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FIRE HAZARD FORECAST BY THE REGIONAL CLIMATE CHANGE PROJECTION USING THE ETA MODEL: A CASE STUDY IN BAHIA, BRAZIL*

PREVISÃO DE RISCO DE INCÊNDIO PELA PROJEÇÃO DE MUDANÇAS CLIMÁTICAS REGIONAIS USANDO O MODELO ETA: UM ESTUDO DE CASO NA BAHIA, BRASIL

Rodrigo Rudge Ramos Ribeiro
Getulio Vargas Foundation (Brazil)
ORCID 0000-0002-3198-1679 rodrigo.rudge@fgv.br

Miguel Angel Trejo-Rangel
National Institute for Space Research (Brazil)
ORCID 0000-0003-1734-1656 miguel.rangel@inpe.br

Samia Nascimento Sulaiman
Federal University of ABC, Risk Management Laboratory (Brazil)
ORCID 0000-0002-2789-2286 samia.s@ufabc.edu.br

ABSTRACT

This article proposes a method for predicting fire occurrence, considering regional climate change projection using the Eta model, with a 20 km resolution, for the RCP4.5 and RCP8.5 scenarios. Fire occurrence in the state of Bahia was calculated as a function of the three main sensitivity factors on a daily time-scale: days without precipitation, precipitation, and maximum temperature. Historical fire occurrences from 1998 to 2018 and meteorological data from 1960 to 2018 were obtained from official institutes, and weather forecast parameters from 2018 to 2050 were downscaled from the web platform PROJETA. The correlations between the meteorological factors and fire occurrence were calculated for the historical data and a weight factor corresponding to a control simulation. Afterwards, a correction factor was determined, based on the historical fire occurrence data used for the forecast in the two scenarios. The results indicate that between 2018 and 2050, risk of fire will have an average increase of 27% at the RCP4.5 and 38% at the RCP8.5 scenario.

Keywords: Forecast modelling, fire occurrence, natural hazards, climate change.

RESUMO

Este artigo propõe uma metodologia de previsão de ocorrência de incêndios, considerando a projeção de mudanças climáticas regionais utilizando o modelo Eta, com resolução de 20 km, para os cenários RCP4.5 e RCP8.5. A ocorrência de incêndios, no estado da Bahia, foi calculada em função dos três principais fatores de sensibilidade em uma escala temporal diária: dias sem precipitação, precipitação e temperatura máxima. Ocorrências históricas de incêndios de 1998 a 2018 e dados meteorológicos de 1960 a 2018 foram obtidos de institutos oficiais, e os parâmetros de previsão meteorológica de 2018 a 2050 foram reduzidos da plataforma web PROJETA. As correlações entre os fatores meteorológicos e a ocorrência de incêndios foram calculadas para os dados históricos e um fator de peso correspondente para uma simulação de controle. Posteriormente, foi determinado um fator de correção, com base nos dados históricos de ocorrência de incêndios utilizados para a previsão nos dois cenários. Os resultados indicam que entre 2018 e 2050, o risco de incêndio terá um aumento médio de 27% no cenário RCP4.5 e 38% no cenário RCP8.5.

Palavras-chave: Modelagem de previsão, ocorrência de incêndio, riscos naturais, mudança climática.

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Introduction

Wildland fire is, in many cases, an essential ecosystem component that ensures the sustainability of its processes and communities. Wildland fire plays a key role as an environmental filter, selecting for species and their traits, and shaping ecosystems' communities (Aponte *et al.*, 2016). However, when there are changes in climate alone, they may have the potential to alter the distribution of vegetation types within the region, and climate-driven shifts in vegetation distribution are likely to be accelerated when coupled with stand-replacing fire (Hurteau *et al.*, 2014). Also, it has been shown that the frequency and intensity of wildland fires increase over the coming decades. Then, efforts to fully understand the implications of this growth will assist decision-and policy-makers to develop a more comprehensive understanding of the impact of them, and therefore the benefits of reducing the incidence of fires through GHG mitigation (Lee *et al.*, 2015).

