RESPONSE TO REVIEWS

Reviewer comments are in black and *our answers are in blue*

Dear Editors and reviewers,

We acknowledge these meticulous reviews as they improved the manuscript organization and clarify many aspects of the methods as well as the results. Also, they allowed us to deepen the discussion by pointing out the limitations and the strengths of our approach, as well as our crucial interpretation of hazard maps.

All major comments were answered and the text improved as required. These changes include new numbering of the sections by gathering methods and data and providing a clearer results section and a longer and deeper discussion. Figure 5 has been improved. Figure 7 has been improved as recommended by both the reviewers and is now described in more details in the results section and well discussed in the discussion section. Anew figure (figure 8) was added to support discussion. All minor corrections were done.

REVIEWER 1 : SIMONE TARQUINI

General comments

The manuscript illustrates a comprehensive work about the hazard posed by lava flows at Piton de la Fournaise volcano. The input data presented (DEMs, lava flow maps and relevant parameters among others) are certainly rich, and provide an ideal starting point to carry out the present analysis. As usual with this code, DOWNFLOW provides an incredibly rich database of simulations. In spite of the great databases, I think that the interpretation and discussion of the hazard maps (especially the time series for the Enclos), should be slightly refined/adjusted. I also suggest to add some clarification in the use of the code. Finally, I suggest some refinements in the wording in places, where the editing has been probably hastily bundled. For sure, I have no severe concerns with the present work and I am sure it will be adequately refined.

Major points (in order of line number)

Code tuning

Lines 286-293 – here the authors describe the code calibration. Please remind to the readers which grid resolution are set for each DEM when they have been set up for simulations. This is not trivial, because the LIDAR DEM (in section 2) was described as having a mix of 5 and 1 m resolution. I can argue the authors used a 5 m grid, but clarify this.

This is now clarified (section 2.1)

More importantly, if the authors used a 25 m cell size for the 1997 DEM and 5 m cell size for the other cases, could they explain whether or not such a strong difference has an impact in the output of the tuning?

Yes, the DEM resolution has an impact on the calibration of the model. Although we did not test it here, it is actually well known. We added explicitly this information 'Note that the difference in DEM resolution (25 m for 1997 and 5 m for 2010 and 2016) implies that the random noise in elevation (Δh) is applied on a different spatial frequency. On a given *topography, the lower the pixel size the greater is the amount of random noise that needs to be applied."*

The random noise in elevation is applied at a rather different spatial frequency in the two cases (25 times more often per unit area for the 5 m DEM). In other probabilistic codes (I remember Q-Lavha, Mossoux et al 2016, for example), varying the cell size is part of the tuning session. I know this is not the case with DOWNFLOW, but I would appreciate if the authors can clarify this (possibly not negligible) point so as to avoid possible misinterpretations of results.

Yes you are right this is not the case for DOWNFLOW and when using a 5m DEM we actually have 25 times more perturbation to apply than with a 25m.

At the end of section 5 we added:

"Note that the difference in DEM resolution (25 m for 1997 and 5 m for 2010 and 2016) implies that the random noise in elevation (Δh) is applied on a different spatial frequency (on a given topography, the lower the pixel size the more random noise is applied)."

Evolving haz map Lines 361-370 – This paragraph should be the summa of the whole work, but it is weak instead. The preceding sections painstakingly refined every single factor (vent opening pdf, length frequency, code calibration..), but all this ends up in a vague description.

This part of the manuscript was rewritten in order to comply with both reviewers' suggestions, now section 3.2

I think Figure 7 doesn't help enough (see suggested improvements). For example "we note the development of a high probability area to the north of the terminal shield" (lines 362-363). I am completely lost, unable to see it. Or "This is due to the high number of eruptions occurring to the north of the shield between 1998 and 2006" (lines 363-364); I do look at the rich data provided in Fig S2c, but it shows (to me) an essentially balanced number of eruptions to the north and to the south of the shield.

Figure 7 has been improved according to both reviewers' suggestions

More importantly, the above suggests that the authors are deeming a dominant factor the modification of the pdf (new vents, then higher vent opening pdf, then higher hazard to the North). This could be a perfectly reasonable explanation, but the authors should note that this acts against the (often reminded) impact of morphological changes due to new lava deposits (e.g. "the evolution of the hazard maps resulting from changes in the DEMs" -line 82 in the introduction-). The local stacking of multiple lava flows to the North should act as a damper of the probability of future lava inundation to the North. The latter point is clearly shown by Tarquini and Favalli 2010 (see refs below) and Favalli et al 2011 at Mt Etna. However, Fig 7 (right column) shows that here flow fields tend to pile up multiple times in a few years. Is this an outcome of topographically confined areas?

