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Extreme rainfall and landslides as a response to human-induced climate change: a case study at Baixada Santista, Brazil, 2020

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Abstract

In March 2020, an extreme rainfall in Baixada Santista, Brazil, led to a series of landslides affecting more than 2800 people and resulting losses exceeding USD 43 million. This attribution study compared extreme rainfall in two large ensembles of the UK Met Office Hadley Centre HadGEM3-GA6 model that represented the event with and without the effects of anthropogenic climate change. Antecedent rainfall conditions on two different timescales are considered, namely extreme 60-day rainfall (Rx60day) which relates to the soil moisture conditions and extreme 3-day rainfall (Rx3day) which represents landslide triggering heavy rainfall. In the scenario including both natural and human-induced factors the antecedent 60 day rainfall became 74% more likely, while the short-term trigger was 46% more likely. The anthropogenic contribution to changes in rainfall accounted for 20–42% of the total losses and damages. The greatest economic losses occurred in Guarujá (42%), followed by São Vicente (30%) and Santos (28%). Landslides were responsible for 47% of the homes damaged, 85% of the homes destroyed, all reported injuries, and 51% of the deaths associated with heavy rainfall. Changes in land cover and urbanization showed a pronounced increase in urbanized area in Guarujá (107%), São Vicente (61.7%) and Santos (36.9%) and a reduction in farming area. In recent years, the region has experienced an increase in population growth and a rise in the proportion of irregular and/or precarious housing in high-risk areas. Guarujá has the highest number of such dwellings, accounting for 34.8%. Our estimates suggest that extreme precipitation events are having shorter return periods due to climate change and increased urbanization and population growth is exposing more people to these events. These findings are especially important for decision-makers in the context of disaster risk reduction and mitigation and adaptation to climate change.

Keywords Extreme event · Precipitation · Land cover change · Socioeconomic impacts · Attribution · Southeast Brazil

Extended author information available on the last page of the article

1 Introduction

Natural disasters such as floods and landslides triggered by extreme precipitation have caused hundreds of deaths and injuries, with economic losses and damages costing millions of dollars every year. Recent heavy rainfall episodes in Brazil have led to hundreds of fatalities, extensive homelessness, and billions in financial losses (Dalagnol et al. 2022; Alcântara et al. 2023; Marengo et al. 2023a, b). According to the National Confederation of Municipalities (Confederação Nacional de Municípios—CNM) the economic losses caused by rainfall between 2017 and 2022 during the rainy months (October to March) in affected municipalities accounted for more than BRL 55.5 billion (USD 10.5 billion) (CNM 2022). In addition, nearly 550,000 homes were destroyed or damaged, and more than 28 million people were affected.

Baixada Santista is located on the Sao Paulo State coast (Fig. 1), and is located on the Sao Paulo State coast, particularly in Santos and São Vicente. Landslides in this region are closely linked to significant cumulative rainfall over a period of 3–4 consecutive days, ranging from 250 to 400 mm, followed by intense precipitation episodes within a single day, surpassing 150–200 mm per day (Ross and Fierz 2018). Soil moisture at or close to saturation corresponds to an elevated water table level and increased material plasticity, ultimately destabilizing slopes and triggering landslides (Zhao et al. 2019), particularly when intense and short-lived precipitation events occur (Ávila et al. 2016; Hader et al. 2022). Therefore, soil conditions are a crucial factor in determining the susceptibility of slopes to such precipitation patterns.

An event of heavy precipitation occurred in Baixada Santista on March 2nd and 3rd, 2020. According to the National Center for Monitoring and Natural Disaster Alerts (Centro Nacional de Monitoramento e Alertas de Desastres Naturais—Cemaden), it rained 350 mm in Guarujá, 330 mm in Santos and 230 mm in São Vicente in 48 h. In Santos, the 48 h rainfall total surpassed the 2014–2022 climatological accumulated precipitation of the whole March, of 313 mm (Cemaden gauge data for Nova Cintra Station). High soil moisture conditions existed since mid-February, caused by high precipitation totals throughout the austral summer, and the geological and slope characteristics of the terrain added to the heavy precipitation resulting in a disastrous sequence of landslides in the Baixada Santista (de Freitas et al. 2022). The event affected more than 2800 people causing estimated economic losses of BRL 215 million (USD 44 million).

The atmospheric conditions during the event were characterized by a mid-upper level trough that triggered instability through upward motion over the region. Later, a cyclone developed on the coast of São Paulo State, to the east of the mid-upper level trough. The strong winds led to a strong vertical wind shear, which is optimal for developing heavy precipitation storms (Schumacher and Rasmussen 2020).

Besides the specific triggers for this extreme precipitation event, other studies also showed the increasing vulnerability of Baixada Santista to climate change (Young 2016; Cavalcanti et al. 2017). According to the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística—IBGE), 8.2 million people in 872 Brazilian municipalities are exposed to risk of floods, flash floods and mass movements (IBGE 2018). Climate change can increase the exposure of social systems to the impact of extreme events, causing severe damages to human lives and economies (Kirchmeier-Young et al. 2022). However, the ratio of impacts which can be attributable to anthropogenic influence is poorly explored for Baixada Santista in previous studies,

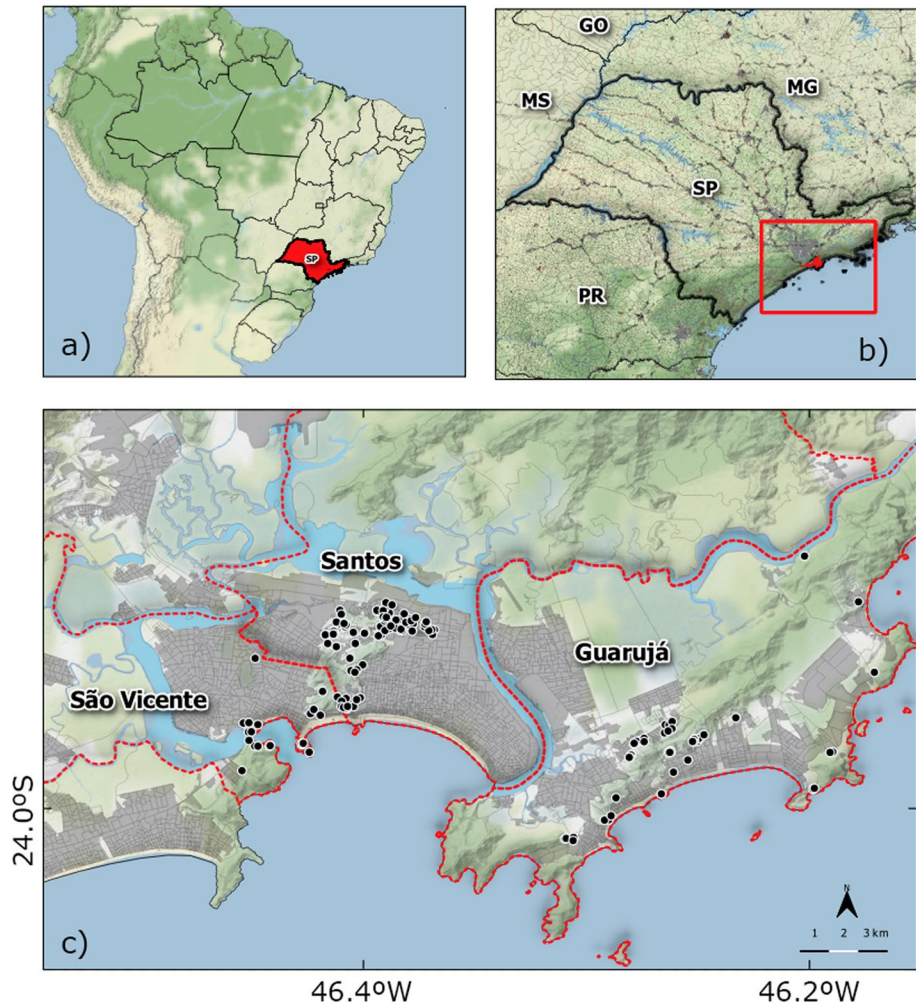


Fig. 1 **a** Location of the São Paulo state with respect to the Brazilian territory (shaded in red); **b** the area for the attribution analysis (red box); **c** the three municipalities which represent Baixada Santista, whose boundaries are shown in the red dashed lines. Black dots show the distribution of landslides occurrences at March 2020 caused by the extreme event

even when damages associated to rainfall and landslides are analyzed in depth (Moreira et al. 2017; Dias et al. 2021; de Freitas et al. 2022).

Attribution analysis is performed using ensemble simulations from global circulation models. These models simulate a real scenario—where both anthropogenic and natural forcings are included, that can be compared with a natural scenario—where simulations are run without the forcings from anthropogenic activities. The Hadley Centre Global Environmental Model (HadGEM) in the last decade has become a robust tool for attribution analysis (Hewitt et al. 2010; Christidis et al. 2013). A state-of-art protocol presented by Christidis et al. (2013) to conduct attribution analysis highlights the use of HadGEM ensembles using distinct forcings for such methodology. This

protocol serves as the foundation for defining extreme events and their key parameters, using observations for event definition and the model to attribute the anthropogenic contribution.

