Authors' Responses to Reviewer 1 (RC1, 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.

Comments

This is a very interesting and well-written article that thoroughly describes the causality, process, and consequence of the catastrophic landslide events over Petrópolis, Rio de Janeiro recently. Explanations for the different driving factors including meteorological conditions, topographic layout, land use changes etc. are well presented. I think this paper is a significant contribution to the community and worthy of prompt publication after a minor revision.

Major comments

1. The introduction of the meteorological background is a little weak. Some in-depth description like synoptic pattern, mesoscale discussion, and most importantly, the mesoscale convective cell that brought the torrential rainfall should be added. In this way, the weather extreme could become more tangible to the readers than just a number of precipitation amount. In addition to the spatial distribution, the vertical extent of the mesoscale convective system could also be indicative of the severity of the event. Therefore, the authors may look into the weather radar data if possible.

Authors: We thank the reviewers for their comments.
We added the following text in the methods:
"To examine the synoptic weather pattern that spawned the mesoscale convective system (MCS) with unprecedented torrential rainfall, the fifth generation of atmospheric reanalysis (ERA5) produced by European Centre for Medium-Range Weather Forecasts (ECMWF; Hersbach et al., 2020) is adopted for the analysis of atmospheric environment. ERA5 features a horizonal resolution of 31 km and 137 vertical levels with hourly output frequency, which provides a detailed picture of the MCS-hatching synoptic background. Meanwhile, the morphology and organization of high precipitation MCS is analyzed using the National Aeronautics and Space Administration (NASA) merged geostationary satellite half-hourly 4-km-resolution Infrared brightness temperature data (Merged IR; Janowiak et al., 2017).

Hersbach, H, Bell, B, Berrisford, P, et al. The ERA5 global reanalysis. Q J R Meteorol Soc. 2020; 146: 1999– 2049. https://doi.org/10.1002/qj.3803
Janowiak, J., Joyce, B., & Xie, P. (2017). NCEP/CPC L3 half hourly 4km global (60S - 60N) merged IR V1. Retrieved from https://doi.org/10.5067/P4HZB9N27EKU"

We added some radar images and wrote a new discussion on them. The in-depth analysis of synoptic weather pattern has been added. The closest GPM overpass was at least 300km away from the MCS event as shown below. Therefore, the internal structure can only be examined after the release of ground-based radar observation. The following text was included:

“Right before the onset of record-breaking rainfall, central Brazil was dominated by a wide-spread subtropical high-pressure center at 500 hPa level (Figure Xa), whose southern boundary pushed to the 22°S parallel above Petrópolis. As revealed in many previous studies (e.g., Maddox et al. 1978; Mitchell et al. 1995; Wang et al., 2019b), the atmosphere directly under the subtropical high-pressure center is most stable because a subsidence inversion layer (capping inversion) is formed as a result of widespread descending air. However, the atmosphere becomes more unstable toward the edge of the high pressure because of the weakening inversion, which promotes the occurrence of convection. Consequently, a ring of precipitation area commonly forms at the periphery of the high pressure, known as a “ring of fire” pattern (Galarneau and Bosart 2006). The 850 hPa specific humidity distribution (Figure Xb) echoes this pattern, as the warm and moist air is being pushed southeastward towards the edge of the subtropical high, and the moisture is further advected to Petrópolis which fuels the convection there. Figure Xc exhibits the concurrent cloud distribution, where the cold color (< 241K) represents the presence of deep clouds whose cloud top temperature is cooler than the surround area without clouds, and A MCS is formed over Petrópolis. In addition to the influence of the high-pressure center, the MCS that affects Petrópolis is further intensified by a long-wave trough as indicated in Figure Xa. The city is located to the bottom of the 500 hPa trough where there is a strong lifting of air that facilitate the intensification of convection. In summary, the edge of a subtropical high intersects with a long-wave trough over Petrópolis, forming a very favorable environment for the occurrence of high precipitation MCS, which later produced the unprecedented torrential rainfall that caused the flood and landslide.

