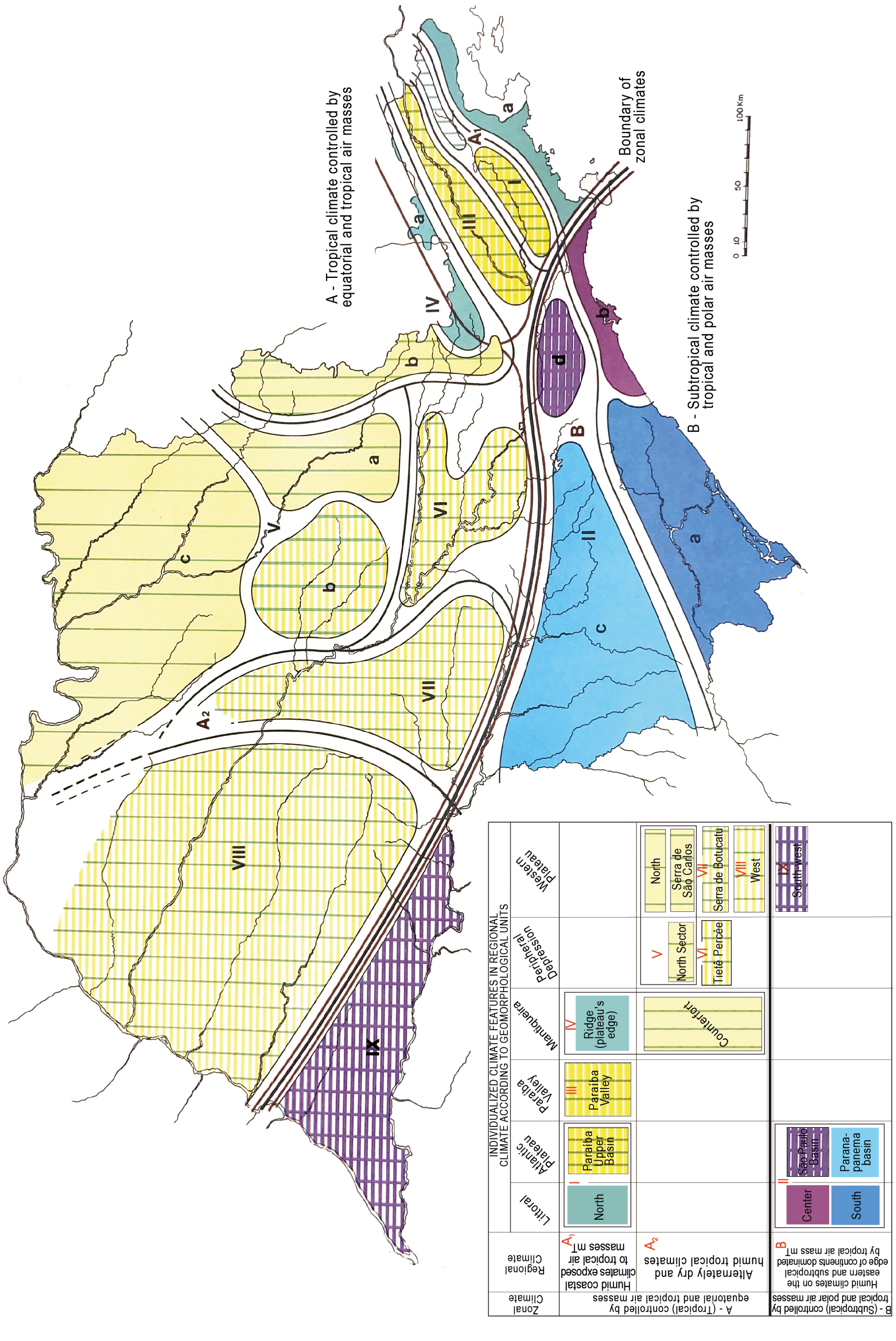

FIGURE 1 – Climate classification of the state of São Paulo (Source: MONTEIRO 1973)

The industrial activity is located and concentrated, mainly, in the metropolitan regions. It represents, from an environmental point of view, a high rate of modification of natural ecosystems, but with less territorial expression. Agriculture, on the other hand, occupies most of the state's territory, mainly upstate São Paulo. Despite being the sector that occupies the largest area of the territory, agriculture represents only 2% of the state's GDP, suggesting low efficiency, as it produces relatively little in large areas (SÃO PAULO 2020). This fact is even more important, as it competes with the conservation of natural areas, which increases the vulnerability to climate change of vast areas of the state.

3 METHODOLOGICAL PROCEDURES

3.1 RCPs Scenarios - Representative Concentration Trajectories

Socioeconomic and greenhouse gas emission scenarios are used in climate research to provide future perspectives with respect to a set of variables, including socioeconomic changes, technology, energy use, greenhouse gas emissions greenhouse, and air pollutants. They are used as input variables to feed the climate model and as a basis for the assessment of possible climate impacts and mitigation options and associated costs (VAN VUUREN et al. 2011).

Representative Concentration Pathways (RCPs) are scenarios that include time series of emissions and concentrations of the entire set of greenhouse gases (GHGs), aerosols, and chemically active gases, as well as land use and land cover (MOSS et al. 2008). Anthropogenic greenhouse gas emissions, which serve as the basis for the RCPs, are primarily due to population size, economic activity, lifestyle, energy use, land use patterns, technology, and climate policies (IPCC 2014).

The word *Representative* means that each RCP provides only one of many possible scenarios that would lead to specific radiative forcing characteristics. The term *pathways* emphasize the long-term concentration levels of interest, and also the trajectory taken over time to achieve this result (MOSS et al. 2010). Four RCPs are presented in the IPCC Fifth Assessment Report (AR5) as a basis for climate forecasts and projections:

- RCP 2.6: A trajectory in which radiative forcing peaks at approximately 3 Wm^{-2} before 2100 and then decreases;
- RCP 4.5 and RCP 6.0: Two intermediate stabilization pathways, in which the radiative forcing would stabilize at approximately 4.5 Wm^{-2} and 6.0 Wm^{-2} after 2100.
- RCP 8.5: A high path for which the radiative forcing reaches more than 8.5 Wm^{-2} until 2100 and continues to increase for some time.

The Weather Prevision Center and Climate Studies (CPTEC) from National Institute for Space Research (INPE) provides climate projections for several models, considering the two scenarios RCP 4.5 and RCP 8.5 as a reference, which were also used in this study.

RCP 4.5 assumes that the terrestrial system will store an additional 4.5 Wm^{-2}, with an equivalent CO_2 concentration on the order of 600 ppm, showing stabilization after the end of the 21st century. This RCP is aimed at a future: 1) a relatively optimistic reduction in emissions; 2) the implementation of consistent reforestation programs, considering the reduction of areas of agricultural crops and pastures due to increases in productivity and changes in human eating habits; 3) the adoption of stringent climate policies; and 4) stable methane emissions and lower energy consumption from fossil fuels (BJØRNÆS 2013).

RCP 8.5 assumes storage of 8.5 Wm^{-2} with an equivalent CO_2 concentration greater than 1000 ppm by the end of the century. This RCP implies a future with no changes to current public policies to reduce emissions, with an increase in CO_2 emissions in 2100 three times greater than the current ones, a rapid increase in methane emissions, expansion of agricultural and pastures to meet demand due to world population growth, projected at 12 billion by 2100. This scenario is also based on a low technological growth rate and high dependence on fossil fuels (BJØRNÆS 2013).

For reference, the most up-to-date record of CO_2 concentration in the atmosphere is carried out by the Mauna Loa Observatory in Hawaii, and recorded an average daily reading of approximately 416 ppm in September 2022 (NOAA 2022).

3.2 Climate models, data and representation

Global climate models (GCMs) are the best tools available to provide future information on climate change in light of different scenarios, as well as to test different hypotheses about the role of each climate driver. However, the spatial resolution of these models varies between 200 and 100 km. Thus, regional climate models (RCMs) play an important role in scaling up and generating increasingly detailed data (CHOU et al. 2014a, b) so that it is possible to better diagnose and assess climate impacts at a local scale.

In recent years, significant advances have been made in the technology and computational architecture of numerical model integration, as well as in the mathematical representation of physical, chemical, and biological processes and their complex interactions in the global climate system. Despite the scientific and technological advances, model results should be used carefully due to at least three categories of uncertainties: i) those related to emission scenarios; ii) those related to the natural variability of the climate system; and iii) those inherent to the model itself in representing physical and anthropic processes (BRASIL 2016a, b, c, d, e). Despite the aforementioned uncertainties, climate projections are innovative and valuable information for mitigating impacts to the society that inhabits the different Brazilian biomes, and improving the planning of adaptation actions and minimization of the effects of climate change (PBMC 2014).

The reduced spatial resolution of global models implies the need for *downscaling methods* (increased spatial resolution) that can be applied to climate change scenarios from global models, in order to obtain more detailed projections for certain regions, with a higher spatial resolution than provided by a global model. This is very useful, particularly for studies of the impacts of climate change, on the management and operation of water resources, natural ecosystems, agricultural activities, and even health (BRASIL 2016).

Considering the Eta regional climate model, INPE assessed different climate change scenarios proposed by the IPCC's AR5 global models, the RCPs, and applied the dynamic *downscaling method* for Brazil. This method consists of scaling up climate change projections from global climate models to obtain more detailed climate projections, that is, with higher spatial resolution, and suitable for specific regions, such as states, coasts, watersheds or valleys, for example. The best detail is obtained by feeding regional atmospheric models with projections from global climate models (BRASIL 2016).

The simulations of the Eta regional climate model, with a resolution of 20 km, carried out by INPE, were evaluated for the historical period (1961 to 1990), using different global models. These simulations reproduced the climate of the historical period in South America reasonably well. The assessment of future climate change indicated a strong reduction in precipitation during the rainy season in the central part of the continent and an increase in precipitation in the southern part of Brazil towards the end of the century, with trends to increase precipitation extremes in the south and southeast of Brazil in the future (CHOU et al. 2014a, b). Changes in climate extremes are the main issues to be analyzed in vulnerable sectors and to propose adaptation measures (LYRA et al. 2017).

The climate projections for the State of São Paulo were prepared from data generated by CPTEC/INPE and made available on the Platform for Climate Change Projections for South America (PROJETA), regionalized by the Eta model (CHOU et al. 2014a, b; BRASIL 2016a, b, c, d, e; LYRA et al. 2017), whose objective is to provide data from climate scenarios with downscaling for a better study of smaller regions or areas.

The scenarios were generated from Eta regional climate model, configured to output at 20 km spatial resolution for South America. This scale-up was produced for global climate models HadGEM2-ES, MIROC5, CanESM2, and BESM (Brazilian Earth System Model). It should be noted that these global climate models (GCMs) were evaluated and selected, among more than 40 climate models available by the Coupled Model Intercomparison Project Phase 5 (CMIP5), as they present better performance to simulate the climate of South America (CHOU et al. 2014a, b; LYRA et al. 2017).

Developed by the UK Met Office from United Kingdom, HAdGEM2-ES integrates the HadGEM model set, which is a collection of global models used to minimize uncertainties and represent and predict complex feedbacks in the climate system (POPE et al. 2007). The name HadGEM2-ES indicates the second version (2) of HadGEM models, which includes Earth System (ES - Earth System) variables, which in addition to the basic configuration of atmosphere-ocean interactions, add carbon cycle processes and tropospheric chemistry (MARTIN et al. 2011). This model satisfactorily simulates the South American climate, with a tendency to underestimate the air temperature near the surface, but better simulates precipitation patterns, including the SACZ (South Atlantic Convergence Zone).

The Model for Interdisciplinary Research on Climate (MIROC), developed by the Japanese scientific community, is now in its fifth version (MIROC5). Compared to the previous versions, version 5 presents better results in relation to precipitation, several zonal mean fields, the equatorial oceanic subsurface, and the ENSO (El Niño–Southern Oscillation) simulation. This model includes in its routines an updated version of the surface model, called Minimal Advanced Treatments of Surface Interaction and Runoff, which predicts the temperature and water volume in six soil layers up to 14 m thick, a canopy layer and three layers of snow (WATANABE et al. 2010).

The second generation Canadian Earth System Model (CanESM2) is the fourth generation of the coupled global climate model developed by the Canadian Center for Climate Modeling and Analysis (CCCma) of Environment and Climate Change. The CanESM2 has the main components of the Earth System model: (i) Atmospheric General Circulation model (AGCM4) in 35 vertical layers; (ii) Ocean GCM4, developed from the NCAR CSM Ocean Model with a horizontal resolution of 256x192 and 40 vertical layers; (iii) CanSim1 sea ice model; and (iv) Canadian Earth Surface Scheme (CLASS2.7) and CTEM1 for terrestrial processes. It couples a physical atmosphere-ocean model (CanCM4) to a model of terrestrial carbon (CTEM) and oceanic carbon (CMOC) (VON SALZEN et al. 2005, LI & BARKER 2005).

