Authors' Responses to Reviewer 2 (RC2, anonymous)

Title: **Deadly disasters in Southeastern South America: Flash floods and landslides of February 2022 in Petrópolis, Rio de Janeiro**

Authors: Enner Alcântara *et al.*

Dear Reviewer,

Thank you for your time and effort in reviewing our manuscript and providing us with constructive feedback and comments that will help improve the quality of the manuscript.

This work was intended to investigate the causes of the landslide that occurred in Petrópolis city, Rio de Janeiro, Brazil, on February 15, 2022. Despite the authors' efforts, several crucial points needed to be revised and remade. Considering that, I suggest reconsidering the manuscript with MAJOR REVISIONS.

Abstract:

The authors mention two datasets. The first one started in 1977, and another one began in 1985. Where did the data from 1932 come from? Is it another dataset?

Authors: It is not another dataset, 1932 is the year when an agency started to register the rain volume for Petropolis' region. It is just an emphasis of the argument, and not part of the analysis for rain gauges dataset (1977-2022) nor the remote sensing dataset (1985-2020).

What means "*urban sprawling .. to*"?

Authors: It was a typo in the abstract. We corrected the sentence.

The authors also say that they will investigate the root cause of the landslide, but in the final sentence; they also say, "heavy rainfall was not the **only cause** responsible for the catastrophic event of February 15, 2022; a **combination** of unplanned urban growth on slopes between 45-60°, removal of vegetation, and the absence of inspection were also significant elements of this natural disaster" in which there is not something especially "new" regarding landslides events.

Authors: It was missing an "S" in the expression "root causes" in the abstract. This expression is always used in plural, because many authors (O'Keefe et al., 1976; Maskrey, 1993; Marchezini, 2009; Valencio, 2012; Chmutina, K., von Meding, 2019, Marchezini and Wisner, 2017; Wisner, 2016) consider that disasters are always a combination of factors, including social and environmental characteristics. The novelty of the investigation does not refer to the causes of landslides events, but actually to the confirmation that the studied disaster could not be avoided by just warning about a rainfall forecast. This confirmation was strongly demanded by the Brazilian society due to the severity of the disaster.

Chmutina, K., von Meding, J. A Dilemma of Language: "Natural Disasters" in Academic Literature. Int J Disaster Risk Sci 10, 283–292 (2019).

MARCHEZINI, V.; WISNER, B. Challenges for vulnerability reduction in Brazil: insights from the PAR framework. In: MARCHEZINI, V. et al. (Ed.). Reduction of vulnerability to disasters: from knowledge to action. São Carlos: Rima, 2017. p. 57-96.

Marchezini, Victor. "Dos desastres da natureza à natureza dos desastres". In: Sociologia dos Desastres: construção, interfaces e perspectivas no Brasil, edited by Norma Valencio, Mariana Siena, Victor Marchezini and Juliano Costa Gonçalves, 48-57. 1 ed. São Carlos: RiMa Editora,2009.

Maskrey, Andrew, ed. Los desastres no son naturales. Panamá: Red de Estudios Sociales en Prevención de Desastres en América Latina, 1993.

O'Keefe, Phil, Ken Westgate, and Ben Wisner. "Taking the 'Naturalness' Out of 'Natural' Disasters." Nature 260, 5552 (1976):566-567.

Valencio, Norma; Oliveira, Regiani; Marchezini, Victor and Mariana Siena. "Desastres e desamparo coletivo: o ente público diante dos grupos afetados". In: Processos desterritorialização e identidades sociais, edited by Marilina Conceição Oliveira Pinto, Maria de Jesus Morais and Jacob Carlos Lima. v. 2, p. 123-144. São Carlos: RiMa Editora, 2012.

Wisner, Ben. "Vulnerability as Concept, Model, Metric, and Tool". Oxford Research Encyclopedia of Natural Hazard Science, (2016), 55p.

Line 44: change for "on February"

Authors: We changed as advised.

Line 45: "amounting to 258 mm". What is the source of this rainfall record?

Authors: We rephrased to: "On that day, the city of Petrópolis received an unusually high amount of rain within three hours, amounting to 258 mm, as measured by rain gauges in the city."

