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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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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 2,800 people and resulting losses exceeding USD43 million. This attribution study compared extreme rainfall in two distinct runs from the UK Met Office Hadley Centre HadGEM3-GA6 model: one with all forcings and the other with natural forcings only, considering antecedent conditions and soil moisture (extreme 60-day rainfall, Rx60day) and heavy rainfall (extreme 3-day rainfall, Rx3day) which may trigger landslides. The long-term set-up 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 homes damaged, 85% of homes destroyed, all reported injuries, and 51% of deaths associated with heavy rainfall. Changes in land cover and increased 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. Population growth estimates also indicate higher exposure to extreme rainfall events. The proportion of irregular and/or precarious housing indicates vulnerability, with Guarujá being the municipality with the highest number (34.8%) of dwellings of this type. 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, Landslides, Socioeconomic impacts, Baixada Santista, Southeast Brazil

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 [1–4]. According to the National Confederation of Municipalities [5], 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). In addition, nearly 550,000 homes were destroyed or damaged, and more than 28 million people were affected.

Part of São Paulo State coast around Santos municipality, the so-called Baixada Santista, comprises areas of high susceptibility to landslides due to their steep slopes, 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 [6]. Besides that, soil moisture at or close to saturation are related to elevated water table level and increased material plasticity, ultimately

destabilizing slopes and triggering landslides [7], particularly when intense and short-lived precipitation events occur [8, 9]. 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 (Cemaden), it rained 350 mm in Guarujá, 330 mm in Santos and 230 mm in São Vicente in 48 hours. In Santos, for instance that amount surpassed the climatological (data available from 2014 to 2022) accumulated precipitation of the whole March, which is 313 mm (Cemaden gauge data for Nova Cintra Station). The high soil moisture conditions 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 and resulted in disastrous sequences of landslides in the Baixada Santista [10]. It affected more than 2800 people causing economic losses estimated of about 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 [11].

Besides the specific triggers for this extreme precipitation event, other studies also showed the increasing vulnerability of Baixada Santista to climate change [12, 13]. According to the Instituto Brasileiro de Geografia e Estatística (IBGE [14]), 8.2 million people in 872 Brazilian municipalities are exposed to risk areas of floods, flash floods and mass movements. Climate change can increase the exposure of social systems to the impact of extreme events, causing severe damages to human lives and economies [15]. However, the exact ratio of impacts which can be attributable to anthropogenic influence is poorly explored for Baixada Santista in previous studies, even when damages associated to rainfall and landslides are analyzed in depth [10, 16, 17].

Attribution analysis is performed using ensemble simulations from global circulation models. These models simulate a real scenario - where anthropogenic forcings are included, that can be compared with a natural scenario - where simulations are run without the greenhouse gases contribution from anthropogenic activities. The Hadley Centre Global Environmental Model (HadGEM) in the last decade has become a robust tool for attribution analysis [18, 19]. A state-of-art protocol presented by [20] to conduct attribution analysis highlights the use of HadGEM ensembles using distinict 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.

There are challenges associated with intense precipitation occurring at small temporal and spatial scales. [20] 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 [21], mainly those related to landslides, where several other parameters sum up to the analysis [22].

In parallel, both landslide and flood occurrences are potentially affected by land use changes, which can reduce the slope stability due to reduced root cohesion and alter the hydrological functioning of the hillslope [23]. Indeed, [24] stated that anthropogenic activities related to land use change may also be concerned in risk assessment studies as they can change landslide susceptibility.

Here we present results of an attribution analysis for the heavy precipitation that occurred in March 2nd-3rd, 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 Material and Methods

2.1 Study Area

The Baixada Santista is situated on the southeast coast of Brazil (Figure 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 km^2 and an estimated population of 1,897,551 inhabitants [25], it ranks as the 17$^{\text{th}}$ 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 [26]. 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.