BESM, whose development took place under the leadership of Brazilian scientists from CPTEC/INPE, offers greater accuracy of regional processes, including those dependent on teleconnections, allowing the modeling of global changes and their regional consequences. This model improves the representation of tropical processes, normally underrepresented in models from abroad (NOBRE et al. 2013). The BESM, also used in this study, consists of the atmospheric general circulation model (AGCM) of the CPTEC/INPE coupled with the ocean model version 4p1 (MOM4p1) and the general ocean circulation model (OGCM), which includes the ocean ice simulator, both of which come from the GFDL (Geophysical Fluid Dynamics) (NOBRE et al. 2013).

Simulations of the four models mentioned were used for the two scenarios RCP 4.5 and RCP 8.5. Data were obtained from PROJETA-CPTEC/INPE for the periods 1961-1990, considered as a reference for the current climate, and for the average for the future 2020-2050.

PROJETA-CPTEC/INPE provides a set of 33 climatic elements and 26 extreme events indices. For the present study, two climatic elements and seven extreme events indices were selected to be analyzed focusing on the territory of the state of São Paulo, according to table 1.

The absolute deviation between the observed period (1961-1990) and the projected period (2020-2050) was calculated for the two scenarios RCP 4.5 and RCP 8.5, for each model and selected variable. Then, the extreme values of the absolute deviations calculated for each model were selected. The positive and/or negative values indicate the trend of increase and/or reduction, respectively, of the analyzed variable.

TABLE 1 – Climatic elements and extreme events indices selected for analysis

Variable	*Description of weather element or extreme event indices*
TP2m	Average air temperature at 2 m above surface
TNn	Minimum value of daily minimum temperature (°C)
TXx	Maximum value of daily maximum temperature (°C)
CSDI	Cold spell duration index - Maximum number of consecutive days in the year when daily Tmin < 10th percentile (day)
WSDI	Warm spell duration index - Maximum number of consecutive days in the year when Tmax > 90th percentile (day).
PRCPTOT	Total wet day precipitation
CDD	Maximum number of consecutive dry days (day)
RX5day	Maximum in 5 day precipitation (mm)
R95p	Very wet day precipitation - Total annual precipitation of days when P > 95th percentile (mm)

Source: PROJETA-CPTEC/INPE (2019)

These extreme values therefore represent the upper and lower limits of the variation range of the absolute deviation obtained for each variable. Subsequently, the highest upper and lower extreme values were selected, aiming to obtain the greatest range of variation between the models, as shown in figure 2.

Evaluating climate projections from four different models was necessary because the use of a single model without bias correction is not advisable, as each one presents a specific trend, which depends on how it was conceived. In this way, the best procedure is to evaluate the amplitude of each projected variable among the four models employed, it is possible to identify, for example, a range of variation in air temperature, or intensity of precipitation, covering both its increase (+ sign) , as well as its reduction (- sign).

These extreme values presented must be understood as critical for the different human activities, as well as for the different functions of living organisms and geodynamic processes.

The data presented is available in *shapefile format* (.shp) as an appendix to this article.

The State Water Resources Policy decentralized the management of water resources in the state of São Paulo, adopting hydrographic basins as management and planning units. The Hydrographic Units for Water Resources Management (UGRHIs) are considered territorial units that allow the decentralized management of water resources and are organized by hydrographic basins regions or a set of them (SÃO PAULO 2020). The state of São Paulo was divided into 22 UGRHIs, as shown in table 2. The numbers of UGRHIs presented in this table will be represented on the maps below for the purpose of locating and discussing the results.

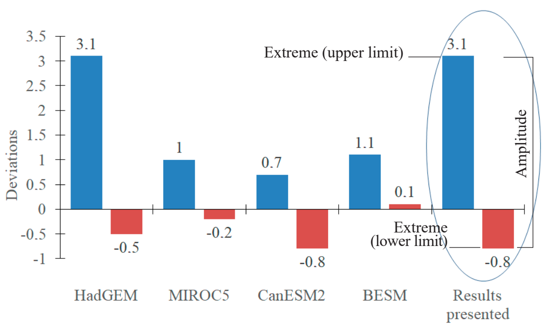

FIGURE 2 – Selection of the amplitude of variation between the maximum and minimum deviations obtained among the projection of climate models in relation to the historical period from 1961 to 1990 for a given variable.

4 RESULTS

The maps (Figures 3 – 11) presented in the sequence illustrate the range between the maximum and minimum deviation obtained for each variable, considering the period from 1961 to 1990, aiming to obtain a range of variations projected by the models, and from there will be possible to evaluate the specific trend of each selected attribute. All figures were designed for the 2020-2050 period, in the RCP 4.5 (left) and RCP 8.5 (right) scenarios. The maps “A” and “C” of each figure represent the maximum and minimum deviations, respectively, obtained for the 4.5 scenario, while “B” and “D” represent the maximum and minimum deviations, respectively, for the RCP 8.5 scenario.

The results obtained for the State of São Paulo from the assessment of climate projections, refer to air temperature, precipitation, and extreme events indices, projected for the 2020-2050 period (Table 1).

TABLE 2 – UGRHIs in the State of São Paulo (source: SÃO PAULO 2020).

UGRHI No.	*Name*
01	Mantiqueira
02	Paraíba do Sul
03	Litoral Norte
04	Pardo
05	Piracicaba/Capivari/Jundiaí
06	Alto Tietê
07	Baixada Santista
08	Sapucaí / Grande
09	Mogi Guaçu
10	Tietê/Sorocaba
11	Ribeira de Iguape/Litoral Sul
12	Baixo Pardo/Grande
13	Tietê/Jacaré
14	Alto Paranapanema
15	Turvo/Grande
16	Tietê/Batalha
17	Médio Paranapanema
18	Sao José dos Dourados
19	Baixo Tietê
20	Aguapeí
21	Peixe
22	Pontal do Paranapanema

4.1 Air temperature

The difference in annual mean air temperature (TP2m) between the projection for the 2020-2050 period and the historical period 1961-1990 for the state of São Paulo is shown in figure 3. Figures 3A to 3D must be analyzed considering that they illustrate the range between the maximum and minimum deviation obtained and represent, therefore, the maximum and minimum deviation, respectively, obtained for the scenarios RCP 4.5 and RCP 8.5.

The deviation between the two periods for the annual average temperature has a positive sign (warming) in both scenarios in all its amplitude. It is observed that in RCP 4.5 the range of variation of the air temperature deviation, between the maximum (Figure 3A) and the minimum (Figure 3C) projected is between 0.5 °C and 2.5 °C. The most severe changes were obtained in the RCP 8.5 scenario, with the lower limit starting from 0.5 °C (Figure 3D) to a maximum of 3.0 °C (Figure 3B) in relation to the average annual temperature for the 1961-1990 period. In general, the projected warming occurs in all state territory, but the magnitude and spatial distribution differs in the two analyzed scenarios: in RCP 8.5 the northern half of the state presents a projection of increase between 2.5 °C and 3.0 °C compared to the 1961-1990 average. This intensity of warming does not occur only in the eastern and southern parts of the state.

The spatial distribution of the projected changes for the annual mean air temperature shows a latitudinal variation, with a decrease towards the south of the state and near to the ocean, with an increase in its deviation the further away from the ocean. The central and northern of the state, even considering the lower limits of the projections, present higher values in relation to the rest of the state.

The deviation of the lowest annual minimum air temperature (TNn) between the future projection (2020-2050) and the historical period (1961-1990) for the state of São Paulo is expressed in figure 4.

As for the annual average temperature, figure 4 shows an increasing trend, from 0.5 °C to 3.5 °C for all scenarios evaluated, with the highest increase being restricted to the northeast of the state of São Paulo (Jales and surroundings). In the RCP 8.5 scenario, a wider change can be seen, with an increase between 1.5 °C and 2.5 °C, covering a large part of the central-west and southwest of the state.

The spatial variation of this element is similar to that observed for the average annual temperature, and the distance from the ocean seems to have greater influence on this climatic element in the upper limit of the two evaluated scenarios, with the smallest deviations closer to the coast, and the deviation increases while the distance from the ocean also increases. The largest deviations occur in the northwest of São Paulo, with 3 °C above the 1961-1990 average (Figures 4A and 4B).

The magnitude of the minimun deviations in both scenarios is smaller, reaching a maximum of 1.5 °C in RCP 8.5 (Figure 4C and 4D), in relatively restricted areas (Baixo Ribeira de Iguape and Serra da Mantiqueira and sections of the northern sector of the Peripheral Depression). In this case, the proximity to the ocean does not seem to have an important influence, because both along the coast and in the western part of the state, the smallest deviations occur. On the other hand, in a more optimistic scenario (RCP 4.5/Figure 4C) highest areas of the Serra da Mantiqueira show the smallest deviations, while in the pessimistic scenario (Figure 4D) the situation is reversed, allowing the interpretation that the role of relief can be differentiated.

Regarding the maximum annual temperature (TXx), the deviations between the 2020-2050 projection and the historical period 1961-1990 (Figure 5) show, as for the previous variables, only a trend towards an increase in temperature.

In general, the warming is more widespread throughout the state. The lowest values of warming occurs along the coastline, with the minimun deviations between 0.5 and 1.5 ºC in the coastal UGRHIs (03-Litoral Norte, 07 - Baixada Santista and 11-Ribeira de Iguape/Litoral Sul), while the maximums, that predominate in the state, start from 3.0 to 4.0 ºC above the normal 1961-1990 (RCP 4.5), up to 6.0 °C at the upper limit of the RCP 8.5 scenario (Figure 5B). The highest warming in the state is projected for central area of the state considering the upper limit of the scenario RCP 8.5 (Figure 5B). However considering the minimum deviation of both scenarios and the upper limit of the RCP scenario 4.5, the center and north of the state appear with greater warming (Figure 5A, 5C, and 5D).

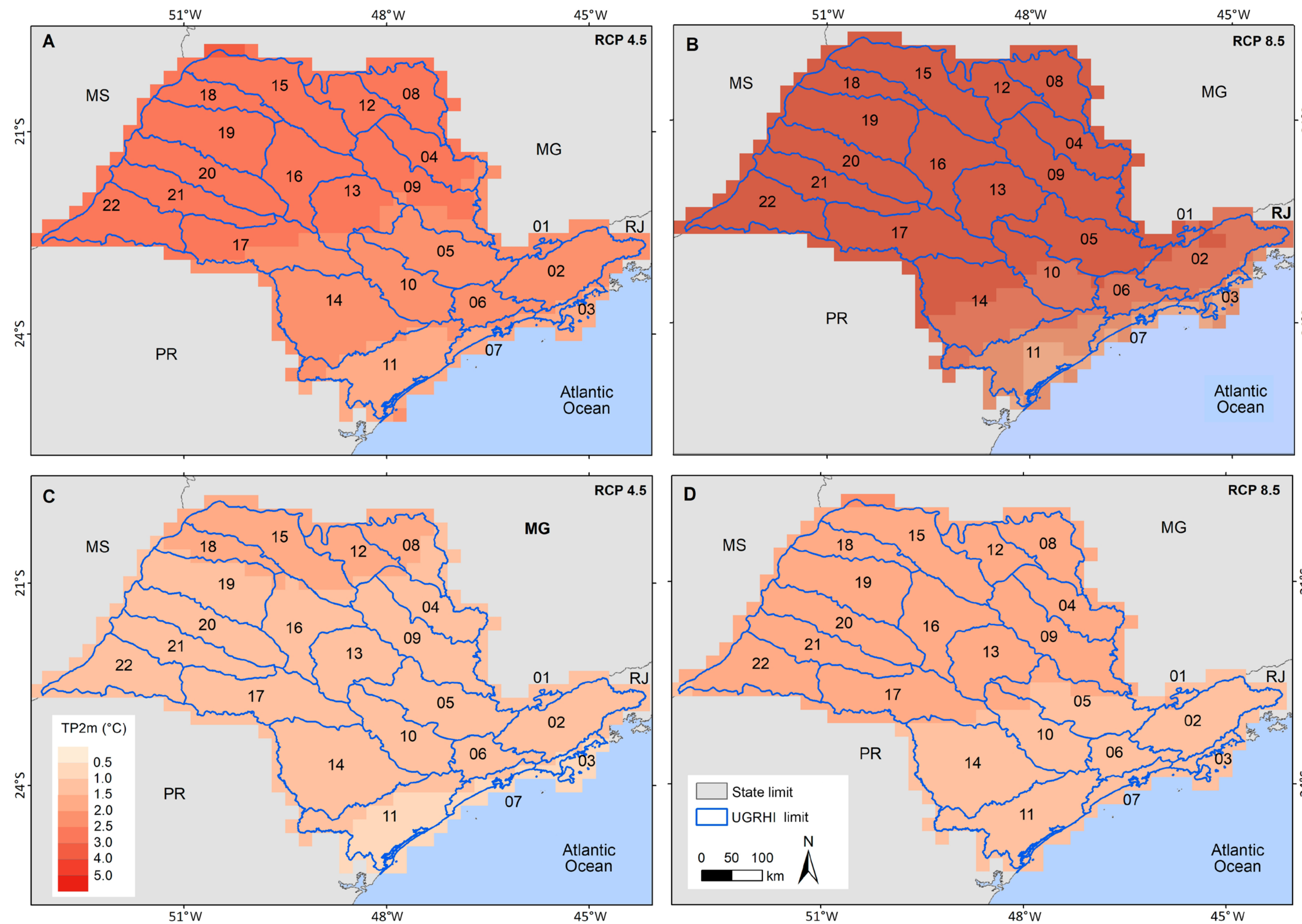

FIGURE 3 – Maximum (upper images) and minimum (lower images) deviations of the annual mean air temperature – TP2m (°C) between the 2020-2050 projection and the historical period 1961-1990 for the State of São Paulo under the RCP scenarios 4.5 (A and C) and RCP 8.5 (B and D). Sources: CPTEC/INPE (2019), IGC (2011) and IBGE (2013). Geographic Coordinate System, Datum SIRGAS 2000. Prepared by Nádia Lima (2022).