According to the Intergovernmental Panel on Climate Change (IPCC), climate change will likely increase the global risk of extreme fire events (Stocker *et al.*, 2013). Throughout the century, situations of hot winds and even hotter anticyclonic events will arise and increase, resulting in an increase of the potential of large fire events (Duane *et al.*, 2019). In general, climate conditions are a fundamental driver of fire spread, and fire patterns are strongly sensitive to regional climate variability and (Silva *et al.*, 2016; Eugenio *et al.*, 2019). According to what is registered by NASA (2020) between 1980-2019, the mean temperature of land and ocean surface in the Southern Hemisphere indicates a tendency of temperature increase. The surface temperature in 2019 was around 0.50 degrees Celsius warmer than in the previous three decades, making it the hottest year in history (fig. 1). Temperature anomalies indicate how much warmer or colder it is than the normal average over the period of 1951-1980. Scientists expect global mean surface temperatures to increase an additional 0.3-0.7 degrees Celsius from 2016–2035 (Pachauri *et al.*, 2014).

Fires primarily occur after prolonged dry spells where the air temperature is high and climate change will produce conditions more conducive to severe fires (Stephens *et al.*, 2020). Dry vegetation can then be easily ignited, starting a wildfire that quickly spreads out of control with strong winds. Most fires near populated areas are caused by human activity, while a smaller portion occur naturally because of lightning events. Alongside accidental fires, a significant number are also started deliberately. For the risk hotspot regions, models can be used to estimate occurrence of these events. However, because of several man-made and natural factors, modelling this risk is complex and influenced by subjective assessments. The risk is especially high in climate zones where there is enough rainfall to allow vegetation to flourish part of the time, yet also have long periods of warm weather with little precipitation. Under these conditions, plants gradually dry out and become highly flammable. This has been reported in different regions of the world like Asia, North America, Europe, and the United States (Liang *et al.*, 2017; Duane *et al.*, 2019; Halofsky *et al.*, 2020; Stephens *et al.*, 2020; Vilà-Vilardell *et al.*, 2020).

Brazil is exposed to a variety of natural hazards, such as droughts and excessive rainfalls, which are the most frequent and damaging events. Fire is one of the most important types of disturbance affecting forest landscape ecosystems, especially in semiarid biomes and grassland. There are some locations in Brazil, such as Mato Grosso State, which a large part of its area (55.06%) is under high to extreme risk of fires (Mota el al. 2019) or Sorocaba in the São Paulo State, where 69 fires were recorded from January 1st, 2005 to December 31st, 2016 (Ziccardi *et al.*, 2018). Fire corresponds to the classification of disasters related to the intense reduction of water precipitation. This phenomenon can occur due to natural causes as well as human actions, such as climatic and environmental factors, which are decisive for increasing the rate of fires. The frequency and distribution of fires in Brazil are strongly associated with climatic conditions; the increase in temperature and changes in seasonal and annual rainfall have a large influence on fire occurrence

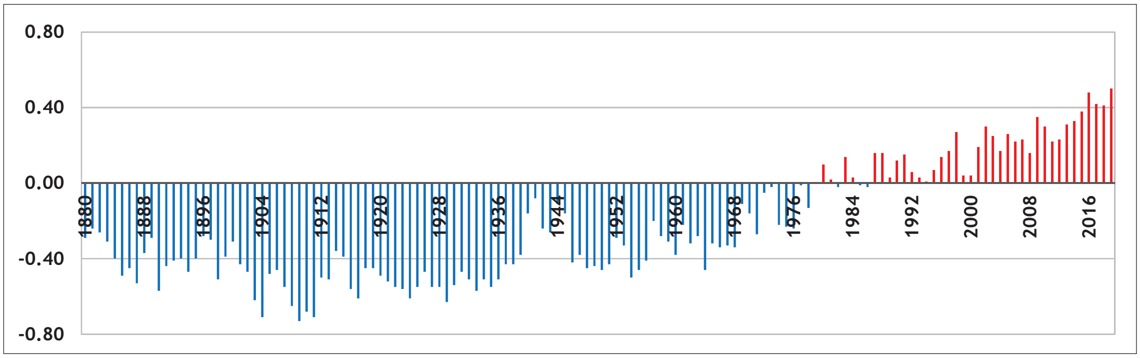

Fig. 1 - Southern Hemispheric temperature, deviation from the mean (Data source: NASA, 2020).

