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Rainfall disasters under the changing climate: a case study for the Rio de Janeiro mountainous region

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Abstract

Climate change impacts the erosive power of rain, influencing mountainous landscapes' vulnerability to natural disasters. This study evaluated the spatiotemporal projections of daily rainfall erosivity (R_{day}), an efficient warning index for rainfall disasters, under climate change. The objectives of this study were to project spatially R_{day} across the Mountain Region of the Rio de Janeiro State (MRRJ), one of the most vulnerable regions to rainfall disasters in Brazil, and to analyze the frequencies of R_{day} values throughout the twenty-first century. Two greenhouse gas emission scenarios (RCP 4.5 and 8.5), approximating the current status in South America, and a high-resolution climate model (the HadGEM2-ES physically downscaled to 5 km resolution by the Eta/CPTEC model) were applied to estimate daily rainfall values over the MRRJ. The mapping of the maximum R_{day} values in 30 years (R_{maxday}) showed that the entire MRRJ is highly susceptible to rainfall disasters throughout the twenty-first century, with intensification around 2040–2071. Urban areas, where fatalities have been recorded, have been the most vulnerable due to the high frequency of heavy rainfall. The projections for the twenty-first century indicated that 17 (under RCP4.5) and 15 (under RCP8.5) events like the "mega-disaster" could hit the study region. Thus, public policy efforts should focus on effective stormwater management actions to mitigate the impacts caused by such disastrous events in this century.

Keywords Daily rainfall erosivity · Natural disasters · Mountainous region · Climate change Brazil

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1 Introduction

Natural disasters are the consequences of extreme events that cause significant impacts on the social, economic, environmental, or even psychological balance of people (Alexander et al. 2021). For example, floods and landslides caused by heavy rainfall are the most frequent natural disasters that affect humanity, causing thousands of deaths annually worldwide (Alexander et al. 2021).

Based on several studies worldwide, Lukić et al. (2013) reported that natural hazards have increased over time. From an economic point of view, the damages caused by natural hazards increased from several tens of billion dollars in the first seven decades of the last century to 380 billion dollars in 2011. The same was observed for fatalities, which globally impacted more than 24,000 lives per year between 1977 and 1997 to over 70,000 in 2011. Analyzing statistics published by Lukić et al. (2013), in America continent, 63% of the hazards are due to hydrological and meteorological events, such as severe storms, floods, and landslides. In Asia and Africa, 80% and 36% of natural hazards have occurred because of hydrological and meteorological events. In Europe and Oceania, natural hazards are considerably lower, 12% and 8%, from hydrological and meteorological causes.

Significant impacts of climate change have been observed in extreme heat, droughts, coastal flooding, erosion, wildfires, floods, and landslides. In South America, these drivers impact agricultural production, water availability, desertification of tropical biomes, and mass change in glaciers, which increase floods, soil erosion, and landslides (IPCC 2022).

Natural disasters have hit South America, increasing the trends in climatic variability and extreme events, such as rainfall and droughts. In some regions of South America, especially in the southeast, a trend in precipitation has been observed. Projects from RCP4.5 and RCP8.4 scenarios indicate an increase of 25% in this region of South America (IPCC 2022), which can potentially increase the occurrence of rainfall hazards in several regions, like the mountains of southeast Brazil, where Rio de Janeiro is located. It is essential to highlight the magnitude and frequency of extreme rainfall in South America and its projections. Chou et al. (2014a) projected a decrease in heavy rainfall considering an increase of 1.5 °C; however, Imbach et al. (2018) projected an increase in the frequency of the R50mm, i.e., an increase in the number of days with rainfall greater than 50 mm for global warming of 2 °C and 4 °C.

In Brazil, landslides and floods are the main ones responsible for the greatest impacts from natural hazards with a number of fatalities (CEPED, 2013). These hazards are triggered by extreme rainfall, leading to many fatalities in this country every year, especially in areas geomorphological prone to landslides, such as the mountains region of southeast Brazil. Thus, the increase in the frequency and intensity of extreme rainfall, in combination with the high degree of susceptibility of the population in risk areas, has triggered these disasters in the country, especially in mountainous regions with high geological risk (Fernandes and Rodrigues 2018; Amorim and Chaffe 2019). Some mountainous regions of Brazil are places where geomorphological features, deforestation of the Atlantic Forest, recurrent heavy rainfall (Freitas et al. 2012), and the uncontrolled growth of urban areas potentiate the consequences arising from natural disasters (Mello et al. 2020). One of the regions most affected by extreme rainfalls is the Mountain Region of the Rio de Janeiro State (MRRJ), which is one of the most vulnerable to rainfall disasters in the country (Freitas et al. 2012; Brasil 2012; Bitar 2014; Oliveira et al. 2016). This region suffered many events that resulted in several fatalities, such as the so-called "mega-disaster" in 2011 (Alves et al. 2022). The most recent hit the city of Petropolis in February 2022, causing the death of 231 people (Alcântara et al. 2022). This event, in meteorological terms, was extraordinary, bringing 252 mm of rain in three hours.

Determining indexes applied to alert/warning systems to mitigate the impacts caused by rainfall disasters is always challenging. The document of the World Conference for Disaster Reduction in Japan in 2005 warns of the need to develop indicator systems at different levels of scope to enable a better diagnosis and response to risk situations and vulnerability by decision-makers (Silva et al. 2016). In this sense, some studies have evaluated the efficiency of the Monitoring and Alert System (MAS) ("Early Warning System") indicators in reducing risks related to economic impacts, in addition to the risks of fatalities (Webster 2013; Alvalá et al. 2019). As intense rainfalls trigger these events in Brazil, indexes are used as an early warning based on their temporal behavior. Weather forecasting can be reliable if made up to 72 h in advance (Oliveira et al. 2016). Thus, rainfall (accumulated and its intensity) composes most of the MASs (Calvello et al. 2015; Mello et al. 2020; Alves et al. 2022).