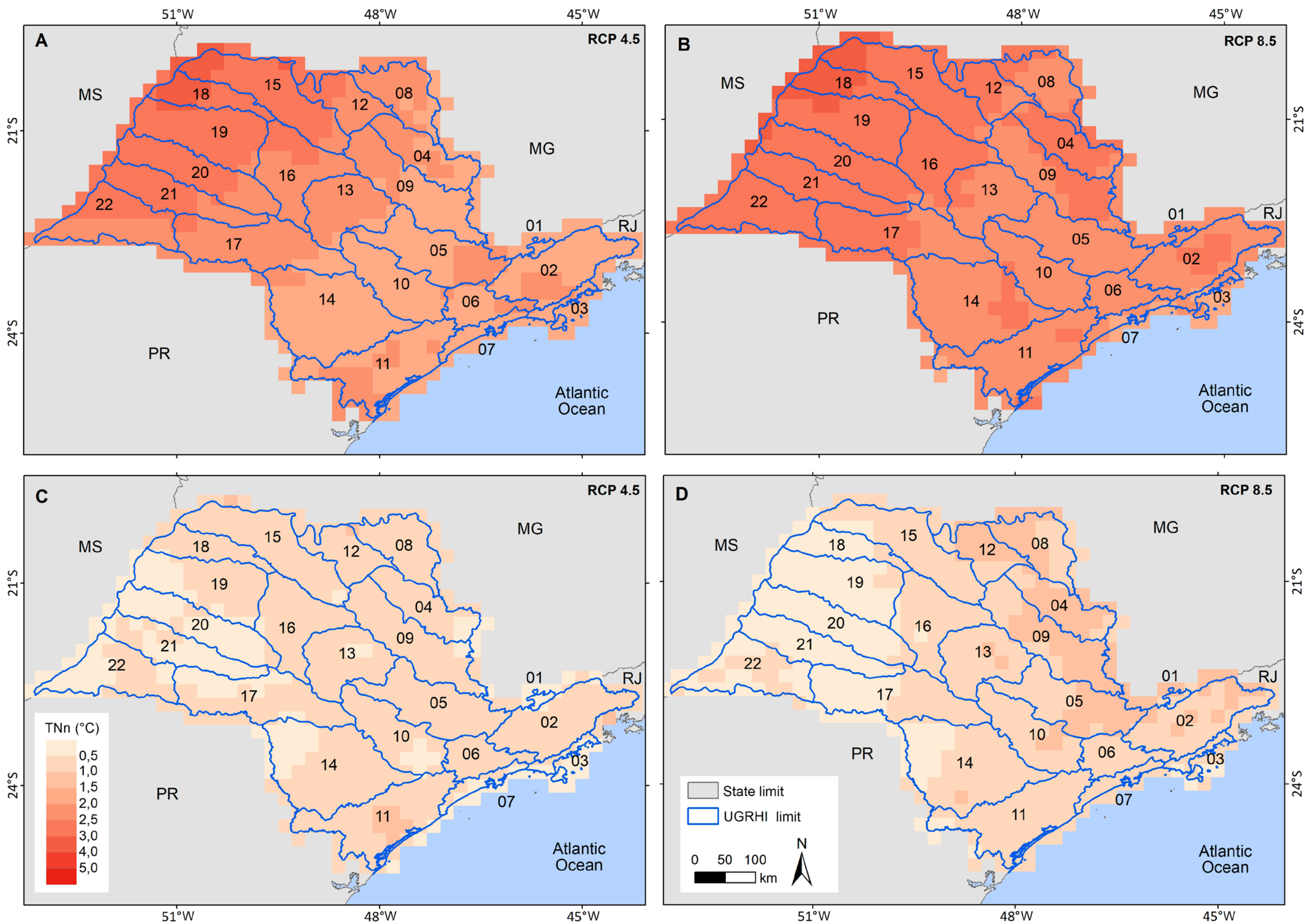

FIGURE 4 – Maximum (upper images) and minimum (lower images) deviations from the lowest annual minimum temperature – TNn (°C), between the 2020-2050 projection and the historical period 1961-1990 for the State of São Paulo under the RCP scenarios 4.5 (A and C) and RCP 8.5 (B and D). Sources: CPTEC/INPE (2019), IGC (2011) and IBGE (2013). Geographic Coordinate System, Datum SIRGAS 2000. Prepared by Nádia Lima (2022).

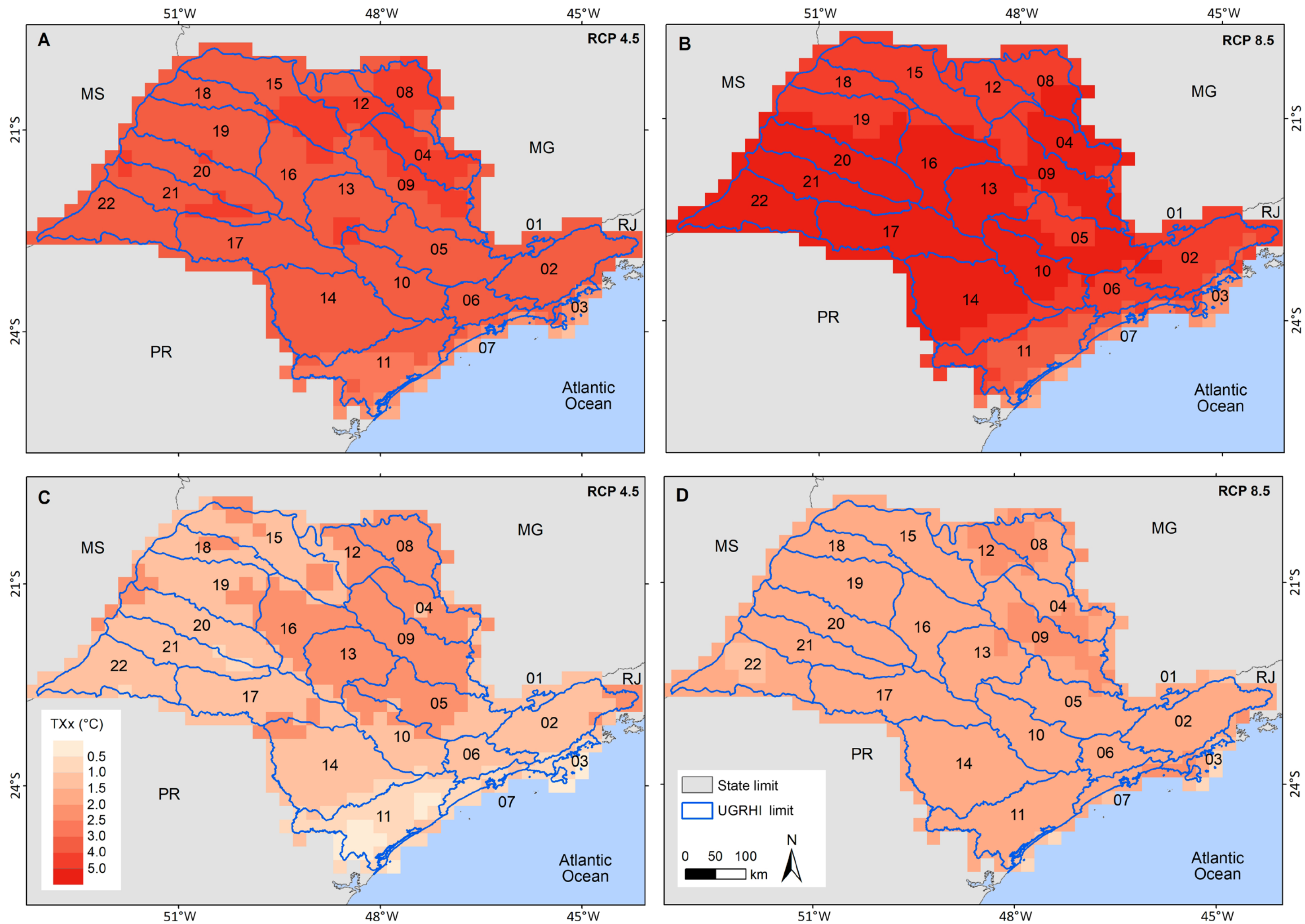

FIGURE 5 – Maximum (upper images) and minimum (lower images) deviations from the highest annual maximum temperature – TXx (°C) between the 2020-2050 projection and the historical period 1961-1990 for the State of São Paulo under the RCP 4.5 scenarios (A and C) and RCP 8.5 (B and D). Sources: CPTEC/INPE (2019), IGC (2011) and IBGE (2013). Geographic Coordinate System, Datum SIRGAS 2000. Prepared by Nádia Lima (2022).

There is a reduction in the maximum number of consecutive days in the year with minimum temperature below the 10th percentile (CSDI) in all projected scenarios (Figure 6).

The spatial distribution and magnitude of the minimum deviations of this indice (Figures 6C and 6D) is similar, but there is a tendency to reduce from south to north of the state, mainly in the tropical portion (see boundary of zonal climates in figure 1). For the RCP 4.5 scenario (Figure 6A), along the middle and lower course of the Tietê River, small areas presents an increase of up to 1.5 days in CSDI, suggesting a certain cooling of these areas in certain periods of the year. In the maximum deviation of the RCP 8.5 scenario, practically the entire state presents a reduction of cold waves between 1 and 3 days, with small isolated areas where this reduction is up to one day.

There is a significant increase in the indicator of duration of heat waves in the state of São Paulo, when considering the maximum number of consecutive days in the year when the maximum temperature is greater than the 90th percentile (Warm Spell Duration Index – WSDI) (Figure 7), present in both projected scenarios, considering maximum (Figure 7A and 7B) and minimum (Figure 7C and 7D) deviations.

In the most pessimistic scenario (Figure 7B) this increase is greater than 150 days in the north of the state, whereas considering the optimistic scenario (Figure 7C) the smallest projected increase is 25 days in the south of the state, which is also significant.

The increase in the duration of this index is mainly influenced by latitude, with projections being inversely proportional to latitude, which means, the lower the latitude, the longer the duration of projected heat waves, and vice versa. The proximity to the ocean also influences these projections, as the coast is where the increase is less intense for both scenarios.

4.2 Precipitation

Different from the air temperature, the precipitation presents greater dispersion of data throughout the state depending on the projected scenario, being possible to observe regions with increase and others with reduction in relation to the period 1961-1990. In all scenarios, there is a trend of reduction in precipitation (Figure 8). The increase in total annual precipitation is projected in both scenarios, but only at the maximum deviation (Figures 8A and 8B) and restricted to coastal areas (UGRHI 03 - Litoral Norte, 07 - Baixada Santista and 11 - Ribeira de Iguape/ Litoral Sul), which present values up to 700 mm in relation to the annual average of 1961-1990. The in Serra da Mantiqueira and Serrania de Lindóia show an increase up to 250 mm in the annual total.