Intense precipitation events at small temporal and spatial scales present notable challenges, wherein the performance of precipitation within the models is inferior compared to other variables (Roebber et al. 2004). As highlighted by Hallak and Pereira Filho (2011), even numerical solutions at high spatial resolutions exhibit inherent errors associated with precipitation amount and phase (e.g. the spatial positioning of precipitating systems). Zilli et al. (2017) showed that both seasonal and daily precipitation trends present an increase in frequency and intensity at the coast of São Paulo state (including Baixada Santista). Hence, it is necessary to frame the extreme precipitation event for different scales, improving the output from statistical methods used to separate the natural and anthropogenic signals. Also, a link between extreme events and susceptibility to disasters needs to be made, since the exposure to disasters is also subjected to positive trends along the last decades (Cortez et al. 2022), mainly those related to landslides, where several other parameters sum up to the analysis (Teixeira et al. 2022).

In parallel, both landslide and flood occurrences are potentially affected by land use changes, which can affect the slope stability due to changes in root cohesion and alteration of the hydrological functioning of the hillslope (García-Ruiz et al. 2010). Indeed, Chen et al. (2019) stated that anthropogenic activities related to land use change may also be relevant in risk assessment studies as they can change landslide susceptibility.

Here we present results of an attribution analysis for the heavy precipitation that occurred on March 2–3, 2020, in Baixada Santista. The aim of this study is to focus on landslide-triggering heavy precipitation events and to assess the change in occurrence and intensity of heavy precipitation due to anthropogenic climate change. We performed the attribution analysis in order to quantify the impacts associated with these events and estimate the damages attributable to anthropogenic influence.

2 Materials and methods

2.1 Study area

The Baixada Santista is situated on the southeast coast of Brazil (Fig. 1) and encompasses the municipalities of Bertioga, Cubatão, Guarujá, Itanhaém, Mongaguá, Peruíbe, Praia Grande, Santos, and São Vicente. With an area of 2,419,930 km² and an estimated population of 1,897,551 inhabitants (IBGE 2021), it ranks as the 17th most populous metropolitan region in Brazil. Although more than 60% of the region is covered with vegetation, it has extremely high degree of urbanization (over 97%) and significant population density (Foundation SEADE 2020). The region hosts the most important port complex in Brazil and the second largest in Latin America, located in the municipality of Santos. Additionally, the Baixada Santista contributes to the economy through industrial activities, tourism, and trade. In this study, our focus is on three municipalities of the Baixada Santista: Santos, Guarujá and São Vicente. These cities were chosen since they were the most affected cities during the event.

According to the Köppen-Geiger's climate classification, the Baixada Santista region has a humid subtropical (Cfa) climate (Alvares et al. 2013). Throughout the year, the temperature generally varies from 18 to 32 °C and is rarely below 16 °C or above 35 °C.

The annual precipitation ranges from 1600 to 2000 mm y^{-1} (Queiroz et al. 2019). The rainy season occurs from October to March (ONDJFM) and the dry season follows during the remaining months, between April and September (AMJJAS) (Rao et al. 2016). The climate in the Baixada Santista region is influenced by various factors, including the South Atlantic Convergence Zone (SACZ), the passage of cold fronts and convective systems. Figure 1c shows the location of the landslides occurrences triggered by the extreme precipitation event in March 2020 in the Baixada Santista region.

2.2 Socioeconomic impacts

In this study, the socioeconomic impacts data were compiled from the Integrated Disaster Information System (S2iD—<https://s2id.mi.gov.br/>). S2iD is a platform within the National System of Protection and Civil Defense, designed to facilitate the search for information related to occurrences of disasters and risk management across the Brazilian territory, which employs process computerization and provides access to systematized information. These information describe the magnitude of the disaster in Baixada Santista, which was affected by heavy precipitation and subsequent flash flood, inundation and landslides.

The collected data were systematically analyzed according to the type of disaster, their occurrence, and damages and losses (human, material and economic). The category of human damages includes the number of deaths, injured, sick, homeless and displaced people. Material damages comprises the number of destroyed and damaged buildings resulting from the disaster, and the costs of that damage. The economic losses included the costs of damages both for the public sector (medical care, drinking water supply, sewer system, urban cleaning, pest and vector control, transport, electricity generation and distribution, education) and for the private sector (services).

We also analyzed separately the occurrence of landslides and their impacts in these three municipalities. Data on susceptibility to landslides due to gravitational mass movements and floods, together with the classification into areas of high, medium and low risk, were obtained from the shapefile from the Geological Survey of Brazil (Serviço Geológico do Brasil—CPRM), available at: <https://www.cprm.gov.br>. The locations of the landslides that resulted in human damages and economic losses were assessed from the Technological Research Institute (Instituto de Pesquisas Tecnológicas—IPT) inspection report for each affected municipality. The costs of monetary impacts were given in Brazilian Reais (BRL), and the conversion to U.S. dollars (USD) followed a 4.85:1 conversion rate applicable for the period of March 2020.

2.3 Land cover changes and urbanization

Changes in land use and land cover are important conditioning factors in landslide susceptibility triggered by extreme precipitation. The evolution in the land cover (natural formations), land use (farming) and urbanization in the last 36 years for the three most affected municipalities by the disaster was assessed through data and maps from Collection 7 of MapBiomas (available on the MapBiomas platform, <https://plataforma.brasil.mapbiomas.org/>), which provides detailed annual information from 1985 to 2021. The population density for each municipality was obtained from the latest official 2010 census data and from the estimated population for 2021 (IBGE 2021). Information on population exposed to the risk of natural disasters and the occupation trend of irregular housings in the three

most affected municipalities by extreme precipitation and landslides were obtained from IBGE (2018, 2020).

2.4 Observational meteorological data

The precipitation data from CPC was used throughout the study. The CPC is a division of the National Oceanic and Atmospheric Administration (NOAA) that created the Global Unified Gauge-Based Analysis of Daily Precipitation dataset. By interpolating gauge observations, the dataset offers gridded data of daily precipitation for the entire planet's surface with resolution of 0.5° of latitude per longitude from 1979 onwards (Chen et al. 2008). This dataset is widely used for climatological studies in Brazil (Rocha et al. 2009; Ferreira and Reboita 2022); it also has a good correlation with the observed data (Silva et al. 2007) and it is freely available at <https://psl.noaa.gov>.

The MERGE precipitation product (Rozante et al. 2010) was a useful reference comparison for the 2020 event, but unfortunately can not be used to validate the model climatological precipitation as there is insufficient overlapping climatological reference periods (available data from 2000 onwards). It does however provide a comparison threshold for the 2020 event. Hence, it was firstly used for defining the area of interest and event parameters. MERGE integrates satellite data from IMERG (Huffman et al. 2015) and rain gauge data from different sources, providing a gridded dataset with a 5 km horizontal resolution and a temporal resolution of one hour, freely available through National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais—INPE) at <http://ftp.cptec.inpe.br/modelos/tempo/MERGE/GPM/HOURLY/>. The spatially accumulated precipitation from MERGE during the extreme event over Baixada Santista is presented in the supplementary information (Fig. S.1).

To characterize the soil moisture, we used the product Level 4 Surface and Root-Zone Soil Moisture Analysis Update Data (L4_SM) from the Soil Moisture Active Passive (SMAP) satellite (Reichle et al. 2022). This product uses a customized version of NASA's Goddard Earth Observing System (GEOS-5) model which assimilates the surface brightness temperature in the L-band of SMAP. For this study, the integrated soil moisture profile from the surface to the depth of impermeable rock was used; the L4_SM/SMAP has a spatial resolution of 9 km and a temporal resolution of 3 h, starting from April 2015.

2.5 Climate model and scenarios

The attribution of human-induced climate change was analysed through ensembles of the Hadley Centre Global Environmental Model version 3 (hereafter HadGEM3-GA6) with prescribed sea surface temperatures and sea ice concentration from HadISST1 (Rayner et al. 2003). This study utilizes two distinct experiments conducted with the HadGEM3-GA6 model namely 'historical' and 'historicalNat' (Christidis et al. 2013). The historical experiment includes both natural forcings, such as solar and volcanic activity, and human-induced changes, like land-use alterations and greenhouse gas emissions. In contrast, the historicalNat experiment uses only natural forcings, maintaining greenhouse gas levels at their 1850 values, without considering human-induced factors. 1850-like sea surface temperature and sea ice concentration fields are prescribed by subtracting an average CMIP5 pattern as calculated by Stone and Pall (2021) from those observed and recorded in HadISST1. In this way, the observed pattern for the date of the event is preserved in the naturalized pattern. The land surface scheme includes fractions of

nine surface types to each grid cell; while some of them are similar between the two experiments, others like urban fraction, grass, broad leaf, etc. are modified. For instance, in the historicalNat the urban fraction is kept constant (zero value) during the whole simulation whereas in the historical experiment there is an increase in the mean fraction until 2010 (Ciavarella et al. 2018). Both experiments span from 1960 to 2013, and each of them consists of 15 individual simulation runs each. A more comprehensive description of the attribution system using the HadGEM3-GA6 model can be found at Ciavarella et al. (2018) and Vautard et al. (2019a).