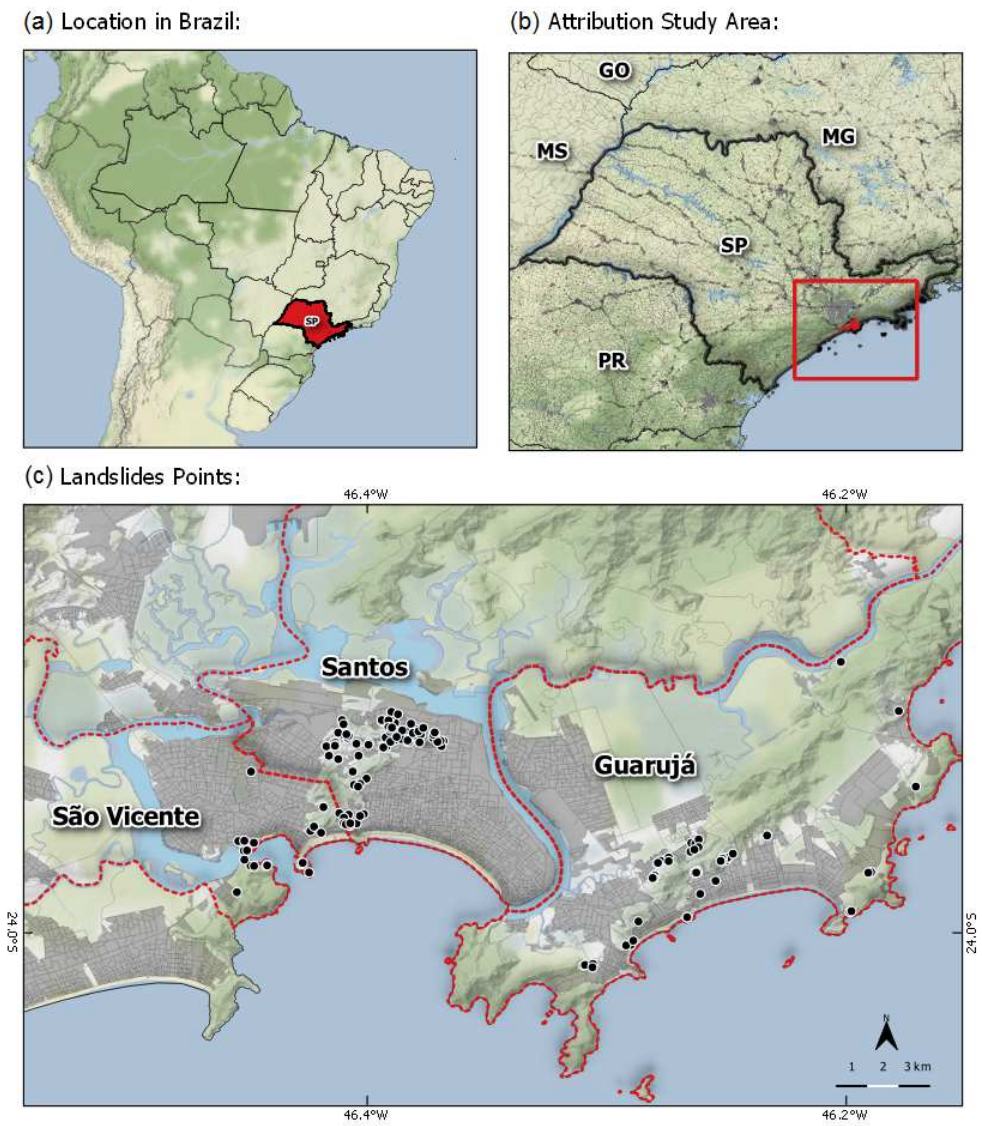


Fig. 1 (a) Location of the São Paulo state with respect to the Brazilian territory (shaded in red); (b) the area for the attribution analysis (red box); (c) the three municipalities which represent Baixada Santista, whose boundaries are shown in the red dashed lines. Black dots show the distribution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

According to the Köppen-Geiger's climate classification, the Baixada Santista region has a humid subtropical (Cfa) climate [27]. Throughout the year, the temperature generally varies from 18° C to 32° C and is rarely below 16° C or above 35° C. The annual precipitation ranges from 1,600 mm y^{-1} to 2,000 mm y^{-1} [28]. The rainy

season occurs from October to March (ONDJFM) and the dry season follows during the remaining months, between April and September (AMJJAS) [**?**]. 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, and other situations. Material damages comprises the number of destroyed and damaged buildings resulting from the disaster, and the costs of that damage; and for economic losses there were 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) as 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, and the classification into areas of high, medium and low risk, were obtained from the shapefile from the Serviço Geológico do Brasil - CPRM (available at https://www.cprm.gov.br). The location of the landslides that resulted in human damages and economic losses was assessed from the Technological Research Institute (IPT) inspection report for each affected municipality. The costs of monetary impacts were exhibited in Brazilian Reais (BRL), and the conversion to U.S. dollars (USD) followed a 4.85:1 conversion rate regarding 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

[25]. 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 [14, 29].

2.4 Observational Meteorological Data

The estimated precipitation product from MERGE [30] was used to define the area of interest and event parameters. MERGE combines satellite and rain gauge data and offers a high level of accuracy with a horizontal resolution of 5 km and a temporal resolution of one hour (available at http://ftp.cptec.inpe.br/modelos/tempo/MERGE/GPM/HOURLY/) and therefore significantly improves the estimation of both the location and quantity of precipitation compared to the Climate Prediction Center (CPC) dataset. However, since MERGE is available only from 2010 onwards, it was not possible to use it for the climatological analysis (which requires long-term data for comprehensive examination). The spatial accumulated precipitation from MERGE over the Baixada Santista for this extreme event is given in the supplementary information (Figure S.1).

The precipitation data from CPC was then 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^{o} from 1979 onwards [31]. This dataset is widely used for climatological studies in Brazil [32, 33]; it also has a good correlation with the observed data [34] and it is freely available at https://psl.noaa.gov.

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 [35]. 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-A (hereafter HadGEM3) [18]. The historical experiments (historical and historicalNat) cover the period 1960 to 2013 and each have 15 members. The main difference between the experiments are in the forcings; while the historicalNat comprises solar and volcanic forcing, holding the greenhouse gases constant at 1850 levels, the historical simulations include both the natural forcing and land-use and greenhouse gases changes [19]. A more complete description of HadGEM3 can be found in [36, 37].

The precipitation from the historical dataset from HadGEM3 model was used for the validation process focused on the climatological period of 1981 to 2010. For simulations of the extreme event itself, two large 525 member ensembles were analysed

for the period October 2019 to March 2020. 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 Figure 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 derived. 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 [38]. 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 [38]. We opted to proceed with two different metrics regarding maximum precipitation. The first metric focused on the short-term aspect of the event and aimed to look at the event trigger, comprising the extreme magnitude of the event. The second metric integrated a longer time period and served as a proxy for antecedent soil moisture magnitude. After conducting several tests (Figure S.2) we defined those metrics by calculating a daily rolling 3-day and 60-day accumulation of precipitation, aggregated by taking the spatial maximum for the defined box for the study area (47.5°W, 25°S, 45°W, 23°S). We subsequently refer to these metrics as RX3day and RX60day. The neighbouring regions were also included in the analysis, allowing the model some degree of freedom in representing the precipitation spatial pattern (Figure S.1). The CPC precipitation for the gridpoint closest to the landslides site is shown in Figure S.2; the $RX3day_{max}$ related to the event exceeded the climatological 99th quantile. Meanwhile, the $RX60day_{max}$ exceeded the climatological 95th quantile, being also the greatest $RX60day_{max}$ value since 2011.

To assess 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 Figure 2, we present the ensemble distribution of the maximum averaged precipitation normalized by the climatology from 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 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.