Line 46: From where is this information "rainfall the city had seen since 1932"?

Authors: This data were obtained by INMET (Brazilian Institute of Meteorology) using data from a rain gauge in Petrópolis (number 83804), which operates from October 01, 1912 to August 01, 1960. This information was added to the revised version.

Line 48: 250 mm of rainfall. Why different rainfall records? Is it from different rain gauges?

Authors: It may be confusing. According to Climatempo (www.climatempo.com.br**) the 30-year climatology for rainfall in Petropolis on February is 250 mm. On line 48 the amount 250 mm appears again but this time it refers to the accumulated rainfall between 4:20 to 7:20 pm on February 15, according to CEMADEN.**

Line 49: From where the authors affirm that "expected rainfall for the month of February to be 185 mm"?

Authors: In Line 49, the rainfall climatology for that month in Petropolis should be 250 mm and not 185 mm, as provided by the Climatempo (www.climatempo.com.br**) agency. We corrected the rainfall data in the revised version.**

Line 50: The previous extreme rainfall record was 1932 or 2011?

Authors: The previous extreme rainfall record was in January 10-11 2011, with 248.5 mm. Now, on February 15 the new record was 250 mm in 3 hours. Previous record as 168.2 mm on 20 August 1952. 1932 was the year when the station of Petropolis started to operate, and authorities began keeping records in 1932.

Line 53: "According to CNN." Is there no federal agency that could give precise information?

Authors: This line refers to news released by CNN based on reports from the Civil Defense after an interview with Brazil's Civil Defense Secretariat on February 16, 24 hours after the disaster. Many people from CEMADEN and the Civil Defense (Federal and from Rio de Janeiro) were interviewed, and that material is well based on solid information. Unfortunately, the Civil Defense Secretariat has not issued any formal statement or technical report that we can use as reference. However, a Technical Report produced by the Brazilian Geological Survey, CPRM, that analyzed the disaster of February 2022 in Petropolis; we would like to keep the link to CNN and to add this reference:

Serviço Geológico do Brasil, CPRM (2022). Avaliação técnica pós-desastre, Petropolis, RJ 2022. www.cprm.gov.br, Ministry of Mines and Energy MME, 9 p. (available from https://rigeo.cprm.gov.br).

Line 58: The authors should say summer austral months. Besides that, the summer austral begins in December. For a better fit, the authors should say warm/rainy season.

Authors: We rephrased to "While this is the deadliest flood and mudslide in the history of Petrópolis, heavy rains are not uncommon during Brazil's summer austral months, and the warm/rainy season goes from November to March".

Line 58: "In December 2021, floods killed at least 33 people and displaced some 50,000 in the country's northeast (Marengo et al 2022)." How is this information relevant to the manuscript? Do the authors intend to study some teleconnection patterns?

Authors: We agree; we excluded the paragraph from the revised version. However, it was just an example of another disaster (flood) triggered by heavy precipitation during the austral summer of 2021-2022. This event has different causes but also shows that most of the disasters occurs during the warm rainy season in the region.

Line 66: I suggest the authors remove all the nonfederal agencies' websites. The information is not reliable. I tried to access https://newsbeezer.com/brazileng/with-171-dead-the-tragedy-inpetropolis-is-the-largest-ever-recorded-in-the-municipalitys-history-rio-de-janeiro/ and the result as NOT FOUND.

Authors: We agree, and we cited the following in the revised version:
Guerra, A.: Catastrophic events in Petrópolis city (Rio de Janeiro state), between 1940 and 1990. GeoJournal 37, 349-354, https://doi.org/10.1007/BF00814015. 1995.

We have also added a technical report from 2022 about the Petropolis disaster produced by the Brazilian Geological Survey CPRM from the Ministry of Mines and Energy.

Lines 71-76: Again, the authors are using not reliable sources to describe the past natural disasters in Rio de Janeiro state. I guess if there is any reliable academic and scientific work made that could be used instead.

Authors: We agree, and we cited the following in the revised version:
Guerra, A.: Catastrophic events in Petrópolis city (Rio de Janeiro state), between 1940 and 1990. GeoJournal 37, 349-354, https://doi.org/10.1007/BF00814015. 1995.

