

Simulation of future climate scenarios and the impact on the water availability in southern Brazil

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ABSTRACT. Water is an essential natural resource that is being impacted by climate change. Thus, knowledge of future water availability conditions around the globe becomes necessary. Based on that, this study aimed to simulate future climate scenarios and evaluate the impact on water balance in southern Brazil. Daily data of rainfall and air temperature (maximum and minimum) were used. The meteorological data were collected in 28 locations over 30 years (1980–2009). For the data simulation, we used the climate data stochastic generator PGECLIMA_R. It was considered two scenarios of the fifth report of the Intergovernmental Panel on Climate Change (IPCC) and a scenario with the historical data trend. The water balance estimates were performed for the current data and the simulated data, through the methodology of Thornthwaite and Mather (1955). The moisture indexes were spatialized by the kriging method. These indexes were chosen as the parameters to represent the water conditions in different situations. The region assessed presented a high variability in water availability among locations; however, it did not present high water deficiency values, even with climate change. Overall, it was observed a reduction of moisture index in most sites and in all scenarios assessed, especially in the northern region when compared to the other regions. The second scenario of the IPCC (the worst situation) promoting higher reductions and dry conditions for the 2099 year. The impacts of climate change on water availability, identified in this study, can affect the general society, therefore, they must be considered in the planning and management of water resources, especially in the regional context.

Keywords: Moisture index; PGECLIMA_R; stochastic simulation; regional climate change; Brazil.

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Introduction

Climate change is regarded as a potential driver of modifications in the hydrological cycle. These modifications may affect all water-consuming sectors and undermine water security. Thus, simulation of future scenarios to facilitate the assessment of climate risks in water availability should be used in the management of water resources (Kim, Kim, Jun, & Kim, 2014; Kwon, Sivakumar, Moon, & Kim, 2011).

Possible climate change scenarios are created based on results estimated by global climate models (GCMs), considering changes in air temperature and rainfall (Li, Xu, Liu, & Zhang, 2014). GCMs are tools used by the Intergovernmental Panel on Climate Change (IPCC) to simulate the current climate and also to perform future climate projections.

In the fifth report of the IPCC (2013) it is suggested, in an optimistic perspective, a scenario with a temperature increase between 0.3 and 1.7°C until the end of the 21st century. Under a more pessimistic view, it is suggested an increase between 2.6 and 4.8°C. It is important to highlight that these scenarios are based on the emissions of greenhouse gases in conjunction with socioeconomic factors, changes in technology, and the adoption or not of a sustainable development policy.

GCMs can provide information on climate change of great utility to the continental scale, but may not accurately represent changes in the local climate. Therefore, it is necessary to use the downscaling technique, which consists of the regionalization of climatic scenarios. This technique can be obtained using regional models (dynamic downscaling) or statistical functions (statistical downscaling) (Jacobeit, Hertig, Seubert, & Lutz, 2014; Sirajul Islam, Aramaki, & Hanaki, 2007).

An example of the use of statistical downscaling is the application of stochastic weather generators (WG's). WG's can simulate long daily climatic series, with similar statistic characteristics of the historical series. It is

used in research that involves the simulation of future climate scenarios on a regional scale. Among climatic data generators, we can mention the CLIGEN (Nicks & Harp, 1980), WGEN (Richardson & Wright, 1984), Lars-WG (Semenov & Barrow, 1997), and in Brazil CLIMABR (Oliveira, Zanetti, & Pruski, 2005) and more recently PGECLIMA_R (Virgens Filho, Oliveira, Leite, & Tsukahara, 2013) stand out. The reduction in GCM results has, in recent years, become one of the most important research topics in studies of hydrology and water resources (Sivakumar, 2011).

Climate change impact assessment on water availability can be performed through the application of a soil water balance, for current and future climate conditions. The climatological water balance, proposed by Thornthwaite and Mather (1955), is one of the most used methodologies to account for this soil water balance, which considers the input and output components of the system. Precipitation represents the main input component and potential evapotranspiration represents the main water output in the system. Potential evapotranspiration can be estimated by the method of Thornthwaite (1948), a method that has as input variables only the average air temperature and the locations of the geographic coordinates.

Evapotranspiration is a useful indicator of changes in the water cycle and climate conditions. Gao, Xu, Chen, and Singh (2012) verified decreasing trends of annual rainfall and evapotranspiration during 1960-2002 in Haihe River basin. Therefore, a negative impact was observed in the water cycle, raising water scarcity, and reducing water supply, which caused a restriction on regional development.

Changes in temperature, rainfall, and evapotranspiration affect the water availability in the soil. Thus, the impact of climate change on the water cycle also has a direct effect on the agricultural development and productivity. Considering the scenarios of the fifth IPCC report, recent studies have evaluated projections for water balance components and their impacts in terms of agricultural productivity in southern Brazil (Ferreira & Miranda, 2021; Santos et al., 2020; Pinheiro, Graciano, & Kaufmann, 2013; Resende, Miranda, Cooke, Chu, & Chou, 2019).

Moreover, based on the water balance, the climatic indexes, aridity index (I_a), humidity index (I_h), and a moisture index (I_m) proposed by Thornthwaite (1948), can be used to characterize the water regime, complementing the local information on the water availability in the soil.

The importance and use of the humidity index as an indicator of climate change are discussed by Leao (2014). The author verified the impact of climate change on soil moisture and observed future drying conditions in Victoria, Australia. Similar results were observed by McCabe and Wolock (1992) who analyzed the effects of long-term climate change on the humidity index in the Delaware River basin. The results showed that changes in air temperature and precipitation can decrease I_m , which implies significantly drier conditions in the Delaware River basin.

Considering the importance of hydrological monitoring for water resources management and agricultural development on a regional scale, this research aimed to evaluate the possible impacts of climate change on soil water availability in Paraná State, located in the southern region of Brazil. The stochastic generator PGECLIMA_R was used for the computational simulation of climatic scenarios projected for the end of the 21st century.

Material and methods

Study area and database

Paraná State is situated in the southern region of Brazil and has an area of 199.307,922 km². To facilitate the analysis of results, the Paraná State was divided geographically into five regions: northern, southern, eastern, western, and central). In this study, we used the following climate data: rainfall (PREC), minimum air temperature (TMIN), and maximum air temperature (TMAX), both in Celsius degrees. The historical series corresponds to an observation period of 30 years (1980 to 2009), which allows characterizing the region's climate, as well as identifying trends and detecting possible climate changes. The data were measured by 28 conventional meteorological stations across the Paraná State, belonging to the Instituto Agrônômico do Paraná-IAPAR (Figure 1).