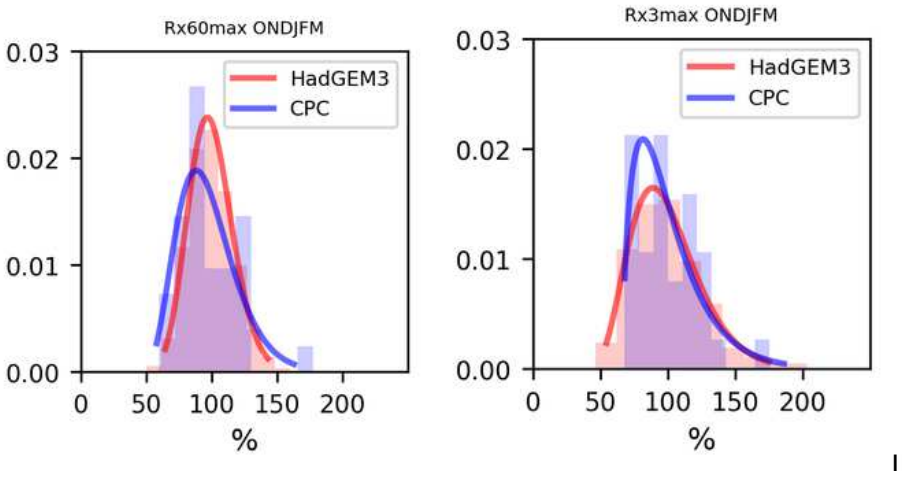


Fig. 2 Histograms and gamma-fitted distributions of the normalized maximum averaged precipitation for a) $RX60day_{max}$ and b) $RX3day_{max}$ in ONDJFM (from 1979 to 2013) for HadGEM3 and CPC datasets. The climatology considers the period of 1981-2010.

Regarding the $RX60day_{max}$ index, we observed a linear relationship between the accumulated precipitation and soil moisture estimated from SMAP (R^2=0.56 between $RX60day_{max}$ and L4_SM soil moisture, Figure 3). This agreement validates our hypothesis that $RX60day_{max}$ is able to represent soil moisture status.

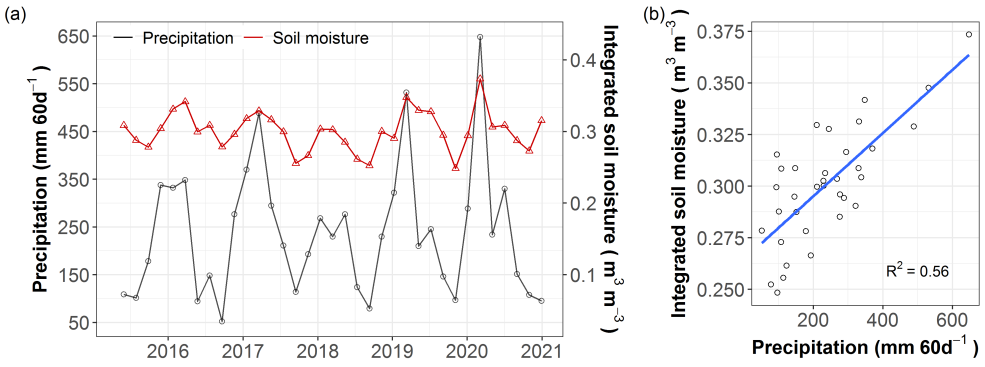


Fig. 3 (a) 60-day accumulated precipitation (in mm 60d^{-1}, black line and circles) and mean integrated soil moisture in the soil profile (in m^3 m^{-3}, red line and triangles); (b) scatterplot between integrated soil moisture and 60-day accumulated precipitation, same units than (a). The blue line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

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 [38]:

$$PR = \frac{P_{ALL}}{P_{NAT}} \tag{1}$$

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 1,000 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.

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

$$RP = \frac{1}{P_{ALL}} \tag{2}$$

which represents the averaged time interval for such an event to occur for each scenario. Nevertheless, as stated above, the event was defined as the occurrence of extreme values of both $RX60day_{max}$ and $RX3day_{max}$. Therefore, a joint analysis was accessed by counting the number of points that exceed both $RX30day_{max}$ and $RX60day_{max}$ thresholds from CPC, then divided by the total number of points for both ALL and NAT scenarios to form the joint probability ratio.

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

$$FAR = 1 - \frac{1}{PR} \tag{3}$$

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: nearly 54% occurred at Santos, 33% at Guarujá and 13% at São Vicente municipalities (Figure 4). The episodes overlap regions of higher susceptibility characterized by higher elevations and abrupt slope gradients [39]. Those terrain features are superposed to areas which experienced positive trends in urbanization growth and reduction in forest cover. In fact, field inspections reported at the landslides sites commonly report forest and soil altered by improper buildings and litter accumulation. Those features represent an additional hazard besides extreme rainfall.

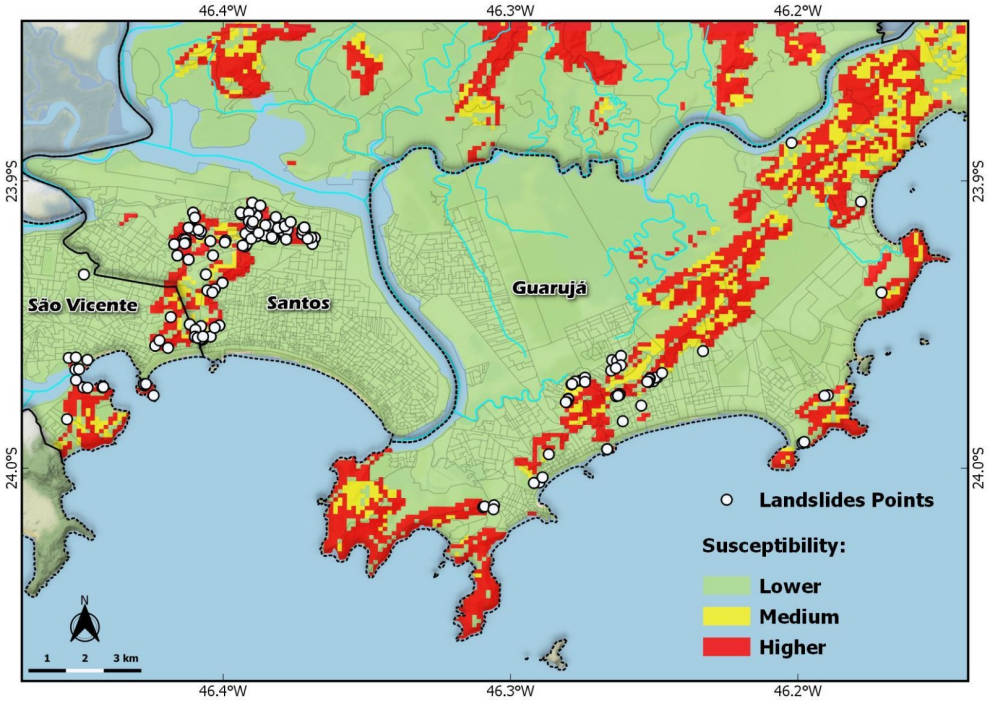


Fig. 4 Landslide susceptibility map (in colours) along with the occurrence points on March, 2nd-3rd, 2020.