The precipitation from the historical dataset from HadGEM3-GA6 model was used for the validation process focused on the climatological period of 1981–2010. For simulations of the extreme event itself, two ensembles with 525 members each were analysed for the period October 2019–March 2020. These were branched and extended from the historical and historicalNat ensembles mentioned above. One ensemble known as historicalNatExt included only natural forcings (*NAT*) whilst the second ensemble known as historicalExt included both natural and external forcings (*ALL*).

The normalized maximum accumulated precipitation values were considered for both historical period and the extreme event analyses. These values were calculated for different rolling sums of precipitation and for each member of the ensemble. To obtain the normalized maximum accumulated precipitation, the maximum rolling sum of precipitation for the season was divided by the climatological (1981–2010) average value of the maximum rolling sums. Hence, normalized values exceeding 1 (or 100%) indicate that the maximum accumulated precipitation for the season surpassed the climatological average. For the event distributions, the maximum accumulated precipitation across the region of interest (red box in Fig. 1b) is considered (see next section for further information), whereas for the climatological evaluation the average precipitation for the Baixada Santista region was first calculated, and then the maximum accumulated precipitation was taken. This approach was chosen to eliminate potential false outliers that may be present in the CPC data.

2.6 Anthropogenic climate change attribution

The main purpose of the attribution analysis is to measure the effect of human-induced climate change on an extreme event; in this case, precipitation and landslides events at Baixada Santista. The event of March 2020 was characterized by a restricted spatial scale, which interacted with a very heterogeneous complex terrain, urbanized areas and land-sea contrast. These characteristics pose challenges for conducting attribution analysis since reanalysis data and observations often struggle to accurately capture the full range of parameters associated with such events (Otto 2017). In this section, we present the analysis methods used to deal with those limitations.

Geographical and temporal definition of an extreme event is one of the biggest challenges in attribution studies (Otto 2017). We opted to proceed with two different metrics regarding maximum precipitation. The first metric focused on the accumulated 3-day rainfall aimed to represent the event trigger. The second metric considered rainfall accumulation over a 60-day period and served as a proxy for antecedent soil moisture magnitude.

A series of tests to determine which accumulation periods would best represent the extreme event were conducted. Cemaden gauge station data from Chico de Paula, located in the city of Santos, was used for defining relevant precipitation accumulation periods.

This station was chosen as it had the most complete time series (without missing data) and was located closest to both the observed landslide sites and the centroid of the model grid cell which covered the observed landslides. In terms of the short-term trigger, we analysed accumulations over 1–6 days. The 3 day rainfall accumulation associated with the event was chosen, as although the landslides occurred on the 2nd and 3rd of March, heavy precipitation was already occurring on the 1st of March (de Freitas et al. 2022). This indicates that the cumulative precipitation over these 3 days might have been a critical factor for landslide occurrence. Also, the 3 day rainfall accumulation exceeded the climatological 99th quantile, while 4–6 days accumulations fall below the 99th quantile (Fig. S.2). As a proxy for antecedent soil moisture rainfall accumulations over 30–150 days were considered. For this metric the 60 day rainfall accumulation preceding the event was chosen, as it exceeded the climatological 95th quantile and was the highest 60 day accumulation recorded since 2011. Also, a linear relationship was observed between the accumulated precipitation and soil moisture estimated from SMAP ($R^2 = 0.56$ between $RX60day_{max}$ and $L4_SM$ soil moisture, Fig. 2). This correlation validates our hypothesis that the 60 day accumulated precipitation is a suitable proxy for soil moisture status. Furthermore, as the temporal range increases above 60 days the index indicates less extreme precipitation, with values falling below the 95th quantile (Fig. S.2).

Having established the relevant precipitation accumulation periods to represent the trigger event (3 day) and antecedent soil conditions (60 day) we then consider how to represent this for validation and attribution analysis in both the CPC and HadGEM3-GA6 data. For both accumulation times the maximum running accumulation value over the whole wet season (ONDJFM) is chosen. To further allow the model some degree of freedom in representing the spatial precipitation pattern the maximum value from all model grid points in the study area ($47.5^\circ\text{--}45^\circ\text{W}$, $25^\circ\text{--}23^\circ\text{S}$ —Fig. 1) of this metric is chosen (Fig. S.1). This is hereafter referred to as $RX3day_{max}$ for the triggering rainfall event and $RX60day_{max}$ for the proxy antecedent soil conditions. The time series for $RX3day_{max}$ and $RX60day_{max}$ are given in Fig. S.2 with Fig. 3 illustrating the compound effect between the two time scales.

The HadGEM3 model has been extensively used for climatological studies, and its performance in representing precipitation patterns has been thoroughly evaluated in global studies (Roberts et al. 2019; Vautard et al. 2019b; Müller et al. 2021; Yazdandoost et al. 2021, e.g.), including its application in South America (Monerie et al. 2020). To assess

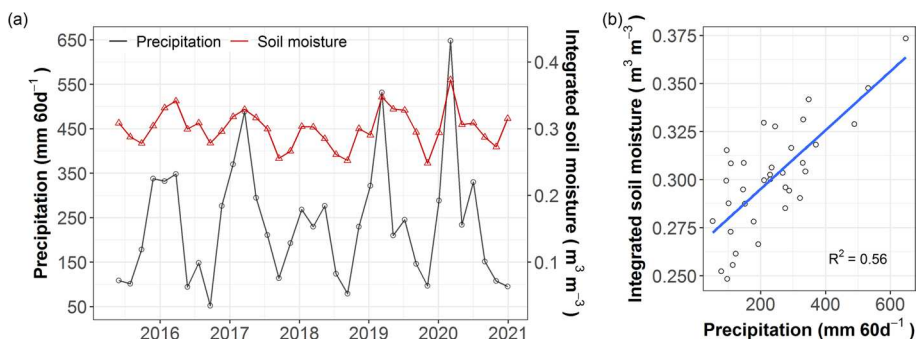


Fig. 2 **a** Sixty-day accumulated precipitation (in $\text{mm } 60\text{d}^{-1}$, black line and circles) and mean integrated soil moisture in the soil profile (in $\text{m}^3 \text{m}^{-3}$, red line and triangles); **b** scatterplot between integrated soil moisture and 60-day accumulated precipitation, same units than (a). The blue line represents the linear fit $y = 0.00015x + 0.26$, with both coefficients significant (p -value < 0.05) and $R^2 = 0.56$

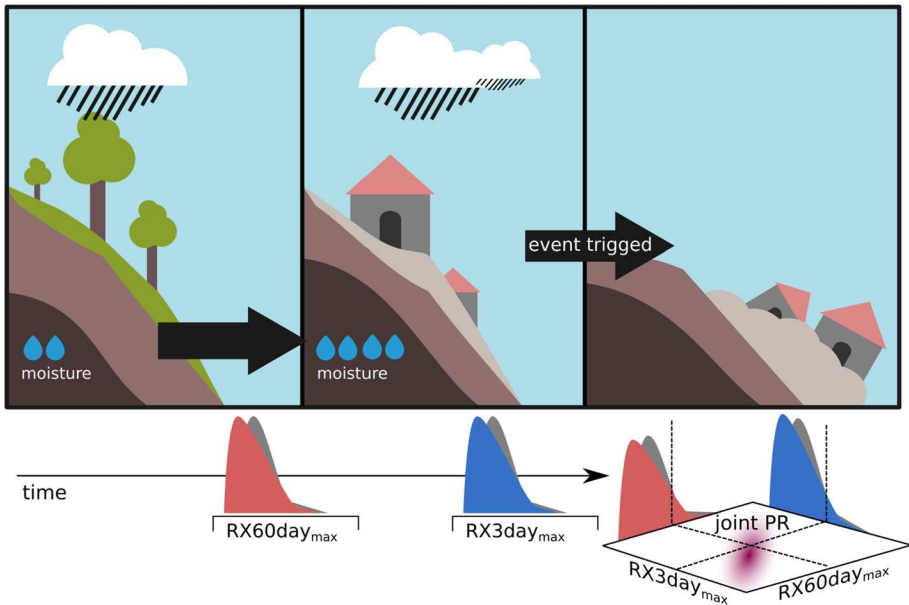


Fig. 3 Anthropogenic influence on extreme precipitation in Baixada Santista varies over different time-scales. $RX60day_{max}$ index indicates a sub-seasonal scale increase in soil saturation, while $RX3day_{max}$ indicates short-term intense rainfall triggering landslides in vulnerable areas. The RX_{Joint} index represents the combined effect of long and short-term extreme precipitation can have at Baixada Santista

the climatological performance of the historical runs in representing the rainy season in the Baixada Santista region, we conducted tests using precipitation data from October to March. In Fig. 4, we present the ensemble distribution of the maximum averaged precipitation normalized by the climatology for the two metrics $RX60day_{max}$ and $RX3day_{max}$. The comparison reveals that the model tends to be slightly wetter than the CPC dataset in terms of $RX60day_{max}$, as evidenced by the right-shifted distribution and a higher peak in the