Fig. 1 - *Temperatura do hemisfério sul, desvio da média (Fonte dos dados: NASA, 2020).*

(Benfica, 2019). The historical analysis of fire occurrence in Brazil, between 1998-2019, reveals that 2007 was the year with the most fires, occurring most during August and September. During this period Brazil had a total of 393,915 fires (fig. 2).

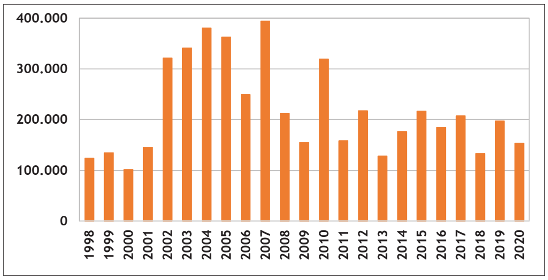

Fig. 2 - Historical fire occurrence in Brazil – number of fires (Data source: INPE, 2020).

Fig. 2 - *Histórico de ocorrência de fogos no Brasil - número de focos de incêndio (Fonte dos dados:* INPE, 2020*).*

The analysis fire occurrence distribution over Brazilian states between 1998-2019, indicates that fires had spread over every state (fig. 3). The state of Bahia had 5,6% of the cases, and in the Amazon Biome region, fire represented 69% of all national cases. The dimensions of vulnerability that make up the risk of disasters associated with forest fires are complex and diverse, presenting features that involve economic, political and institutional factors, in Brazil the impact measurement is underestimated (Anderson *et al.*, 2019).

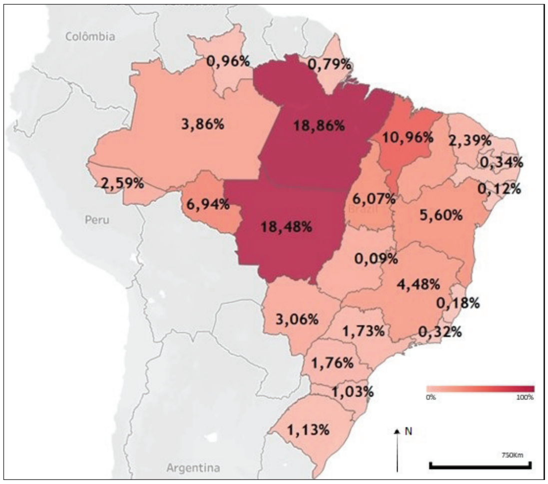

Fig. 3 - Distribution of fires in Brazil between 1998-2019 – % of the number of fires (Data source: INPE, 2020).

Fig. 3 - *Distribuição de incêndios no Brasil entre 1998-2019 - % do número de focos de incêndio (Fonte dos dados:* INPE, 2020*).*

The climate models are useful to help understand how the Earth's climate is changing, while also anticipating natural and human-driven variations on a global scale in the future. However, climate model's coarse scale limits the study of finer-scale processes, as is the case of fire. In this regard, a strong effort has been made by the scientific community to provide refined information about future climate using Regional Climate Models (RCMs).

The present study aims to assess the future fire hazard in the Brazilian state of Bahia, using a correlation index of meteorological aspects and fire occurrence in a regional regime. For this purpose, a regional downscaling of meteorological aspects was made by the PROJETA platform of the regional model. An assessment of the two RCM models has been calculated to indicate the fire risk change over a Brazilian region between 2018 and 2050.

Study Area

Most of the fires in Brazil that occur in the North and Northeast regions represent approximately 70% of the cases of the whole country. The analysis in the present study focuses on the Brazilian state of Bahia, in the Northeast region, and has a land area of 565,733 km^2 (IBGE, 2020). This region has tropical humidity, rainy tropical, and hot arid climates; with an average annual temperature of 27.8°C and average annual rainfall of 846 mm. This area is also a hotspot of extreme high temperatures, with a high risk of fire occurrence in Brazil, especially the region of the Chapada Diamantina located in the center of the state. Chapada Diamantina occupies about 10% of the state's territory and has an average annual maximum temperature of 29.9°C and average annual rainfall of 1,128mm (INMET, 2020). Contains some of its highest elevations, most of it above 500 metres. The analysis of fire occurrence in Bahia state, indicates that from the 417 municipalities, only 13% of them were affected by fires (CEPED, 2013). These municipalities are located in central region of the state, which is also the Chapada Diamantina region (fig. 4), where a tendency of an increased number of fires is observed. This is most likely related to climate aspects and the human occupation around the National Park of Chapada Diamantina (Rodrigues *et al.*, 2011).