We have also added a technical report from 2022 about the Petropolis disaster produced by the Brazilian Geological Survey CPRM from the Ministry of Mines and Energy

Line 82: What is "Marengo al Alves 2012"?

Authors: Marengo and Alves (2012); we included the reference in the revised version about the natural disasters that affected the highlands of Rio de Janeiro (including Petropolis) in January 2011.

Marengo, J. A.; Alves, L. M. . The 2011 intense rainfall and floods in Rio de Janeiro. Bulletin of the American Meteorological Society, v. 93, p. S176, 2012.

Line 92: 415 mm of **rainfall.** What are the sources of this rainfall data?

Authors: It is from the city of Petrópolis Civil Defense and was mentioned in the Flood List site (https://floodlist.com/america/brazil-floods-landslides-petropolis-march-2022)

Line 100: This hypothesis is not something new. For sure not only in Petropolis but in several regions of the world.

Authors: The novelty of the investigation does not refer to the causes of landslides events, but actually to the confirmation that the studied disaster could not be avoided by just warning about a rainfall forecast. This confirmation was strongly demanded by the Brazilian society due to the severity of the disaster.

We changed to: "Extreme localized rainfall saturates the soil quickly, disaggregating the soil, destroying trees and roots, carrying large amounts of mud downhill. Therefore, in cities like Petropolis, this situation can be worst due to the combination of poor infrastructure, with people living in hills with 45-60° slopes."

Line 101: What do the authors say about the public government educating the residents about the region's vulnerability?

Authors: Disasters of serious consequences, such as the last one in Petropolis, mean the accumulation of structural and non-structural problems along time. Structural aspects refer to drainage, slopes contention, urban services, and engineering works in general. Non-structural actions, like environmental education, community meetings and prevention advice, are as important as the structural ones. Both are necessary to tackle risks. Currently there are ongoing practices in Petrópolis, as the NUPDEC Vale do Cuiabá, which is a group of people who live in risk areas and are in contact with the local civil defense to have coordinate actions. Even though, there is much more to achieve to make the city resilient. Along with education programs about vulnerability, there must be livelihood programs to either allocate communities outside risk areas or to make risk areas safer or less dangerous, when the reallocation is not an option.

Figure 1: The presentation order of the figure should be inverted.

Authors: The Figure was corrected as advised.

Line 130: How many stations of INMET was used? What means INMET?

Authors: The long-term precipitation time-series was created from 2 weather stations from INMET (A603-Duque de Caxias and A610-Pico do Couto), 2 weather stations from INEA (2243238-Xeren and 2243235-Andorinhas), and one from Cemaden (Sao Sebastiao). We included this revised legend and also the meaning for INMET (Brazilian Institute of Meteorology).

Lines 137: "The hourly rain gauge observations from June 1976". Could the authors explain how the data was an hourly record in that period? I assume only conventional measures were made in that time if they were.

Authors: Yes, the data comes from the INEA monitoring network (http://www.inea.rj.gov.br), the Rio de Janeiro State Environmental Institute).

Line 139: "(http://www.inea.rj.gov.br/ar-agua-esolo/monitoramento-hidrometeorologico/)" There is any information about the rain gauge data (especially de 1973 year), the start of the observations, the spatial distribution. The authors must explain this.

Authors: All these data come from the INEA monitoring network (http://www.inea.rj.gov.br), the Rio de Janeiro State Environmental Institute) and it is freely available under request.

Line 146: "(not shown)". Why discuss that in the manuscript if the authors do not show critical information?

Authors: We excluded the not shown from the revised version and we included the following references:

Huffman, G.J., Bolvin, D.T., Braithwaite, D., Hsu, K.-L., Joyce, R.J., Kidd, C., Nelkin, E.J., Sorooshian, S., Stocker, E.F., Tan, J., Wolff, D.B. and Xie, P. (2020) Satellite Precipitation Measurement: Volume 1. Levizzani, V., Kidd, C., Kirschbaum, D.B., Kummerow, C.D., Nakamura, K. and Turk, F.J. (eds), pp. 343-353, Springer International Publishing, Cham.