The regions with the lowest average air temperatures are the southern and central regions. During the coldest months, the average temperature is 14.74°C ± 1.24 in the south, and 15.32°C ± 1.13 in the central region. In the hottest months, the mean temperature is 23.23°C ± 1.39 and 23.4°C ± 1.40, respectively, in the southern and central regions. The highest temperatures occur in the northern region with 18.36°C ± 0.32 in

the coldest month and $25.29^{\circ}\text{C} \pm 0.42$ in the hottest month. In the eastern region, the average air is $16.16^{\circ}\text{C} \pm 1.59$ in the coldest month and $24.28^{\circ}\text{C} \pm 1.90$ in the hottest month. The western region has $17.04^{\circ}\text{C} \pm 1.17$ in the coldest month and $25.16^{\circ}\text{C} \pm 1.34$ in the hottest month.

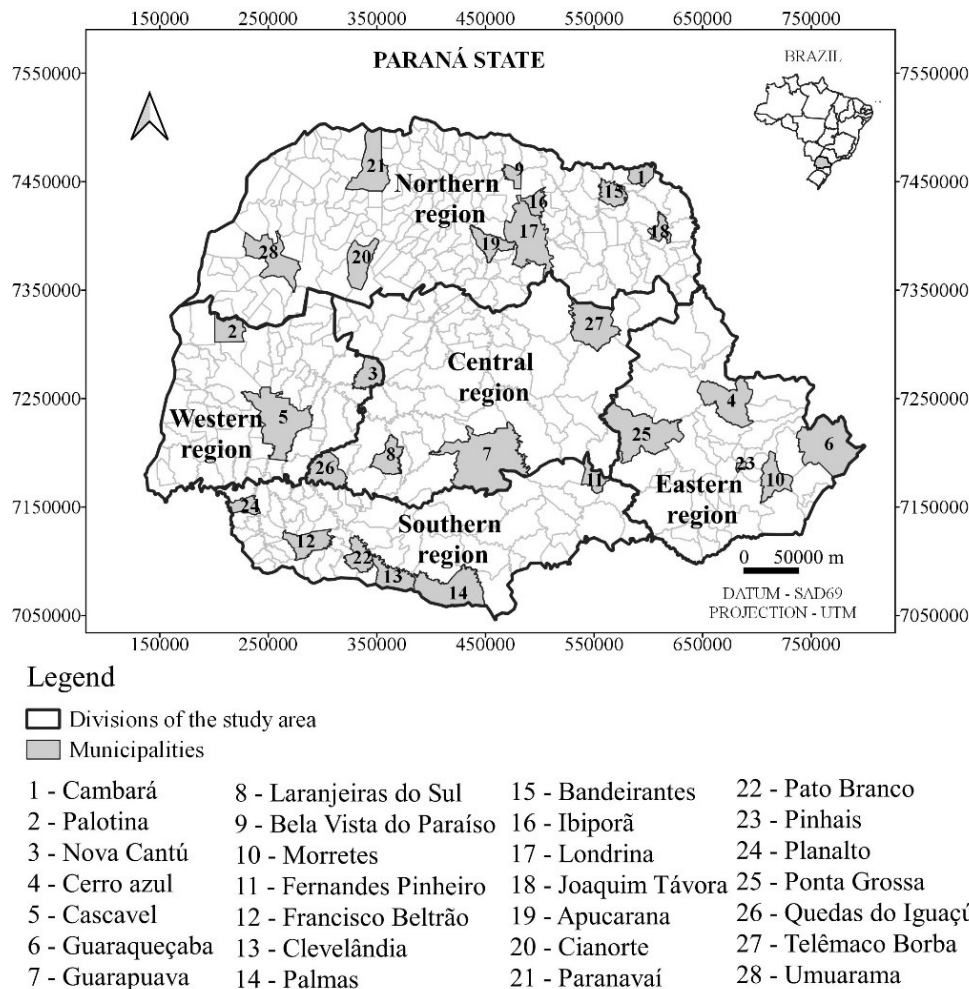


Figure 1. Location of the study area (Paraná State) (UTM Projection - SAD69 - Zone 22S), divided into five regions and with the municipalities distributed across the state. The municipalities correspond to the 28 conventional meteorological stations belonging to the Agronomy Institute of Paraná-IAPAR. Source: Elaborated by the author. Vectorial basis: IBGE (2014).

Simulation of climate scenarios

Three climate scenarios were used to assess the impacts of climate change on water availability. Each scenario considered different changes of climate variables, TMIN, TMAX, and PREC.

The series climate change was simulated for a period of 90 years, through the generator PGECLIMA_R.

For the first and second scenarios, air temperature changes were based on projections from the fifth IPCC report (IPCC, 2013). The upper end of the suggested range was considered. Thus, in a better perspective, we projected a temperature increase of 1.7°C and, in the worst-case scenario, an increase of 4.8°C . In the third scenario, a temperature change was projected based on the trend of climate variables in each municipality of the Paraná State.

To estimate the magnitude of these trends, it was applied the linear regression for every municipality and month of the year. It is assumed that trends from 1980 to 2009 will continue over the next 90 years. Thus, the angular coefficient of the equations was multiplied by 90.

For precipitation, in the first scenario, a 3% increase was considered for every 1°C variation in air temperature. In the second scenario, a 5% increase was considered for every 1°C variation. In the trend scenario, considered that in the trend of each municipality, you can have an increase or reduction in air temperature, depending on the month in question. Thus, in this scenario, we opted to design in the simulation a 4% increase for every 1°C variation in air temperature.

Estimate and specialization of water availability

The monthly averages of 2039, 2069, and 2099 were used to evaluate the effects of climate change at the end of each 30-year period. The average of the three simulations for each period were used. Using simulated monthly averages from each municipality, scenario, and year, water balance was estimated.

According to Pereira, Angelocci, and Sentelhas (2007) when the water balance is applied to characterize the water availability of a region, the choice of the Available Water Capacity (AWC) value is made depending on the type of culture, instead of soil type. Regardless of the type of soil, one can adopt AWC values between 75 and 100 mm, for annual crops and between 100 to 125mm, for perennial crops. Thus, we adopted for this work the value of AWC=100, since that, this value can be selected for the two types of culture.