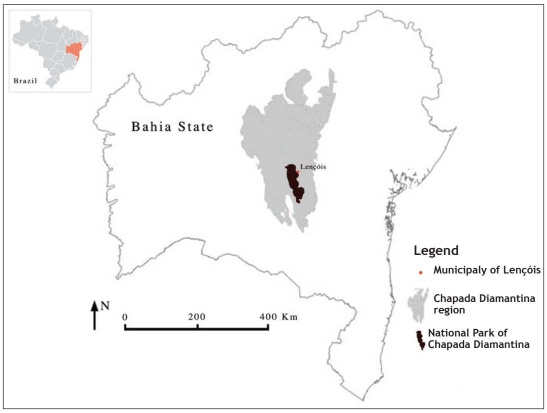

Fig. 4 - Study area of Bahia in Brazil

Fig. 4 - *Área de estudo da Bahia no Brasil.*

According with Torres *et al.* (2017), one of the factors that explain the fire occurrence is the land decline, being as higher the slop e of the terrain. The Chapada Diamantina National Park (PNCD), an integral protection unit, suffers recurrent fires and represent the highest number of fires recorded among the federal integral conservation units (dos Santos *et al.*, 2020; Franca-Rocha *et al.*, 2017).

Every year the region of Bahia suffers from a large number of forest fires, which devastates the local fauna and flora. Forest fires are common in Bahia during the dry season, which runs from July to October. They can be caused by natural reasons (e.g. lightning) or human activities caused accidentally (carelessness) or intentional (actions by arsonists) (Lacerda, 2013). An analysis of the number of fire occurrences in the study area indicates that, between 2004-2009, 73.6% had no determined causes; among those whose causes were known, approximately 13% are attributed to natural phenomena and 87% due to anthropic actions (Rodrigues *et al.*, 2011). Fire can be also used in a controlled practice in agriculture, which despite involving destruction, the burning of vegetation is an important way of land preparation for sowing and planting or for renewing pastures. This controlled practice is responsible for 37% of the number of fire occurrence in the Bahia state and 97% Chapada Diamantina National Park (PNCD) between 2019-2017, according to the data from the PREVEFOGO (National Center for the Prevention and Fighting of Forest Fires), which is linked to IBAMA, responsible for monitoring and fighting fires in conservation units in Brazil.

The official figures from National Institute for Space Research (INPE) show that, between 1998 and 2018, in Bahia, the forest fires recorded in average by year was 12,618. The fire that occurred in 2008 at the National Park of Chapada Diamantina, was located at the center of Bahia (photo 1). The 41% (638.4 km^2) of the park's area was affected by the fire (Mesquita *et al.*, 2011).

Photo 1 - Wildfire in the National Park of Chapada Diamantina in 2008 (Source: Lençóis Voluntary Brigade).

Fot. 1 - *Incêndio florestal no Parque Nacional da Chapada Diamantina em 2008 (Fonte: Brigada Voluntária de Lençóis).*

Methodological approach

The method is focused on fire hazard occurrence by quantitative and qualitative data analysis from four sources: (i) historical fire occurrence between 1998 and 2018 for the Bahia state; (ii) historical meteorological data between 1960 and 2018 for the Bahia state; (iii) meteorological forecast data between 2018 and 2050 for the Bahia state; and (iv) qualitative data collection of the occurrence in the Chapada Diamantina region with fire combatants and local authorities. The qualitative data was collected by the authors *in locu* during 2018 with interviews on the fire occurrence. The quantitative data was using monthly meteorological parameters and after presented in annual values for analysis. The fire hazard change was measured by comparing the impact of the RCP 4.5 and RCP 8.5 scenarios on fire occurrence. The Representative Concentration Pathway (RCP) is a greenhouse gas concentration trajectory used for climate modelling and research for the Intergovernmental Panel on Climate Change (IPCC) fifth Assessment Report (AR5). The two RCP select consider an intermediate and business as usual scenario.