Reis, A.A., Fernandes, W.S., Ramos, M-H. Assessing two precipitation data sources at basins of special interest to hydropower production in Brazil. Brazilian Journal of Water Resources. 25, 2020. Doi: 10.1590/2318-0331.252020190068

Line 253: The authors discuss Figure 4 before Figure 2. Please change it.

Authors: We changed as advised in the revised version.

Line 253: "The average for the entire month of February is approximately 200 mm". Please reference the information given.

Authors: According to Climatempo (www.climatempo.com.br) the 30-year climatology for rainfall in Petropolis on February is 250 mm.

Line 254: What means "summer, , S"?

Authors: A "." was missed. We corrected in the revised version.

Line 256: Why January and February? I hope the authors can say where the rainfall data come from. Besides that, how is the reliability of this data? How do the authors compare rain gauges with different time series and spatial distribution? Especially given the complex orography of the city.

Authors: These months are the peak of the rainy season in Southeast Brazil, where Petropolis is located. The data from CEMADEN is quite reliable and homogeneous and all of them have the same period of observations. In all of them, regardless of if they are in lower of upper terrain, the peak of the rainy season is the same, may be same differences due to exposure and different elevation, affecting the amount but the seasonal cycle is the same.

Figure 2: Where are the spatial distribution of the 5 weather stations? Figure 3: Why did the authors make this comparison?

Authors: The spatial distribution of the five weather stations is in Figure 1c and described in the text Line 165-167: ". Since there is no single weather station with enough temporal coverage, rainfall data from five different weather stations located up to 15 kilometers from the highest accumulated rainfall location (Figure 1c) were considered"

Figure 3 show the boxplot for monthly precipitation for January and February considering the period 1977-2022, the monthly precipitation climatology (1977-2022) (blue line) and the accumulated precipitation for 2022 (red line). The boxplot is important to analyze the distribution for precipitation over the entire period, indicating the quartiles, the minimum and maximum values and the outliers (atypical values) in these months. We performed this comparison to analyze also monthly precipitation. In the text, line 346-348 there is an explanation about the results of figure 3: "From our results, mean precipitation for the region in January is 304.19 mm while that in February is 229.28 mm (Figure 3). January 2022 registered an accumulated rainfall of 581.4mm, the second biggest value in entire series. In February, the accumulation was 650mm, the largest value for the 46-years series and considered as outlier for the month (circle)."

Figure 4a: The number means the rainfall recorded? The numbers are too small. Please redo this figure.

Authors: The Figure was corrected as advised.

Figure 4b: Why did the authors choose Alto da Serra station? Is that near to the landslide local?

Authors: We choose Alto da Serra Station because is the only station with water level and rainfall data. We included this information in the revised version.

Line 293: "The INEA hydrological station, Alto da Serra (2243315) was the only one with data of this event". This information is not true.

Authors: Yes, it is true. We choose Alto da Serra Station because is the only station with water level and rainfall data of the event.

Figure 7: Why are the authors comparing these time images?

Authors: The role of antecedent rainfall and soil moisture condition prior to a rainfall event have been shown by several researchers to be a significant factor in landslides. (e.g. Zhuo et al. 2019, Marino et al. 2020, Palazzolo et al. 2022). As the accumulated rainfall increases, the soil water content and pore water pressure increases. This results in increase in water permeability and lateral water flux within surface soil. This situation is more inductive to landslide occurrence and less rain would be required to initiate landslide than it would be for a drier slope. Therefore, we used the soil moisture index to show the soil moisture prior to the landslides in Petrópolis.

Marino, P., Peres, D.J., Cancelliere, A. et al. Soil moisture information can improve shallow landslide forecasting using the hydrometeorological threshold approach. Landslides 17, 2041–2054 (2020). https://doi.org/10.1007/s10346-020-01420-8

Palazzolo, N., Peres, D. J., Creaco, E., and Cancelliere, A.: Potential improvements of landslide prediction by hydro-meteorological thresholds: an investigation based on reanalysis soil moisture data and principal component analysis, Nat. Hazards Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/nhess-2022-175, in review, 2022.