Indeed flows tend to pile up in the south of the terminal shield. As it can be seen in Figure 7, although the emplacement of the large 2015 eruption changed the topographies and therefore affect the probability of future lava flow invasion toward lesser value, this did not prevent the 2017 flow to emplace exactly there. This is now explain in section 3.2 and using figure 8.

Otherwise, lava flows are so thin here, that they do not promote the usual topographic inversion (which inhibits superposition)?

Both instances at once? I am not asking to clarify this – beyond the present scope – , but it is important to describe/clarify the different role played in the evolving haz map by factors such as changes in the vent opening pdf and DEM modifications due to new lavas. For sure, an assessed step to strengthen the discussion about the evolving hazard in a clear and objective way, is to derive the maps of the hazard difference as shown in the references above.

We accordingly clarify this point (section 3.2 and using figure 8)

To support statements such as "Figure 7 also illustrates that the hazard maps were able to predict where subsequent lava flows actually occurred" (lines 366-367) I suggest to overlap the contour of such subsequent lava flows to the haz map (as in Favalli et al 2009c and in the references above), otherwise the reader simply cannot grasp the (eventual) correctness of the statement.

Done

The authors indicate the voluminous 2007 flow as a case of poor prediction of the map. They state the "issue" with this eruption is due to a vent at an exceptionally low elevation (i.e. in a low pdf area). The point of the eruptive cycles is clear and convincing (as discussed ahead), and exceptional end-cycle eruptions can be tricky. But I didn't find this point particularly intriguing.

I was intrigued, instead, by two evidences (if I see well enough) in the haz maps of Figure 7, which emerge when haz maps are compared with the following lava flows (right column Fig 7 or Fig S2): 1) – In the 1997 haz map the purple (5-10%) and dark blue areas (>10%) form a broad peak covering almost completely the southernmost third of the EF. In contrast, the flows in Fig S2c appear piled up elsewhere (mostly <5%), with a poorly covered peak. Please check if I am right. It is possible that this suggests a "too high" peak of vent openings in the southern flank of the shield ? 2) – In the 2016 haz map (if I see correctly..) the 2018 lava flow covers, to a significant extent, a green (low probability) area midway between crater and southern rim of enclos. Being downhill from a peak of vent openings, this low haz area should be the result of a "topographic shield". It would be interesting to explore/explain why it has been nonetheless inundated (if this is true). If this comment turns out to be correct, it wouldn't "invalidate" the map, it would simply show that it is necessary to be cautious in using it.

Yes you saw correctly. This is now clarified in the discussion in the section "Validating hazard mapping with recent eruptions"

Additional specific comments (in order of line number)

line 63 – "Bretar et al 2013" is this the correct reference? Check please

Yes it is correct.

line 75 – modify "in a such this dynamic" into "in such a dynamic" (tentative suggestion..)

Done

Line 81 – "from the three DEMs acquired"

Done

line 140 – "open ion the Grandes.."

Done

Section 2

line 168 – perhaps removes all this ".., and indeed up-to-date, .."

Done

line 169 – consider the deletion "For this study we could use to three DEMs"

Done

line 170 – "vertical resolution" appears an odd wording, it could be "vertical accuracy" ? Please rephrase

Done

lines 171-173 – please specify that this DEM is later referenced to (in Figs captions) as the "LIDAR DEM from IGN – released in 2010"

Done

Section 5

If I am not wrong, the description of the DOWNFLOW code is slightly inaccurate. It is hard to suggest something about DOWNFLOW to the authors (being the code programmer among them..), but I feel uncertain about the current text and I have some suggestions.

All suggestions were taken into account.

line 270 – I can propose to change "follow the steepest" with "follow approximately the steepest", so as to suggest why DOWNFLOW introduces the random perturbation to account for lava flow paths.

Done

line 272-278 – I would say DOWNFLOW do not computes "all the possible flow paths" (line 273), but just a number N of steepest descent paths (which are later found to fit lava flow paths..);

Done

instead of a random noise "(with a value of ±Δh)" a noise in elevation randomly varying within the interval±Δh can be clearer?

Done. (see ection2.4)

Line 278 – "occurred immediately after" why the need of being "hurry"? it is important that the topography hasn't significantly changed in the meantime, but if the topography is (just locally) updated, the authors could have adequately tuned Δh) and N by considering not the first, but the second, or third.. or 100th lava flow.

This was rewritten accordingly

Line 280 – consider substituting "cut at actual the length" with "cut at the actual length" (but it could be an English wording I am unaware of..)

Done.

