Nat. Hazards Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/nhess-2020-239-AC1, 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

Interactive comment on "Assessing the impact of explosive eruptions of Fogo volcano (São Miguel, Azores) on the tourism economy" *by* Joana Medeiros et al.

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Received and published: 28 September 2020

General comments:

The authors wish to thank the reviewer Dario Pedrazzi for the constructive comments provided throughout the manuscript. This study was developed in the scope of the research project ERUPÇÃO, funded by the Azores Regional Government, which aims to assess the impact of explosive volcanic eruptions on the sea economy, tourism, and agriculture and their impact on the economic system and social well-being in the Azores. This manuscript presents the first set of results of the economic impact of volcanic activity on the tourism sector, taking Vila Franca do Campo municipally as case

study. Forthcoming studies will deal with the impact on other economic sectors. The kind of approach we present can indeed be extended to other areas of São Miguel Island, and even to other volcanic regions, and using different numerical models, however this would go well beyond the goal of the manuscript, which is to demonstrate the importance and the applicability of this methodology to quantify the economic loss resulting from future explosive eruptions.

Specific comments:

Comment L 111 to 134: maybe I would shrink a little bit this part. The description seems a bit long.

Reply L 111 to 134: We have slightly reduced the text and rewrote the paragraphs as "Fogo A was one of the largest eruptions recorded on São Miguel. Its deposit encompasses a complex and widespread succession of trachytic pyroclastic products emitted from the summit caldera (e.g. Walker and Croasdale, 1971; Booth et al., 1978; Bursik et al., 1992; Wallenstein, 1999; Pensa et al., 2015a,b). The eruption started with a short-lived hydromagmatic phase, followed by a Plinian eruptive column that produced a major pumice fall deposit. The radial and almost symmetrical distribution of the fall deposit indicates that weak wind was blowing from the W during the eruption. The eruptive column experienced partial collapses that generated small volume PDCs and, in the final stage, the total collapse of the column led to the emplacement of a voluminous ignimbrite, reaching > 20 m thick in Ribeira Grande graben (Wallenstein, 1999; Pensa et al., 2015a,b; Wallenstein et al., 2015). The last sub-Plinian eruption of Fogo volcano occurred in CE 1563. The deposit corresponds to a stratified succession of trachytic pumice and ash fall layers (e.g. Walker and Croasdale, 1971; Booth et al., 1978; Wallenstein, 1999; Aguiar, 2018). The eruption started on June 28th in the centre of the caldera, on a previously existing cone (know as Pico da Lagoinha or Pico das Berlengas) (Frutuoso [1522-1591†], 1981). The first phase was hydromagmatic and was followed by a sub-Plinian eruptive column with frequent hydromagmatic pulses. Tephra was mostly dispersed to the eastern part of the island due to predominant

WSW-blowing wind (Walker and Croasdale, 1971; Wallenstein, 1999; Aguiar, 2018). The eruptive activity lasted five days and ceased on July 3rd. A basaltic flank eruption occurred on Pico Queimado dome (then called Pico do Sapateiro), on the north flank of Fogo volcano, four days after the onset of the sub-Plinian eruption. A subsequent phreatic explosion was also reported inside the caldera on February 1564 (Frutuoso [1522-1591†], 1981; Wallenstein et al., 2015; Aguiar, 2018)."

Comment L 156: why did you choose VORIS, which is a probabilistic tool rather than some other?

Reply L 156: We decided to use VORIS because it is an user-friendly tool that allows to perform different types of numerical simulations, i.e. tephra fallout and PDCs, in the same software package directly implemented in ArcGIS. This allowed us to easily overlap the results of the simulations with the mapped exposed elements. The numerical simulations of tephra fallout were computed using an advection-diffusion model, while the simulations of PDCs were performed with the energy cone model, both of which are deterministic models. Numerous papers use VORIS to perform this kind of simulations (e.g. Bartolini et al. (2014) J. Volcanol. Geotherm. Res., 285, 150–168; Becerril et al. (2014) Nat. Hazards Earth Syst. Sci., 14, 1853–1870; Scaini et al. (2014) J. Volcanol. Geotherm. Res., 278–279, 40–58; Becerril et al. (2017) Nat. Hazards Earth Syst. Sci., 17, 1145–1157; Pedrazzi et al. (2018) J. Volcanol. Geotherm. Res., 366, 27–46; Kueppers et al. (2019) Front. Earth Sci., 7, 122).