The socioeconomic impacts of the disaster in Baixada Santista on March, 2nd-3rd, 2020, are shown in Figures 5, 6 and Table T.1, T.2 and T.3 (supplementary

information). According to official data, the intense precipitation event affected 2,842 people in the three municipalities (1,193 in Guarujá, 1,216 in Santos and 433 in São Vicente), resulting in 44 deaths, 47 injured, 388 homeless and 2,363 displaced (Figure 5a, left). Guarujá was the most affected municipality and reported 33 deaths, 37 injured and 1,123 displaced and homeless people, followed by Santos with 8 deaths, and São Vicente with 3 deaths. On the other hand, the human impacts caused by only landslides in Baixada Santista were 14% of the total affected people, but we observed that 52% of deaths were due to landslides (13 in Guarujá, 8 in Santos and 2 in São Vicente), as well as of all 47 reported injured people (Figure 5 a, right). Guarujá was the worst affected municipality with 74% of the human damages caused by landslides that occurred in March, 2020.

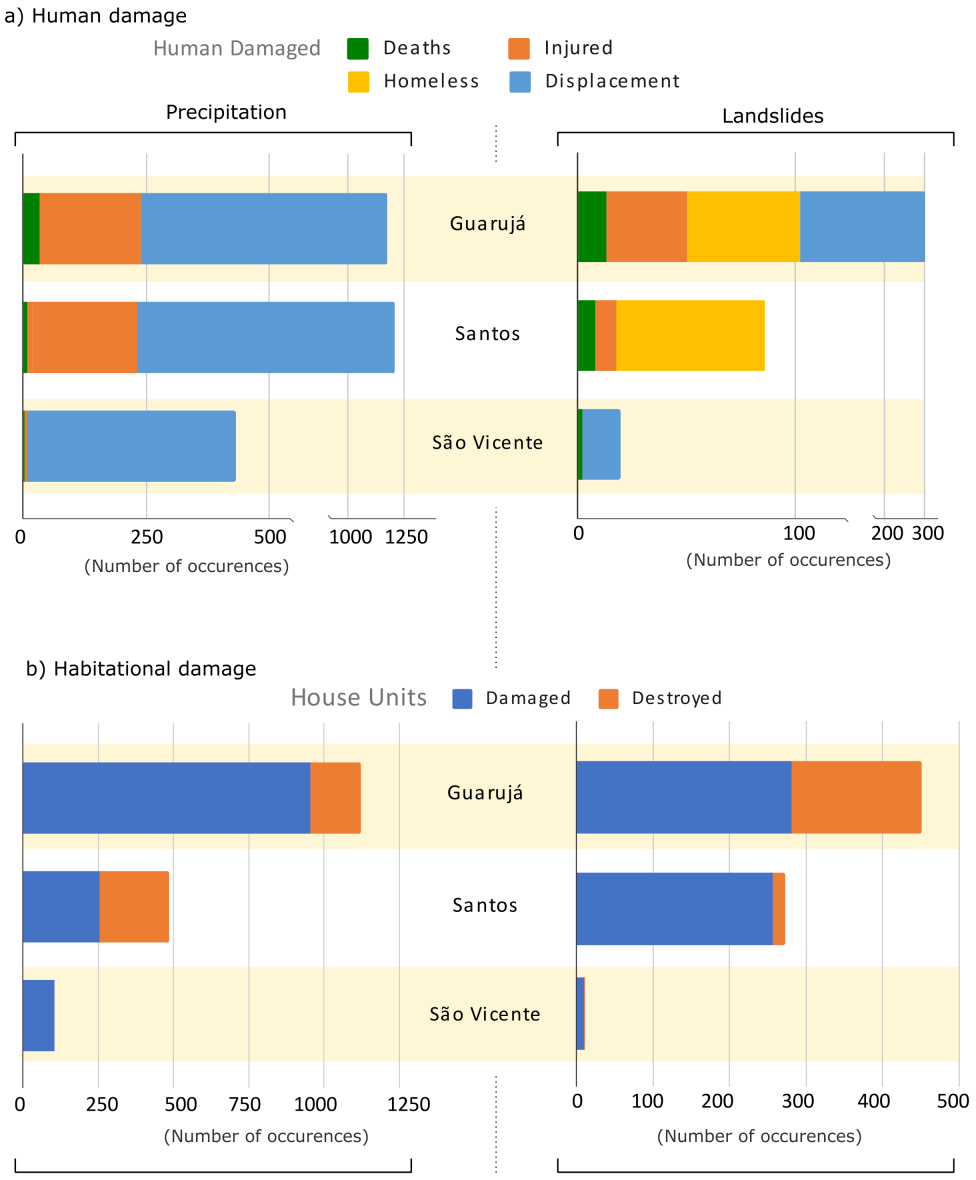


Fig. 5 Occurrences of a) human damages and b) habitational damages caused by the extreme precipitation (left panel) and landslide (right panel) in the three most affected municipalities of Baixada Santista in March, 2020 (Guarujá, Santos and São Vicente).

The extreme rainfall also caused significant housing damages in Baixada Santista; there were 1,294 damaged and 399 destroyed units, where 66% of the cases occurred in Guarujá, 28% in Santos and 6% in São Vicente (Figure 5b). 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 landslide disaster (Figure 4), this was the most affected municipality in the region (Figure 6).

Figure 6 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 (Figure 6a). Of this total, 24% were in damaged dwellings and 72% in public infrastructure work. Guarujá accounted for 43% of the losses, São Vicente for 30% and Santos for 27%. Figure 6b shows the total costs for public service losses estimated at BRL 3.3 million (USD 682.4 thousand). The economic losses 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%).

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 due to lack of local identification not to lack of occurrences.