The extreme event indices, which present the maximum number of consecutive dry days in the year (CDD), reflects the duration of drought periods (Figure 9). For the upper limit for the two scenarios considered, an increase in the duration of consecutive dry days is projected for the entire state. In the most extreme case (Figure 9B) there is an increase in the dry period between 5 and 10 consecutive days, with small areas on the coast and north of the state, in which this period will increase from 10 to 15 days. Regarding the lower limit (Figure 9C), the RCP 4.5 scenario shows a reduction in the dry period up to 5 days in a large area of the north and west of the state, and in some small areas in the east. At the same lower limit, but in a pessimistic scenario (RCP 8.5), an increase in most of hte state up to 5 days is projected for this index, with small isolated areas that indicated reduction in the north, northwest and, west of the state.

The total annual precipitation of days when precipitation is greater than the 95th percentile, or very wet day precipitation (R95p), is an indicator of high intensity precipitation (Figure 10). There is a great variability of this index between the upper and lower limits of both scenarios in the state of São Paulo, with a projection of increasingly intense rainfall in the upper limits of the RCP 4.5 and RCP 8.5 scenarios, but also a reduction in the lower limits for both scenarios.

The largest increments in the most intense precipitation are expected in the upper limit of the RCP 4.5 scenario, with increases in intense precipitation of up to 200 to 300 mm located in the basins of the Alto Ribeira (UGRHI 11 - Ribeira de Iguape/ Litoral Sul), Alto Paranapanema (UGRHI 14 - Alto Paranapanema) and lower course of the Paranapanema river, as shown in figure 10A. The rest of the state shows a tendency to increase from 100 to 200 mm, except in the northern section (up to 50 mm) (Figure 10A). For the upper limit of the RCP 8.5 scenario the increases are smaller; most of the state presents up to 100 mm in the most intense rains; the Serra da Mantiqueira and some areas of the Alto Ribeira de Iguape are the places

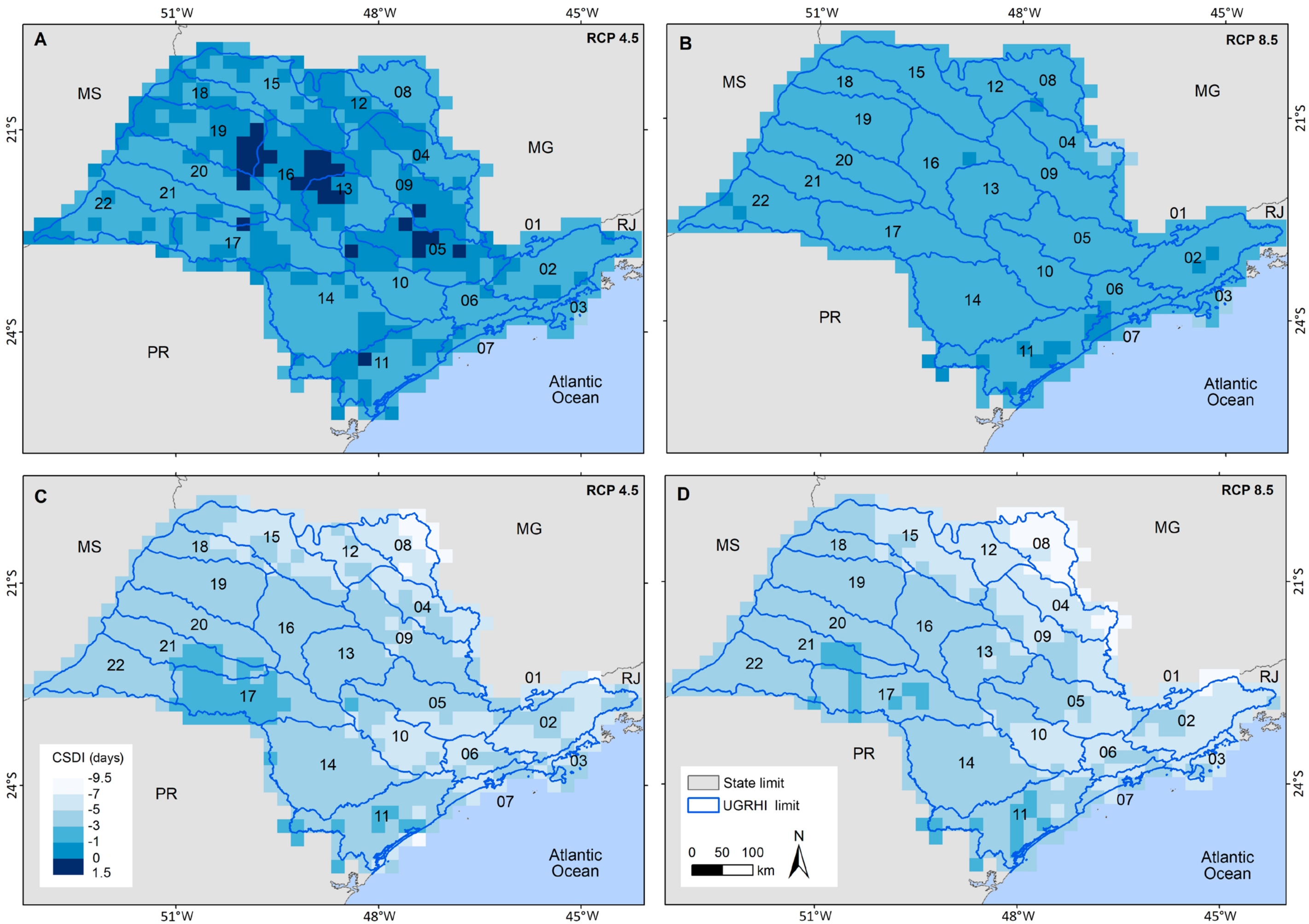

FIGURE 6 – Maximum (upper images) and minimum (lower images) deviations from the maximum number of consecutive days in the year when minimum temperature is lower than the 10th percentile – cold spell duration index – CSDI between the 2020-2050 projection and the historical period 1961-1990 for the State of São Paulo under the scenarios RCP 4.5 (A and C) and RCP 8.5 (B and D). Sources: CPTEC/INPE (2019), IGC (2011) and IBGE (2013). Geographic Coordinate System, Datum SIRGAS 2000. Prepared by Nádia Lima (2022).

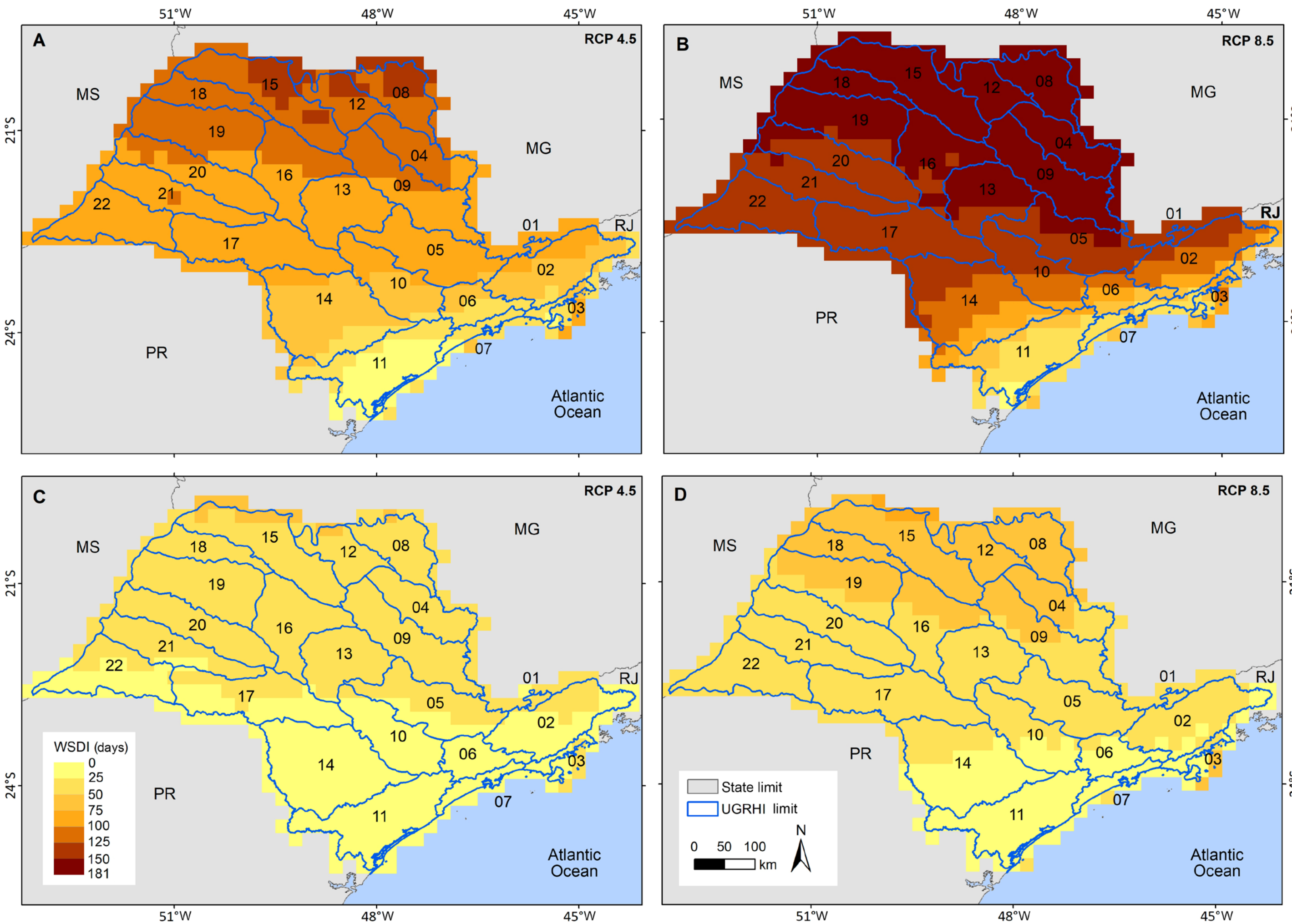

FIGURE 7 – Maximum (upper images) and minimum (lower images) deviations from the maximum number of consecutive days in the year when Maximum Temperature is greater than the 90th percentile (day) (warm spell duration index – WSDI between the 2020-2050 projection and the historical period 1961-1990 for the State of São Paulo under the scenarios RCP 4.5 (A and C) and RCP 8.5 (B and D). Sources: CPTEC/INPE (2019), IGC (2011) and IBGE (2013). Geographic Coordinate System, Datum SIRGAS 2000. Prepared by Nádia Lima (2022).