Potential evapotranspiration (PET) was estimated using the Thornthwaite method (1948) and the water balance using the Thornthwaite and Mather method (1955). For the simulated data, the water balance was calculated on a monthly scale to provide real-time water availability in the years 2039, 2069, and 2099. After the estimates, the climate indexes were determined according to Thornthwaite (1948), using the following equations, also used in Leao (2014):

$$I_a = 100. (WD \text{ PET}^{-1}) \quad (1)$$

$$I_h = 100. (WS \text{ PET}^{-1}) \quad (2)$$

$$I_m = I_h - 0,6. I_a \quad (3)$$

Where: I_a represents the aridity index which indicates the water scarcity expressed as a percentage, calculated by the ratio of water deficiency (DQ) to PET, both annually. The moisture index (I_h) represents the water surplus expressed as a percentage calculated by the ratio of the water surplus (WS) to PET, both annually. The I_m (humidity index) represents the periods of excess and deficiency of water that occur throughout the year.

For the spatial distribution of the results, we perform the interpolation by the ordinary kriging geostatistical technique using ArcGIS software. The variable I_m was interpolated according to the recommendation of Gardiman, Magalhães, Freitas, and Cecílio (2012) and Silva, Cecílio, Xavier, Pezzopane, and Garcia (2011) for interpolation of hydrological variables.

Results and discussion

The projected temperature changes in the simulation occur progressively, so, the increases of 1.7 and 4.8°C or trend changes will occur completely in 2099.

The air temperature values, for the historical period, vary from 17°C in the southern region to 22°C in the northern region. For the 2039 period, the increase in air temperature is evident in the far northern, mainly in the worst-case scenario (4.8°C), where the temperature reaches 25°C (Figure 2).

In the period 2069, it is possible to observe the temperature increase in all regions of the state for the increase of 4.8°C. The temperature values in this scenario range from 20°C in the southern region to 26°C in the northern region. Furthermore, it was observed an evident increase in the northern region for the other scenarios, where the temperature reaches 24°C (Figure 2).

During the 2099 period, temperature increases were observed in all regions in the 1.7 and 4.8°C scenarios. In the worst-case, the temperature reaches 28°C in the northern region. In the trend scenario, the temperature increases occurred only in the northern region, demonstrating that only the locations in this region showed a more representative increase trend (Figure 2).

Similar results were found by Melo, Sanquetta, Corte and Virgens Filho (2015) and Santos et al. (2020) who observed air temperature increases in all climate scenarios projected for the Paraná State. Considering the more pessimistic scenario of the IPCC, the largest increases occurred in the northwest and northeast regions, and the smallest increases occurred in the central-southern region of Paraná.

For the historical period, it was observed that the PET values varied from 800 mm in the southern region to 1200 mm in the northern region. In 2039, the increase occurs in the northern region, being more evident in the worst-case scenario (4.8°C), where the PET reaches 1400 mm (Figure 3).

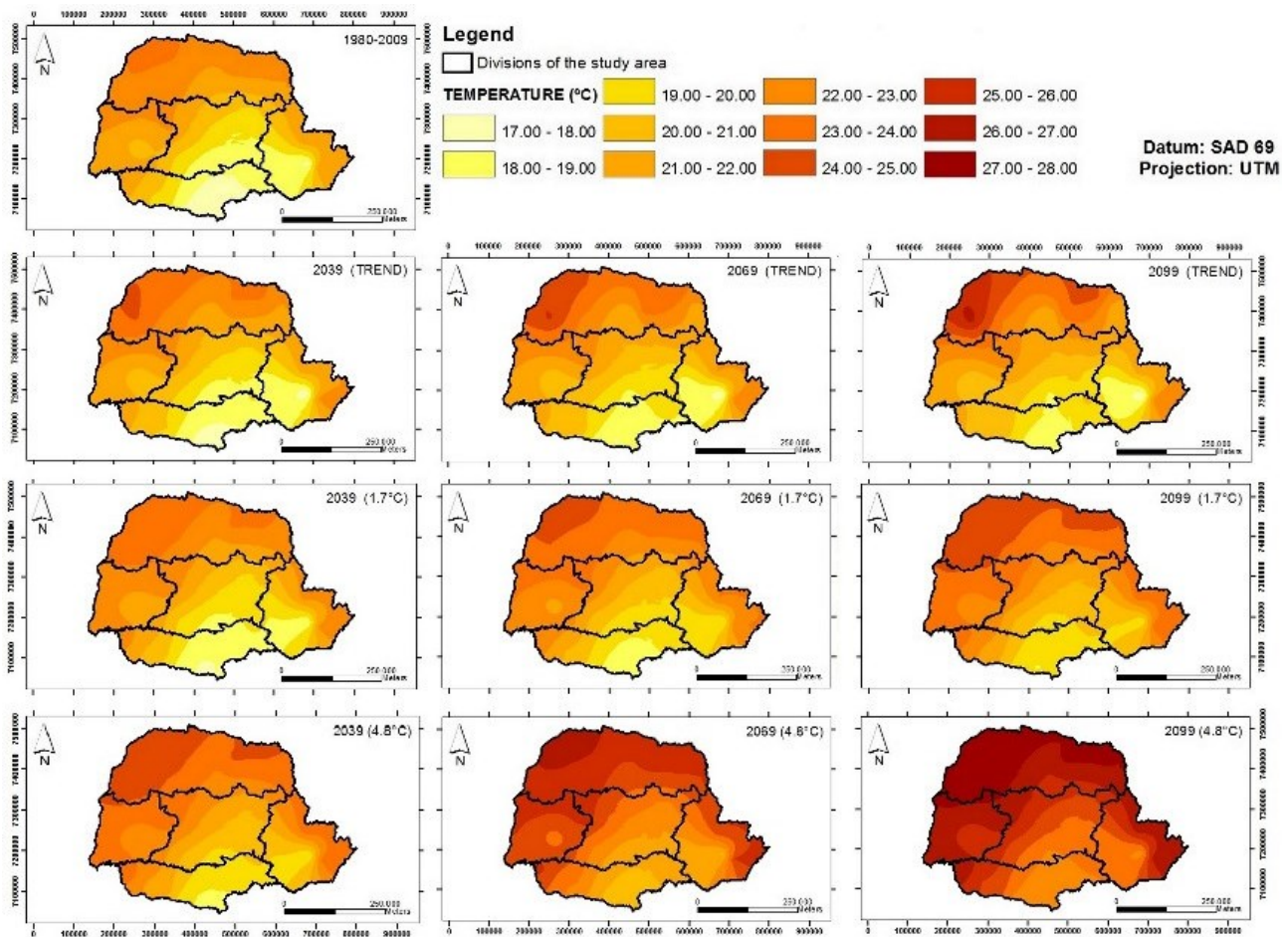


Figure 2. Averages temperature values interpolated for the years 2039, 2069 and 2099, facing the three simulated climate scenarios (1.7°C, 4.8°C, and trend).