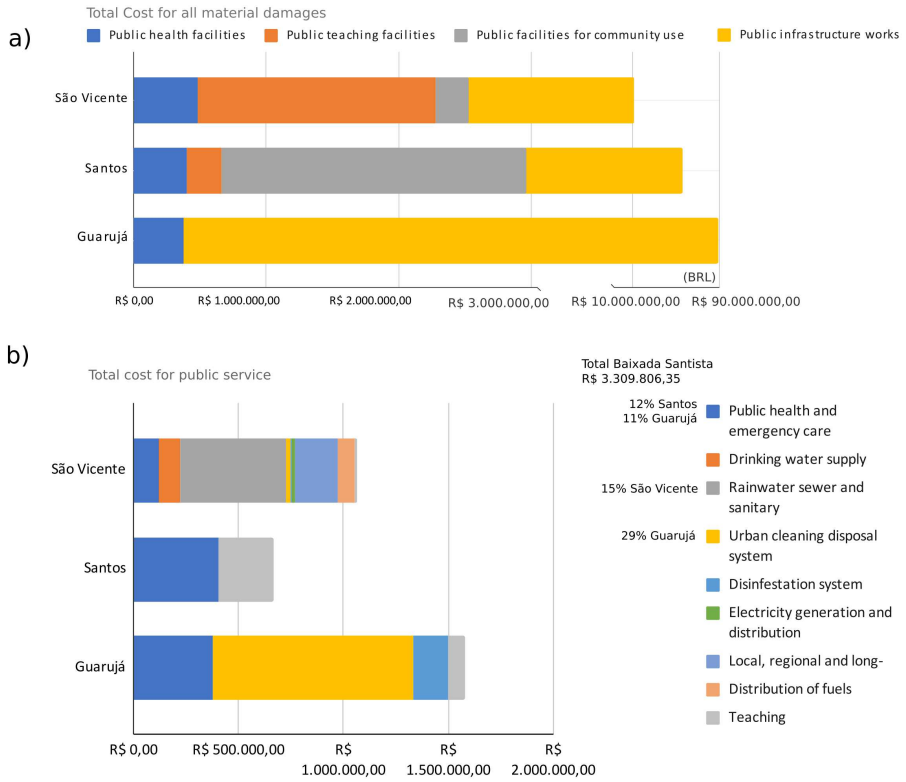


Fig. 6 Economic impacts caused by the extreme rainfall in São Vicente, Santos and Guarujá (Baixada Santista region). (a) Total cost for all material damage (in BRL); (b) total cost for nine categories of public services (the legend shows the municipalities with higher percentages at the category).

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 to 2021 (Figure 7 and Table T.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 (Figure 7b). 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%) (Figure 7a). These urbanization data also coincide with the population growth in the three municipalities of Baixada Santista in recent years (Figure 7c). 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).

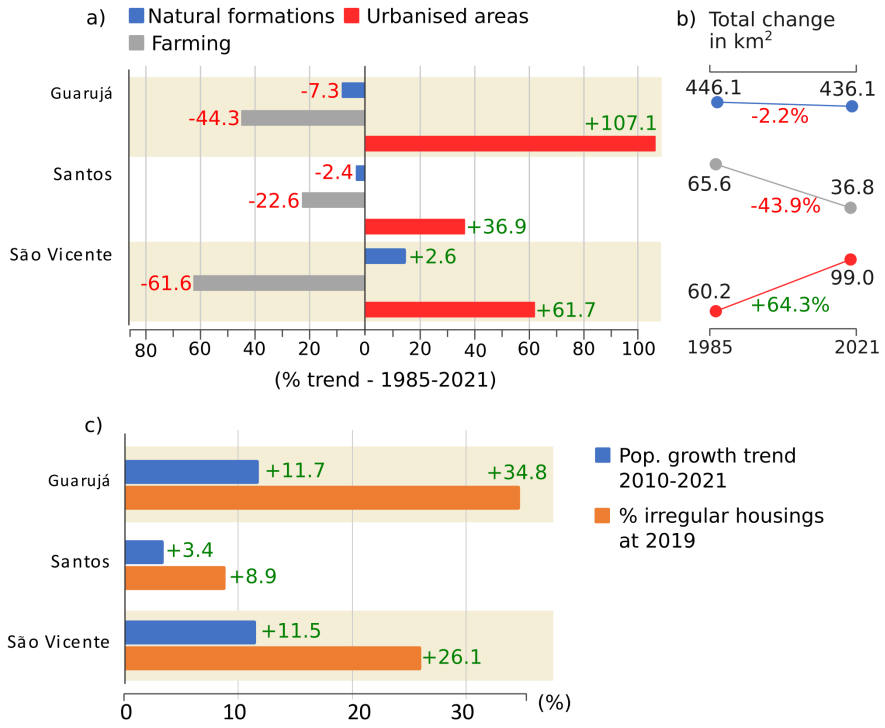


Fig. 7 Land cover change and the expansion of urbanised areas in the municipalities of Guarujá, Santos and São Vicente. (a) - (b) Change in natural cover areas (natural formations), land use (farming) and urbanisation between 1985 and 2021 and (c) population growth in the period from 2010 (last official IBGE census) to 2021 (estimated population) and occupation of risk areas with irregular and precarious housings.

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 (Figure 8). 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.

Table 1 presents a summary of the main indices analyzed in this study. The estimated PR values differed significantly between the two precipitation accumulation metrics, namely $RX60day_{max}$ and $RX3day_{max}$. The PR value for $RX60day_{max}$ was 1.74, indicating a higher probability of occurrence compared to 1.46 for $RX3day_{max}$. Consequently, FAR estimates were 0.42 for $RX60day_{max}$ and 0.31 for $RX3day_{max}$, respectively. These findings suggest that climate change has increased the likelihood of accumulated precipitation events associated with both $RX60day_{max}$ and $RX3day_{max}$ by more than 30% compared to a scenario driven solely by natural forcings.