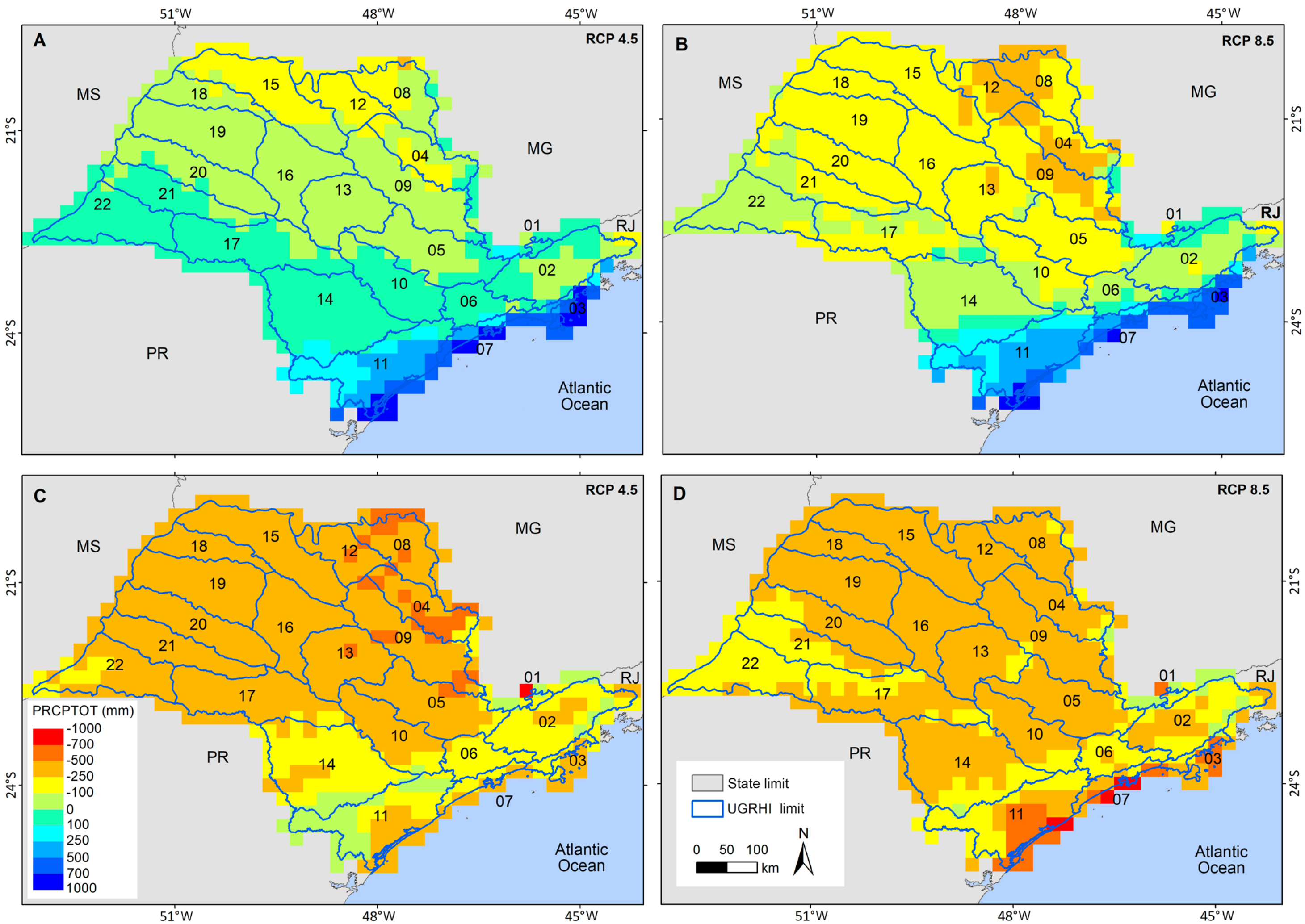

FIGURE 8 – Maximum (upper images) and minimum (lower images) deviations from Total Precipitation (mm) – PRCPTOT, for the State of São Paulo between the 2020-2050 projection and the historical period 1961-1990 for the state of São Paulo under the scenarios RCP 4.5 (A and C) and RCP 8.5 (B and D). Sources: CPTEC/INPE (2019), IGC (2011) and IBGE (2013). Geographic Coordinate System, Datum SIRGAS 2000. Prepared by Nádia Lima (2022).

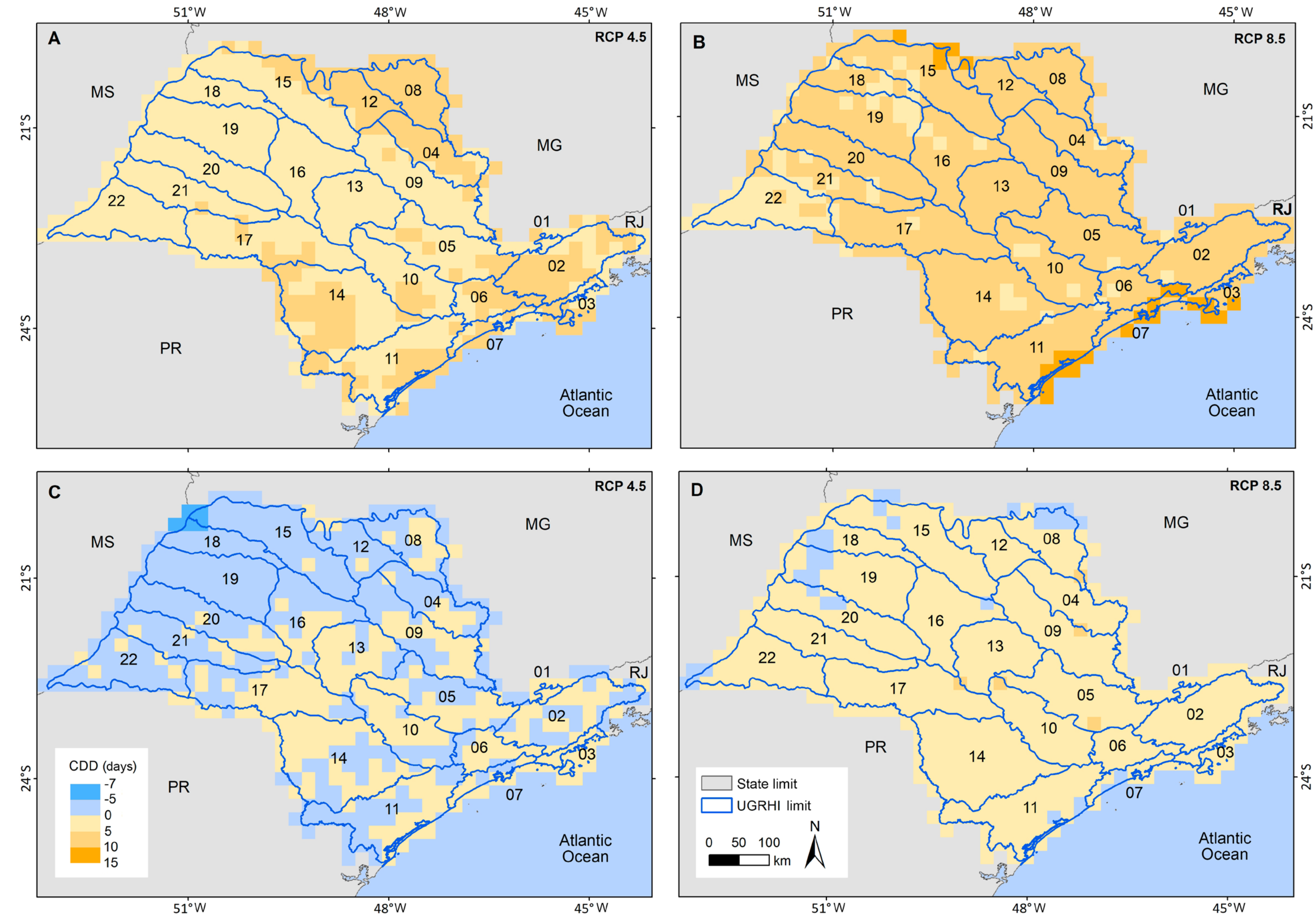

FIGURE 9 – Maximum (upper images) and minimum (lower images) deviations from the maximum number of consecutive dry days in the year – CDD for the State of São Paulo between the 2020-2050 projection and the historical period 1961-1990 for the state of São Paulo under scenarios RCP 4.5 (A and C) and RCP 8.5 (B and D). Sources: CPTEC/INPE (2019), IGC (2011) and IBGE (2013). Geographic Coordinate System, Datum SIRGAS 2000. Prepared by Nádia Lima (2022).

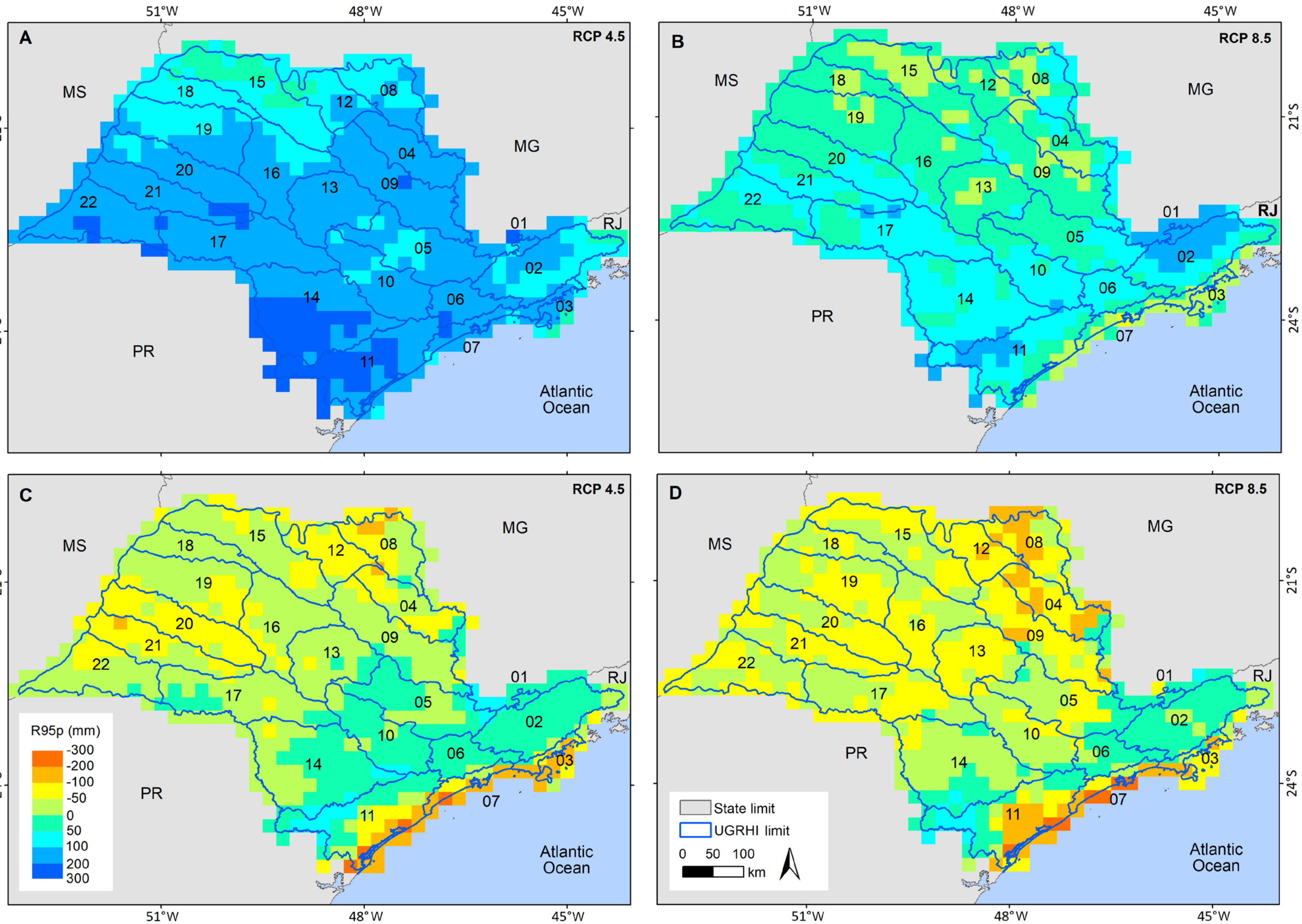

FIGURE 10 – Maximum (upper images) and minimum (lower images) deviations from Total Annual Precipitation of days when rainfall is greater than the 95th percentile - very wet day precipitation (mm) – R95p between the 2020-2050 projection and the historical period 1961-1990 for the State of São Paulo under scenarios RCP 4.5 (A and C) and RCP 8.5 (B and D). Sources: CPTEC/INPE (2019), IGC (2011) and IBGE (2013). Geographic Coordinate System, Datum SIRGAS 2000. Prepared by Nádia Lima (2022).

where the projected increase is more expressive (up to 200 mm). In small areas along the coastline and in the north of the state, there is a reduction up to 50 mm in the most intense rainfall (Figure 10B).

The lower limits of both scenarios (RCP 4.5 and RCP 8.5) indicate a tendency to reduce the volume of intense rainfall in almost the entire state, except the area occupied by the Atlantic Plateau, with a projection of an increase up to 100 mm. The rest of the state, including the coastal zone, is projected to reduce precipitation up to 300 mm (Figure 10C and 10D). Thus, the range projected for 2040 is quite high, with areas that may have intense rainfall increased by 300 mm, or reduced in the same proportion.

Regarding the maximum precipitation accumulated in five consecutive days (RX5day), the upper limits of the projections in the two scenarios (Figure 11A and 11B) indicate that there may be an increase in rainfall totals, with the exception of parts of the center and north of the state, and along the coastline. The most significant increases in this index occur in the RCP 4.5 scenario in the subtropical climate area (Figure 1), while the smallest increases north of the zonal boundary, in the Mantiqueira Mountains, Paraíba Valley and Serra do Mar and north center of the state.

The largest increases, between 30 and 45 mm in relation to the historical reference period (1961-1990), are projected south of the zonal boundary, in the Serra de Paranapiacaba, divide area between the Alto Paranapanema and Ribeira de Iguape basins, extending to the southern area of the São Paulo Metropolitan Region. From Alto Paranapanema to the Pontal do Paranapanema and neighboring regions, the deviation above the normal 1961-1990 varies between 20 and 30 mm. In the Serra da Mantiqueira and Serra do Mar, at the north of the zonal boundary (tropical climate - Figure 1) the projected increase varies between 10 and 20 mm; in the center and north of the state up to 10 mm, with small areas of reduction in RX95day up to 10 mm on the border with Minas Gerais. In the RCP 8.5 scenario, the projection presents a spatial structure relatively similar to that of the RCP 4.5 scenario, but with lower intensity, with the largest increments of up to 20 mm, and increases of areas with reduction of the precipitation totals (up to 10 mm) in the center and north of the state.