Some indexes are widely used in Brazil and the world, such as the accumulated rainfall in the last 24, 48, 72, and 96 h, the rainfall intensity (mm/h), or their combinations (Oliveira et al. 2016; Calvello et al. 2015; Silva et al. 2020). Some studies also used rainfall erosivity and other rainfall indexes to identify areas more prone to landslides in Europe. Lukić et al. (2021) applied the Angot Precipitation Index to study rainfall erosivity behavior in the Vojvodina region, Serbia, and observed a good performance of this index to identify the aggressiveness of rainfall and its correlation with soil water erosion. Ponjiger et al. (2021) applied the daily rainfall erosivity and respective density erosivity to identify areas more susceptible to water erosion in the Pannonian Basin, Central Europe. Although they applied the model and respective parameters proposed by Zhang et al. (2002) to China, they identified the seasons in which rainfall erosivity has been marked, enhancing the assessment of the aggressiveness of rainfall erosivity in southern Europe. Morar et al. (2021) also studied rainfall erosivity as a predictor for natural hazards in the Ciuperca region, Romania, using monthly rainfall data. Besides rainfall erosivity, they applied the Precipitation Concentration Index (PCI) and Modified Fournier Index (MFI), both good indexes related to the aggressiveness of rainfall. In another study carried out in Belgrade, Serbia, Lukić et al. (2018) also applied the PCI and MFI and observed a moderate aggressiveness of rainfall, which, together with the geological features, demonstrated the vulnerability of the studied region to natural hazards triggered by rainfall.

However, these indexes may be inefficient in some cases (Calvello et al. 2015; Mello et al. 2020). Thus, Mello et al. (2020) established an alert climate index (R_{day}) related to the maximum daily rainfall erosivity for the Mantiqueira range region (Southeast Brazil) based on the impact of the rain, rainfall amount, and rainfall intensity. This index is based on rainfall erosivity, a climatic index that portrays the impacts of energy dissipated by raindrops on the surface. Thus, it is a more comprehensive index than the others to predict hazards, especially fatalities. This concept was initially proposed and defined by Wischmeier and Smith (1958) as the product between the kinetic energy of raindrops (Ek) and the maximum rainfall intensity in 30 consecutive minutes (I_{30}), designated as EI_{30}. When applied on a daily scale, it can help better understand the role of heavy rainfall in natural disasters (Alves et al. 2022; Mello et al. 2020).

A rainfall network with a temporal resolution < 15 min for the computation of daily rainfall erosivity (R_{day}) is often lacking in Brazil. Thus, applying a model for R_{day} estimation based on daily rainfall data, which are more accessible and spatially distributed, is critical to linking heavy rainfall events to natural disasters (Chen et al. 2020). In this aspect, Alves et al. (2022) developed a similar index for MRRJ. This index is based on Yu and Rosewell's (1996) study, which proposed a method to estimate the seasonality of R_{day}, and on the index established by Mello et al. (2020).

In this context, climate change and its impacts on the magnitude and frequency of rainfall disasters are uncertain, especially in regions with significant orographic influences (Lyra et al. 2017). Disasters involving landslides have become more frequent and severe during the last decades (CEPED 2013), especially in mountainous regions of Brazil (Mello et al. 2020). Such facts demonstrate evident changes in the heavy rainfall pattern (IPCC 2013), and rapid population growth, which result in disorganized urbanization (IPCC 2022).

It is a fact that climate change has impacted the rainfall pattern in Brazil, with clear changes in rainfall erosivity. However, most studies have focused on annual rainfall erosivity (or RUSLE's *R*-factor) (Riquetti et al. 2020; Mello et al. 2015), which needs to be further understood as impacts on extreme rainfall events. This study brings as novelty an assessment of climate change impacts on daily rainfall erosivity (R_{day}), being the first investigation in this regard in Brazil. Studies of climate change impacts on daily rainfall remain little studied in tropical and mountainous regions, and their contribution to preventing rainfall hazards is essential. Using a daily rainfall erosivity model, it is possible to assess the frequency of heavy rainfall, respective R_{day}, and impacts of rainfall disasters using daily rainfall projections over the century.

The objectives of this study were to (1) apply a seasonal model to calculate R_{day} for the MRRJ throughout the twenty-first century, using a high-resolution climate model (HadGEM2-ES physically regionalized by the ETA-CPTEC model in the 5 km spatial scale—the 5-km Eta-HadGEM2-ES), and the RCP4.5 and 8.5 IPCC scenarios, (2) map the maximum daily rainfall erosivity (R_{maxday}) to assess the most vulnerable areas of MRRJ throughout the present century, and (3) to project the frequency of R_{day} > 500 MJ mm (ha h)$^{-1}$ day^{-1} (a threshold for the harmost events) throughout the twenty-first century.

2 Materials and methods

2.1 Some aspects of the mountain region of the Rio de Janeiro State (MRRJ)

The MRRJ is located in the Serra do Mar and is characterized by mountainous to steep relief, with altitudes ranging from 400 to 2350 m (Fig. 1). It is located in the unit called "Planalto Reverso" (Garcia and Francisco 2013), and the soils are predominantly shallow and moderately permeable and have low natural fertility (Pinto et al. 2018).

The geographic location of the three most populous municipalities, Petrópolis (792 km^2), Teresópolis (773 km^2), and Nova Friburgo (936 km^2), and the digital elevation model for the entire region are shown in Fig. 1. The location of the rainfall stations from the National Water and Sanitation Agency (ANA) and the 130 grid points for which the daily rainfall data of the climate projections used in this study are also presented. These three municipalities represent almost 80% of the entire MRRJ population (IBGE 2010) and have been the most affected by rainfall disasters in Brazil (Alves et al. 2022; Coelho Netto et al. 2013).