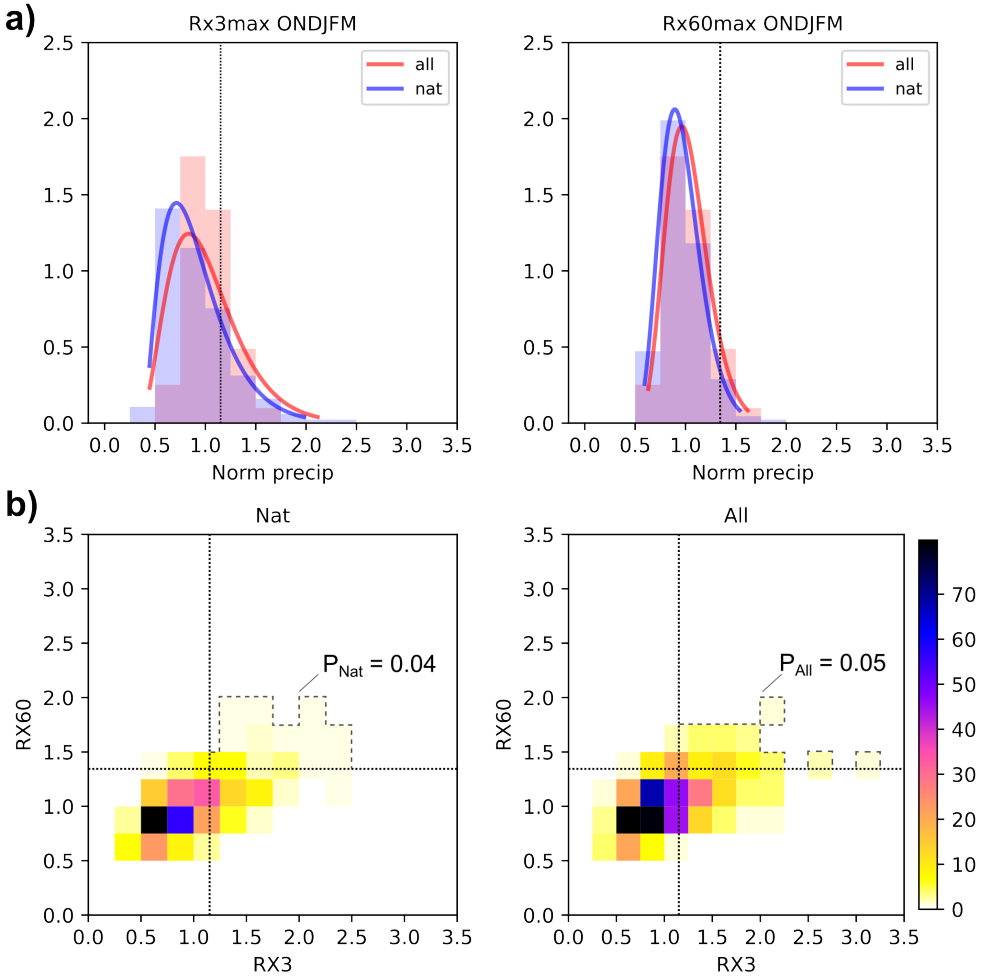


Fig. 8 a) Histograms and gamma-fitted distributions of the maximum precipitation for $RX3day_{max}$ and $RX60day_{max}$ and b) combined histograms in ONDJFM 2019-2020 for both NAT and ALL HadGEM3 scenarios. The dotted black lines are the CPC threshold for the event and the dashed grey lines indicate the values from the joint probability. The values are normalised by the climatology (1981-2010).

The analysis of return periods provides valuable insights into the influence of anthropogenic climate change on extreme precipitation events. In the natural scenario (NAT), the estimated return periods for $RX60day_{max}$ and $RX3day_{max}$ were found to be 21 and 5 years, respectively. However, in the anthropogenic and natural scenario (ALL), 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. [CI]

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) defined by the CPC dataset and for both ALL and NAT experiments. 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 1,000 bootstraps simulations.

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]

In particular, the analysis highlights the event observed on March 2nd and 3rd, 2020, suggesting that anthropogenic climate change has resulted in a significant rise in the occurrence of long-term precipitation accumulation leading to landslides (approximately 42% increase for $RX60day_{max}$). Furthermore, it has also contributed to a higher frequency of short-term trigger precipitation, like those observed in early March 2020 (approximately 31% increase for $RX3day_{max}$). 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 increased the occurrence risk of both the long-term antecedent wet surface conditions together with the short-term extreme precipitation by approximately 19%.

3.4 Attributable impacts of human-induced climate change

Based on the attribution analysis, 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 already reported before. During the heavy rainfall event, more than 2,800 people were affected and over 4,500 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 short-term 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 long-term occurrence, the analysis estimated that 1,194 people were affected, with 171 people likely affected by landslides. When considering both short-term and long-term risks together, the cases likely attributable to human activities were 568 people affected by the precipitation event and 81 people affected by landslides (Figure 9). Additionally, the damage extended to 343 houses due to precipitation and 147 houses due to landslides.