The lower limit in both scenarios also has relatively the same spatial structure. Most of the territory has a reduction in totals, being more intense in the RCP 8.5 scenario in the center and north of the state, and in the metropolitan regions of Campinas and São Paulo, with a reduction up to 30 mm. The coast of the state presents the highest values in the reduction of this index (up to 55 mm). The upper Ribeira de Iguape valley, for both scenarios, and also the Serra da Mantiqueira and the surroundings of Piracicaba (only for RCP 4.5) present elevation in RX5day.

5 DISCUSSION

The State of São Paulo is located on the Atlantic coast, an area sensitive to extreme rainfall events given the climate conditions (TARIFA 1994). The projections related to precipitation (Figures 7, 8, 9 and 10) indicate the possibility of an increase in the annual totals and in the rates of extreme rainfall events. TARIFA (1994) already pointed out that changes in the vegetation cover of hydrographic basins aggravated the impacts caused by such events, as the magnitude of disasters triggered by meteorological events is increased. This situation should be even worse in metropolitan regions, where population density and the high degree of anthropogenic derivation of natural geosystems greatly increase the socioeconomic and environmental vulnerability of these places. It is worth noting that the demand for water on the coast is already high (SÃO PAULO 2020), especially during the summer, and if there is a reduction in annual totals, as shown in figures 8C and 8D, serious water supply problems can be intensified, such as also highlight by ZÁKHIA et al. (2021) and FERREIRA & VALVERDE (2022). On the other hand, the increase in annual totals may indicate an increased risk of landslides and other erosive processes triggered by rainfall, especially in Serra do Mar, where natural susceptibility is high (ROSSINI-PENTEADO & FERREIRA 2017). These projections may also result in impacts on coastal ecosystems, such as mangroves, which are sensitive even under more conservative climate change scenarios (WARD et al. 2016, GABLER et al. 2017, DUKE et al. 2019). It is noteworthy that temperature anomalies and their extreme indices considered for the state of São Paulo, in all scenarios, can have impacts of different magnitudes on natural resources, ecosystem services, health, thermal comfort, among others.

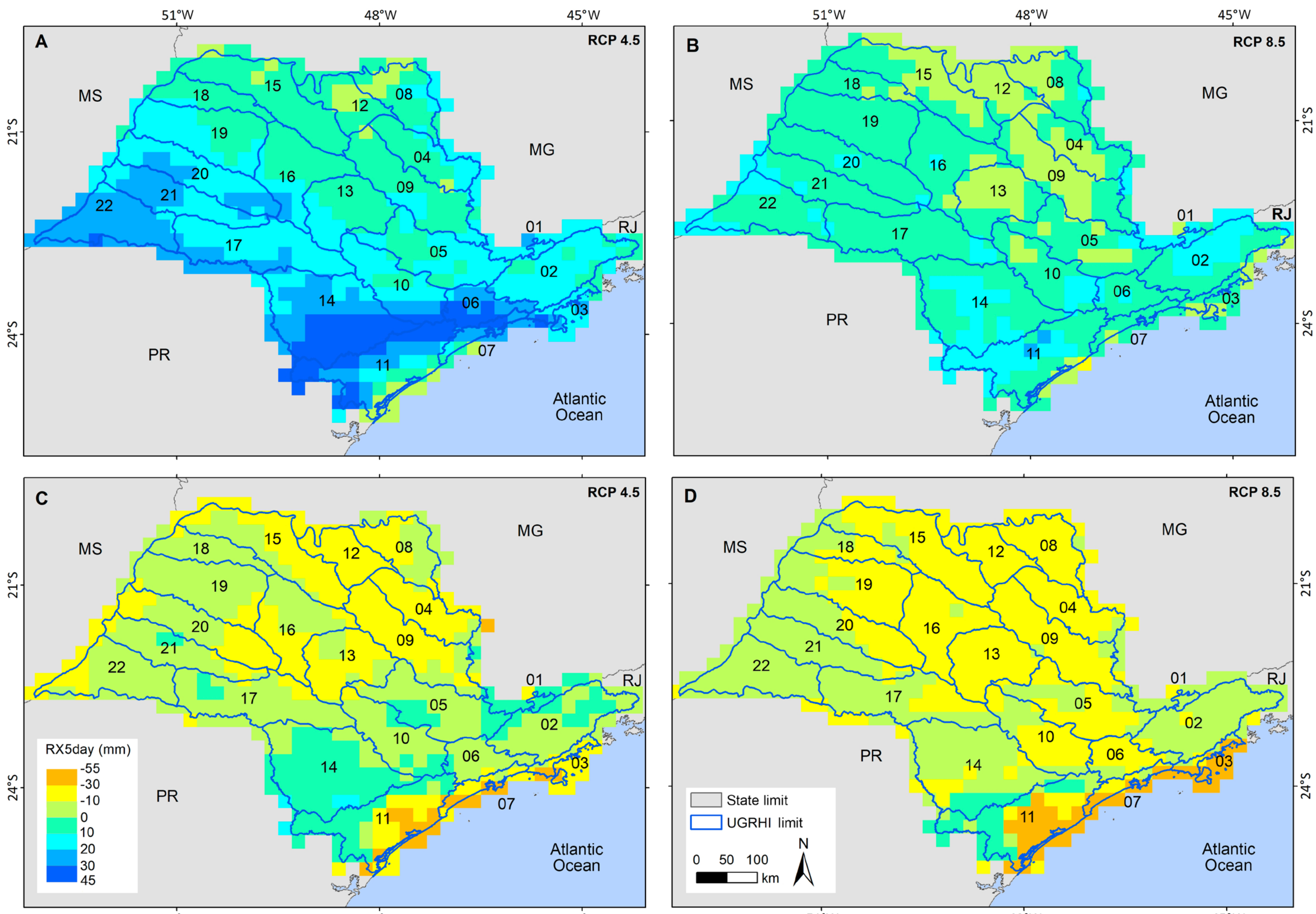

FIGURE 11 – Maximum (upper images) and minimum (lower images) deviations from the maximum annual precipitation in 5 consecutive days (mm) – RX5day between the 2020-2050 projection and the historical period 1961-1990 for the State of São Paulo under the RCP 4.5 scenarios (A and C) and RCP 8.5 (B and D). Sources: CPTEC/INPE (2019), IGC (2011) and IBGE (2013). Geographic Coordinate System, Datum SIRGAS 2000. Prepared by Nádia Lima (2022).

ARMANI et al. (2021) point out that the projected climate change scenarios for the Metropolitan Region of São Paulo (RMSP) may limit the reproduction and proliferation of the dengue transmitting mosquito during the summer, due to warming above the ideal limit. On the other hand, there will be an anticipation (for spring) and extension (for autumn) of the ideal limits of mosquito proliferation, and consequently, which was before restricted to epidemics of a few months, it could be endemic or hyperendemic.

Regarding precipitation, MARENGO et al. (2013) projected an increase in total precipitation and intense precipitation for the RMSP, as well as a greater contribution to total precipitation from more intense rainfall events. The authors also highlighted the possibility of longer dry periods for the RMSP, indicating water supply problems for this region (FERREIRA & VALVERDE 2022).

The projections also indicate the possibility of a reduction in total annual precipitation and in other extreme events indices, suggesting problems in water supply, waterway operation and agriculture. Small and medium rural producers, responsible for the production of food for the Brazilian people, are more vulnerable to variations in precipitation, as well as the reservoirs that supply the Metropolitan Regions of the State of São Paulo (ZÁKHIA et al. 2021, FERREIRA & VALVERDE 2022). The area with the greatest increase in temperature (Figure 3) is the recharge area of the Guarani aquifer, an important source of water supply, which may have an overload in relation to water demand (SÃO PAULO 2020).

Projections indicate an increase of up to 10 days in the consecutive dry days (CDD) index over the period 1961-1900 for the most part of the state of São Paulo, corroborating the results of FERREIRA & VALVERDE (2022), who associate it with the reduction of water availability in hydrographic basins, which may increase the risk of shortages in urban areas and eventual problems in the irrigation of agricultural areas (ZÁKHIA et al. 2021). ASSAD *et al*. (2013) stated that the effects of the atmosphere warming, as projected, would have negative economic impacts on Brazilian agricultural production, mainly in pastures and grains, projecting a reduction in grain production of around 4.6 million tons in 2030.

The results achieved in this work corroborate other studies (VIOLA et al. 2014, LYRA et al. 2017, ZÁKHIA et al. 2021, REBOITA et al. 2022), resulting in an important guide for the elaboration of climate adaptation and mitigation policies. However, it is still necessary to consider that models are developed and/or improved in the evaluation of the global social cost TARIFA & MELLO (1983), mainly in economic terms, since the current policy and the socioeconomic organization continue to cause negative reflexes in the productive sector, health, and social well-being.

In addition, all models indicate a trend of temperature increase, and HadGEM2-ES is the one that projects the largest deviations from the average of the historical period (1961-1990), a fact that VALVERDE & MARENGO (2010) already indicated. The projected increase in air temperature and indices of extreme thermal events presents, in a way, the same magnitude as those presented by other authors (VALVERDE & MARENGO 2010, MARENGO et al. 2012, VIOLA et al. 2014, BRASIL 2016, LYRA et al. 2017, ZÁKHIA et al. 2021, FERREIRA & VALVERDE 2022, REBOITA et al. 2022). LYRA et al. (2017) also point to the shortening of the cold period.

Regarding precipitation, the results obtained by LYRA et al. (2017) only indicate a decrease in precipitation, especially in the rainy season, and in the rates of extreme rainfall events. This is a typical trend presented by HadGEM2-ES (ZÁKHIA et al. 2021), that is, conditions closer to those projected for the lower limits of the results presented in this study. Based on Thornthwaite's classification, LORENÇONE et al. (2022) concludes that in the Pantanal biome, from 2041 onwards, there will be a reduction in the area classified as humid (B1, B2 and B3) and an increase in the sub-humid dry class (C1), due to the intensification of the Baixa do Chaco projected to the area (VALVERDE & MARENGO 2010, MARENGO et al. 2012). On the other hand, the increases in precipitation values and their extreme indices were the result of other climate models, mainly MIROC5, whose sensitivity and parameter adjustments indicate a tendency towards humidification (ZÁKHIA et al. 2021). In our study, it represents, for the most part, the upper limits of precipitation projections and their extreme indices. It is worth mentioning that the different climate models can project different results, as observed by BOMBARDI & CARVALHO (2008), who, using MIROC, did not detect any delay in the beginning of the rainy season, nor in the duration in relation to the historical period, although the median of the total accumulated in this season has increased by 80 mm, concentrated in the northern region of Brazil.

These projections also indicate changes in atmospheric circulation patterns in South America, with the weakening of the tropical circulation and the strengthening of the subtropical circulation, marked by the intensification on the surface of the Chaco low and the subtropical highs (Atlantic and Pacific) (VALVERDE & MARENGO 2010, MARENGO et al. 2012). The scale-up process carried out using the Eta model was accurate to highlight topographic and Atlantic Ocean effects in order to better represent the meteorological processes over the State of São Paulo. This improvement was also pointed out by CHOU et al. (2012), when the first scale-up tests began to run on Eta.

Even under projections of severe warming and reduction of precipitation, such as those presented here, the conservation of tropical forests is important, as the carbon sequestered by the vegetation tends to remain preserved, as well as efforts towards the recovery of deforested areas, since the restauration of half of these areas has the potential to store 56 to 69% of CO_2 (KOCH & KAPLAN 2022).

TARIFA & MELLO (1983), decades ago, already pointed out that it would be necessary for society learns to deal with the safety limit for the use of natural resources in order to avoid or moderate the effects of climate change. The authors suggested that the process be initiated in the evaluation and planning of critical areas, aiming at the possibility of recovering or reusing them, where the problems were more evident. This task could be improved after recent advances in the systematic registration of natural disaster occurrences (BROLLO & FERREIRA 2016, SÃO PAULO 2022).

The global models currently used are already evolved to support political, social and economic decisions, as they already include, in addition to physical processes, a significant part of human interference in the atmosphere at different scales. Climate models are the best tools available to science to make climate predictions (VALVERDE & MARENGO 2010) and better support political and technical decisions.