In 2069, it is possible to observe the increase in PET in all regions analyzed. Considering the 4.8°C increase scenario, the observed values varied from 1000 mm to 1600 mm. This condition represents an evident increase in the northern region for the other scenarios, where the PET reaches the value of 1400 mm (Figure 3).

Considering the period of 2099, the increase in PET was observed in all regions for 1.7°C and 4.8°C scenarios. In the worst-case, the PET reaches 1800 mm in the northern region. In the trend scenario, it can be noted that the increase occurred only in the northern region, where there was also an air temperature increase in the municipalities of this region.

The evapotranspiration represents the water losses from the soil-plant system to the atmosphere. This process is positively affected by raises in air temperature; thus, these changes may alter future water conditions and the yield of crops. Ferreira and Miranda (2021) and Santos et al. (2020) observed increases in evapotranspiration in the Paraná State, with the largest increases also occurring for the worst-case scenarios of the IPCC.

It is observed for the current scenario, the PREC decreases from the south to the northern of Paraná State (Figure 4). The highest values are found in the extreme regions of the east (coast) and the southern region. The lowest rainfall indexes are found in the northern region and between northern and east (northeast). Similar results were found by Silva et al. (2015) and Nascimento Júnior and Sant'Anna Neto (2015) who noted that the PREC variability is associated with geographical characteristics and air mass inputs.

It is verified in the historic period that the southern region presents the maximum PREC values approximately between 2000 and 2200 mm. In the northern region, this variation is between 1400 and 1600 mm.

When analyzing the PREC values between the scenarios, notes increase and reduction in PREC, which may be related to the high variability of precipitation in the Paraná State. In 2039, there was an increase in the extremes of the eastern and southern regions for the IPCC scenarios. While, for the trend scenario, there were reductions in PREC in the northern region (Figure 4).

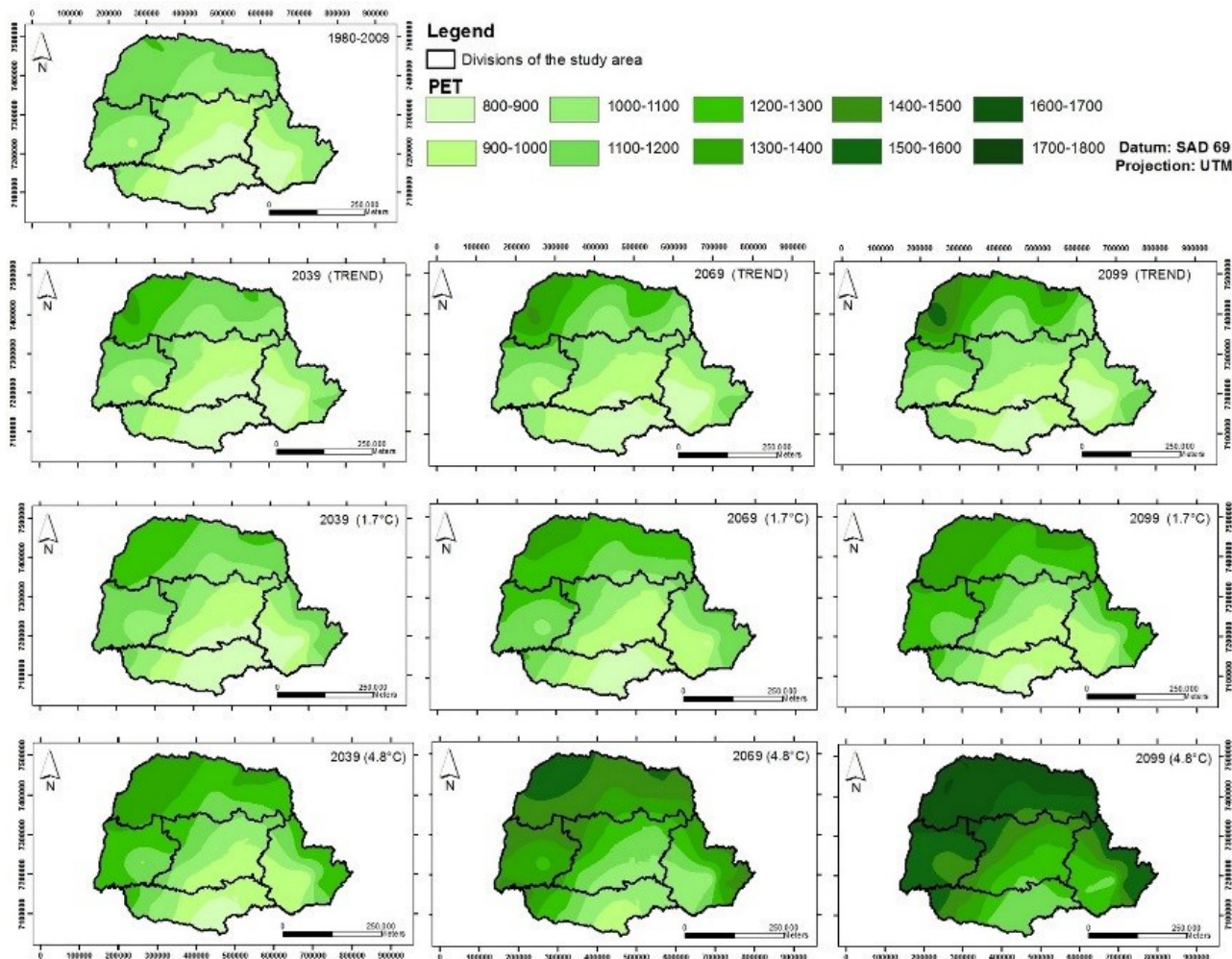


Figure 3. PET estimated temperature values interpolated for the years 2039, 2069 and 2099, facing the three simulated climate scenarios (1.7°C, 4.8°C, and trend).

In 2069, increases in the extremes of the eastern and southern regions occurred for the trend scenario and were more accentuated in the scenario of 4.8°C. The reduction in the northern region also occurred for the trend scenario. The same pattern of change occurred in 2099, but the increases were pronounced in all scenarios. For the 4.8°C scenario, this condition was verified in all regions of the State of Paraná, with a PREC reaching values close to 3000 mm in the southern region and reducing to up to 1000 mm in the northern region (Figure 4).

Similar results were found by Ferreira and Miranda (2021) and Resende et al. (2019) that analyzed the future PREC scenarios for the Paraná State, considering the IPCC scenarios. The authors highlighted the great variability of PREC and noted that its changes may vary between municipalities in the state. Therefore, there may be both a reduction and an increase in the PREC for future conditions.