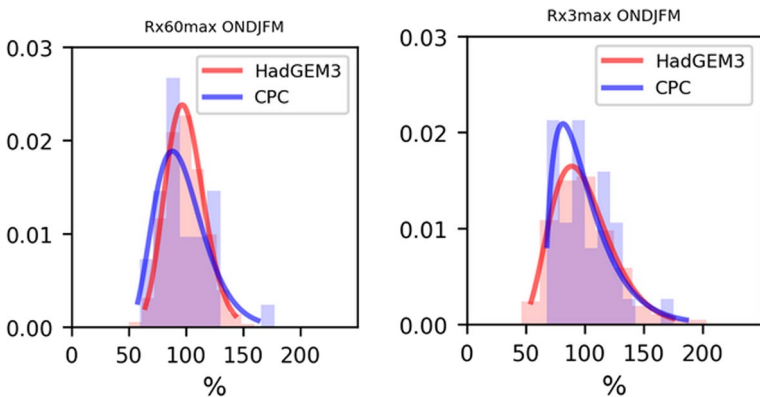


Fig. 4 Histograms and gamma-fitted distributions of the normalized maximum averaged precipitation for **a** $RX60day_{max}$ and **b** $RX3day_{max}$ in ONDJFM (from 1979 to 2013) for HadGEM3 and CPC datasets. The climatology considers the period of 1981–2010

model's curve. Conversely, for $RX3day_{max}$, the model captures drier conditions than the CPC dataset. Despite these slight differences, the deviations between the model and CPC precipitation data are not significant enough to warrant a bias correction procedure for the attribution analysis.

To evaluate the likelihood of precipitation exceeding the observed value for the event and to compare *ALL* and *NAT* scenarios, we calculated the Probability Ratio (*PR*), following the methodology described by Otto (2017):

$$PR = \frac{P_{ALL}}{P_{NAT}} \quad (1)$$

where P_{ALL} and P_{NAT} are the probability of exceeding the precipitation threshold as defined by CPC for the event in the *ALL* and *NAT* scenarios, respectively. To perform significance tests, we conducted 1000 bootstrap simulations by permuting the precipitation series and fitting their probability density functions (PDFs) to a gamma function; the 95% confidence interval was taken by using the 2.5th and 97.5th percentiles from those series. In this study, the event was defined as the occurrence of extreme values of both $RX60day_{max}$ and $RX3day_{max}$.

The P_{ALL} and P_{NAT} can also be used to estimate the return period (*RP*):

$$RP = \frac{1}{P_{ALL}} \quad (2)$$

which represents the averaged time interval between events which exceed the precipitation threshold for each scenario. Therefore, a joint analysis was performed in which P_{ALL} and P_{NAT} were calculated by dividing the number of ensemble members that exceed both the $RX3day_{max}$ and $RX60day_{max}$ thresholds (as defined by CPC) by the total number of ensemble members in the scenario experiment. The ratio of these, as in Eq. 1, then represents the joint probability ratio.

From the *PR*, it is possible to calculate the Fraction of Attributable Risk (*FAR*):

$$FAR = 1 - \frac{1}{PR} \quad (3)$$

which provides a valuable metric for quantifying the portion of socioeconomic damages resulting from a particular event that can be attributed to human activities. Values closer to one means that a high proportion of the event impacts can be attributed to human activities.

3 Results

3.1 Socioeconomic impact assessment

During the extreme rainfall event in Baixada Santista, 158 landslides were recorded (Geological Survey of Brazil—CPRM 2015): nearly 54% occurred at Santos, 33% at Guarujá and 13% at São Vicente municipalities (Fig. 5). The episodes overlap regions of higher susceptibility characterized by higher elevations and abrupt slope gradients. Those terrain features are superposed to areas which experienced positive trends in urbanization growth and reduction in forest cover. In fact, field inspections commonly report forest and soil

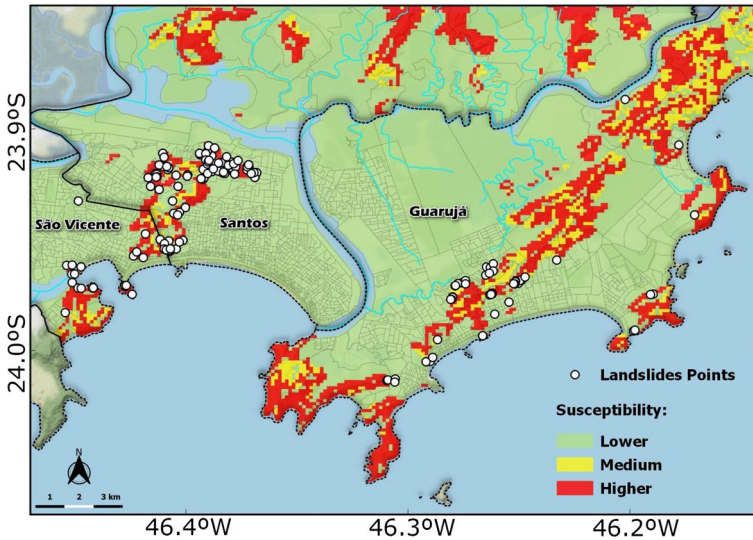


Fig. 5 Landslide occurrence and susceptibility for the Baixada Santista Region. The colors show different degrees of susceptibility (shaded green, yellow and red), and the white dots indicate the recorded landslides from March 2 to 3, 2020

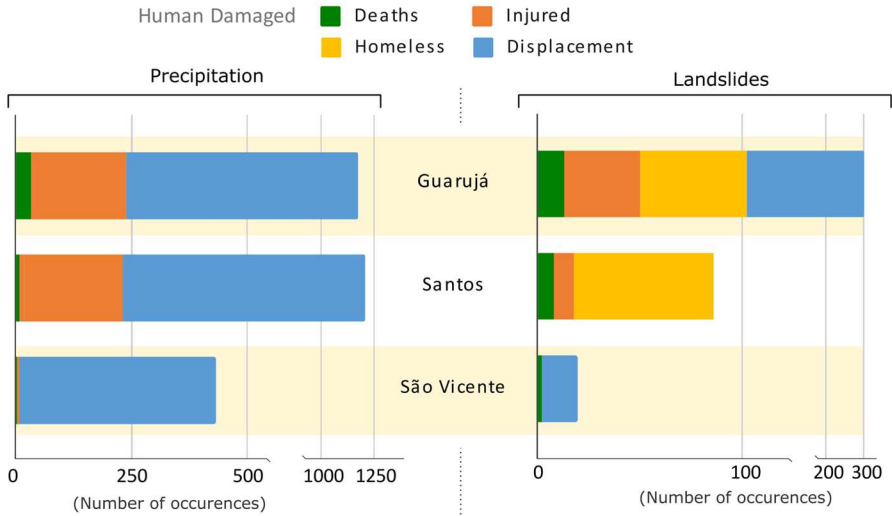
alterations due to improper buildings and litter accumulation at landslide sites. Those features represent an additional hazard besides extreme rainfall.

The socioeconomic impacts of the disaster in Baixada Santista on March, 2nd-3rd, 2020, are shown in Figs. 6, 7 and supplementary Tables ST.1, ST.2 and ST.3. According to official data, the intense precipitation event affected 2842 people in the three municipalities (1193 in Guarujá, 1216 in Santos and 433 in São Vicente), classified as 44 deaths, 47 injured, 388 homeless and 2363 displaced in total (Fig. 6a, left). Guarujá was the most affected municipality and reported 33 deaths, 37 injured and 1123 displaced and homeless people, followed by Santos and São Vicente. Even though the human impacts reported and classified as landslides in Baixada Santista were 14% of the total affected people, 52% of the total number of deaths were due to landslides (13 in Guarujá, 8 in Santos and 2 in São Vicente; Table T.1), as well as of all injured people (Fig. 6 a, right; Table ST.1). Guarujá was the worst affected municipality with 74% of the human damages caused by landslides that occurred in March, 2020. It is important to note that the extreme precipitation was the main trigger for landslides, and in Santos, for instance, the latter was responsible for the total number of deaths (Table ST.1).

The extreme rainfall also caused significant housing damages in Baixada Santista; there were 1294 damaged and 399 destroyed units, where 66% of the cases occurred in Guarujá, 28% in Santos and 6% in São Vicente (Fig. 6b). Of the total number of damaged dwellings, 43% (733 units) were caused by landslides. It is interesting to note that, although Guarujá reported only 20% of the landslides that occurred in Baxiada Santista (Fig. 5), this was the most affected municipality in the region (Fig. 7).