Line 284 – "If this ratio (μ) is one then the two areas coincide perfectly and the simulation is valid",) for sure, the simulation is not valid only if μ = 1.. a similar wording do not help understanding, please reword.

This is rewritten as follow: "Under this condition, μ is a measure of the "goodness of fit" between simulated and actual parameters, where if μ = 1 then the two areas coincide perfectly and if μ →0 then the simulation becomes increasingly unrealistic. Best fit parameters are *usually obtained for μ =0.5 (Tarquini and Favalli, 2011). Proietti et al. (2009) and Spataro et al. (2004) evolve this approach slightly by considering a fitting function of $e_1=\sqrt{\mu}$. This yields the same results, but gives numerical values closer to one."*

I would ask the programmer of the code to check a bit closer this section.

Section 6

lines 304-305 – Please clarify the function for lava flow length frequency distribution. I've seen the histogram in Figure 5, and IF I correctly understand.. a step-wise, discontinuous function is straightforwardly derived from the plot of the number of flows in each bin obtaining normalized frequencies. It is possible to make this function a bit more explicit so as to clarify the function P(Lij) used in equation 2? I see that something is added more ahead at the end of section 7, but it is probably better to clarify upfront here (by adding also a further panel to Fig 5?)
Yes, you understand correctly. This is now clarified in section 2.5 and a new graph (in figure 5b) was added to show an example of the probability function.

Section 7 *(now section 2.6)*

lines 311-312 – the array of computational vents, the different DEMs used and the number of simulations carried out is mixed in the same sentence in a somewhat confusing way, and the reader can make a picture about this only after reading the following sections. I would define at first the sole array of computational vents. If I correctly understand, the two portions of the array (inside and outside enclos) have been used for different purposes (different maps). Only the inside enclos array has been used multiple times over different DEMs (with different vent opening pdf and flow length etc.), while the outside Enclos array is used only once, over the 2010 DEM. Perhaps, it could be also worthy to clarify that, in each haz map presented, only one DOWNFLOW simulation is considered for every single node of the array. This is just to make clear to the reader that – in contrast with what may happens with some other codes – a single DOWNFLOW simulation (combined with P(Lij)) is able to account for a variety of scenarios.
This part was re-written for clarification (see section 2.6)

Section 7.2 *(now section 3)*

line 352 – "recurrence time" I am good with table 3 but I missed the use of a "time" parameter throughout the manuscript.. I remember that Favalli et al (2009c) included the "recurrence interval" (time) in a formula to quantify the hazard. Please make explicit how the recurrence time is used or that it is not used here.
Here we use the recurrence time not to give a time constraint to the hazard map (as done in Favalli et al 2009c) but to correctly rank the overall probabilities of the future vent opening in the different areas since the spatial distribution of scoria cones fails to do so for the reason explained in section 2.6.

Line 362 – "(above 1800 m asl)" please, at least in one of the figures (not in all figures, to avoid overloading information), includes elevation contour lines (e.g. 500 m spaced) to support the reading of the maps, otherwise people less familiar with the altimetry of the volcano can hardly follow similar hints.

The 1800 m asl outline is actually the dashed line between Enclos Fouqué et Grande Pentes in figure 1. The dashed lines were added to Figure 6 as well, and this is now specified in the figure captions.

Line 387 – "representativeness of future eruptions", future eruptions or past eruptions?

Future eruptions: here we want to discuss whether using the database we have (based on past eruptions) is good or not for future eruptions.

Lines 406-409 – "However, .. (Fig 6)." The clarity of this sentence could probably be improved, but I completely agree. All in all, after all the work presented (and pending upon further refinements..), it seems that the impact of the topographic changes is limited. It seems that the frequent topographic resurfacing due to new lava flows keeps a "smooth" topography here, and do not introduces new "cumbersome" features (e.g. thick lava bulges such as happens at Mt Etna) which substantially affect the paths of future flows.

It depends on the volume of lava extruded, in some cases the changes can have a dramatic effect. For example, in a published article (Harris et al. 2019) we show that the changes in topography due to the 2015 eruption (35.5 Mm^3) needed to be taken into account in order to model the trajectory of the April 2018 lava flows that occurred in the same area.

Lines 410-445 – the point of the cycles (stressed on lines 426-427) could be confirmed/strengthened (or not) by plotting the length data of Figure 5 along a time abscissa. A tip could be to account for the bias obviously introduced by the length cut at the sea by considering the volume (Vlastelic et al 2018), thus using the volume data as a proxy for the missing full length (e.g. the 2007 flow length)

Vlastelic et al 2018 have already plotted the volume against time to define the cycles. The length vs. time do not reveal something more than what was showed by Vlastelic et al. 2018. Unfortunately, the relationship between volume and length is not straightforward. We therefore have now added some nuances in our discussion.