Zhuo, L., Q. Dai, D. Han, N. Chen, B. Zhao and M. Berti, "Evaluation of Remotely Sensed Soil Moisture for Landslide Hazard Assessment," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 12, no. 1, pp. 162-173, Jan. 2019, doi: 10.1109/JSTARS.2018.2883361.

Figure 9: Why did the authors not differentiate between the images? All of them appear to be the same.

Authors: Figures 9A to 9F show the transition classes every 5 years for the study area, named AOI (Area of Interest) as mentioned in its legend. Despite them appearing to be the same, they aren't. In this figure is possible to verify the urban area (in dark red) for each period and the advancement of the urbanized area (class named as urban sprawl, in blood red) in the vicinity of the hill, as well as the reduction of forest area (forest to pasture or urban sprawl classes). The graphic in Figure 9 reinforces the analysis with quantitative data on urban expansion and forest loss. A comment about Figure 9 was inserted in the text (lines 336 – 438).

Line 428: What are the mesoscale convective cell's extraordinary characteristics (a common meteorological phenomenon)? Could the authors explain how specific the atmospheric environment for developing the recorded rainfall amount was?

Line 429: If the SACZ is a usual system during the austral summer over the region, how does this specific SACZ produce this huge rainfall volume?

Line 431: What were the particular characteristics of the cold front?

Lines 431-435: The authors are concluding results that were not shown. Please show the results.

Authors: For comments on lines 428, 429, and 431-435, we have prepared this new text that is included in the revised version of the paper:

"Figure 12 shows the surface winds and temperature for the 18:00 UTC on February 15. It is noticed the cold front with the temperature gradient and changes in wind direction. Southerly winds on the mountain region where the urban part of the of the city of Petrópolis (region prone to landslides) turned the "orographic cloud" (cloud that positions on the top of mountains for hours and that normally do not precipitate) into a convective cell, which is very rare. Due to the sudden formation and the null displacement of the storm, the weather

radars also did not allow its anticipated tracking. It is noteworthy that the current state of knowledge and meteorological forecast does not allow predicting where each individual cloud will form, with which this event could not be predicted in advance.
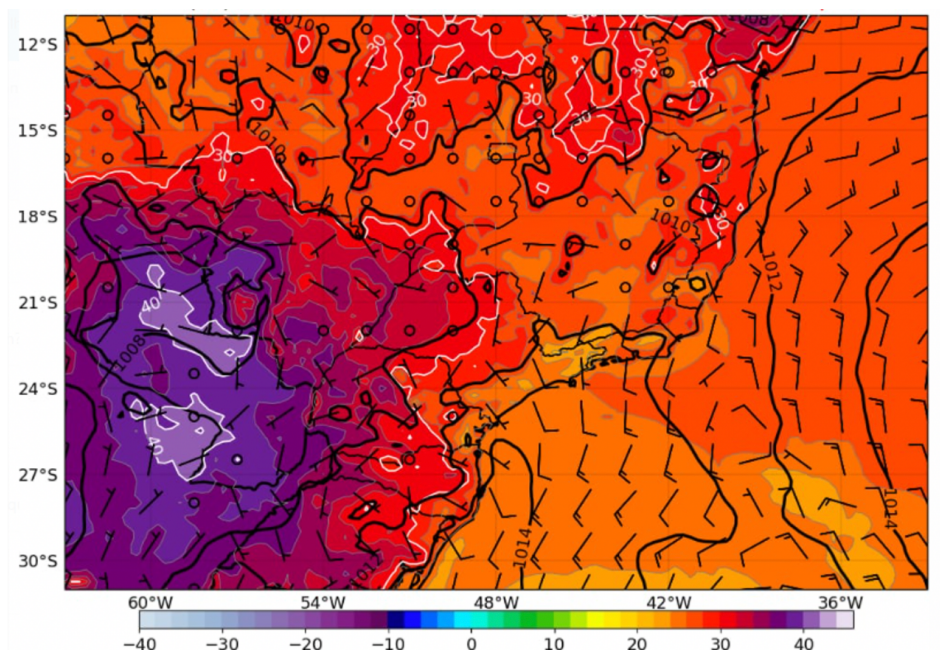

Figure 12. GFS analysis at 18:00 UTC for February 15 2022 for the Petrópolis region. Shades represent surface temperature, isolines represent sea level pressure and the barbs shows wind speed (in knots).