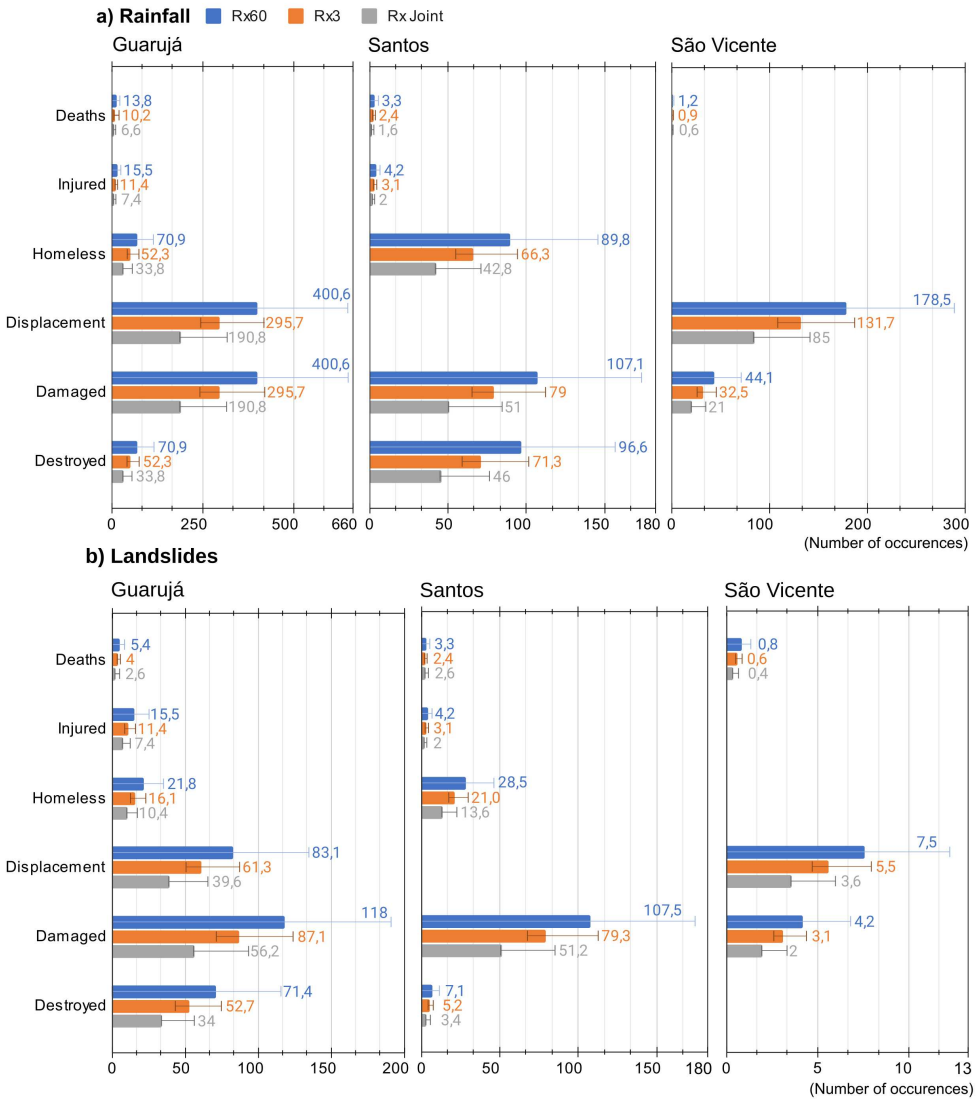


Fig. 9 FAR applied for human damages reported for the municipalities of Baixada Santista. Number of occurrences attributable (a) to rainfall and (b) caused only by landslides.

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, in the short term, the economic losses likely attributable to anthropogenic activities amounted to BRL 66.7 million (USD 13.8 million), while in the long term this total could reach BRL 90.4 million (USD 18.6 million). However, when considering the probability of the occurrence of both the associated short-term and long-term 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) (Figure 10).

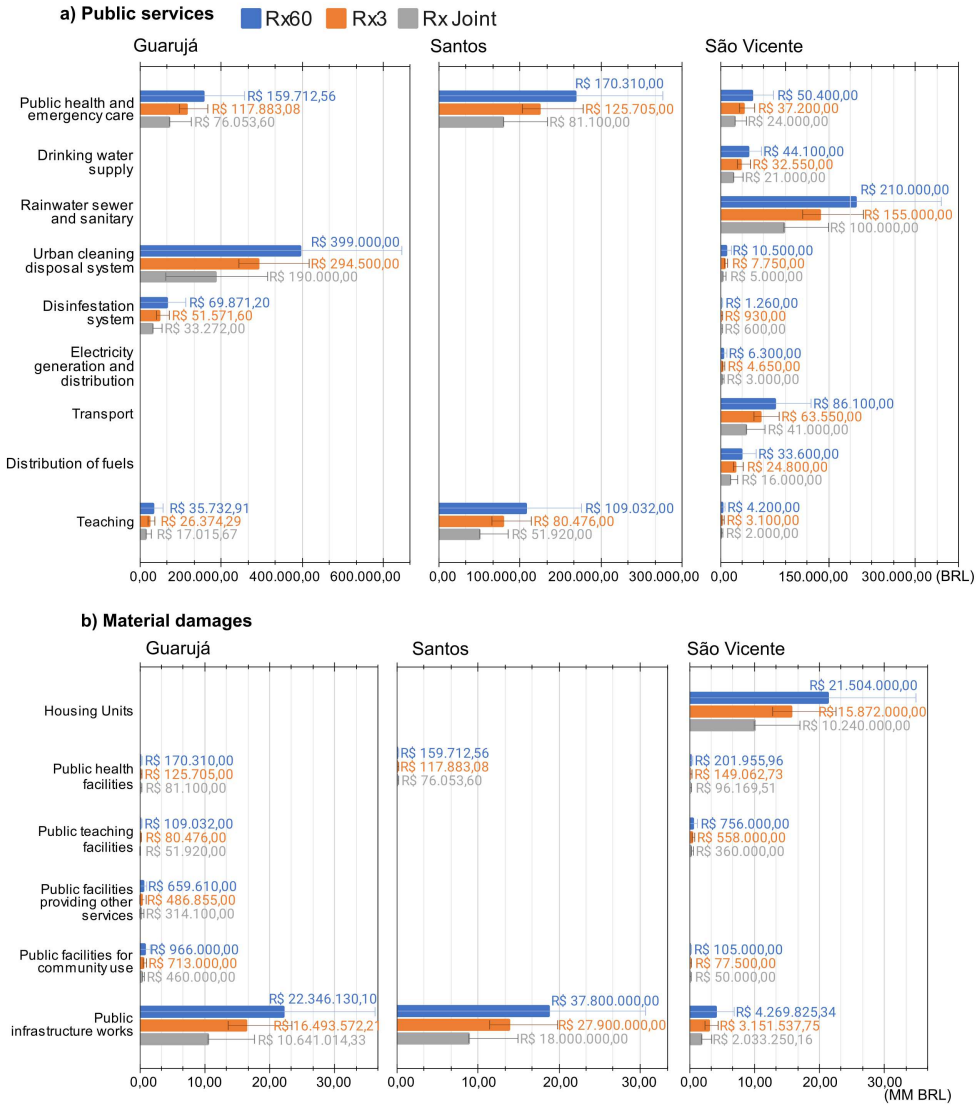


Fig. 10 FAR applied for the economic losses reported for the municipalities of Baixada Santista. Costs attributable to rainfall for (a) public services and (b) material damage losses. (Missing data are due to lack of available records from the disaster, not to lack of occurrence).