The entire MRRJ was originally covered by Atlantic Forest, which was removed to make way for plantations, pastures, and urban centers. Despite currently being fragmented and degraded, especially around urban areas, the Atlantic Forest still represents more than 50% of the region's vegetation cover (Coelho Netto et al. 2013; Garcia and Francisco 2013;

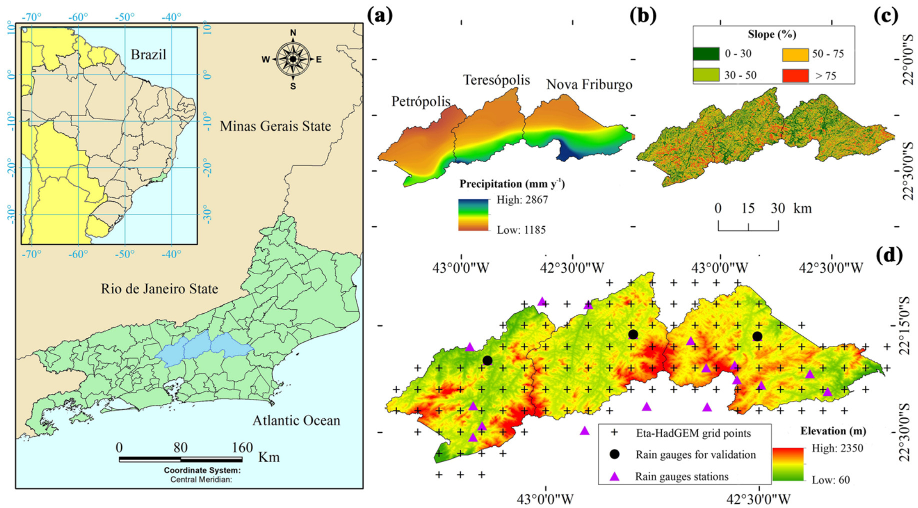

Fig. 1 The geographical location of MRRJ (**a**), with emphasis on Nova Friburgo, Petrópolis, and Teresópolis, annual precipitation map (**b**), relief (slope) map (**c**), and the grid points obtained by the 5-km Eta-HadGEM2-ES model and locations of the ANA rain gauges (**d**)

Cardozo and Monteiro 2019). Garcia and Francisco (2013) found that this biome is present in the steepest and most elevated places. It suffers from fires during the dry period, resulting in the destruction of its vegetation cover, making the surface more susceptible to landslides caused by rain in the summer.

The climate of the MRRJ is Cwb (Köppen climate-type), meaning a mild temperate climate with dry winters and rainy summers. The average annual temperature is approximately 16 °C, and the average temperature of the hottest month is below 22 °C (Coelho Netto et al. 2013). Summers are rainy (more than 70% of rainfall occurs between October and March) (André et al. 2008), and winters are cold and dry (Dourado et al. 2012). The rainfall pattern in the MRRJ is driven by several climatic phenomena, such as (1) frontal systems, which act throughout the year and which, combined with the humidity of the Atlantic Ocean, bring significant amounts of rain, (2) convective rains in summer, (3) South Atlantic Convergence Zone (SACZ) during the summer, (4) orographic effects, (5) tropical and subtropical cyclones, and (vi) maritimity (Reboita et al. 2010).

2.2 Daily rainfall erosivity (R_{day}) model to MRRJ

The seasonal model of daily rainfall erosivity fitted by Alves et al. (2022) is based on the studies by Yu and Rosewell (1996) and was used for this study.

$$R_{day} = 3.3888 \cdot \left[1 + 0.4659 \cdot \cos\left(\frac{2 \cdot \pi \cdot j}{24} - \frac{\pi}{6}\right)\right] \cdot P\mathrm{day}^{1.2028} \tag{1}$$

In which j is the fortnight (ranging from 1 to 24) and P is the daily precipitation in a 24-h interval (mm). It is important to highlight that this model represents the MRRJ since it was determined based on data from 68 stations with precipitation data with a temporal resolution of 10 min. The precision statistics presented and discussed by the author showed satisfactory results for estimating the R_{day} (calibration: C_{NS} = 0.51; P_{bias} = − 0.56) and (validation: C_{NS} = 0.50; P_{bias} = − 2.22).

Equation 1 is applied to the daily rainfall data obtained from the ANA rain gauges to the historical data (baseline) and the climate projections provided by the Global Circulation Climate Model (GCM) (HadGEM2-ES) downscaled by a physical model, the Eta/CPTEC (5-km Eta-HadGEM2-ES).

Maximum daily rainfall erosivity (R_{maxday}) maps were developed considering the highest R_{day} values observed at each grid point provided by the 5-km Eta-HadGEM2-ES model (Fig. 1) for the historical period (1961–2005) and three different periods throughout the twenty-first century (2006–2040, 2041–2070 and 2071–2099). In addition, percentage variation maps of future periods were prepared and referred to the historical data. These maps make it possible to detect areas with greater susceptibility to natural disasters caused by extreme precipitation events throughout the century.

2.3 Climate change projections of R_{day} using a high-resolution climate model for the MRRJ

The Eta Regional Climate Model (RCM) was refined by Chou et al. (2012) and Marengo et al. (2012) to provide downscaling of climate change projections in South America at a spatial resolution of 0.20° × 0.20° (20 km horizontally and 38 layers vertically) nested to the HadGEM2-ES, MIROC5, BESM and CANESM2 global climate models (GCMs). Its most recent version was described in detail by Mesinger et al. (2012) and evaluated for long-term simulations by Pesquero et al. (2010), Flato et al. (2013), and Chou et al. (2012, 2014a, b).

The orographic influence on precipitation should be considered to improve the simulation results (Brito et al. 2016; André et al. 2008). Therefore, the spatial resolution of 20 km produces insufficient results for analyzing the frequency of extreme events that cause natural rainfall disasters (Chou et al. 2014a). Thus, a downscaling process was carried out using the Eta-CPTEC model for a 5-km resolution to overcome the coarse resolution (20 km), nesting it to the HadGEM2-ES GCM under the RCP4.5 and RCP8.5 emission scenarios in the period from 1961 to 2100. However, due to the high-computational demand, only the Eta-HadGEM2-ES was regionalized for the 5-km scale and is only available for Southeastern Brazil (where MRRJ is located). Lyra et al. (2017) detailed this higher spatial-resolution version.