Comment L 167: bulk I guess

Reply L 166: We rewrote the sentences as "For the most probable scenario (a VEI 4 sub-Plinian eruption), we considered a total bulk volume of 1 km3 (Booth et al., 1978) and a column height of 18 500 m (Carey and Sparks, 1986). For the worst-case scenario (a VEI 5 Plinian eruption), we used a total bulk volume of 3.2 km3 (Booth et al., 1978) and a column height of 27 000 m (Bursik et al., 1992)." We also changed from "Erupted volume" to "Bulk volume" in table 1.

Comment L 170: is this the most likely point to host a new eruption because you have a susceptibility map or something similar?

Reply L 170: We do not have a susceptibility map because we do not know the exact location of the vents of previous explosive eruptions of Fogo volcano. The isopach maps of the recent deposits suggest that in the last 5000 years all explosive eruptions, except one, occurred inside the caldera, although we do not know the precise location of their vents. For this reason and for simplification purposes, we assumed the centre of the caldera as the source for a possible future explosive eruption.

Comment L 171: reference to a web site?

Reply L 171: According to Pimentel et al. (2006), the wind data from the Integrated Global Radiosonde Archive dataset of the National Centers for Environmental Information, formerly the National Climatic Data Centre was acquired online (https://www.ncdc.noaa.gov/data-access/weather-balloon/integrated-global-radiosonde-archive) for the Lajes/Santa Rita station (Azores) WMO ID: 08508, and was compiled between 1947 and 2003, at mandatory levels from 1.5 km (850 mb) up to 26.5 km (20 mb). We have added the website link in the text.

Comment L 186: I am not sure about writing all this paragraph since it is well explained in Felpeto et al. 2007.

Reply L 186: We shortened the text and rewrote the paragraph as "Simulations of PDCs were performed with the energy cone model (Malin and Sheridan, 1982), which provides a fast and conservative approach to assess the maximum potential extent of these volcanic products (e.g. Alberico et al., 2002, 2008; Felpeto et al., 2007; Toyos et al., 2007). The maximum potential extent of a PDC is directly related to the VEI of the eruption and the topography around the vent. A higher VEI implies that the PDC can reach larger distances (Alberico et al., 2008).

Comment L 333: because of the software. it only considers a general PDC

Reply L 333: We did not distinguish between dense and dilute PDCs because this distinction may be dubious at times. It is impossible to predict what kind of PDC will be generated in future explosive eruptions. There is a continuous spectrum of currents between the two end-members, which includes all gradations between dense and dilute PDCs. The two types of PDCs may occur in close association and even during the same event. Therefore we considered a general PDC in the simulations.

Comment L 377: you might show it in the figure to give a better idea

Reply L 377: We think that adding the isopachs map of Walker and Croasdale (1971) in figure 3b would make it harder to read. We opted to add a more specific reference in the sentence "(see the isopach map of the Fogo 1563 deposit in figure 20 of Walker and Croasdale, 1971)".

Comment L 383 to 396 I find this part very general.