See section 4.3

Section 8.1.2 *(now section 4.3)*

as for the modeling, I would recommend to fix the point of the cell size (noted above) before stressing on the different Δh. I note that id you take 2Δh as the obstacle, then the obstacle height difference when Δh = 2 and Δh = 5 is 6 instead of 3 as reported (line 456).

This is now corrected

The comment about the difference between the post 1997 and post 2007 lava flows could benefit from the plot suggested above for lines 410-445.

Done

9 Conclusions *(now section 5)*

Beside what stated, an idea could be to highlight the different weight of the topographic changes with respect to the paths of future lava flow (and thus hazard) at different volcanoes. At Piton this factor appears to have a mild effect, as opposed to what has been found at other volcanoes such as Etna. Recent lava flow maps derived for Nyamulagira (Smets et al. see below) suggest a behavior similar to the one observed in the enclos (frequent lava flow superposition suggesting limited topographic inversion).

Line 754 – ..(green dotes..)
Done

Line 774 – remove reference to the green line (there is no inset as in Fig 1 here)
Done

Figure 4 – left column, it is not easy to separate the inside and outside of the polygons of lava flows. What about a dotted pattern inside or some partial transparency?
We found that it is actually better to outline the flows with an empty polygon rather than a dotter pattern or partial transparency. The outlines are now in white and more visible

Figure 6 remove "green line" from the caption
Done

Figure 7 right column, I would find clearer if the intervals are set to 1998-2010, 2010-2016, 2016- 2019.
The point here is also to show how good the hazard map would be if we only had done the hazard map in 1998, 2010 or in 2016.

Figure S1

In the legend, the black line is not the lava flow length, but rather a kind of "approximate lava flow axis" (which are then used to derive lava flow length).
Yes. This is now specified in the caption as well as in the legend

Speaking only about the outside enclos lava flows (impossible to decipher the inside), it seems that there are several flows without an axis (e.g. towards the southern coast). Perhaps these have not been accounted for because of some reason I forgot now (please confirm in the caption if this is the case or resolve otherwise). Could you confirm that the long-stretched lava flow axis along the riviere the langevin – riviere the remparts are assesed as single lava flows (perhaps partly eroded or sunk below river deposits) ?
Extracting the lava flow length outside the Enclos is difficult for the oldest flows because for example the flows in the southern flank were not entirely mapped, and it is therefore complicated to extract their length. These flows were therefore ignored (same for the outside Enclos area to the east of the Enclos). Therefore it is true that this close bias our results.
Both lava flow in the Riviere Langevin and Riviere des Remparts are considered as single long flow (although eroded).

Figure S1 caption – perhaps substitute "Map of the extracted lava flow length" with something like "lava flow axes used to measure the maximum length of flows"
Done as mentioned above

Figure S2 caption – the four intervals indicated in the current caption do not mach at all the labels.. and there are hiatuses (?).

Ups, indeed this was an error- corrected now

The present collection of lava coverage is extremely useful. In order to allow the reader to profit at best from this collection, I propose to increase the number of panels to further promote interpretation of haz maps.

This is the entire full collection of lava coverage as compiled by Derrien 2019 (provided in great details) and completed with the 2019 eruption.

This 4 panels represent the lava flows during the main cycles.

We prefer to keep them like this rather than increasing the number of panels. We add here that this collection is available upon request to OVPF-IPGP.

Improvement of Figure 7 has benefit from some of this lava flow coverage data.

References (if not already cited in the manuscript)

We included the references that were suitable

Mossoux, S., Saey, M., Bartolini, S., Poppe, S., Canters, F., & Kervyn, M. (2016). Q-LAVHA: A flexible GIS plugin to simulate lava flows. *Computers & Geosciences*, *97*, 98-109.

Smets, B., Wauthier, C., & d'Oreye, N. (2010). A new map of the lava flow field of Nyamulagira (DR Congo) from satellite imagery. *Journal of African Earth Sciences*, *58*(5), 778-786.

Smets, B., Kervyn, M., d'Oreye, N., & Kervyn, F. (2015). Spatio-temporal dynamics of eruptions in a youthful extensional setting: Insights from Nyamulagira Volcano (DR Congo), in the western branch of the East African Rift. *Earth-Science Reviews*, *150*, 305-328.

Tarquini, S., & Favalli, M. (2010). Changes of the susceptibility to lava flow invasion induced by morphological modifications of an active volcano: the case of Mount Etna, Italy. *Natural hazards*, *54*(2), 537-546.