Figure 7 shows the economic impact caused by the extreme precipitation and landslides together. The total cost of damaged or destroyed properties in each municipality sums more than BRL 212 million, or USD 43.7 million (Fig. 7a). Of this total, 24% were in damaged dwellings and 72% in public infrastructure work. Guarujá

a) Human damage



b) Habitational damage

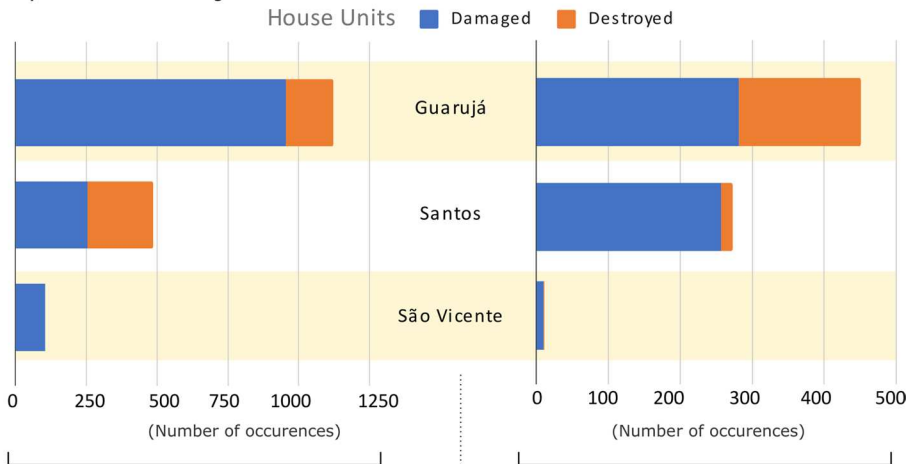


Fig. 6 Occurrences of **a** human damages and **b** habitational damages caused by the extreme precipitation (left panel) and landslides (right panel) in the three most affected municipalities of Baixada Santista in March, 2020 (Guarujá, Santos and São Vicente)

accounted for 43% of the losses, São Vicente for 30% and Santos for 27%. Figure 7b shows the total costs for public service losses estimated at BRL 3.3 million (USD 682.4 thousand). The economic losses in public services in Guarujá accounted for 48%, followed by São Vicente (32%) and Santos (20%). Among the economic impacts in public services, the highest expenses were associated with the urban cleaning, garbage collection and disposal system (29%), public health and emergency care (27%) and rainwater sewer and sanitary sewer system (15%).

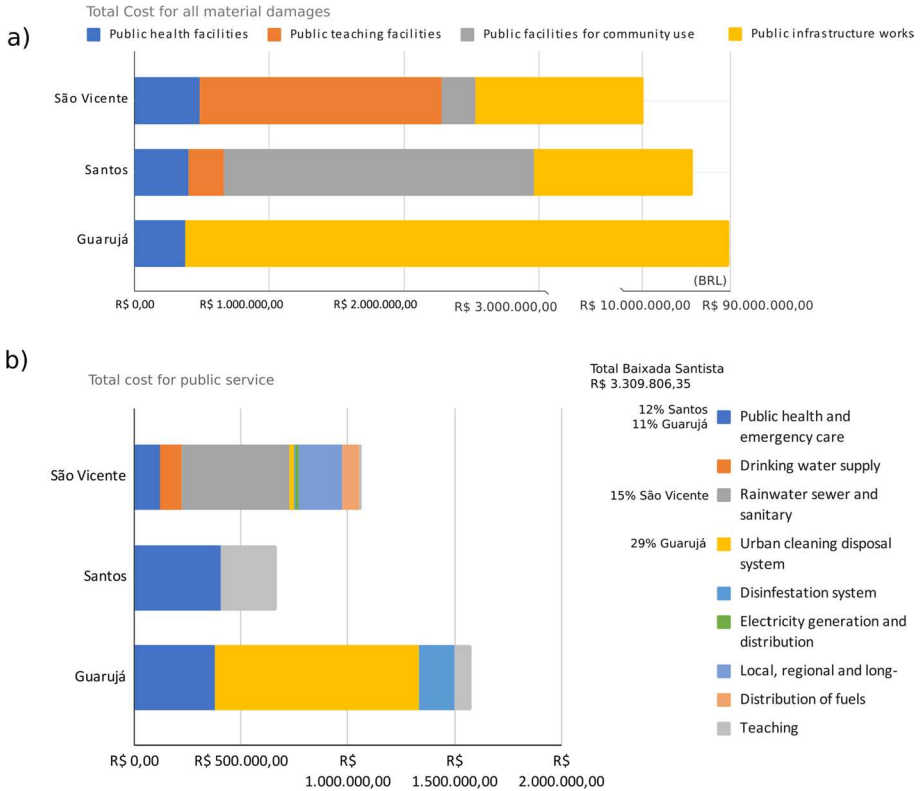


Fig. 7 Economic impacts caused by the extreme rainfall in São Vicente, Santos and Guarujá (Baixada Santista region). **a** Total cost for all material damage (in BRL); **b** total cost for nine categories of public services (the legend shows the municipalities with higher percentages at the category)

It is important to point out that both the numbers of occurrences of human damage and economic losses reported here may be underestimated. The data were obtained from municipal civil defense reports on the day and place of the disaster. Later updates were not found in the S2iD database, therefore missing data are likely due to a lack of local identification not to a lack of occurrences.

3.2 Land cover change and urbanisation

According to MapBiomas, the areas of natural formations and land use decreased in Baixada Santista, while the urbanized areas had a significant growth during the period 1985–2021 (Fig. 8 and Table ST.4). The region is predominantly composed by the Atlantic Forest biome and 76% of the territory is currently occupied by natural formations, 6.4% by farms and 17% are urbanized areas. Guarujá and Santos (São Vicente) had a slight decrease (increase) in natural formations (Fig. 8b). On the other hand, the farming area suffered a drastic reduction, mainly in São Vicente (61.6 %), contrasting with the increase in urbanization in the three municipalities. The growth of urbanized areas was most pronounced in Guarujá, more than doubling in the last 36 years (107%), followed by São Vicente (61.7%) and Santos (36.9%) (Fig. 8a). These urbanization data also coincide with the population

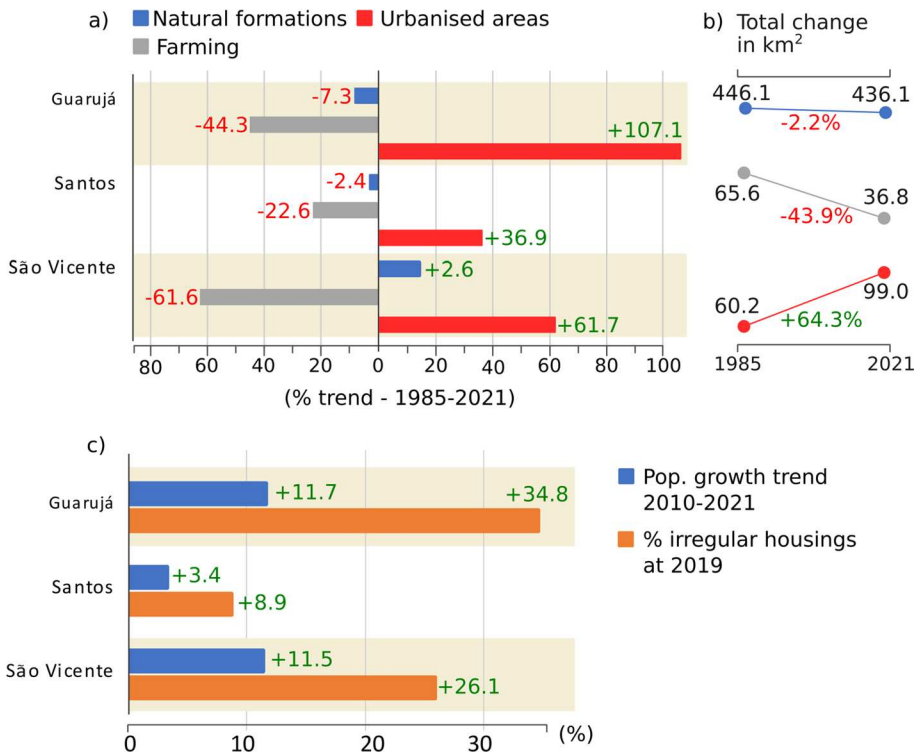


Fig. 8 Land cover change and the expansion of urbanised areas in the municipalities of Guarujá, Santos and São Vicente. **a–b** Change in natural cover areas (natural formations), land use (farming) and urbanisation between 1985 and 2021 and **c** population growth in the period from 2010 (last official IBGE census) to 2021 (estimated population) and occupation of risk areas with irregular and precarious housings

growth in the three municipalities of Baixada Santista in recent years (Fig. 8c). According to the 2010 census and population estimates in 2021 by IBGE, Guarujá and São Vicente had a population growth of almost 12% (from 290,752 to 324,977 and from 332,455 to 370,839 inhabitants, respectively), while Santos had a more modest increase of 3.4% (from 419,400 to 433,991 inhabitants). Estimates obtained from IBGE data showed that in 2019 there were 71,120 irregular and/or precarious housings in Baixada Santista (20% of the total dwellings in the region). Guarujá was the municipality with the highest number of this type of buildings (29,081 units), followed by São Vicente (27,664 units) and Santos (14,375 units).