The meteorological forecast used the Eta Model with a 20 km resolution. The Eta Model is a state-of-the-art atmospheric model used for research and operational purposes. The model is a descendent of the earlier HIBU (Hydrometeorological Institute and Belgrade University) model. Over the years, it has been improved by researchers from the Center for Weather Forecasting and Climate Studies (CPTEC) of the National Institute for Space Research (INPE) from Brazil (Chou *et al.*, 2005; 2012). The Eta Model is based on the vertical coordinate, sensitive to mountain areas, which makes the coordinate suitable for studies in steep topographic regions such as the Andes in South America (Brito *et al.*, 2019).

The historical fire occurrence between 1998 and 2018 was obtained at the National Institute for Space Research (INPE) of Brazil (INPE, 2020). The historical meteorological data from 1960 to 2018 was obtained by the Meteorological Institute (INMET) of Brazil, specifically by the meteorological station placed in the municipality of Lençóis, located in the center of Bahia State, at an altitude of 438 m, latitude 12°33′56″S, and longitude 41°24′38″W. The meteorological forecast data from 2016 to 2050 was generated using the PROJETA platform from the Brazilian Weather Prevision Center and Climate Studies (CPTEC) and INPE (Chou *et al.*, 2014a Chou *et al.*, 2014b, *Lyra et al.*, 2018). The downscaling was made using the global model MIROC5 (Model for Interdisciplinary Research on Climate), with a resolution of 20 km in the scenarios RCP4.5 and RCP8.5, for the 2006-2050 (forecast).

The method is centered on fire hazard occurrence based on modelling simulations of meteorological data from days without precipitation, precipitation, and maximum temperature. The fire occurrence forecast was obtained from the equation function of meteorological projections data, past fire occurrence, and past meteorological data. The method is divided into five calculation steps as described below:

- Firstly, the annual correlations between the historical fires' occurrence and meteorological historical data between 1998 and 2018 (Equation 1) was calculated.

  $$\text{Correlation}_i\ (x, y_i) = \Sigma\ (x - x')\ (y_l - y_i')\ /\ (\surd(x - x')^2\ (y_i - y_i')^2)$$

  x = fire occurrence

  y_i = meteorological data

  The correlations were calculated between the two indexes to access annual variability. The statistical evaluations consider the relationship between a dependent (fire occurrence) and an independent variable (meteorological data) to calculate the determination coefficient.

- Secondly, based on historical data, for each correlation factor and the equation for fire occurrence (Equation 3) using a matrix method for three variables, the correspondent weight factor (α, ß, μ) was calculated (Equation 2).

  $$\text{Weight factor}_i = C_1\ /\ \Sigma\ (C_1 + C_2 + C_3)$$

- Thirdly, the historical fire occurrence was calculated while considering three main sensitive historical meteorological factors: days without precipitation (positive relation), precipitation (negative relation), and maximum temperature (positive relation) between 1998 and 2018 (Equation 3).

  $$\text{Fire occurrence}_{\text{Historical}} = \Sigma\ f\ (\alpha * C_1 - \beta * C_2 + \mu\ C_3)$$

  C_1 = correlation with days without precipitation
  α = correspondent weight factor

  C_2 = correlation with precipitation
  ß = correspondent weight factor

  C_3 = correlation with maximum temperature
  μ = correspondent weight factor

- Fourthly, in order to calculate a correction factor for each scenario, a control simulation was developed, and the results were equated with the real historical fire occurrence data and fire forecast from 2006 to 2018 (Equation 4).

$\text{Correction factor}_i$ = median (historical number of fire occurrence / projection number of fire occurrence)

- Finally, the average of the correction factors was used for the forecast in the two scenarios RCP4.5 and RCP8.5 between 2018 and 2050 (Equation 5).

  $$\text{Fire occurrence}_{\text{Forecast}} = \Sigma\ (\text{Fire occurrence}_{\text{Historical}}) * \text{correction factor}$$

The climate impact on fire risk results from the interaction between climate-related hazards (including hazardous events and trends) and the vulnerability and exposure of human and natural systems. A risk associated with climate depends of two main factors: vulnerability and exposure (IPCC, 2012). Therefore, this is the very first analysis, which is based on comparing the RCP 4.5 and RCP 8.5 scenarios and the assumption that the other aspects will not change until 2050, in order to forecast fire hazards.