Considering the estimates for all scenarios and analyzed periods, the municipalities presented the aridity index (I_a) varying from 0.0 mm to 10.5 mm. It shows that the Paraná State does not present and will not submit high values for the water deficit in future conditions. Based on the classification of Thornthwaite (1948), all locations would be classified low or no water deficiency, even in the face of climate change. In this case, this fact can be justified because Paraná State would present high rainfall indexes.

Thus, for the assessment of water availability, it was opted to interpolate and spatially analyze just the values of moisture index (I_m) in different conditions and regions of Paraná State. It is important to emphasize that the climate index values are estimated based on the annual values of deficit and water surplus. So, throughout the year, values of deficits as of surplus are represented. When there is a reduction of I_m , it can be said that there was a reduction of the water excess and an increase of I_a (or the water deficit).

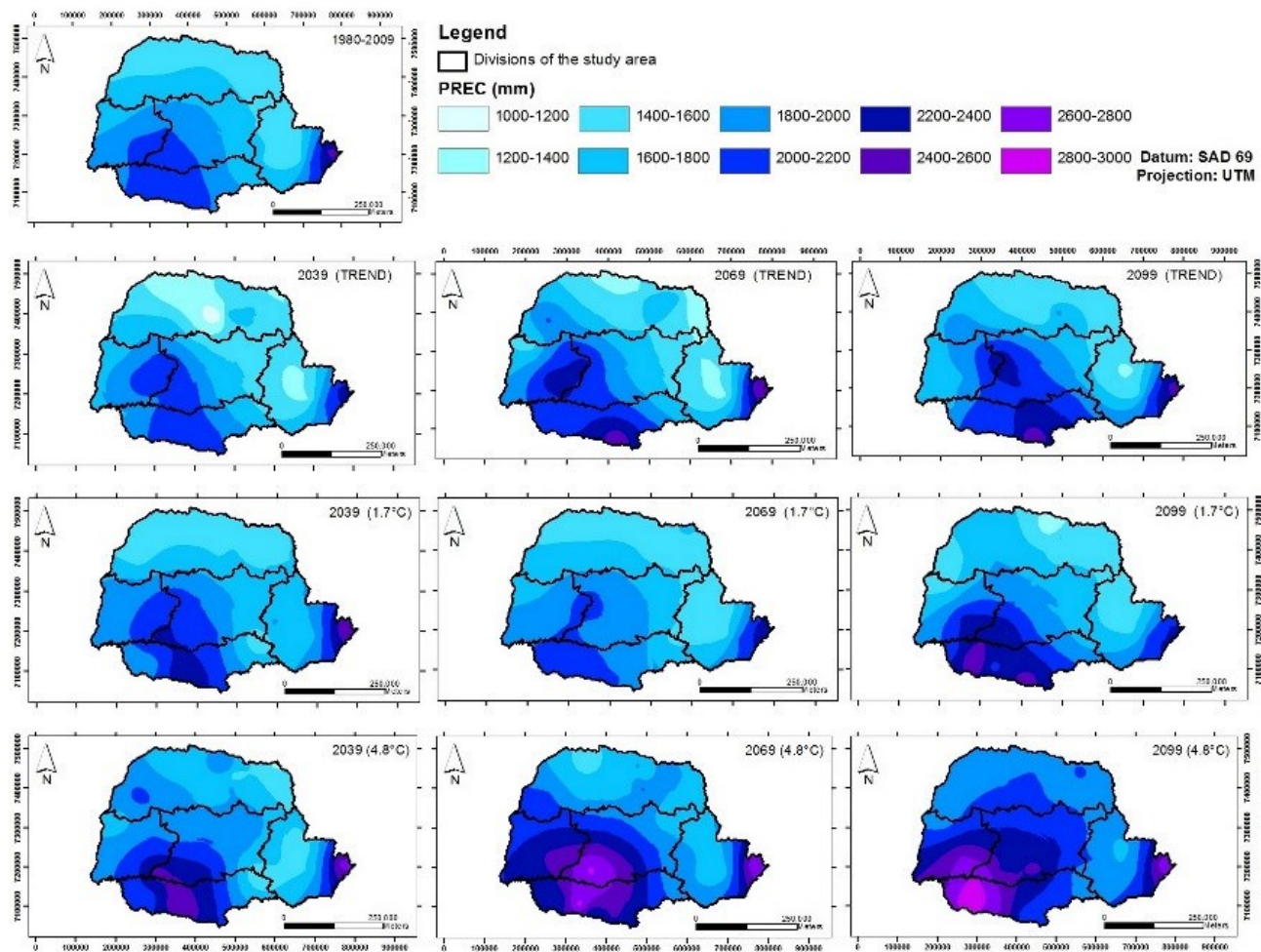


Figure 4. PREC's values interpolated for the year 2039, 2069, and 2099 facing the three simulated climate scenarios (1.7 °C, 4.8 °C, and trend).

Water availability to the historic period (1980 to 2009)

Parana State showed great variability in water availability, and the results show a difference in mean I_m values between the regions analyzed. The northern region presented lower water availability, with an average value of I_m equal to 37.44 ± 8.45 mm. In contrast, water availability was highest in the southern region, with a mean I_m value equivalent to 116.84 ± 25.10 mm. The central region had an average mean value of 109.01 ± 25.02 mm, and the eastern and western regions had mean values of 80.97 ± 28.90 mm and 78.37 ± 35.94 mm, respectively. Moreover, the analysis of variance (ANOVA) indicated that, at a significance level of 0.05, there was a significant difference among the regions analyzed.

After the spatialization of water availability, it is observed that the current conditions presented values of I_m between 22.1 mm to 158.9 mm. It is observed on the map, that in the period from 1980 to 2009 (Figure 5) the northern region shows a predominance of the minimum values of I_m between 20 and 40 mm, whereas in the southern region the largest values are checked (140 - 160 mm). This result reaffirms the water difference between these regions. The regions central, eastern, and western have values of I_m intermediaries, ranging between 60 and 140 mm. According to Aparecido, Rolim, Richetti, Souza, and Johann (2016), the Paraná State show I_m values ranging from 0 to 80 mm, where the highest values are predominant in the high latitudes and lower indices occur in the lower latitudes of the State, as well as on the coast.

Water availability estimated for 2039

In 2039, in the three climate scenarios, there was the inclusion of the first range of values of I_m (0 to 20 mm) and the range with values from 160 to 180 mm (Figure 5).

The I_m 's varied from 17.6 to 171.1 mm for the first scenario (increase of 1.7°C) and from 7.2 to 171.9 mm for the second scenario (increase of 4.8°C). The modifications of the I_m in these scenarios were less significant, appearing in a smaller area. This is because the rainfall remained stable or did not present a significant change.