6 CONCLUSIONS AND FINAL REMARKS

Climate projections for the 2020-2050 period in the state of São Paulo were produced in relatively high resolution (20 km), using the *downscaling technique* through the CPTEC Eta regional model, under two RCP scenarios (RCP 4.5 and RCP 8.5) from four climate models (HadGEM2-ES, MIROC5, CanESM2 and BESM). The results were presented in terms of deviations of the future period (2020-2050) in relation to the historical period 1961-1990. From the results presented, it can be concluded that:

1. from the temperature point of view, all models used for both scenarios and their lower and upper limits point to the warming of the atmosphere, that is, the models converge in all projections for temperature. Although it is not possible to say exactly the magnitude of the warming, it is possible, with current knowledge and available techniques, to say that the atmosphere will be warmer and that society will need to adapt to very different limits from those habitual.
2. the projected warming tends to be less intense on the shoreline due to the control exerted by the ocean, while increases to the northwest section of the state, further from the Atlantic. Higher areas, such as the Serra da Mantiqueira, showed different behavior in the thermal trend depending on the scenario (RCP 4.5 or RCP 8.5), suggesting that the relief plays a different roles depending on the RCP scenarios.
3. there is a projection of a reduction in the duration of cold waves (CSDI), and this trend increases from the south to the north of the state. On the other hand, an increase in the duration of heat waves (WSDI) is projected, with spatial variation similar to that of cold waves, with an increase in duration from south to north.
4. regarding annual precipitation totals and related extreme events indices, there is no consensus of trend among the models used in the study. Therefore, the greater the amplitude between the maximum and minimum limits of precipitation, the greater must be the adaptation capacity of the society.
5. a reduction in annual precipitation totals is projected for most of the state; in the north and northwest all models and scenarios indicate a downward trend. From the climatological point of view, and with the consensual projections on temperature, the reduction in precipitation is the worst scenario to be faced, given the essential aspect of water to life. Agriculture and water supply in cities can seriously suffer under these conditions if adjustments in consumption, storage and

recovery actions in water producing areas (springs) are not adequate to the new reality.

6. the indices related to intense precipitation (R95p and RX5day) showed great amplitude between the maximum and minimum values projected in the analyzed scenarios. It is worth noting that, above all, the increase in these indicators deserves special attention, since intense precipitations triggers of natural disasters, such as landslides, floods and accelerated erosion, mainly affecting regions that are naturally susceptible from a geotechnical point of view, such as UGRHI 11 (Ribeira de Iguape/Litoral Sul), UGRHI 14 (Alto Paranapanema), UGRHI 06 (Alto Tietê), UGRHI 07 (Baixada Santista), UGRHI 03 (Litoral Norte), among others.

Researchs to improve the results achieved is already being carried out, aiming to characterize seasonal variations for the same data set and models, in order to complement the database platform of the ZEE (Ecological-Economic Zoning) of the State of São Paulo. Efforts have also been made to improve the scale of data representation (downscaling) using the CPTEC Eta model, increasing the resolution of data representation for the entire state to 5 km. It is noteworthy that this was the first approach to climate projections for the State of São Paulo, aiming at its incorporation into territorial environmental planning with a focus on specific variables and indices of climatic extremes, with the definition of a methodological process that can be replicated for future studies on other topics.

It should be noted that future climate scenarios are projected according to the radiative forcing, concentrations of greenhouse gases and other relevant socioeconomic drivers, but there is a degree of uncertainty of the simulations. However, improvements in modeling are permanent and very fast, and models are the best tool that science currently has to discuss climate projections and base decisions.

7 ACKNOWLEDGMENTS

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8 REFERENCES

ALEXANDER, L.V.; ZHANG, X.; PETERSON, T.C.; CAESAR, J.; GLEASON, B.; KLEIN TANK, A.M.G.; HAYLOCK, M.; COLLINS, D.; TREWIN, B.; RAHIMZADEH, F.; TAGIPOUR, A.; RUPA KUMAR, K.; REVADEKAR, J.; GRIFFITHS, G.; VINCENT, L.; STEPHENSON, D.B.; BURN, J.; AGUILAR, E.; BRUNET, M.; TAYLOR, M.; NEW, M.; ZHAI, P.; RUSTICUCCI, M.; VAZQUEZ-AGUIRRE, J.L. 2005. Global observed changes in daily climatic extremes of temperature and precipitation. *Journal of Geophysical Research*, 111: 1-22. https://doi.org/10.1029/2005JD006290

ARMANI, G; TAVARES, R.; RIBEIRO, F.S.; MIRANDA, M.J. 2021. *São Paulo/SP: incidência e espacialização da dengue na metrópole paulistana*. *In*: F.A. Mendonça (Org.) A dengue no Brasil: uma perspectiva geográfica. Curitiba, CRV Editora, 1ª ed., p. 379-422.

ASSAD, E.; PINTO, H.S; NASSAR, A.; HARFUCH, L.; FREITAS, S.; FARINELLI, B.; LUNDELL, M.; FERNANDES, E.C.M. 2013. *Impacts of climate change on brazilian agriculture*. Washington, International Bank for Reconstruction and Development / The World Bank, 86 p. Available in https://openknowledge.worldbank.org/bitstream/handle/10986/18740/687740Revised00LIC00web0brasil02030.pdf?sequence=1&isAllowed=y Accessed in Sep. 2022.

BJØRNÆS, C. 2013. *A guide to Representative Concentration Pathways*. CICERO, Center for International Climate and Environmental Research, 5 p.

BOMBARDI, R.J.; CARVALHO, L. 2008. Variability of the monsoon regime over Brazil: the present climate and projections for a 2xCO2 scenario using MIROC model. *Revista Brasileira de Meteorologia*, 23(1): 58-72. https://doi.org/10.1590/S0102-77862008000100007

BRASIL. Ministério da Ciência, Tecnologia e Inovação. Secretaria de Políticas e

Programas de Pesquisa e Desenvolvimento. Coordenação-Geral de Mudanças Globais de Clima. 2016a. *Modelagem climática e vulnerabilidades setoriais à mudança do clima no Brasil*. Brasília, Ministério da Ciência, Tecnologia e Inovação.

BRASIL. Ministério da Ciência, Tecnologia e Inovação. Secretaria de Políticas e Programas de Pesquisa e Desenvolvimento. Coordenação-Geral de Mudanças Globais de Clima. 2016b. *Terceira Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima – Resumo Executivo e Sumário*. Brasília, Ministério da Ciência, Tecnologia e Inovação. Available in http://unfccc.int/resource/docs/natc/branc3es.pdf. Accessed in Sep. 2022.

BRASIL. Ministério da Ciência, Tecnologia e Inovação. Secretaria de Políticas e Programas de Pesquisa e Desenvolvimento. Coordenação-Geral de Mudanças Globais de Clima. 2016c. *Terceira Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima – Volume I*. Brasília, Ministério da Ciência, Tecnologia e Inovação. Available in http://unfccc.int/resource/docs/natc/branc3v1.pdf. Accessed in Sep. 2022.

BRASIL. Ministério da Ciência, Tecnologia e Inovação. Secretaria de Políticas e Programas de Pesquisa e Desenvolvimento. Coordenação-Geral de Mudanças Globais de Clima. 2016d. *Terceira Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima – II*. Brasília, Ministério da Ciência, Tecnologia e Inovação. Available in http://unfccc.int/resource/docs/natc/branc3v2.pdf. Accessed in Sep. 2022.

BRASIL. Ministério da Ciência, Tecnologia e Inovação. Secretaria de Políticas e Programas de Pesquisa e Desenvolvimento. Coordenação-Geral de Mudanças Globais de Clima. 2016e. Terceira Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima – Volume III. Brasília, Ministério da Ciência, Tecnologia e Inovação. Available in http://unfccc.int/resource/docs/natc/branc3v3.pdf. Accessed in Sep. 2022.

BROLLO, M.J.; FERREIRA, C.J. 2016. *Gestão de riscos de desastres devido a fenômenos geodinâmicos no Estado de São Paulo: Cenário 2000-2015*. São Paulo: Instituto Geológico, 72 p. (Boletim, 67). Available in http://bit.ly/2LgEqbm

CHOU, S.C.; MARENGO, J.A.; LYRA, A.A.; SUEIRO, G.; PESQUERO, J.F.; ALVES, L.M.; KAY, G.; BETTS, R.; CHAGAS, D.J.; GOMES, J.L.; BUSTAMENTE, J.F.; TAVARES, P. 2012. Downscaling of South America present climate driven by 4-member HadCM3 runs. *Climate Dynamics,* 38: 635-653. https://doi.org/10.1007/s00382-011-1002-8

CHOU, S.; 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. 2014a. Assessment of Climate Change over South America under RCP 4.5 and 8.5 Downscaling Scenarios. *American Journal of Climate Change*, 3: 512-527. http://dx.doi.org/10.4236/ajcc.2014.35043

CHOU, S.C; LYRA, A.; MOURÃO, C.; DERECZYNSKI, C.; PILOTTO, I., GOMES, J.; BUSTAMANTE, J.; TAVARES, P.; SILVA, A.; RODRIGUES, D.; CAMPOS, D.; CHAGAS, D.; SUEIRO, G.; SIQUEIRA, G.; NOBRE, P.; MARENGO, J. 2014b Evaluation of the Eta Simulations Nested in Three Global Climate Models. *American Journal of Climate Change*, 3: 438-454. http://dx.doi.org/10.4236/ajcc.2014.35039

CPTEC/INPE – CENTRO DE PREVISÃO DE TEMPO E ESTUDOS CLIMÁTICOS/ INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS. 2019. *Dados gerados pelo CPTEC/INPE disponibilizados na plataforma PROJETA*. Available in www. projeta.cptec.inpe.br. Accessed in 01 Mar. 2019.

DUKE, N.C.; FIELD, C.; MACKENZIE, J.R.; MEYNECKE, J.-O.; WOOD, A.L. 2019. Rainfall and its possible hysteresis effect on the proportional cover of tropical tidal-wetland mangroves and saltmarsh–saltpans. *Marine and Freshwater Research*, 70(8): 1047-1055. https://doi.org/10.1071/MF18321

FERREIRA, B.C.C.; VALVERDE, M.C. 2022. Análise dos índices de extremos de precipitação em cenários futuros na bacia do Rio Ribeira de Iguape - São Paulo. *Revista Brasileira de Meteorologia,* 37(1). http://dx.doi.org/10.1590/0102-7786370067

GABLER, C.; OSLAND, M.J.; GRACE, J.B.; STAGG, C.L.; DAY, R.H.; HARTLEY, S.B.; ENWRIGHT, N.M.; FROM, A.S., MCCOY, M.L.; MCLEOD, J.L. 2017. Macroclimatic change expected to transform coastal wetland ecosystems this century. *Nature Climate Change*, 7: 142-147. https://doi.org/10.1038/nclimate3203

GRIMM, A.M.; NATORI, A. 2006. Climate change and internaual variability of precipitation in South America. *Geophysical Research Letters*, 33: L19706. http://dx.doi.org/10.1029/2006GL026821

IBGE – INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. 2022. *Estimativas da população residente no Brasil e Unidades da Federação com data de referência em* 1º de *julho de 2021*. Available in https://biblioteca.ibge.gov.br/visualizacao/livros/liv101849.pdf. Accessed in 10 Jun. 2022.

IPCC – INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* R.K. Pachauri and A. Reisinger (eds.). IPCC, Geneva, Switzerland, 104 p.

IPCC – INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* R.K. Pachauri and L.A. Meyer (eds.). IPCC, Geneva, Switzerland, 151 p.