The Representative Concentration Pathways (RCPs) of IPCC are scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs), aerosols, chemically active gases, and land use/land cover (Moss *et al.*, 2008). The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics.

Simulations were performed in the Bahia region over South America. The downscaling was done of monthly values of maximum surface temperature, days without precipitation, and precipitation that were all extracted from the selected study area considering two scenarios simulations: RCP4.5 and RCP8.5 performed for the years 2018–2050, these are:

- RCP4.5 an intermediate stabilization pathway in which radiative forcing is stabilized at approximately 4.5 Wm^{-2} and 6.0 Wm^{-2} after 2100 (the corresponding ECPs assuming constant concentrations after 2150);
- RCP8.5 one high pathway for which radiative forcing reaches levels greater than 8.5 Wm^{-2} by 2100 and continues to rise for some amount of time (the corresponding ECP assuming constant emissions after 2100 and constant concentrations after 2250).

Web platform PROJETA

The web platform PROJETA, which is an acronym for "Projections of climate change for South America downscaled by the Eta model", was built to automatically access, prepare, and make the dataset of the downscaling climate change scenarios available to users. These projections are based on global climate downscaling models carried out by the Eta Model at CPTEC/INPE. The PROJETA project is a partnership between CPTEC/INPE and the University of Passo Fundo, promoted by the Brazilian Ministry of the Environment and funded by the German agency Deutsche Gesellschaft für Internationale Zusammenarbeit.

The premise of PROJETA is the automatization of the extraction process and the availability of data from regionalized climate projections for Brazil. This allows broad and unrestricted access to various available climate parameters and aims to meet access demands for climate projection data, treated and compatible with sectoral analysis programs and platforms. To obtain data on the web platform, the authors first choose the model RCP and climate scenario 4.5 and 8.5 with a resolution 20km. Afterwards, frequency selection is done to the database daily, through 2018–2050, using more than 30 years for this analysis. Later, the variables (days without precipitation; precipitation; maximum temperature) were selected. Finally, the area of interest of analysis is selected, in this case the state of Bahia. The generated data was then sent by PROJETA to the authors. The data received was statistically treated to allow the analysis.

Results and discussion

The quantitative results of historical fire data analysis, taken between 2004 and 2018, indicate that according to the INPE, the fire occurrence in the Bahia state was an average of 13,506 outbreaks cases by year; the year 2007 being the maximum record of cases with 29,468 cases and a minimum in 2018 with 4,956 cases. This is a fact that may further stress many ecosystems and human communities (Stephens *et al.*, 2020). Therefore, it is of particular importance to anticipate altered disturbance behaviour so that impacts on rural and natural-resources dependent livelihoods can be minimized (Vilà-Vilardell *et al.*,+ 2020). The statistical analysis of forest fire causes in the period of 1998 to 2002 in the state of Bahia, showed that the leading fire causes are incendiary (46%), followed by undetermined causes (27%), and pasture management (14%). The other associated events are forest operations (6%), miscellaneous (4%), lightening (2%), and smokers (1%) (Santos, 2004). The results of the qualitative data indicated the fire occurrence is mainly related to climate conditions (drought and with high temperatures), associated with some human activities caused accidentally (e.g. road accident) or intentional (e.g. manage pastures).

Forecast of fire occurrence

The results of the fire occurrence forecast indicate an average increase of 27% at the RCP4.5 and an increase of 38% RCP8.5 scenario for the state of Bahia (fig. 5). The historical data shows a decrease of events, which may be related to climate and public policy factors such as the creation of the program Bahia Without Fire in 2010 (SEMA, 2020).

Evolution of fire hazard

The results indicate that, fire occurrence is observed and increasing, overall the fire hazard had a significant increase of 21% comparing the RCP 4.5 and RCP 8.5 scenarios in the state of Bahia (this value was calculated considering the total sum of the annual difference of fire occurrence). In 2033, the maximum increase of 166% is observed (fig. 6).