In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2013), greenhouse gas concentration scenarios are based on two "Representative Concentration Pathways" (RCP), which are expressed in terms of radiative forcing to the end of the twenty-first century. The scenarios used in this study were RCP8.5 and RCP4.5 (Van Vuuren et al. 2011), the only ones available for South America. RCP4.5 is considered an intermediate scenario that assumes greenhouse gas emissions stabilization from the middle of the twenty-first century. This scenario considers a global radiative forcing of approximately 4.5 W m^{-2}. On the other hand, RCP8.5 is a scenario that considers an increase in greenhouse gas emissions by the end of the century, meaning that no implementation of climate policies and continued acceleration of the use of fossil fuels.

Historical (baseline) data (1961–2005) and climate projections (2006–2099) of daily rainfall for calculating R_{day} values considering both scenarios were obtained from the Weather Forecast and Studies Center of the National Institute for Space Research (*CPTEC/*

INPE) on the platform called "PROJETA" (Holbig et al. 2018) (https://projeta.cptec.inpe.br/#/about).

The validation of the 5-km Eta-HadGEM2-ES model to estimate R_{day} was conducted with the application of the seasonal model of daily erosivity in the period from 1980 to 2005 (26 years) to calculate the long-term annual average rainfall erosivity (*R*-factor) considering the data obtained from three ANA rain-gauge stations and the 5-km Eta-HadGEM2-ES for the same period. Daily rainfall < 13 mm was not considered erosive, according to the Alves et al. (2022) study, and thus was not considered in the *R*-factor calculation.

2.4 Critical thresholds of R_{day} MRRJ

R_{day} thresholds are values proposed to identify and alert areas most vulnerable to natural disasters (Mello et al. 2020). These limits have been established through a joint analysis of R_{day} values calculated for rainfall events that caused disasters concomitantly with the consequences observed in recent decades. As a result, the following values were proposed for the MRRJ by Alves et al. (2022):

1. $R_{day} > 1500$ MJ ha^{-1} mm h^{-1} day^{-1}: "very high" possibility of fatalities; "very high" number of homeless; and "very high" possibility of damage in general.
2. R_{day} between 1000 and 1500 MJ ha^{-1} mm h^{-1} day^{-1}: presents a "high" possibility of fatalities, a "very high" number of homeless, and a "high" possibility of causing damage to infrastructure and economy.
3. R_{day} between 500 and 1000 MJ ha^{-1} mm h^{-1} day^{-1}: "medium" possibility of fatalities in urban areas and "low" in rural areas, "medium" impact in terms of homeless, and "medium" possibility of causing damage to infrastructure and economy.
4. $R_{day} < 500$ MJ ha^{-1} mm h^{-1} day^{-1}: "very low" possibility of fatalities, a "low" number of homeless, and a "low" possibility of damage to the economy and infrastructure.

The established R_{day} limits were used to classify the R_{maxday} maps, and the thresholds $1000 < R_{day} < 1500$ MJ ha^{-1} mm h^{-1} day^{-1} and $R_{day} > 1500$ MJ ha^{-1} mm h^{-1} day^{-1} were also specifically used to analyze the frequency of events causing natural disasters throughout the twenty-first century as they imply possible fatalities. Therefore, the frequency of these events over the baseline and the three periods (1976–2005, 2011–2040, 2041–2070, 2070–2099) was analyzed. It is possible to observe a slight change in the intervals considered to analyze the frequency of these events used to map the R_{maxday} to consider periods of 30 years of data. Thus, 3900 events were analyzed for each time slice, 30 for each of the 130 grid points generated by the 5-km Eta-HadGEM2-ES model (Fig. 1).

Figure 2 presents a flowchart with the steps to calculate the daily rainfall erosivity for the baseline and time slices throughout the century and the conversion of these values to assess the rainfall hazards in MRRJ.

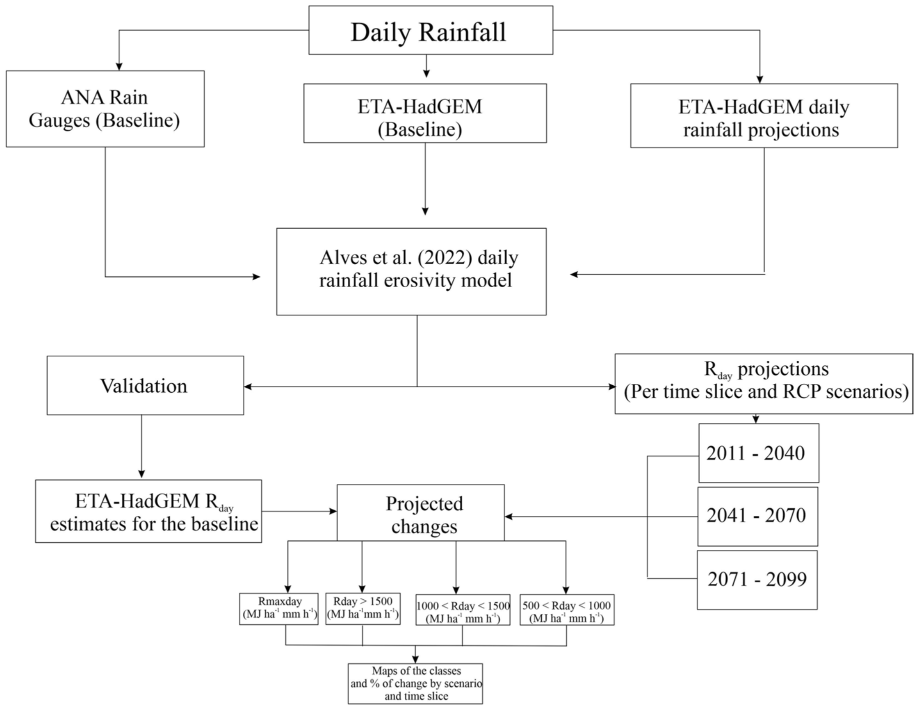

Fig. 2 Flowchart with the methodology used to assess the rainfall hazards in MRRJ

3 Results and discussion

3.1 Performance of the high-resolution climate model (5-km Eta-HadGEM2-ES model) to calculate rainfall erosivity in the MRRJ