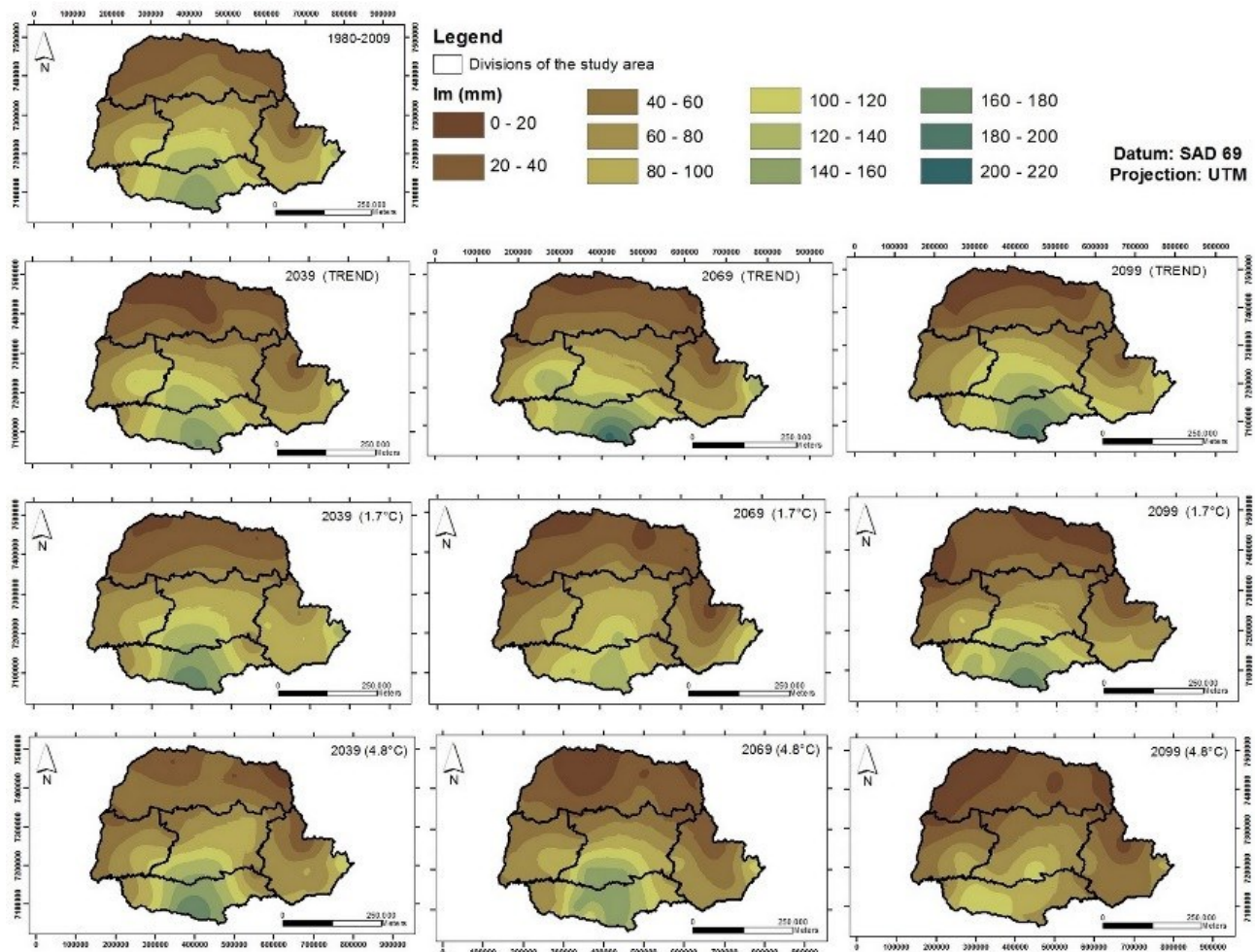


Figure 5. Values of I_m interpolated for the years 2039, 2069 and 2099, facing the three simulated climate scenarios (1.7°C, 4.8°C, and trend).

In the trend scenario (TREND), where the I_m varied from 4.0 to 164.2 mm, there was a reduction in the index in the northern region. This is because the extreme northern presented an increase in temperature and, consequently, in PET. This change associated with the reduction in the PREC was responsible for the increase in WD and I_a , and in the reduction of the value of I_m .

In the extreme south, there was a discrete increase of I_m punctually and next to Palmas municipalities, Clevelândia and Pato Branco (Figure 1). This increase can be explained because the changes in temperature were not enough to change the PET (Figure 5), however, the changes in the PREC increased the excess water and consequently the I_m . Results of increased excess water were also obtained by Horikoshi and Fisch (2007) due to an increase of 0.5°C in conjunction with the increase in the PREC projected for the period 2010-2039 in the Taubaté municipality of São Paulo State.

For the first scenario (1.7°C) there was also a small increase in I_m in the eastern region of the State, now in the central and western regions, there were no relevant changes. However, for the second (4.8°C) and third scenarios (TREND) the I_m reduced in eastern, central, and western regions, so that the second scenario was responsible for a greater reduction.

Water availability estimated for 2069

In 2069, the values of I_m ranged from 8.9 to 140.2 mm for the first scenario, from 2.2 to 153.8 mm for the second scenario, and from 10.8 to 206.8 mm in the third scenario (Figure 5).

In the northern and eastern regions, I_m has been reduced in all future scenarios and the second scenario (increase of 4.8°C) is responsible for a reduction more evident. For the first (1.7°C) and third scenarios (TREND), this result can be explained by the increase of the PET, and stability or reduction of the PREC. Now, in the second scenario, this result was a consequence of the PET significant increase that even with a slight increase in PREC was responsible for the reduction of I_m . In the southern and western regions of the state, the proportional increase of 1.7 and 4.8°C was responsible for drier future conditions relative to the historic

period. However, the trend scenario (third scenario) was responsible for the I_m increase in these regions. This is because the temperature change designed with the data trend was responsible for stability or even reduction of the variable PET, maintaining or reducing the water demand. The inclusion of values ranging from 200 to 220 mm in the southern region can be observed, representing the maximum values found for water conditions.

Changes in the central region were also most evident in the second scenario (increase of 4.8°C), where the index varied further between locations.

In evaluating the impact of climate change on runoff in the Paraná State between 2046 and 2071, changes of different magnitudes were observed by Resende et al. (2019) under two different IPCC scenarios. For both scenarios, the authors reported a runoff increase in the Irati municipality in the southern region of the state. Similarly, the Castro municipality, located in the east, showed an increase in the variable, which was greater in the worst-case scenario.