Conclusions

The analysis of the scenarios was able to reproduce the main meteorological patterns and historical data on a regional scale that allowed the evaluation of the sensitivity of fire hazard changes expected until 2050, which would increase over time and could be used in the future for assessing a complete risk assessment. This study shows a systematic increase in the fire hazard that is observed in the Brazilian region of Bahia. Therefore, the method chosen seems to be appropriate since it allowed the authors to obtain results using available tools for downscaling data on a

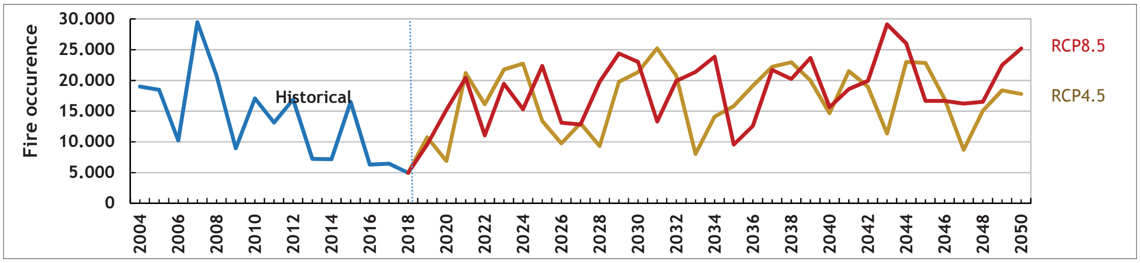

Fig. 5 - Annual fire occurrence from 2004-2018, and forecast at the RCP4.5 and RCP8.5 scenarios in the state of Bahia for 2018-2050 (Data source: PROJETA, 2020).

Fig. 5 *- Ocorrência histórica de incêndios (2004-2018) e previsão nos cenários RCP4.5 e RCP8.5 no estado da Bahia (2018-2050) (Fonte dos dados: PROJETA, 2020).*

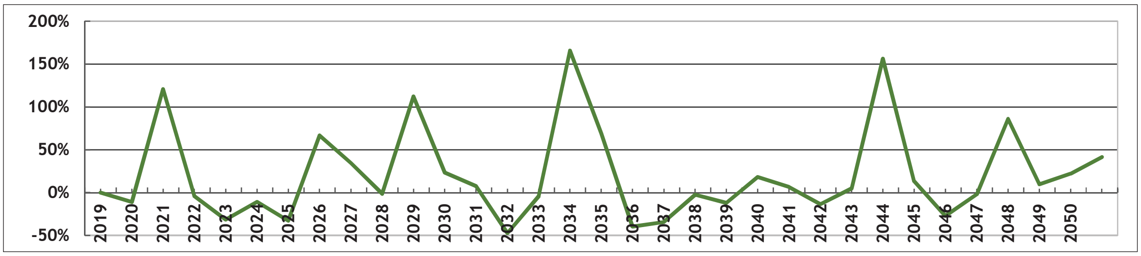

Fig. 6 - Fire hazard analysis comparing the two forecast simulations for the RCP4.5 and RCP8.5 scenarios in the state of Bahia (2018-2050 (Data source: PROJETA, 2020).

Fig. 6 *- Análise de risco de incêndio comparando as duas simulações de previsão no cenário RCP4.5 e RCP8.5 5 no estado da Bahia (2018-2050) (Fonte dos dados:PROJETA, 2020).*

regional scale. However, it is important to mention that the method does not consider variables such as public policies and other political decisions, which may influence the occurrence of fires in Bahia. However, the three climate variables and the web tool PROJETA enables the support of further risk assessments to propose and implement public policies for reducing fire hazards. To improve the fire forecast modelling, it is necessary to have more fire data available, since there is only data from 1998. According to INPE, the data from 1992 to 1997 is not provided as they are not compatible with current data (from 1998) that uses a different statistics treatment. However, as the result graphs indicated upward and downward peaks of fire outbreaks, a circular variation of the intensification and reduction period of the fires can be shown by 2050. Thus, it can help the planning and monitoring of related mitigative and preventative actions.

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