To evaluate the high-resolution climate model in estimating daily rainfall erosivity, we examined its capability to account for RUSLE's *R*-factor estimation, i.e., the long-term average annual rainfall erosivity, given that *R*-factor values and patterns are well-known in the study region. Therefore, the *R*-factor for the ANA rain gauges of Petrópolis, Nova Friburgo, and Teresópolis (Fig. 1) was detailed. The *R*-factor calculated for these three rain gauges using daily rainfall projected by the high-resolution climate model showed a good agreement with the *R*-factor calculated based on the daily rainfall observed in the ANA rain-gauge stations. The *R*-factor was 8537, 10,554 and 7639 MJ ha^{-1} mm h^{-1} $year^{-1}$, respectively, to Petrópolis, Nova Friburgo, and Teresópolis, using the observed daily rainfall. Considering the daily rainfall from the 5-km Eta-HadGEM2-ES climate model, *R*-factor was 9566 (an overestimate of 10.29%) to Petrópolis, 9,886 (an underestimate of 6.67%) to Nova Friburgo, and 6057 MJ ha^{-1} mm h^{-1} $year^{-1}$ (an underestimate of 15.82%) to Teresópolis. These results demonstrate a good correspondence between the *R*-factor estimated based on the climate model and observations. Furthermore, we can state that this model was able to cope with the strong orographic influence on the rainfall in the region since the ANA rain gauges are located in different locations and altitudes of the MRRJ (Fig. 1b).

Yin et al. (2013) demonstrated through 11 GCM simulations that the HadGEM2-ES model had the best performance under surface conditions and atmospheric circulation (Chou et al. 2019). Furthermore, in analyzing 19 global climate models, Gulizia and Camilloni (2015) concluded that HadGEM2-ES presented the highest spatial correlation between simulated precipitation values and those observed for South America in the baseline. These studies support the 5-km Eta-HadGEM2-ES model to appraise erosivity events throughout the twenty-first century. It is also needed to highlight the relevance of using a physical model for downscaling the outputs from a GCM in mountainous regions to better capture the orographic effects (Chou et al. 2014a), which is a considerable aspect of the MRRJ climate pattern.

The estimation of R_{day} has been useful in identifying the most vulnerable areas to natural disasters and analyzing the frequency of events associated with these disasters. Although the results of this study were only applied to the MRRJ, the proposed methodological framework can be transferred to other vulnerable areas in the country since there are data with a temporal resolution of 15 min for modeling R_{day}.

3.2 R_{maxday} mapping in the MRRJ throughout the twenty-first century

Figure 3 shows the spatial distribution of R_{maxday} and its percentage variation throughout the twenty-first century regarding the baseline in MRRJ considering the 5-km Eta-HadGEM2-ES model projections. R_{maxday} corresponds to the maximum value calculated by considering a time series with at least 20 years of daily rainfall erosivity (Mello et al. 2020).

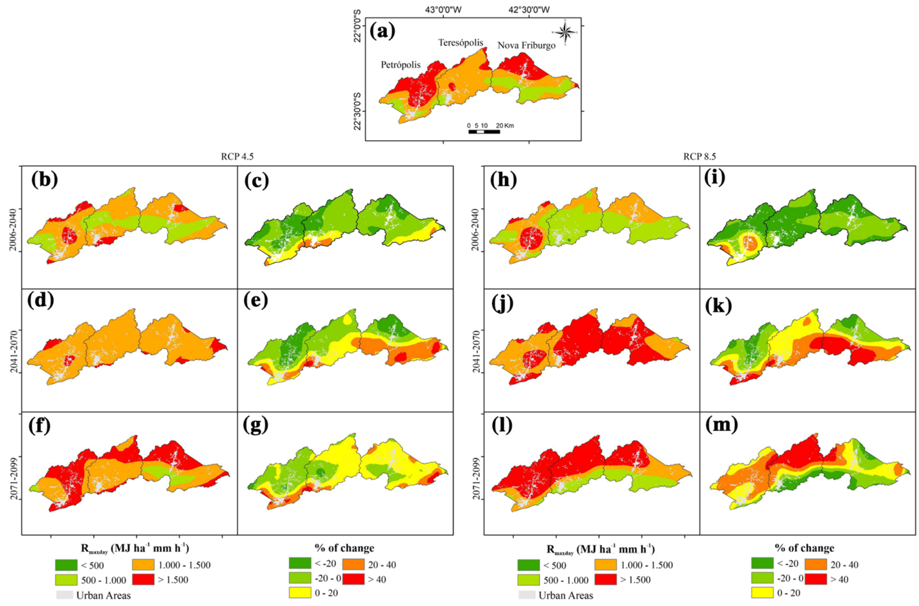

Fig. 3 R_{maxday} baseline map (**a**) and maps of the R_{maxday} and respective relative changes in relation to the baseline throughout the twenty-first century (RCP4.5: **b**–**g**; RCP8.5: **h**–**m**)

Considering the baseline map (3a) and maps for the time slices in the RCP4.5 (3b−3g), almost the entire MRRJ is hit by rainfalls that result in R_{maxday} values that cause disasters with different consequences. However, regardless of the climatic scenarios, the period with the most extensive spatial coverage of R_{maxday} values > 1500 MJ ha^{-1} mm h^{-1} day^{-1} is from 2070 to 2099 (Fig. 3f—RCP4.5 and 3l—RCP8.5), especially for the RCP8.5, where the positive relative changes (Fig. 3l, m) dominate the north region of the largest municipalities. Worthwhile that it is essential to highlight the concentration of these events in the urban areas of Petrópolis and Nova Friburgo, which might result in fatalities.

The 2011–2040 time slice (Fig. 3b, h, respectively, for RCP4.5 and RCP8.5) presented R_{maxday} values predominantly in the $500 < R_{\mathrm{maxday}} < 1000$ MJ ha^{-1} mm h^{-1} day^{-1} class in Nova Friburgo and Teresópolis, especially for RCP8.5 (Fig. 3h). However, for this same time slice, an increase in R_{maxday} in Petrópolis in the ranges that encompass values > 1000 MJ ha^{-1} mm h^{-1} day^{-1} was detected, meaning an increase in the magnitude of the events that can potentially cause significant hazards and fatalities. Thus, in this time slice, which we are crossing now, Petrópolis has been the most vulnerable municipality of the MRRJ to rainfall hazards. This aspect has been observed recently (Alves et al. 2022).