3.3 Event attribution

The PDFs of all ensemble members indicate the probability of occurrence of the event in both scenarios, with the CPC threshold marked by the black vertical line (Fig. 9). The right-hand side tails of the $RX3day_{max}$ and $RX60day_{max}$ distributions crossing the CPC threshold suggest a higher likelihood of moderate and extreme precipitation occurrences due to anthropogenic climate change in *ALL* compared to *NAT* simulations.

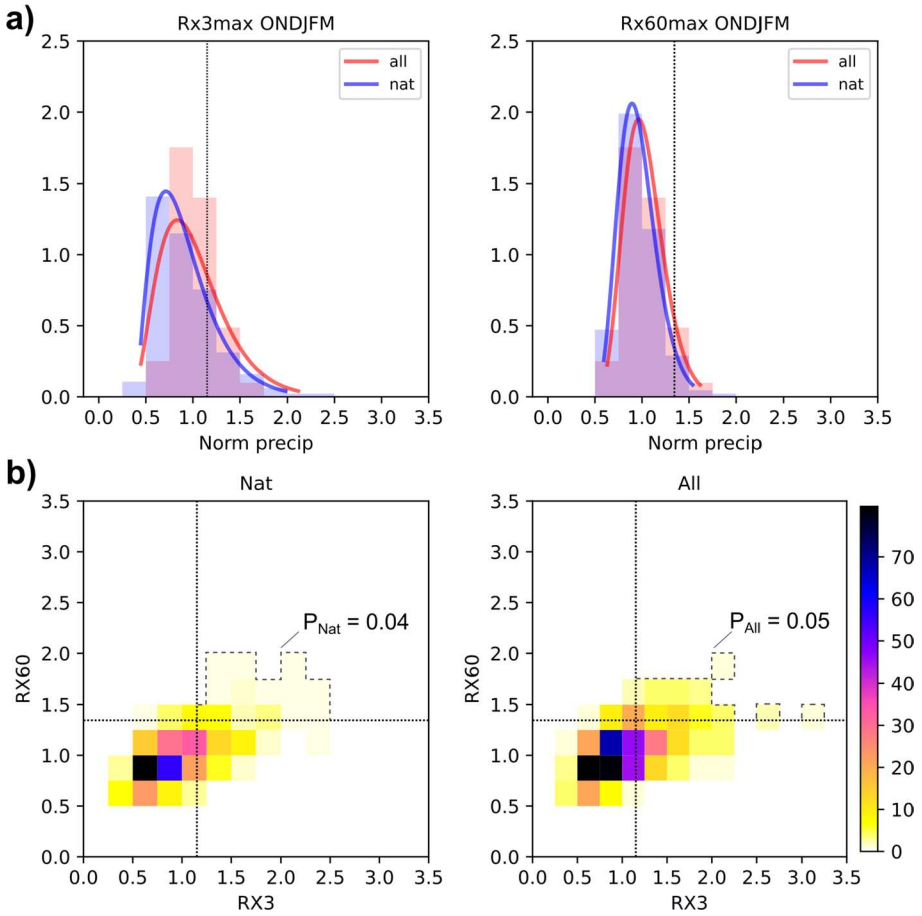


Fig. 9 **a** Histograms and gamma-fitted distributions of the maximum precipitation for $RX3day_{max}$ and $RX60day_{max}$ and **b** combined histograms in ONDJFM 2019–2020 for both NAT and ALL HadGEM3 scenarios. The dotted black lines are the CPC threshold for the event and the dashed grey lines indicate the values from the joint probability. The values are normalised by the climatology (1981–2010)

Table 1 Attribution results for the extreme precipitation event at Baixada Santista in 2020 using distinct Rx metrics as well as the combined metrics (joint) based on the CPC dataset and for both ALL and NAT experiments

RX	60day _{max}	3day _{max}	Joint
CPC _{threshold}	1.34	1.15	–
PR	1.74 [0.35, 2.67]	1.46 [1.20, 1.74]	1.25 [1.03, 2.94]
FAR	0.42 [– 1.89, 0.62]	0.31 [0.17, 0.42]	0.20 [0.03, 0.66]
RP _{ALL}	12 [10, 16]	3 [3, 4]	21 [11, 21]
RP _{NAT}	21 [3, 31]	5 [4, 6]	26 [17, 40]

The precipitation was normalized and fitted into a gamma distribution. The confidence intervals [CI] were computed by the 2.5th and 97.5th percentile using 1000 bootstraps simulations

Table 1 presents a summary of the main indices analyzed in this study. The estimated PR values for $RX60day_{max}$ and $RX3day_{max}$ are estimated at 1.74 [95% CI: 0.35, 2.67] and 1.46 [95% CI: 1.20, 1.75], respectively. These values both exceed 1, indicating stronger increase in occurrence probability due to anthropogenic climate change. While the PR for $RX60day_{max}$ is numerically higher than for $RX3day_{max}$, the overlapping confidence intervals suggest that the difference between the PR values for the two metrics is not statistically significant. The Fraction of Attributable Risk (FAR) for $RX60day_{max}$ is 0.42 [95% CI: 0.18, 0.62], and for $RX3day_{max}$ is 0.31 [95% CI: 0.17, 0.42], indicating that both metrics demonstrate a substantial increase in the likelihood of extreme precipitation events—more than 30% and 40% for $RX3day_{max}$ and $RX60day_{max}$, respectively—under anthropogenic influences as opposed to natural forcings alone.

The analysis of return periods provides valuable insights into the influence of anthropogenic climate change on extreme precipitation events. In the *NAT* scenario, the estimated return periods for $RX60day_{max}$ and $RX3day_{max}$ were found to be 21 and 5 years, respectively. However, in the *ALL* scenario, the estimated return periods significantly decreased to 12 and 3 years for $RX60day_{max}$ and $RX3day_{max}$, respectively, indicating that anthropogenic climate change has substantially increased the frequency of such events.

In particular, anthropogenic climate change has increased the likelihood of both $RX60day_{max}$ (representing saturated soil conditions) and $RX3day_{max}$ (representing landslide triggering precipitation) at levels exceeding those observed in early March 2020 in Baxiada Santista by approximately 42% and 31% respectively. These results underscore the profound impact of anthropogenic climate change on the frequency and severity of extreme precipitation events. In addition, the joint analysis indicates a higher probability of occurrence in the *ALL* scenario, exceeding the thresholds defined for both RX values, compared to the *NAT* scenario. The tail distribution in the *ALL* experiment is skewed towards the top-right quadrant, indicating a higher likelihood of joint occurrence of both $RX60day_{max}$ and $RX3day_{max}$ due to anthropogenic climate change, as compared to the *NAT* scenario.

The estimated joint PR was 1.25 (95% CI 1.03–2.94), while the FAR was estimated at 0.20 (95% CI 0.03–0.66). The RP were estimated at 26 years (95% CI 17–40) and 21 years (95% CI 11–21), for the *NAT* and *ALL* scenarios, respectively. This means that anthropogenic climate change has increased the risk of concurrent occurrence of 60 day antecedent wet surface conditions and 3 day extreme precipitation by approximately 19%.

3.4 Attributable impacts of human-induced climate change

The attributable impacts of human-induced climate change for the extreme precipitation event in March 2020 were analyzed (Table 1). For this we used the correspondent fraction of FAR for each socioeconomic damage and losses reported in Sect. 3.3 (Table 1). During the heavy rainfall event, more than 2800 people were affected and over 4500 dwellings were damaged and destroyed in the three most affected municipalities. Out of this total, the analysis estimated that a proportion likely attributable to anthropogenic climate change resulting from the $RX3day_{max}$ risk was responsible for 881 people and 531 houses affected, of which 126 people and 228 houses were specifically affected due to landslides. For the $RX60day_{max}$ occurrence, the analysis estimated that 1194 people were affected, with 171 people likely affected by landslides. When considering both $RX3day_{max}$ and $RX60day_{max}$ risks together, the cases likely attributable to human activities were 568 people affected