4 Discussion

Our findings indicate that the accumulated precipitation associated with both $RX60day_{max}$ and $RX3day_{max}$ had a probability of occurrence attributed to anthropogenic climate change higher than 46%, suggesting that the disaster in Baixada Santista encompassed elements at both long (60-day) and short (3-day) timescales. The connection between short and long-term precipitation is mediated by soil moisture, which correlated well with the long term rainfall accumulation ($RX60day_{max}$, Figure 3). This correlation 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 [7, 10].

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 RX_{max} 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 $RX3day_{max}$. Overall, our 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 occur over longer time scales.

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 [40]. In the New Zealand, the insurance costs attributed to climate change during the decade 2007-2017 were estimated in USD 140 million [41]. 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 [2]. 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.

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 Avila et al.

(2016) [8] 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 [42, 43], 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 [44].

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) [2]. 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 long term precipitation by 74%, while for the short-term, this increase is 46%. However, combining both short-term and long-term events, the increase due to human induced climate change was approximately 25%. Using a non-stationary model to study the effect of urbanisation on extreme rainfall, Lu et al. (2019) [45] 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) [46] 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 in order of 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) [16] 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 2000s. 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. Figure 11 summarises our findings that the likelihood of disasters in Baixada Santista is influenced by both longer and shorter term extreme precipitation. Our analysis of the RX indices suggests that extreme precipitation events are increasing due to anthropogenic influences. This compound effect has the potential to cause more significant human and economic losses.

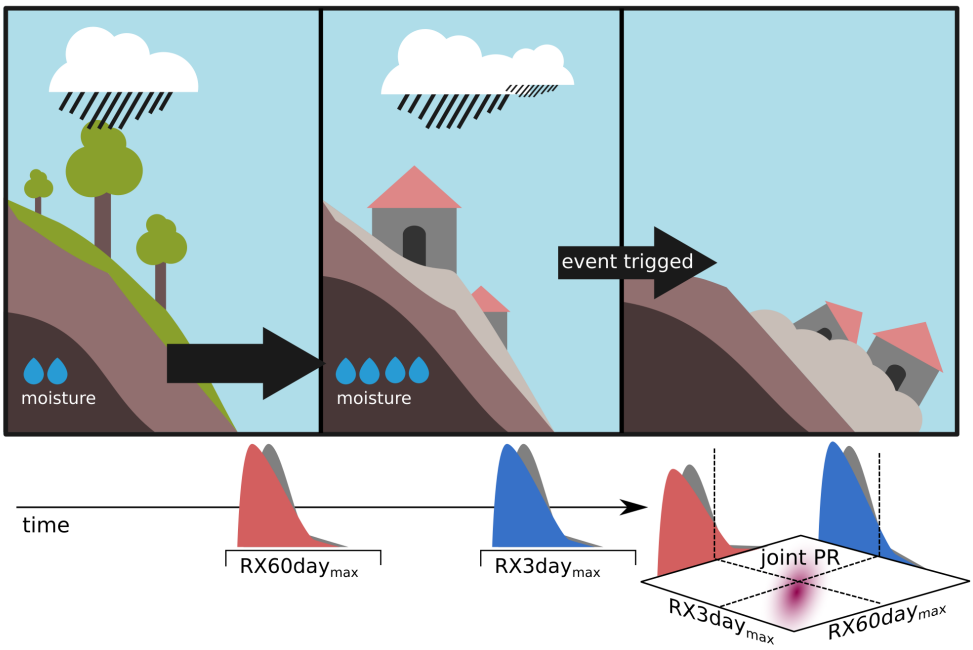


Fig. 11 Anthropogenic influence on extreme precipitation in Baixada Santista varies over different timescales. $RX60day_{max}$ index indicates a long-term increase in soil saturation, while $RX3day_{max}$ indicates short-term intense rainfall triggering landslides in vulnerable areas. The RX_{Joint} index represents the combined effect of long and short-term extreme precipitation can have at Baixada Santista

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 at both long and short time scales. The long-term effect reflects the level of soil saturation, while the short-term precipitation acts as a trigger for landslide disasters.

The analysis revealed that anthropogenic climate change likely contributed to the event, resulting in the affectation of over 2,800 individuals and the damage or destruction of more than 4,500 dwellings. Specifically, 881 people and 531 houses were likely affected due to anthropogenic climate change in the short term, with an additional 126 people and 228 houses impacted by landslides. In the long term, 1,194 people were affected, along with 171 individuals likely affected by landslides. Combining short-term and long-term risks, approximately 568 people were affected by the precipitation event, with 81 individuals impacted by landslides. The study also highlighted material damage costs as the primary contributor to economic losses, amounting to BRL 66.7

million (USD 13.8 million) in the short term and potentially rising to BRL 90.4 million (USD 18.6 million) in the long term. However, when considering both short-term and long-term thresholds, the estimated economic losses attributed to human-induced climate change were lower, amounting to BRL 43 million (USD 8.9 million).

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, along the last 36 years. Such changes certainly contributed to increase impervious areas and reduce the slope stability, magnifying the landslide occurrences.

At last, 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.

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Statements & Declaration

5.1 Funding and Competing Interests

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Conceptualization: DCS, NMC, DVS, LMH, RMPG, LMD, AJH, RCA, SL, SS; *Methodology:* DCS, NMC, LMH, RMPG, LMD, RCA, SL, FCL, SS; *Software:* DCS, NMC, RCA; *Validation:* DCS, NMC; *Formal analysis and investigation:* DCS, NMC, DVS, LMH, RMPG, LMD, AJH, FCL, SS; *Data curation:* NMC, DVS, LMH, RMPG, CAB, DM, MRMA, AJH; *Writing - original draft preparation:* DCS, NMC, DVS, LMH, LMD; *Writing - review and editing:* DCS, NMC, DVS, LMH, RMPG, LMD, RCA, SL, SS; *Visualization:* DCS, NMC, DVS, RMPG, LMD, AJH; *Funding acquisition:* SL, SS; *Supervision:* RCA, SL, FCL, SS

5.3 Data Availability Statement

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.

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