Maps of the relative changes are also presented for both scenarios and were generated to understand the spatial variation of R_{maxday} values regarding the baseline. Positive values mean an increase in R_{maxday}, and negative values represent a decrease in magnitude. Compared to the baseline, there is a decrease in R_{maxday} for the 2011–2041 time slice (Fig. 3c and i). Except for the southern of the three municipalities and the southwest and central region of Petrópolis, negative values were predominant, meaning a decrease in the R_{maxday} values in MRRJ throughout the century. Although this decreases, R_{maxday} still represents a very harmful situation for MRRJ and needs to be considered carefully in the following decades.

The 2011–2040 time slice projections are less uncertain than the other time slices as we are in the middle of this period, allowing better initial conditions and assumptions for running the model (IPCC 2022). In this situation, we can expect an increase in the R_{maxday} values for areas of the MMRJ, requiring a careful implementation of actions to minimize rainfall hazards, especially in the Petrópolis region.

These results imply that further attention to the areas that showed positive changes in R_{maxday} must be implemented by the federal and state governments, focusing on the summer and spring periods as such areas are the most vulnerable in the present to landslides and will be throughout the century. Actions like improving the warning systems and meteorological and geological monitoring stations need to be expanded. In contrast, the municipalities need to plan strategies to minimize fatalities, such as ready emergency staff that can respond shortly to the crises and rethink the occupation of these areas in the middle term.

3.3 Frequency of the greatest R_{day} events in MRRJ throughout the twenty first century

Figure 4 shows the frequency of R_{day} in the 130 grid points (Fig. 1d) in MRRJ and another 86 in the neighborhood, resulting in 216 points from the 5-km Eta-HadGEM2-ES outputs for the RCP4.5 and 8.5 scenarios. The range of the baseline and the climate projection data is 30 years for comparative purposes.

The class with the highest frequencies, regardless of the RCP scenario and the period considered, is between 500 and 1000 MJ ha^{-1} mm h^{-1} day^{-1} (Fig. 4). The events in this

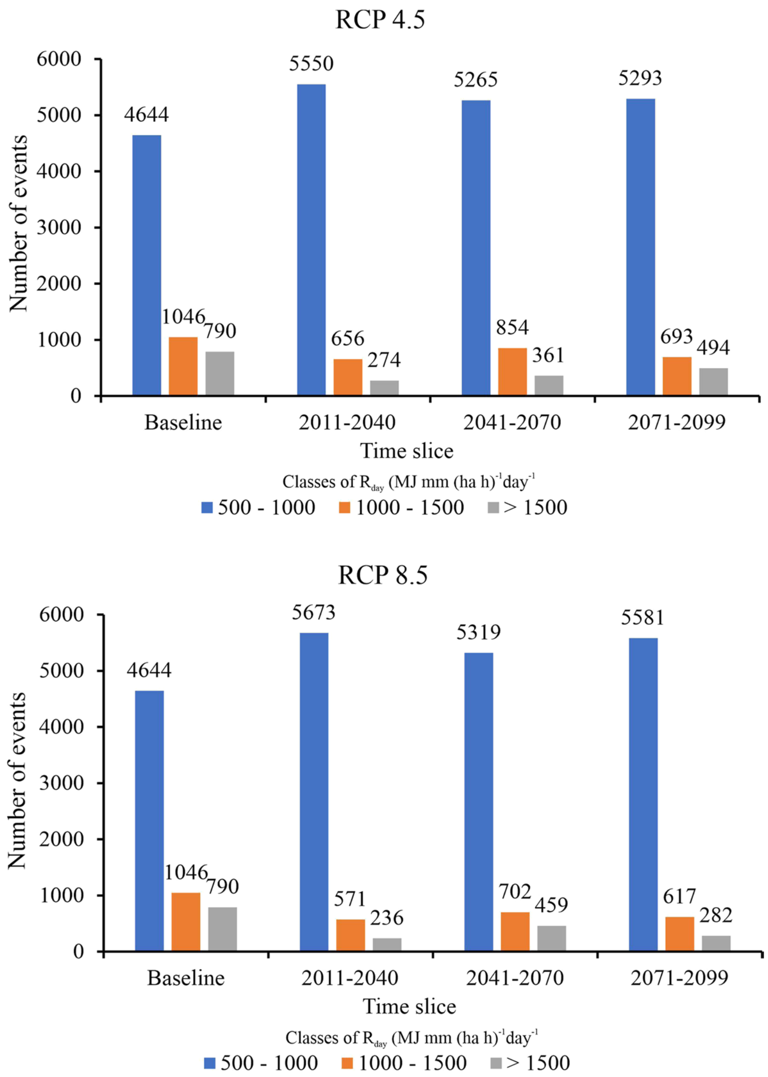

Fig. 4 The frequency of the R_{day} projected by the 5-km Eta-HadGEM2-ES model that can result in natural disasters in the MRRJ in the RCP4.5 (**a**) and 8.5 (**b**) scenarios for the baseline and the three different periods throughout the twenty-first century

class represent 85, 81, and 82% of the occurrences for the 2011–2040, 2041–2070, and 2070–2099 periods, respectively, for RCP4.5. Considering the RCP8.5 scenario, 87, 82, and 86% of the events fall in this range, respectively. In the baseline, 72% of the events were observed in this class. Greater frequencies in the RCP8.5 in relation to the RCP4.5, and for both scenarios, were projected, i.e., significant increases regarding the baseline for this class. Therefore, climate change is expected to increase the number of events in this class, highlighting that they can cause several damages, fatalities included (Alves et al. 2022). Frequencies for this class for RCP8.5 were slightly higher than those for RCP4.5, meaning a reduction of the events that can potentially cause hazards, following the classification proposed by Alves et al. (2022) for MRRJ, i.e., a medium possibility to generate homelessly, damages on the basic infrastructure and fatalities.