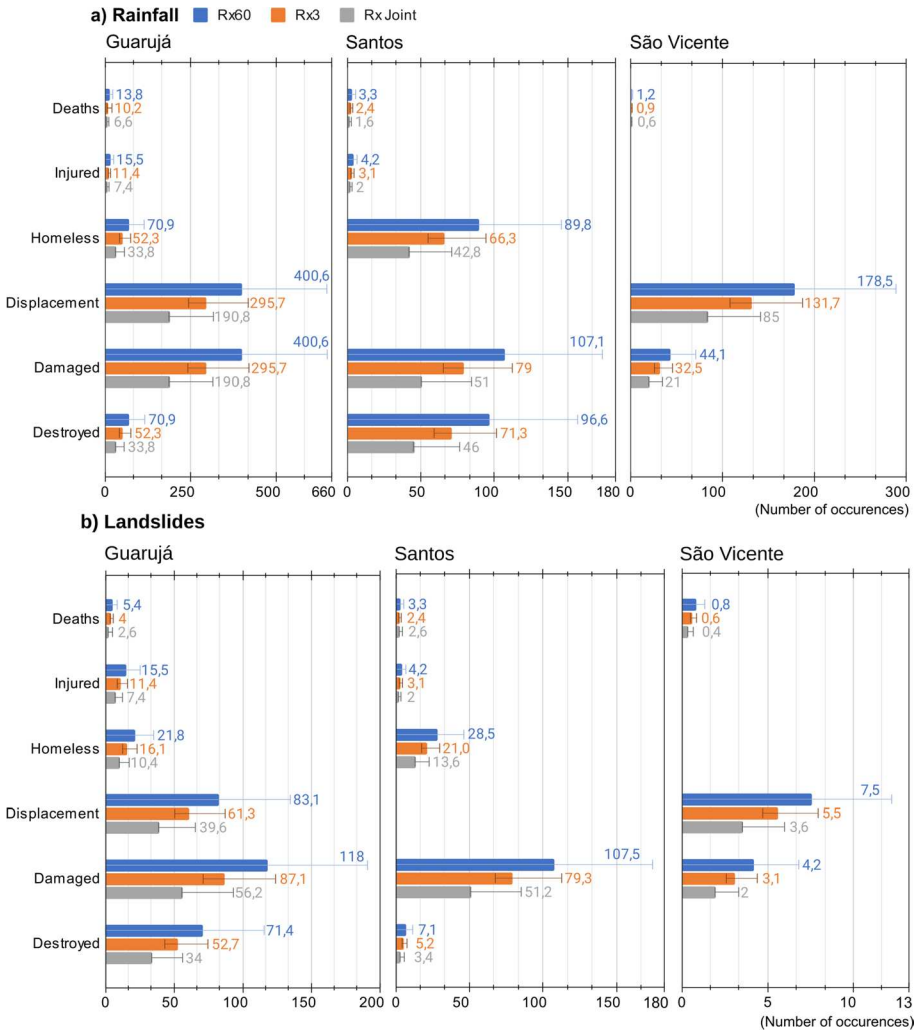


Fig. 10 FAR applied for human damages reported for the municipalities of Baixada Santista. Number of occurrences attributable **a** to rainfall and **b** caused only by landslides

by the precipitation event and 81 people affected by landslides (Fig. 10). Additionally, the damage extended to 343 houses due to precipitation and 147 houses due to landslides.

In terms of economic damages, the category with the highest monetary loss per capita was material damage costs, accounting for 98% of the total. Therefore, considering the 3 day accumulations, the economic losses likely attributable to anthropogenic activities amounted to BRL 66.7 million (USD 13.8 million), while for the 60 day accumulations this total could reach BRL 90.4 million (USD 18.6 million). However, when considering the probability of the occurrence of both the associated $RX3day_{max}$ and $RX60day_{max}$ thresholds, the analysis revealed that the economic losses attributed to human-induced climate change were estimated to be lower compared to their individual assessments. Specifically, the estimated economic losses amounted to BRL 43 million (USD 8.9 million) (Fig. 11).

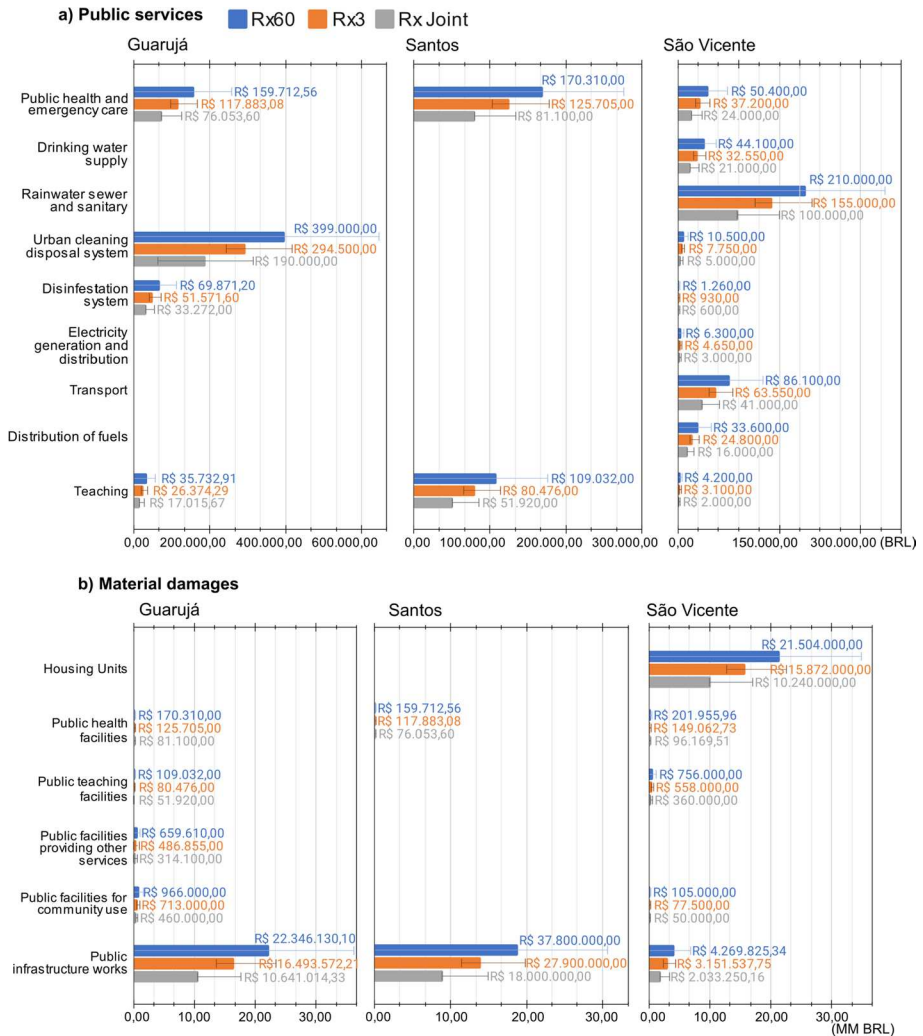


Fig. 11 FAR applied for the economic losses reported for the municipalities of Baixada Santista. Costs attributable to rainfall for **a** public services and **b** material damage losses. (Missing data are due to lack of available records from the disaster, not to lack of occurrence)

4 Discussion

Our findings indicate that $RX60day_{max}$ and $RX3day_{max}$ had a probability of occurrence attributed to anthropogenic climate change higher than 46%. This suggests that the human-induced changes to precipitation contributed to the disaster in Baixada Santista, encompassing elements at both long (60-day) and short (3-day) timescales. The 60-day accumulated precipitation correlates well with the soil moisture conditions prior to the event (Fig. 2) and the 3-day accumulated precipitation represents the intense landslide triggering rainfall. Both of these metrics serves as an indicator of the favourable conditions

for landslide events considering both the soil moisture content and the relative intensity of rainfall capable of triggering such events (Zhao et al. 2019; de Freitas et al. 2022).

In this study, our estimates for PR showed higher value for $RX60day_{max}$ than $RX3day_{max}$, although the confidence limits for $RX60day_{max}$ indicate some ambiguity in whether anthropogenic climate change increased the likelihood, as the lower limit is less than 1 (Table 1). Despite both metrics indicating an increase in the likelihood of occurrence of extreme events in the ALL scenario, the two estimates highlight different aspects of the precipitation. The RP_{ALL} for $RX60day_{max}$ was estimated for 12 years, contrasting with 3 years estimated for $RX3day_{max}$; these findings suggest that while short-term extreme rainfall events can have a more frequent recurrence, the prolonged precipitation patterns necessary for soil saturation are less common and generally span a duration of a couple of months.

Despite the reported increase in $RX60day_{max}$ under the ALL scenario compared to NAT , the Baixada Santista, located in the subtropical region, is predominantly considered a transitional area for climate change signals concerning wet or dry conditions. Studies by de Godoy et al. (2021) and Reboita et al. (2021, 2022) indicated negligible changes in very wet days ($R95p$) and consecutive dry days (CDD) for the Baixada Santista during the austral summer. However, these findings lacked statistical significance due to the models' general inconsistency regarding the direction of the signal. Additionally, although Zaninelli et al. (2019) identifies hydroclimatological shifts across South America, significant alterations in the Baixada Santista are not evident. This lack of consensus among models highlights the complexity of predicting climate impacts in transition regions like the Baixada Santista, where the interplay between different climatic influences results in a nuanced climate change signal.