Water availability estimated for 2099

In 2099, the values of I_m ranged from 1.1 to 179.2 mm for the first scenario (increase of 1.7°C), from 9.3 to 119.8 mm for the second scenario (increase of 4.8°C) and from 10.3 to 194.4 mm for the third scenario (TREND) (Figure 5).

In the latter period, all the regions of the Paraná State experienced reductions in I_m for the first (1.7°C) and second scenario (4.8°C) analyzed. The reduction was more pronounced in scenario two (4.8°C). However, under the first scenario (1.7°C), there was a point increase in the extreme south.

The scenario of the trend (TREND) was also responsible for the reduction of I_m in the northern region. However, no significant changes were made in the central, eastern, and western regions. Moreover, this scenario was also responsible for an increase in I_m in the extreme south of the State of Paraná.

It can be said that the decline of I_m occurred progressively, less intense in 2039 and more intense in 2099, analyzing the evolution of water conditions in the periods. Similar findings were obtained by Salati, Salati, Campanhol, and Nova (2007), where excess water decreased by 70% in 2040 and 100% in southern Brazil in the Prata Basin in 2100.

This reduction, in the present study, followed in a gradual way in terms of area, expanding from the northern region toward the south, along with the analyzed periods. Given that changes in the central, eastern, and western regions have accompanied this latitudinal (north-south) behavior.

The scenarios were responsible for I_m reductions mainly in the northern region. The worst water condition occurred in 2099, where the second scenario (4.8°C) was responsible for more drastic reductions in all the regions of the State. For the first (1.7°C) and second scenarios (4.8°C), the temperature increase was responsible for the increased water demand and I_a in most locations of the Paraná State. Thus, this justifies a reduction in the water availability, even with the PREC's increase. That is, the difference between the supply (PREC) and the water demand (PET) becomes negative, thus increasing the I_a and reducing the I_m in most locations.

The same result was pointed out by Garcia (2010). When evaluating two IPCC scenarios and the impacts on the water balance of Ituverava-SP, Garcia (2010) showed that the rise in temperature causes an increase in PET, and water demand (PET) can not be supplied even if there is an increase in the total PREC.

The trend scenario (TREND) was responsible for I_m reduction in the northern region and for its increase in the extreme south, which also occurred in the first scenario (1.7°C). This occurs because the temperature changes in the extreme south, following the trend, and the increase of 1.7°C, were not responsible for the PET increase, thus the amount of PREC supplies the water demand (PET).

For the third scenario (TREND), it can be observed that the locations with high temperatures and low rainfall (northern locations) experienced decreases in I_m . In opposition, the locations with moderate temperatures and greater PREC (extreme south) suffered an increase in I_m . Thus, the increase or reduction of the I_m happens locally. These results also occurred in the same way in 2039, when the temperature change (Figure 2) was still low.

As has been noted, the northern region presents a strong reduction in water availability for all future climate scenarios analyzed. Because it is a region with low PREC, the increase in temperature, designed in the three scenarios, becomes responsible for the increase PET and the annual water deficit. However, in the south, the water condition depends on each scenario designed, because for the second scenario (4.8°C), reductions in the total area occur and for the first (1.7°C) and third scenario (TREND) an increase of I_m occurs in specific regions in the extreme southern region of the State.

Different results were found by Pinheiro et al. (2013) in Southern Brazil, they observed that both the IPCC A2 (more pessimistic) and B2 (more optimistic) scenarios were responsible for the increase in surface runoff. The A2 scenario caused a 268% increase in runoff, while the B2 scenario generated increases of 118%.

Conclusion

It can be concluded that both IPCC scenarios were responsible for reductions in water availability in the majority of Paraná State, especially in the northern region.

However, the trend scenario, in terms of spatial distribution, is different from the other scenarios. In this scenario it is possible to observe the increase in I_m in places where it rains more and the reduction in places where it rains less.

Anyway, the water conditions simulated in 2099 for all scenarios present a great environmental, social and economic concern, which must be considered in the planning of water resources by regional managers.

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References

- Aparecido, L. E. d. O., Rolim, G. d. S., Richetti, J., Souza, P. S. d., & Johann, J. A. (2016). Köppen, Thornthwaite and Camargo climate classifications for climatic zoning in the State of Paraná, Brazil. *Ciência e Agrotecnologia*, 40(4), 405–417. DOI: <http://doi.org/10.1590/1413-70542016404003916>
- Ferreira, N. C. R., & Miranda, J. H. (2021). Projected changes in corn crop productivity and profitability in Parana, Brazil. *Environment, Development and Sustainability*, 23, 3236–3250. DOI: <http://doi.org/10.1007/s10668-020-00715-z>
- Gao, G., Xu, C.-Y., Chen, D., & Singh, V. P. (2012). Spatial and temporal characteristics of actual evapotranspiration over Haihe River basin in China. *Stochastic Environmental Research and Risk Assessment*, 26(5), 655–669. DOI: <http://doi.org/10.1007/s00477-011-0525-1>
- Garcia, A. (2010). Balanço hídrico de Ituverava(SP) sob condições de cenários climáticos futuros. *Nucleus – Revista Científica da Fundação Educacional de Ituverava*, 7(1). DOI: <http://doi.org/10.3738/nucleus.v7i1.295>
- Gardiman, B. S., Magalhães, I. A. L., Freitas, C. A. A. d., & Cecílio, R. A. (2012). Análise de técnicas de interpolação para espacialização da precipitação pluvial na bacia do rio Itapemirim (ES) Analysis of interpolation techniques for spatial rainfall distribution in river basin Itapemirim (ES). *Ambiência*, 8(1), 61–71. DOI: <http://doi.org/10.5777/AMBIENCIA.2012.01.05>
- Horikoshi, A. S., & Fisch, G. (2007). Balanço hídrico atual e simulações para cenários climáticos futuros no Município de Taubaté, SP, Brasil. *Ambiente & Água - An Interdisciplinary Journal of Applied Science*, 2(2), 33–46. DOI: <http://doi.org/10.4136/ambi-agua.25>
- Intergovernmental Panel on Climate Change [IPCC]. (2013). *Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge, UK: Cambridge University Press.
- Jacobeit, J., Hertig, E., Seubert, S., & Lutz, K. (2014). Statistical downscaling for climate change projections in the Mediterranean region: methods and results. *Regional Environmental Change*, 14(5), 1891–1906. DOI: <http://doi.org/10.1007/s10113-014-0605-0>
- Kim, S., Kim, B. S., Jun, H., & Kim, H. S. (2014). Assessment of future water resources and water scarcity considering the factors of climate change and social–environmental change in Han River basin, Korea. *Stochastic Environmental Research and Risk Assessment*, 28(8), 1999–2014. DOI: <http://doi.org/10.1007/s00477-014-0924-1>
- Kwon, H.-H., Sivakumar, B., Moon, Y.-I., & Kim, B.-S. (2011). Assessment of change in design flood frequency under climate change using a multivariate downscaling model and a precipitation-runoff model. *Stochastic Environmental Research and Risk Assessment*, 25, 567–581. DOI: <http://doi.org/10.1007/s00477-010-0422-z>