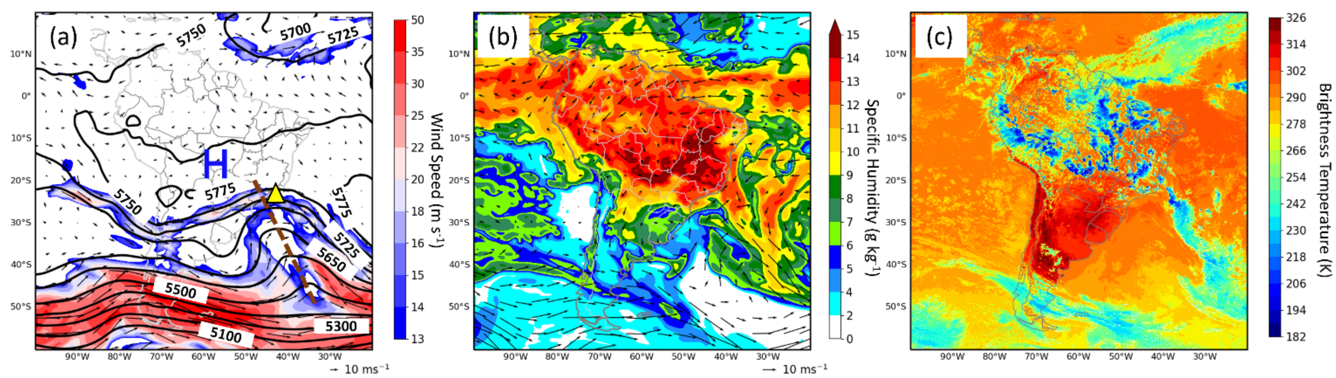

Figure X: Large-scale environmental variables and satellite observation at 16:00 (local time). (a) wind speed (shading), geopotential height (contour), and winds (arrow) at 500 hPa, where the trough line is indicated using a brown dash line and the location of Petrópolis is highlighted by a yellow triangle. (b) Specific humidity (shading) and winds (arrow) at 850 hPa. (c) Merged IR brightness temperature, where cold color represents the presence of deep clouds.

Maddox, R. A., L. R. Hoxit, C. F. Chappell, and F. Caracena, 1978: Comparison of meteorological aspects of the Big Thompson and Rapid City flash floods. Mon. Wea. Rev., 106, 375–389, https://doi.org/10.1175/1520-0493(1978)106<0375:COMAOT>2.0.CO;2.

Mitchell, M. J., R. W. Arritt, and K. Labas, 1995: A climatology of the warm season Great Plains low-level jet using wind profiler observations. Wea. Forecasting, 10, 576–591, https://doi.org/10.1175/1520-0434(1995)010<0576:ACOTWS>2.0.CO;2.

Wang, J., Dong. X., Kennedy, A., Hagenhoff, B., Xi, B. (2019). A regime-based evaluation of southern and northern great plains warm-season precipitation events in WRF. Weather Forecasting, 34, 805– 831. https://doi.org/10.1175/WAF-D-19-0025.1.

Galarneau, T. J., and L. F. Bosart, 2006: Ridge Rollers: Mesoscale disturbances on the periphery of cutoff anticyclones. 21st Conf. on Weather Analysis and Forecasting/17th Conf. on Numerical Weather Prediction, Atlanta, GA, Amer. Meteor. Soc., 3.2, https://ams.confex.com/ams/WAFNWP34BC/techprogram/paper_94414.htm.”

2. The inhomogeneous distribution of landslide occurrences of west-facing vs. east-facing slope is interesting. In addition to the listed multiple reasons, could the orographic barrier effect also play a role in the difference of landslide susceptibility on the lee side of hill vs. the windward side, given the prevalence of easterly wind? (Kumar et al., 2017).

Reference:
Kumar, A., A. K. L. Asthana, R. Singh, R. Jayangondaperumal, A. K. Gupta, and S. S. Bhakuni, 2017: Geomorphology assessment of landslide hazards induced by extreme rainfall event in Jammu and Kashmir Himalaya, northwest India. Geomorphology, 284, 72–87, https://doi.org/10.1016/j.geomorph.2017.01.003.

Authors: The prevailing wind was westerly and in fact it may be orographic influences. However, this is beyond the scope of this study. The orographic barrier effect can only be examined through numerical weather modeling which, and it is matter of ongoing investigation.