While our analysis indicates a higher probability of occurrence for single-factor events (i.e. for $RX3day_{max}$ and $RX60day_{max}$ solely) compared to the combined-factor event, it is important to clarify that this does not conclusively establish causality. In this study, we adopted the combined-factor approach based on the premise that single-factor metrics alone might not sufficiently account for the observed landslide events. This decision stems from the assumption that the extreme event under investigation likely resulted from the inherent complexities and multi-factorial nature of climatic phenomena, where multiple factors interact in ways that single metrics may not fully capture. However, it is imperative to approach these findings with caution due to the potential limitations inherent in our data and predictive models. This includes recognizing potential data biases and uncertainties in climate modeling. By highlighting these nuances, our study not only contributes to the growing body of research on the impacts of climate change but also underscores the necessity for further investigation into the intricate dynamics of climate systems. A deeper understanding of the synergistic effects of various climatic factors is crucial, as it can provide more comprehensive insights into the mechanisms driving extreme weather events and enhance the effectiveness of climate adaptation and mitigation strategies.

Some attribution studies have directly estimated the fraction of damage associated with human-induced climate change through FAR , providing a broad estimate using a simple risk-based methodology. Based on FAR estimates, studies have shown the magnitude of damage and costs caused by extreme precipitation events due to human-attributed climate change have been very high. For example, in the United Kingdom, approximately USD 9 billion in flood damage was attributed to climate change between 2000 and 2017 (Clarke et al. 2021). In New Zealand, the insurance costs attributed to climate change during the decade 2007–2017 were estimated in USD 140 million (Frame et al. 2020). In a recent extreme precipitation and landslide event that occurred in Minas Gerais, Brazil, estimated

losses in material damage of BRL 26.17–48.60 million (USD 4.84–9 million) were likely attributable to anthropogenic climate change (Dalagnol et al. 2022). In our study, we found a FAR estimate of 42% and 31% for $RX60day_{max}$ and $RX3day_{max}$, respectively. The FAR derived from the joint probability of occurrence (PR_{joint}) was estimated as 20%. The costs of human-induced economic impacts due to climate change in Baixada Santista after the extreme precipitation event in March 2020 amounted more than USD 18 million for the antecedent conditions leading to more saturated soil, or almost USD 14 million for short term trigger event. Considering the more conservative estimate for the joint FAR, the costs amounted almost USD 9 million.

While the Fraction of Attributable Risk (FAR) methodology for estimating economic losses is well-established in the literature, it's important to acknowledge its limitations. Brown (2023) highlights that FAR might overestimate impacts when assessing phenomena linked to continuous variables, suggesting that slight variations, such as a 1 mm change in precipitation, may not lead to impacts according to this method. However, if such a small change in precipitation is sufficient to cross a critical physical threshold, which, for instance, destabilizes a slope and triggers a landslide, then the application of FAR may be justified. Therefore, caution is warranted when evaluating anthropogenic contributions to economic losses in these and related studies. Nonetheless, given the lack of well-defined damage functions, the use of FAR and the results presented remain useful. By including initial estimates of climate change impacts in this manner, comparisons with earlier findings are possible, thereby emphasizing the necessity for climate adaptation and mitigation strategies, and contributing to the development of public policies.

The main outcome derived from our estimates is that the increase of the likelihood of occurrence of extreme events presents a compound effect driven by distinct time scales. The $RX60day_{max}$ represents the longer term precipitation related to soil moisture conditions, while $RX3day_{max}$ captures shorter, intense rainfall events which may trigger landslides. The compound effects involving PR_{joint} still entail uncertainties, and establishing a direct link between precipitation and soil saturation is challenging due to limited observational data. Nevertheless, previous research by Ávila et al. (2016) discusses the association between the frequency of extreme rainfall events and landslides, highlighting strong correlations with RX indexes. Consistent with climatological trends observed in other studies (MdIM et al. 2013; Anderson et al. 2015), these findings also emphasize the significance of local heterogeneity (such as topography and land use) in explaining the occurrence of intense precipitation episodes. Therefore, while our study focuses on the human-induced intensification of extreme precipitation indexes, it is important to recognize that other triggering factors not considered in our work may still play a role (Palharini et al. 2022).

Comparing our estimates with other studies is difficult due differences in regional climate and parameters considered. Extension of damages also depends on the size of the urban area, terrain characteristics and vulnerability conditions of the local population. Considering the estimations using $RX60day_{max}$, our values are similar to those values reported for Minas Gerais by Dalagnol et al. (2022). This similarity can be explained in part by the proximity between both regions of study; despite Baixada Santista being located at the coast, Minas Gerais state is affected by the same meteorological systems that cross São Paulo State.

In our study using the HadGEM3, we found that the return periods are shorter for the ALL compared to NAT experiments, indicating that the frequency of extreme events due to anthropogenic climate change has increased the 60 day accumulated precipitation by 74%, while for the 3-day accumulations, this increase is 46%. However, combining both 3-day and 60-day accumulation events, the increase due to human induced climate change was

approximately 25%. It is noteworthy to mention that while the PR values for $RX60day_{max}$ and $RX3day_{max}$ were calculated from fitted distributions, the joint PR relies on pure counts over threshold, which may potentially underestimate the probabilities. Using a non-stationary model to study the effect of urbanisation on extreme rainfall, Lu et al. (2019) observed that an increase of the recurrence level of $RX1day$ and $RX5day$ by 25.9% and 59.1% for highly urbanised locations, and 34.2% and 36.9% for less urbanised locations, respectively. Debortoli et al. (2017) used a regional climate model nested within two global climate models (HaGEM2-ES and MIROC5) and showed that in various locations on the Brazilian coast, like the northeast coast of São Paulo State, there is a strong evidence of landslide intensification occurring in the future. The increase in vulnerability was estimated between 5 and 15% according to the HadGEM2-ES model, and approximately 40% according to the projection scenario with MIROC5 by the end of the century.

These findings show that decision makers need to consider the effects of extreme precipitation in urban planning and promote more adequate adaptation measures in these affected places. Moreira et al. (2017) investigated the process of urbanisation and occupation of the municipalities in the Metropolitan Region of Baixada Santista and the vulnerability of the population in the face of events triggered by the rains in the 2000 s. Although they had not observed a direct relationship between vulnerability and the number of occurrences related to rainfall, they emphasise that the most vulnerable population is the most affected by these types of extreme events.

5 Conclusion

The extreme precipitation event that occurred in Baixada Santista in March 2020 resulted in severe socioeconomic damages due to direct rainfall impact and numerous landslides, mainly in the municipalities of Guarujá, Santos and São Vicente. Our study identified that 20–42% of the total losses and damages can be attributed to anthropogenic climate change considering both the 60 day and 3 day precipitation accumulations. The 60-day accumulation reflects the level of soil saturation, while the 3-day precipitation acts as a trigger for landslide disasters. Therefore, the public authorities in Baixada Santista region need to implement measures to adapt to climate change, reducing risks from extreme events to the vulnerable population and infrastructure. This includes establishing early warning systems and evacuation plans during occurrence of extreme weather events, and ensuring that emergency services are equipped to deal with the increased frequency and severity of such events.

The analysis indicated that anthropogenic climate change likely contributed to the event, affecting over 2800 individuals and damaging or destroying more than 4500 dwellings. When considering the combined effects of short-term and sub-seasonal scale risks, the event impacted approximately 568 people and resulted in 81 individuals being affected by landslides. Material damage costs emerged as the primary contributor to economic losses, with total estimated costs reaching BRL 43 million (USD 8.9 million), attributed to human-induced climate change.

Although the land use change contribution to this event was not statistically assessed in our study, we found relevant increases of 107, 62 and 37% in the urbanized areas of Guarujá, São Vicente and Santos, respectively, over the last 36 years. Such changes certainly contributed to increase impervious areas and reduce the slope stability, magnifying the landslide occurrences. Decision makers in Baixada Santista should

consider this relationship between historical land-use changes and risks associated with climate change scenarios when implementing public policies and altering the spatial planning of cities. Considering that 20% of dwellings in the region are irregular and/or precarious, further efforts are required to regulate building in high-risk areas, including community engagement and educating the population about the risks of such activity. Future studies should also further explore the contribution of land use changes to these events, as this aspect was not statistically assessed in the current study.

Our estimates suggest a significantly shorter return period for extreme precipitation events due to climate change. Therefore, management of the impact of these extreme events must consider the increasing likelihood of extreme precipitation and urbanization in the future. Attribution of a significant portion of the damages to anthropogenic climate change highlights the urgent need for adaptation and mitigation measures.

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Data availability The data supporting the findings of this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.8341366>. These datasets include data from land cover change, socioeconomic impacts, susceptibility to landslides, gridded HadGEM3 and CPC climatological and for the study period data, the selected pluviometer data and soil moisture data used for the analysis presented in this paper. We encourage researchers to explore and utilize these datasets to replicate, verify, or build upon the results of this study.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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