- Leao, S. (2014). Mapping 100 Years of Thornthwaite moisture index: impact of climate change in Victoria, Australia. *Geographical Research*, 52(3), 309–327. DOI: <http://doi.org/10.1111/1745-5871.12072>
- Li, F., Xu, Z., Liu, W., & Zhang, Y. (2014). The impact of climate change on runoff in the Yarlung Tsangpo River basin in the Tibetan Plateau. *Stochastic Environmental Research and Risk Assessment*, 28(3), 517–526. DOI: <http://doi.org/10.1007/s00477-013-0769-z>
- McCabe, G. J., & Wolock, D. M. (1992). Effects of climatic change and climatic variability on the Thornthwaite moisture index in the Delaware River basin. *Climatic Change*, 20(2), 143–153. DOI: <http://doi.org/10.1007/BF00154172>
- Melo, L. C., Sanquetta, C. R., Corte, A. P. D., & Virgens Filho, J. S. d. (2015). Cenários climáticos futuros para o Paraná: oportunidades para o setor florestal. *Revista Brasileira de Climatologia*, 16. DOI: <http://doi.org/10.5380/abclima.v16i0.41149>
- Nascimento Júnior, L., & Sant’Anna Neto, J. L. (2015). Contribuição aos estudos da precipitação no estado do Paraná: a oscilação decadal do pacífico - ODP. *Raega - O Espaço Geográfico em Análise*, 35, 314–343. DOI: <http://doi.org/10.5380/raega.v35i0.42048>
- Nicks, A. D., & Harp, J. F. (1980). Stochastic generation of temperature and solar radiation data. *Journal of Hydrology*, 48(1), 1–17. DOI: [http://doi.org/10.1016/0022-1694\(80\)90062-1](http://doi.org/10.1016/0022-1694(80)90062-1)
- Oliveira, V. d. P. S. d., Zanetti, S. S., & Pruski, F. F. (2005). CLIMABR parte I: modelo para a geração de séries sintéticas de precipitação. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 9(3), 348–355. DOI: <http://doi.org/10.1590/S1415-43662005000300009>
- Pereira, A. R., Angelocci, L. R., & Sentelhas, P. C. (2007). *Meteorologia Agrícola*. Piracicaba, SP: USP.
- Pinheiro, A., Graciano, R. L. G., & Kaufmann, V. (2013). Simulating effects of climate scenarios on hydrological processes in southern Brazil using a lysimeter. *International Journal of Climatology*, 33(9), 2206–2214. DOI: <http://doi.org/10.1002/joc.3591>
- Resende, N. C., Miranda, J. H. d., Cooke, R., Chu, M. L., & Chou, S. C. (2019). Impacts of regional climate change on the runoff and root water uptake in corn crops in Parana, Brazil. *Agricultural Water Management*, 221, 556–565. DOI: <http://doi.org/10.1016/j.agwat.2019.05.018>
- Richardson, C. W., & Wright, D. A. (1984). WGEN: a model for generating daily weather variables. *ARS – Agricultural Research Service*, (8), 1–83.
- Salati, E., Salati, E., Campanhol, T., & Nova, N. V. (2007). *Relatório Nº4: tendências de variações climáticas para o Brasil no século XX e balanços hídricos para cenários climáticos para o século XXI*. Rio de Janeiro, RJ:FBDS.
- Santos, L. d. C., José, J. V., Bender, F. D., Alves, D. S., Nitsche, P. R., Reis, E. F. d., & Coelho, R. D. (2020). Climate change in the Paraná state, Brazil: responses to increasing atmospheric CO₂ in reference evapotranspiration. *Theoretical and Applied Climatology*, 140, 55–68. DOI: <http://doi.org/10.1007/s00704-019-03057-7>
- Semenov, M. A., & Barrow, E. M. (1997). Use of a stochastic weather generator in the development of climate changes scenarios. *Climatic Change*, 35(4), 397–414. DOI: <http://doi.org/10.1023/A:1005342632279>
- Silva, K. R. d., Cecílio, R. A., Xavier, A. C., Pezzopane, J. R. M., & Garcia, G. d. O. (2011). Interpolação espacial da precipitação no Estado do Espírito Santo. *Floresta e Ambiente*, 18(4), 417–427. DOI: <http://doi.org/10.4322/floram.2011.061>
- Silva, W. L., Dereczynski, C., Chang, M., Freitas, M., Machado, B. J., Tristão, L., & Ruggeri, J. (2015). Tendências observadas em indicadores de extremos climáticos de temperatura e precipitação no estado do Paraná. *Revista Brasileira de Meteorologia*, 30(2), 181–194. DOI: <http://doi.org/10.1590/0102-778620130622>
- Sirajul Islam, Md., Aramaki, T., & Hanaki, K. (2007). GCM-based analysis of water availability along the Tone River and Tokyo metropolitan area under climatic changes. *Regional Environmental Change*, 7(1), 15–26. DOI: <http://doi.org/10.1007/s10113-007-0022-8>
- Sivakumar, B. (2011). Global climate change and its impacts on water resources planning and management: assessment and challenges. *Stochastic Environmental Research and Risk Assessment*, 25(4), 583–600. DOI: <http://doi.org/10.1007/s00477-010-0423-y>

- Thorntwaite, C. W. (1948). An approach toward a rational classification of climate. *Geographical Review*, 38(1), 55–94. DOI: <http://doi.org/10.2307/210739>
- Thorntwaite, C. W., & Mather, J. R. (1955). *The water balance: publications in climatology*. Centerton, NJ: Drexel Institute of Technology.
- Virgens Filho, J. S. d., Oliveira, R. B. d., Leite, M. d. L., & Tsukahara, R. Y. (2013). Desempenho dos modelos CLIGEN, LARS-WG e PGECLIMA_R na simulação de séries diárias de temperatura máxima do ar para localidades do estado do Paraná. *Engenharia Agrícola*, 33(3), 538–547. DOI: <http://doi.org/10.1590/S0100-69162013000300010>