Minor comments

1. Line 26, this sentence is awkward, consider rewriting it.

Authors: We rephrased as advised: “Rainfall data were retrieved from 1977 to 2022, while other remote sensing data from 1985 to 2020, were utilized to map the landslide scars, soil moisture, terrain attributes, line-of-sight displacement (land surface deformation), and urban sprawling.”

2. Line 27, the average ‘monthly’ rainfall.

Authors: Was corrected as advised.

3. Line 42, missing space between ‘city’ and ‘is’.

Authors: Was corrected as advised.

4. Line 44, missing space between ‘on’ and ‘February’.

Authors: Was corrected as advised.

5. Line 45, by rain gauges?

Authors: Yes. We included in the revised version: "…as measured by rain gauges in the city".

6. Line 46, change 'combined' to 'accumulation'.

Authors: Was corrected as advised.

7. Line 53, missing space between 'away' and 'cars'.

Authors: Was corrected as advised.

8. Line 58, change 'some' to 'more than'.

Authors: Was corrected as advised.

9. Line 60, change '1.161' to '1,161'.

Authors: Was corrected as advised.

10. Lien 61, change 'heavy rain' to 'torrential precipitation'.

Authors: Was corrected as advised.

11. Line 101, change 'worse' to 'worst'.

Authors: Was corrected as advised.

12. Line 137, it is difficult to locate the rain gauges from Figure 1d.

Authors: The rain gauges is in Figure 1e in green color; we redone the figure to make it easier to see.

13. Line 165, what resampling method was used?

Authors: The data was obtained from the ASF (Alaska Satellite Facility) and according to the product guide, they used cubic interpolation.

14. Line 192, 'the beginning of 2022'.

Authors: Was corrected as advised.

15. Line 256, 'Figure 2 shows the January-February daily rainfall distribution from 1977 to 2022'.

Authors: Was corrected as advised.

16. Line 265, it's better to include the description of what the box and whisker stands for.

Authors: We agreed and we included the description as advised.

17. Line 271, change 'accumulated' to 'accumulation'. Change 'biggest' to 'largest'.

Authors: Was corrected as advised.

18. Line 279, 'Figure 4a depicts the station-based 24-h rainfall accumulation over Petrópolis'.

Authors: Was corrected as advised.

19. Line 285, no need to show so much blank before the events. May consider shrinking the temporal duration to 2/15/2022 12:00.

Authors: We agreed, and we redone the figure as advised.

20. Line 289, it's two 3-h intervals from 16:00 to 21:00.

Authors: Was corrected as advised.

21. Line 350, panels in Figure 7 are not aligned well.

Authors: We agree, and we redone the figure as advised.

22. Line 427, the description of the mesoscale convective cell needs to improve.

Authors: We included the following text:
"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.