Oppositely, for the $1000 < R_{\text{day}} < 1500$ MJ ha^{-1} mm h^{-1} day^{-1} class and RCP4.5 scenario, a higher frequency throughout the twenty-first century than the RCP8.5 was projected. These events are related to the occurrence of disasters with a “high” possibility of fatalities, a “very high” number of homeless people, and a “high” possibility of causing damage to infrastructure and the economy. However, the behavior considering the three analyzed periods was similar for the two scenarios, where the highest frequency of events in this class was verified for the period from 2041 to 2070, being equal to 13% and 11% for the RCP4.5 and 8.5 scenarios, respectively, and 16% for the historical period.

The $R_{\text{day}} > 1500$ MJ ha^{-1} mm h^{-1} day^{-1} class encompasses the harmost events, which have the lowest frequency. In baseline, it was observed that 12% of these events, and throughout the twenty-first century, 4, 6, and 8% for the RCP4.5 scenario in the 2011–2040, 2041–2070, and 2070–2099 time slices, respectively. Contrary to the tendency observed for RCP4.5, in which there was a progressive increase throughout the twenty-first century (Fig. 4a), the highest frequency observed for the RCP8.5 was in the 2041–2070 time slice, with 459 R_{day} events > 1500 MJ ha^{-1} mm h^{-1} day^{-1}, representing approximately 7% of the total analyzed events.

Concomitantly analyzing the R_{day} classes related to natural disasters with “medium,” “high” and “very high” possibilities of fatalities and damage to infrastructure ($R_{\text{day}} >$ 500 MJ ha^{-1} mm h^{-1} day^{-1}), it is observed that the 2041–2070 time slice was the one with the highest frequencies for both RCP scenarios.

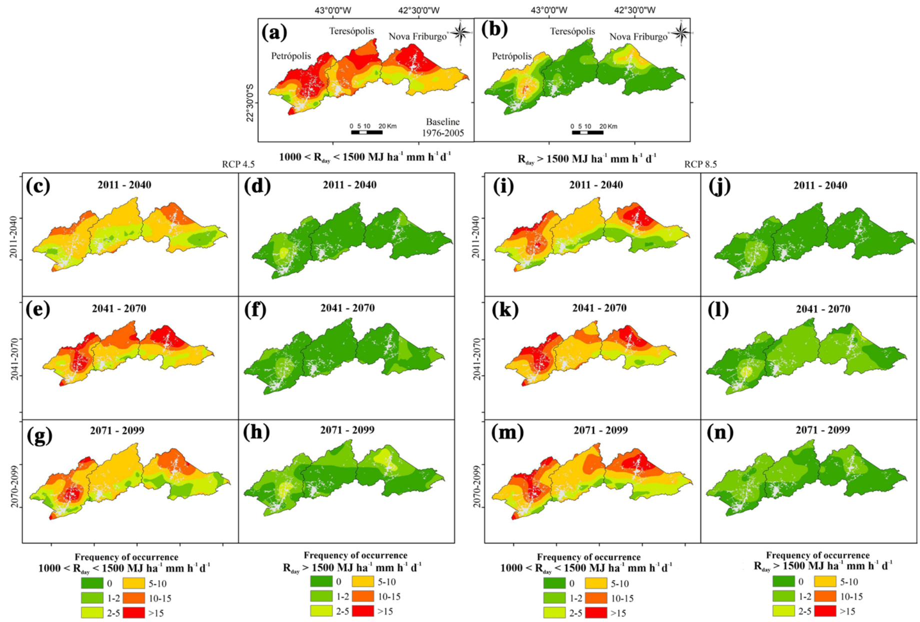

Fig. 5 Frequency maps of events in the classes $1000 < R_{\text{day}} < 1500$ MJ ha^{-1} mm h^{-1} day^{-1} and $R_{\text{day}} >$ 1500 MJ ha^{-1} mm h^{-1} day^{-1} projected by the 5-km Eta-HadGEM2-ES model in MRRJ for the baseline and RCP scenarios

Mello et al. (2021) and Alvarenga et al. (2016) used the Eta-HadGEM2-ES in a resolution of 20 km to simulate climate change impacts on streamflow in watersheds of the Southern Minas Gerais and Mantiqueira Range region, which is in neighborhood MRRJ. In both studies, a decrease greater than 40% in the monthly precipitation of the wet period, i.e., from January to April, was projected. In this study, we obtained a reduction in the frequencies of the harmost R_{day} values (> 1000 MJ ha^{-1} mm h^{-1} day^{-1}) of approximately 30% across the time slices and RCP scenarios as a response to the reduction in the amount of monthly rainfall projected. However, we can infer that there will be an increase in the concentration of rainfall in the wet period since a reduction in the total monthly values is more significant than the frequency of extreme events. Thus, summer will continue as the most dangerous rainfall disaster despite the reduced precipitation.

The spatial occurrence of critical R_{day} events throughout the twenty-first century considering the most severe ones, i.e., $1000 < R_{day} < 1500$ MJ ha^{-1} mm h^{-1} day^{-1} and $R_{day} >$ 1500 MJ ha^{-1} mm h^{-1} day^{-1} classes is, respectively, shown in Fig. 5.

The northern region of Nova Friburgo and the central region of Petrópolis are those with the highest occurrences of R_{day}, for both RCP scenarios, in the $1000 < R_{day} <$ 1500 MJ ha^{-1} mm h^{-1} day^{-1} class (Fig. 5a, g), being greater than 15 occurrences regardless of the time slice. However, between 10 and 15 events were projected for both regions considering RCP4.5 in the 2011–2040 time slice.

Both scenarios have greater spatial coverage of the highest R_{day} values in the 2041–2070 time slice. Compared to the baseline, it is predicted that there will be a decrease in such events in MRRJ in the twenty-first century. This decrease is more noticeable for Teresópolis, where there was a greater frequency of events in the $1000 < R_{day} <$ 1500 MJ ha^{-1} mm h^{-1} day^{-1} class for the baseline, whereas the frequency in this class from projections varies from five to ten events.