Figure 13 (lower side) shows the radar images of Pico do Couto site, where the formation of the cloud can be seen exactly above the center of the city of Petrópolis. It should be noted that only the residential area of the municipality was affected by the rain, which lasted more than three hours. The accumulated rainfall over the Petrópolis station (Figure 13, upper side) shows the most intense rain between 19:00 and 21:00 UTC. The highest record of 260 mm in just 4 hours, occurred between the afternoon and evening of February 15, is unprecedented in the city. It can also be noted the curvature of the storm produced by the southerly winds (represented by blue arrows in the figure) which resulted in its long persistence.
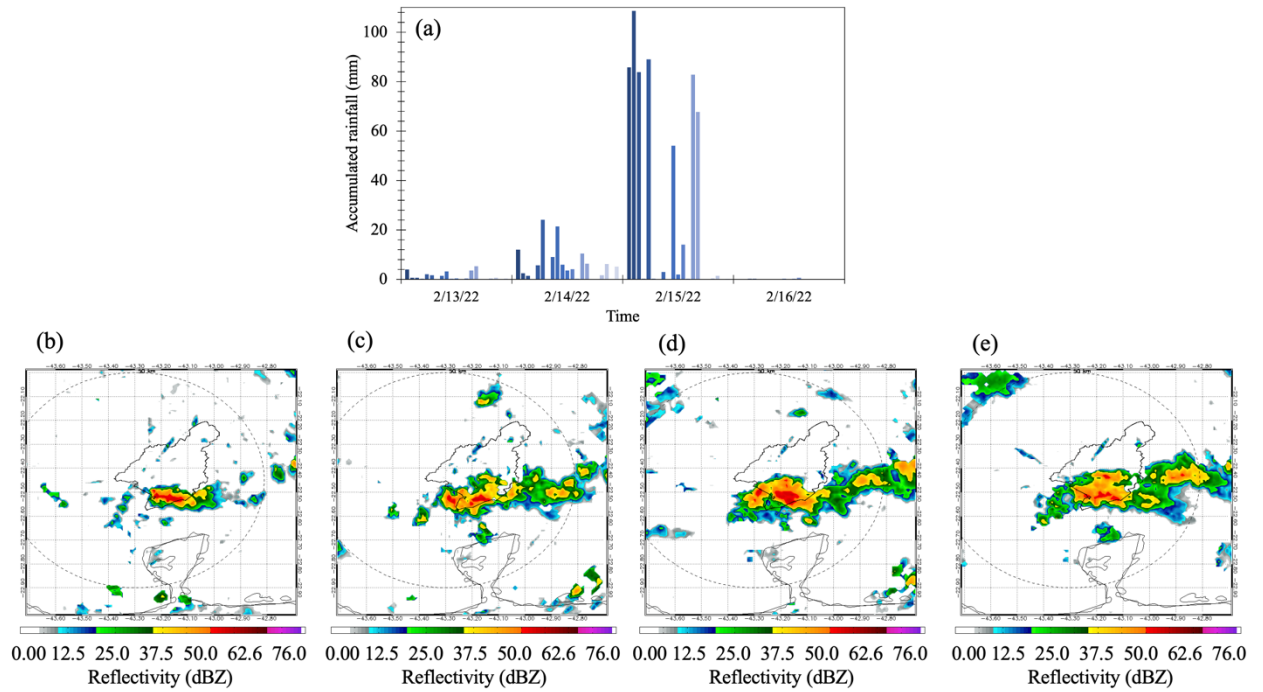
Figure 13. Hourly rainfall for various CEMADEN's weather station in the city of Petropolis during February 13-16 2022 (a), radar images at the Pico do Couto site taken at 7 pm (b), 7:30 pm (c), 8 pm (d) and 8:30 pm UTC for February 15 2022. (Source: CEMADEN).

Line 517: Why does a scientific study need to be compared to media reported?

Authors: We have eliminated these words: "Contrary to what the media reported…"