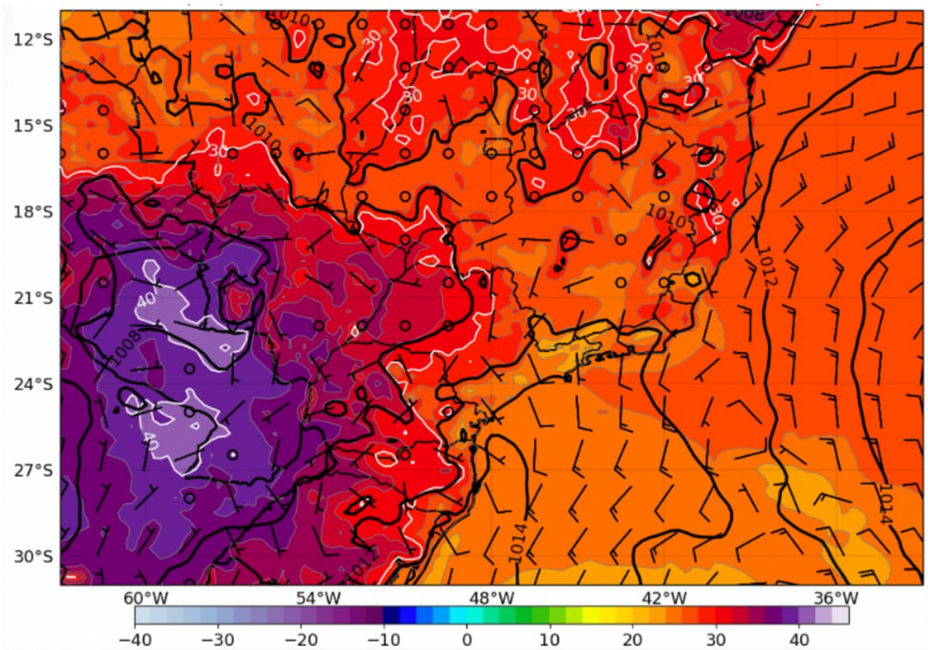

Figure 12. GFS analysis at 18:00 UTC for February 15 2022 for the Petrópolis region. Shades represent surface temperature, isolines represent sea level pressure and the barbs shows wind speed (in knots).

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.

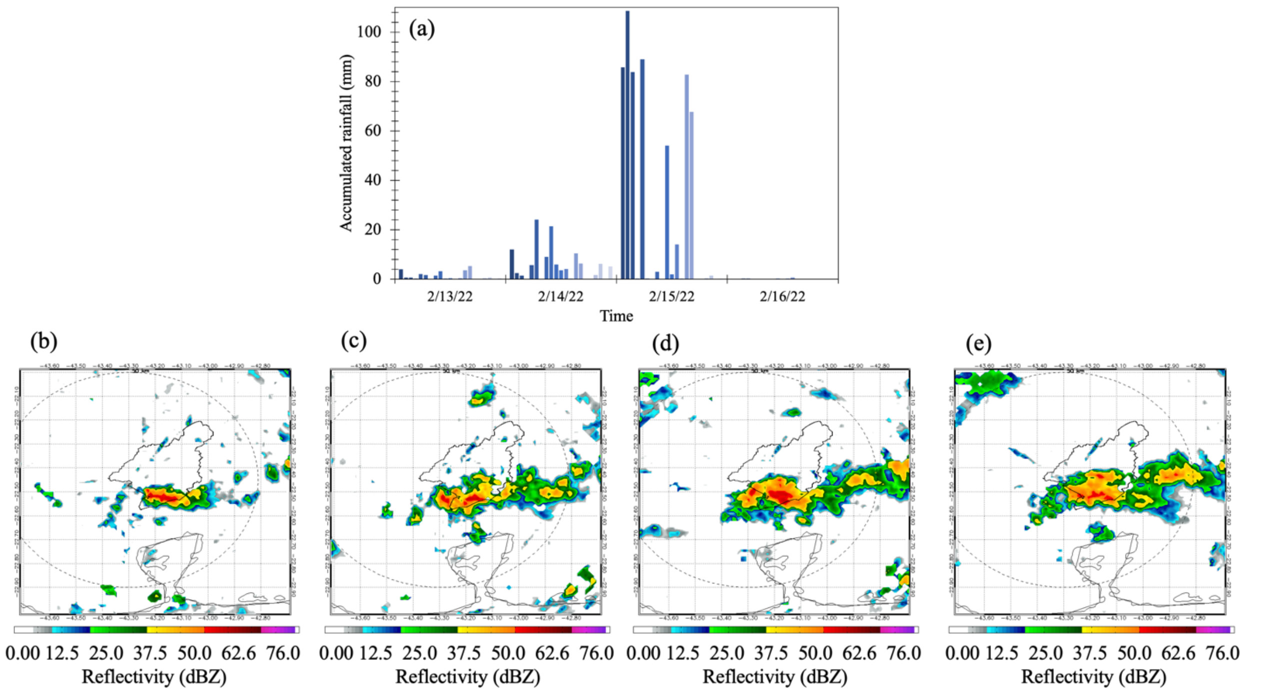

Figure 13. Hourly rainfall for various CEMADEN's weather station in the city of Petropolis during February 13-16 2022 (a), radar images at the Pico do Couto site taken at 7 pm (b), 7:30 pm (c), 8 pm (d) and 8:30 pm UTC for February 15 2022. (Source: CEMADEN).