The lowest frequencies were observed in the southern Nova Friburgo and Teresópolis and in the southwest Petrópolis, where values were predominant between 1 and 5 events in the $1000 < R_{day} < 1500$ MJ ha^{-1} mm h^{-1} day^{-1} class. This frequency class has a more considerable predominance from 2011 to 2040. The baseline showed higher frequencies and spatial range of values within this R_{day} class. It is important to note that this R_{day} class is related to rainfall with a "high" possibility of fatalities, a "very high" number of homeless, and a "high" possibility of damage to infrastructure and the economy. Thus, in the case of Petrópolis and Nova Friburgo, although a decrease in the frequency of these events throughout the twenty-first century, it is understood that the highest occurrences will prevail in urban areas for any period or RCP scenario. Therefore, it is necessary to establish alert indexes and efficient public policies to mitigate the impacts caused by such events in future. Although Teresópolis presented a lower frequency of these events (5 to 10 events) throughout the century, this number of events is high, meaning that this municipality can be hit by a rainfall event in this class once every three years in the 2070–2099 time slice.

The frequency maps of events in the $R_{day} > 1500$ MJ ha^{-1} mm h^{-1} day^{-1} class showed a decrease regarding the baseline. For RCP4.5, it is observed that there would be an increase in the occurrences in the 2070–2099 time slice if compared to the baseline, where the projections for the urban areas of Petrópolis and Nova Friburgo vary from two to five events. Considering the RCP8.5, this frequency of events was observed for the central region of Petrópolis in the 2041–2070 time slice.

Based on the data analyzed and maps, Nova Friburgo and Petrópolis are the most vulnerable to natural disasters with fatalities. However, a significant frequency of events in the $1000 < R_{day} < 1500$ MJ ha^{-1} mm h^{-1} day^{-1} class may occur in Teresópolis, and events in this class can cause disasters with fatalities. Also, there is an increase in the frequency of

R_{day} values in the RCP8.5 compared to RCP4.5, except for the 2070–2099 time slice considering the second R_{day} class analyzed (Fig. 5m).

The R_{day} values calculated for the "mega-disaster" were equal to 900.1, 1962.8, and 2594.6 MJ ha^{-1} mm h^{-1} day^{-1} for Petrópolis, Teresópolis, and Nova Friburgo, respectively, meaning greater impact on the last municipality. Considering the R_{day} value > 1962.8 MJ ha^{-1} mm h^{-1} day^{-1} as the threshold for the "mega-disaster," their frequency throughout the century was 87, 128, and 145 for RCP4.5, 74, 163, and 94 for RCP8.5, for the 2011–2040, 2041–2070 and 2070–2099 time slice, respectively, considering all grid points (Fig. 1d). Thus, with these events spatially distributed over MRRJ, the northern region of Nova Friburgo and the central region of Petrópolis (both in their urban areas) will be the ones with the highest frequencies of events like the "mega-disasters." Considering the grid points closest to Nova Friburgo and Petrópolis, five and nine "mega-disasters" throughout the century for RCP4.5, and four and eight for RCP8.5, respectively, were projected. These "mega-disasters" in both municipalities were projected for different years. Thus, a projection of 14 or 12 "mega-disasters" occurring throughout the twenty-first century for the RCP4.5 and 8.5, respectively, could be projected, which would increase to 17 and 15 when considering Teresópolis.

Our study sheds new insights into the influence of climate change on rainfall disasters. However, we need to point out the limitations of our study that require future studies. For example, only one climate model, downscaled by a physical model (ETA/CPTEC), was adopted here. Because the study region is a mountainous area close to the Atlantic Ocean, i.e., the orographic effect is strong. Although the datasets used in this study are unique for all of South America (5 km), the outputs downscaled in a more satisfactory resolution are indispensable. Nevertheless, the uncertainties associated with the climate model exist, which should be countered using additional models with 5-km resolution and the orographic aspect adequately solved by a physical model.

4 Conclusions and future studies

The studied region is one of Brazil's most vulnerable to extreme rainfall disasters. To overcome the orographic effect on the rainfall in the region, we used the 5-km ETA/HadGEM2-ES model to analyze the frequency of events that cause disasters, fatalities included. The datasets used in this study are from only one global circulation model (GCM) dynamically downscaled to 5 km resolution. This aspect allowed capturing orographic effects on rainfall spatial and temporal distribution. The Eta-HadGEM2-ES model is the unique model available with such a resolution. Therefore, we can advance in terms of the uncertainty of the GCMs for estimating extreme daily rainfall in an acceptable resolution for this purpose. Other GCMs have been considered in South America but using a resolution of 20 km. Several studies have demonstrated no concordance among them regarding extreme precipitation patterns over the century.

Another relevant study consists in evaluating how large-scale atmosphere drivers like multivariate ENSO index, Southern Oscillation Index (SOI), Tropical Southern Atlantic Index (TSA), Pacific Decanal Oscillation (PDO), Antarctic Oscillation (AAO), Atlantic Multidecadal Oscillation (AMO), and ENSO precipitation index can impact extreme rainfall events that cause hazards in southeastern Brazil. For that, it is imperative to expand a broader study regarding R_{day} modeling to assess statistical analyses, especially multivariate ones (artificial intelligence, principal components analysis, Bayesian regression analyses, among others) and establish possible connections.

In terms of conclusions, we can highlight:

a. The MRRJ presents high R_{maxday} values throughout the twenty-first century, showing a large coverage of the extreme rainfall in MRRJ, especially from the first time slice.
b. The frequency of events in the moderate impact class (500–1000 MJ mm (ha h)$^{-1}$) tends to increase throughout the century, meaning fatalities will continue to occur in MRRJ, although in a lower possibility.
c. The projection along this century is that 17 (RCP4.5) or 15 (RCP8.5) events of the same magnitude, respectively, as the one that caused the "mega-disaster" in 2011 in MRRJ.

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Data availability "The datasets generated during and/or analyzed during the current study are available in the Projeta project (https//projeta.cptec.inpe.br)."

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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