Reply L 383 to 396: We rewrote the paragraphs as: “The impact of tephra fallout on buildings and infrastructure will depend on the thickness of accumulated tephra, which is translated as static load. In localities affected by the accumulation of 20 cm or more of tephra, such as those on the central and eastern parts of Vila Franca do Campo, buildings would suffer significant damage. While in localities where the 1 m threshold is exceeded, such as Ponta Garça in the summer period, buildings would likely suffer total collapse, including constructions reinforced with concrete (Blong, 1984; Spence et al., 2005). However, if tephra is wet these critical thickness thresholds are substantially reduced (Spence et al., 2005). This possibility should not be overlooked given the rainy Azorean climate (Hernández et al., 2016). Other elements such as the ground transportation network would also be affected by tephra fallout. As the main roads of Vila Franca do Campo are located on the southern part of the municipality, they are mostly vulnerable to the accumulation of tephra fall deposits during the summer period. Marine transportation can also be affected by tephra fallout as ports and marinas become inoperable. Particularly during the summer period, marine operations along

the south coast of São Miguel would be severely affected and important fishing ports, such as Vila Franca do Campo, would be brought to a halt.”

Comment L 408: which shouldn’t be the same for dilute and dense PDC

Reply L 408: We rewrote the sentence to clarify this issue: “The impact of PDCs on buildings and infrastructure is mostly related to their dynamic pressure and temperature. However, in this case we do not distinguish between dense and dilute currents, and assumed a binary impact approach which considered the absence of damage or total destruction of buildings and infrastructure by PDCs.”

Comment L 443: I would shrink a bit the conclusions

Reply L 443: We rewrote the conclusions as: “This study presents a new approach to quantify the impact of explosive volcanic eruptions on the tourism industry. We determined the economic loss related to future explosive eruptions of Fogo volcano (São Miguel Island), by estimating the benefits generated by the accommodation units of Vila Franca do Campo municipality. Two eruptive scenarios were considered for Fogo volcano, the most probable scenario (a VEI 4 sub-Plinian eruption) and the worst-case scenario (a VEI 5 Plinian eruption). We evaluated the vulnerability of tourism-related buildings and infrastructure in Vila Franca do Campo to tephra fallout and PDCs by analysing their loss of functionality. The Loss Present Value (LPV) method was used to estimate the benefits generated by the accommodation units for different economic scenarios. The simulations show that tephra deposition from a VEI 4 sub-Plinian eruption during the summer period occurs to the east-southeast of Fogo caldera, while during the winter period the deposition is to the east of the caldera. For a VEI 5 Plinian eruption the dispersion patterns are similar but with a larger dispersion area and thicker tephra deposition. The simulations of PDCs show that the central part of São Miguel is the most affected, as currents flow down the flanks of the volcano, reaching the sea on both coasts. The assessment of the economic impact on the tourism sector shows that economic scenario 1 (tephra fallout from a VEI 4 sub-Plinian eruption) has the lowest LPV when compared to economic scenarios 2 and 3 (PDCs from VEI 4 sub-Plinian and VEI 5 Plinian eruptions, respectively), which have similar LPVs. Although economic scenario 3 is not the most likely, as it represents near total destruction of Vila Franca do Campo municipality, it corresponds to the higher economic loss, with approximately 145 million euros over 30 years. Tourism is a growing industry worldwide and in the Azores has had an increasing importance in the economy since 2015. However, the Azores and other active volcanic regions are vulnerable to future eruptions, which may have long-term economic consequences. Volcanic hazard and risk assessment is therefore essential in areas where people live side by side with active volcanoes, to provide the competent authorities with appropriate strategies to mitigate volcanic risk, such as land use planning, emergency management and post-disaster economic recovery planning."

Comment page 24: what system do the coordinates refer to? the same for the other figures. Reply page 24: Figure 1 (a) and (b) are presented in geographic coordinates, datum WGS84. While infigure 1 (c) and figures 2, 3, 4, 5, 7, 8 and 9 the coordinate are in the UTM system, zone 26S, datum WG84. We have added this information in the figures captions.

Comment page 30: ok here the colour of hte exposed elements at risk is not very visible. the same below. Reply pages 30, 31 and 32: On figures 7, 8 and 9 we removed all the other buildings that were in black and changed the Accommodation units colour to black, to try to stand out more.

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