IPCC – INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, USA. http://dx.doi.org/10.1017/9781009157896

KOCH, A.; KAPLAN, J.O. 2022 Tropical forest restoration under future climate change. *Nature Climate Change*, 12: 279-283. https://doi.org/10.1038/s41558-022-01289-6

LI, J.; BARKER, H.W. 2005. A Radiation Algorithm with Correlated-k Distribution. Part I: Local Thermal Equilibrium. *Journal of the Atmospheric Sciences,* 62(2): 286-309. https://doi.org/10.1175/JAS-3396.1

LORENÇONE, J.A.; APARECIDO, L.E.O.; LORENÇONE, P.A.; LIMA, R.F.; TORSONI, G.B. 2022. Assessment of climate change using humidity index of Thornthwaite climate classification in Pantanal biome. *Revista Brasileira de Meteorologia,* 37(1): 99-119. https://doi.org/10.1590/0102-7786370075

LYRA, A.; TAVARES, P.; CHOU, S.C.; SUEIRO, G.; DERECZYNSKI, C.P.; SONDERMANN, M.; SILVA, A.; MARENGO, J.; GIAROLLA, A. 2017. 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: 663-682. http://dx.doi.org/10.1007/s00704-017-2067-z

MACHADO, C.B.; CAMPOS, T.L.O.B.; RAFEE, S.A.A.; MARTINS, J.A.; GRIMM, A.M.; 2021. Extreme rainfall events in the Macro-Metropolis of São Paulo: trends and connection with climate oscillations. *Journal of Applied Meteorology and Climatology*, 60(5): 661-675. https://doi.org/10.1175/JAMC-D-20-0173.1

MARENGO, J.A.; CHOU, S.C.; KAY, G.; ALVES, L.M.; PESQUERO, J.F.; SOARES, W.R.; SANTOS, D.C.; LYRA, A.A.; SUEIRO, G.; BETTS, R.; CHAGAS, D.J.; GOMES, J.L.; BUSTAMANTE, J.F.; TAVARES, P. 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. *Climate Dynamics*, 38: 1829-1848. https://doi.org/10.1007/s00382-011-1155-5

MARENGO, J.A.; VALVERDE. R.; OBREGON, G.O. 2013. Observed and projected changes in rainfall extremes in the Metropolitan Area of São Paulo. *Climate Research*, 57(1): 61-72. http://dx.doi.org/10.3354/cr01160

MARTIN, G.M.; BELLOUIN, N.; COLLINS, W.J.; CULVERWELL, I.D.; HALLORAN, P.R.; HARDIMAN, S.C.; HINTON, T.J.; JONES, C.D.; MCDONALD, R.E.; MCLAREN, A.J.; O'CONNOR, F.M.; ROBERTS, M.J.; RODRIGUEZ, J.M.; WOODWARD, S.; BEST, M.J.; BROOKS, M.E.; BROWN, A.R.; BUTCHART, N.; DEARDEN, C.; DERBYSHIRE, S.H.; DHARSSI, I.; DOUTRIAUX-BOUCHER, M.; EDWARDS, J.M.; FALLOON, P.D.; GEDNEY, N.; GRAY, L.J.; HEWITT, H.T.; HOBSON, M.; HUDDLESTON, M.R.; HUGHES, J.; INESON, S.; INGRAM, W.J.; JAMES, P.M.; JOHNS, T.C.; JOHNSON, C.E.; JONES, A.; JONES, C.P.; JOSHI, M.M.; KEEN, A.B.; LIDDICOAT, S.; LOCK, A.P.; MAIDENS, A.V.; MANNERS, J.C.; MILTON, S.F.; RAE, J.G.L.; RIDLEY, J.K.; SELLAR, A.; SENIOR, C.A.; TOTTERDELL, I.J.; VERHOEF, A.; VIDALE, P.L.; WILTSHIRE, A. 2011. The HadGEM2 family of Met Office Unified Model Climate configurations, *Geoscientific Model Development*, 4: 723-757.

MEEHL, G.A.; ARBLASTER, J.M.; TEBALDI, C. 2005. Understanding future patterns of increased precipitation intensity in climate model simulations. *Geophysical Research Letters*, 32: L18719. http://doi.org/10.1029/2005GL023680

MONTEIRO, C.A.F. 1973. *A dinâmica climática e as chuvas no estado de São Paulo: estudo geográfico sob a forma de atlas*. Instituto de Geografia da Universidade de São Paulo, 129 p.

MONTEIRO, C.A.F. 1976. O clima e a organização do espaço no estado de São Paulo: problemas e perspectivas. *Teses e monografias - IGEOG/USP*, 28: 54 p.

MOSS, R.H.; BABIKER, M.; BRINKMAN, S.; CALVO, E.; CARTER, T.; EDMONDS, J.A.; ELGIZOULI, I.; EMORI, S.; LIN, E.; HIBBARD, K.; JONES, R.; KAINUMA, M.; KELLEHER, J.; LAMARQUE, J.F.; MANNING, M.; MATTHEWS, B.; MEEHL, J.; MEYER, L.; MITCHELL, J.; NAKICENOVIC, N.; O'NEILL, B.; PICHS, R.; RIAHI, K.; ROSE, S.; RUNCI, P.J.; STOUFFER, R.; VANVUUREN, D.; WEYANT, J.; WILBANKS, T.; VAN YPERSELE, J.P.; ZUREK, M. 2008. *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies*. United States. Available in https://www.osti.gov/biblio/940991. Accessed in Sep. 2022.

MOSS, R.; EDMONDS, J.; HIBBARD, K.A.; MANNING, M.R.; ROSE, S.K.; VAN VUUREN, D.P.; CARTER, T.R.; EMORI, S.; KAINUMA, M.; KRAM, T.; MEEHL, G.A.; MITCHELL, J.F.B.; NAKICENOVIC, N.; RIAHI, K.; SMITH, S.J.; STOUFFER, R.J.; THOMSON, A.M.; WEYANT, J.P.; WILBANKS, T.J. 2010. The next generation of scenarios for climate change research and assessment. *Nature,* 463: 747-756. https://doi.org/10.1038/nature08823

NATIVIDADE, U.A.; GARCIA, S.R.; TORRES, R.R. 2017. Tendência dos índices de extremos climáticos observados e projetados no Estado de Minas Gerais. *Revista Brasileira de Meteorologia*, 32(4): 600-614. https://doi.org/10.1590/0102-7786324008

NOAA – NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION. 2022. *Global monitoring Laboratory, GGGRN Data - CO_2*. Available in https://gml.noaa.gov/ccgg/data/co2.html. Accessed in Sep. 2022.

NOBRE, P.; SIQUEIRA, L.P.; ALMEIDA, R.A.F.; MALAGUTTI, M.; GIAROLLA, E.; CASTELÃO, G.P.; BOTTINO, M.J.; KUBOTA, P.; FIGUEROA, S.N.; COSTA, M.C.; BAPTISTA JR., M.; IRBER JR., L.; MARCONDES, G.G. 2013. Climate Simulation and Change in the Brazilian Climate Model. *Journal of Climate*, 26: 6716-6732. https://doi.org/10.1175/JCLI-D-12-00580.1

OBREGON, G.O.; MARENGO, J.A.; NOBRE, C. 2014. Rainfall and climate variability: long-term trends in the Metropolitan Area of São Paulo in the 20th century. *Climate Research*, 61: 93-107. https://doi.org/10.3354/cr01241

PBMC – PAINEL BRASILEIRO DE MUDANÇAS CLIMÁTICAS. 2014. *PBMC, 2014: Base científica das mudanças climáticas. Contribuição do grupo de trabalho 1 do Painel Brasileiro de Mudanças Climáticas ao Primeiro Relatório da Avaliação Nacional sobre Mudanças Climáticas*. T. Ambrizzi, M. Araújo (eds.). COPPE. Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brasil, 464 p.

POPE, V.; BROWN, S.; CLARK, R.; COLLINS, M.; COLLINS, W.; DEARDEN, C.; GUNSON, J.; HARRIS, G.; JONES, C.; KEEN, A.; LOWE, J.; RINGER, M.; SENIOR, C.; SITCH, S.; WEBB, M.; WOODWARD, S. 2007. The Met Office Hadley Centre climate modelling capability: the competing requirements for improved resolution, complexity and dealing with uncertainty. *Philosophical Transactions of the Royal Society A*, 365: 2635-2657. https://doi.org/10.1098/rsta.2007.2087

REBOITA, M.S.; KUKI, C.A.C.; MARRAFON, V.H.; SOUZA, C.A.; FERREIRA, G.W.S.; TEODORO, T.; LIMA, J.W.M. 2022. South America climate change revealed through climate indices projected by GCMs and Eta-RCM ensembles. *Climate Dynamics*, 58: 459-485. https://doi.org/10.1007/s00382-021-05918-2

RIBEIRO NETO, G.G.; ANDERSON, L.O.; BARRETOS, N.J.C.; ABREU, R.; ALVES, L.; DONG, B.; LOTT, F.C.; TETT, S.F.B. 2022. Attributing the 2015/2016 Amazon basin drought to anthropogenic influence. *Climate Resilience and Sustainability*, 1(1): e25. https://doi.org/10.1002/cli2.25

ROSSINI-PENTEADO, D.; FERREIRA, C.J. 2017. *Sistema de classificação "Unidades Territoriais Básicas" (UTB) e mapeamento de risco de áreas urbanas de uso residencial/comercial/serviços à eventos geodinâmicos do Estado de São Paulo*. IG, São Paulo. Available in http://bit.ly/2W7RnZb.

SÃO PAULO (Estado). SECRETARIA DE INFRAESTRUTURA E MEIO AMBIENTE. 2020. *Meio ambiente paulista: relatório de qualidade ambiental 2020*. São Paulo, Secretaria de Infraestrutura e Meio Ambiente, 424 p.

SÃO PAULO (Estado). SECRETARIA DE INFRAESTRUTURA E MEIO AMBIENTE DO ESTADO DE SÃO PAULO). 2022. *Cadastro de eventos geodinâmicos e desastres do Estado de São Paulo 1991-2020*. Planilha eletrônica On-line. Available in: https://docs.google.com/spreadsheets/d/1uElUITGvYArX23E6YpycYLtObaA_YmdK8559wBCY-TI/edit#gid=2018359881.

SCHWALMA, C.R.; GLENDONA, S.; DUFFYA, P.B. 2020. RCP8.5 tracks cumulative CO2 emissions. *PNAS*, 117(33): 19656-19657. https://doi.org/10.1073/pnas.2007117117

TARIFA, J.R. 1994. Alterações climáticas resultantes da ocupação agrícola no Brasil. *Revista do Departamento de Geografia*, 8: 15-27. https://doi.org/10.7154/RDG.1994.0008.0002

TARIFA, J.R.; MELLO, M. 1983. O homem e as mudanças climáticas no Brasil. *In:* CONGRESSO BRASILEIRO DE AGROMETEOROLOGIA, 3, Campinas, *Anais*, p. 319-338.

VALVERDE, M.C.; MARENGO, J.A. 2010. Mudanças na circulação atmosférica sobre a América do Sul para cenários futuros de clima projetados pelos modelos globais do IPCC Ar4. *Revista Brasileira de Meteorologia*, 25(1): 125-145. https://doi.org/10.1590/S0102-77862010000100011

VAN VUUREN, D.P.; EDMONDS, J.; KAINUMA, M. 2011. The representative concentration pathways: an overview. *Climatic Change*, 109: 5. https://doi.org/10.1007/s10584-011-0148-z

VERA, C.; SILVESTRI, G.; LIEBMANN, B.; GONZÁLEZ, P. 2006. Climate change scenarios for seasonal precipitation in South America from IPCC-AR4 models. *Geophysical Research Letters,* 33: L13707. https://doi.org/10.1029/2006GL025759

VIOLA, M.R.; AVANZI, J.C.; MELLO, C.R.; LIMA, S.O.; ALVES, M.V.G. 2014. Distribuição e potencial erosivo das chuvas no Estado do Tocantins. *Pesquisa Agropecuária Brasileira*

49(2): 125-135. https://doi.org/10.1590/S0100-204X2014000200007

VON SALZEN, K.; MCFARLANE, N.A.; LAZARE, M. 2005. The role of shallow convection in the water and energy cycles of the atmosphere. *Climate Dynamics*, 25: 671-688. https://doi.org/10.1007/s00382-005-0051-2

VON SALZEN, K.; SCINOCCA, J.F.; MCFARLANE, N.A.; LI, J.; COLE, J.N.S.; PLUMMER, D.; VERSEGHY, D.; READER, M.C.; MA, X.; LAZARE, M.; SOLHEIM, L. 2013. The Canadian Fourth Generation Atmospheric Global Climate Model (CanAM4). Part I: Representation of Physical Processes. *Atmosphere-Ocean*, 51:(1) 104-125, https://doi.org/10.1080/07055900.2012.755610

WARD, R.D.; FRIESS, D.A.; DAY, R.H.; MACKENZIE, R.A. 2016. Impacts of climate change on mangrove ecosystems: a region by region overview. *Ecosystem Health and Sustainability*, 2(4): e01211. https://doi.org/10.1002/ehs2.1211

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. https://doi.org/10.1175/2010JCLI3679.1

ZÁKHIA, E.M.S.; ALVARENGA, L.A.; TOMASELLA, J.; MARTINS, M.A.; SANTOS, A.C.N.; MELO, P.A. 2021. Impacto das mudanças climáticas em uma bacia hidrográfica no sul do estado de Minas Gerais. *Revista Brasileira de Meteorologia*, 36(4): 667-681. http://dx.doi.org/10.1590/0102-7786360002

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