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.
Reviewer 2 (Hannah Dietterich) raised a large number of forward questions that are totally justified and very interesting. For example, she asked if other numerical models were used, she suggested to incorporate time (probability of inundation at a location over a given time interval), as opposed to just a conditional probability for a future event, or suggested to provide quantification of probabilities in a given area (for example: what is the probability that the road will be cut), etc... Applying all these suggestions, would require significant additional data and great lengthening of the article, as well as data that are outside the scoop of this study. We find more appropriate and valuable for our study to not add more data here. This will ensure our article to be concise (already at length) and accessible for authorities and non-specialist as well. It is very important to recall that there are limited studies (if any) on lava flow hazard map at Piton de la Fournaise, in comparison to other volcanic centers such at Etna, or Hawaii were numerous articles have already been published on the subject.
*Our aim in this article is to provide a first version of a hazard map of Piton de la Fournaise, so it may serve as a reference study for future specific research topics on Piton de la Fournaise such as testing other methods to compute the hazard map or provide probability of inundation as function of time etc… (that would fulfill the reviewer's suggestions). Also through this article we aim at providing a clear article that explains our rather simple approach for the civil protection and authorities to understand is and to use it as support for potential land use planning and management. As mentioned in the last section of the discussion: "*The presented map is thus also intended to aid and guide stakeholders in developing effective mitigation and land use plans that also take into account the main volcanic hazard, with the caveat that our maps are for a "typical" effusive event."

We hope that the article in this new shape and improved content is now suitable for publication given the changes we provided. 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 2 : Hannah Dietterich

Lava flow hazard map of Piton de la Fournaise volcano

Chevrel et al.

In this manuscript, Chevrel et al. present an eruptive history database and methodology to produce numerical lava flow simulations and a probabilistic assessment of lava flow inundation hazard at Piton de la Fournaise. Their method builds on previous work done by these authors at other volcanoes to incorporate the complex spatiotemporal eruptive history of Piton de la Fournaise and, as they importantly highlight, the impact of topographic change at a frequently eruptive volcano on evolution in lava flow hazard. Overall, the manuscript is very good and will be of interest to a broad audience. The data, methods, and analysis are all appropriate, but some elements of the methodology and key discussion points are missing or wanting of more details. Below I summarize some major comments, questions, and suggestions. Pardon the length, these comments are largely minor, this is just a topic I am very interested in. There are also a number of typos and word order errors that just require a close reading with fresh eyes by the authors to fix.

Major comments

Using recent eruptions to assess methods and implications

A unique and powerful element of this work is the assessment of lava flow hazard through time using DEMs and eruptive history data that evolve over recent decades. Although these are used to generally state that changing terrain impacts hazard mapping and that recent flows generally occurred in areas that were previously deemed more likely, a missed opportunity is to use these maps and data to do a full hindcasting assessment and validate the method being presented. How well does the map based on data up to 1997 work for eruptions after 1997? Can this be quantified (e.g., Bevilacqua et al. 2017)? Is it better initially and then gets worse as topography changes more and more? What about up to 2009? This study has the distinction of allowing this critical discussion of how well we expect maps like this to do, what timeframe they're useful for, and where they fail given the availability of data over time and very frequent eruptions. These are topics that are all touched on but they are not framed in this fundamental way, where a hindcasting assessment would organize and strengthen the key conclusions. Showing that the method works well for recent decades would demonstrate validity and support further applications. I recommend adding a section to the discussion on this ("Validating hazard mapping with recent eruptions") and accompanying Fig. 7 with quantification of how well the map did for later flows through time. It is also regularly mentioned, but never demonstrated how topographic changes impact hazard assessment. Since this is a major conclusion of this work, and testable with the time series of hazard maps and eruptions, this is a good opportunity to show the changes caused by topographic evolution with visuals.

Accordingly, a new section in the discussion was added (section 4.1). We did not complete further analyses to quantify how well do the maps predict future eruptions but we instead discuss this matter in more details as recommended and improved figure 7 accordingly. We also provide one more figure (figure 8) to show the difference of hazard probabilities together with the differences in topography.

Treatment of spatiotemporal variability in eruptive behavior

As mentioned and assessed throughout the paper, there is significant variability in the frequency and style of eruptions both spatially and temporally at Piton de la Fournaise, including rare rift zone events, frequent (but episodic?) summit activity, and cyclic patterns in eruption location and magnitude in recent decades. Currently, these are integrated empirically into a conditional hazard map (probability of lava inundation in the next eruption) that incorporates historical data or geologic mapping at various timescales depending on location. However, in the discussion it is then stated that this approach does not integrate all magnitudes or timescales depending on what the "next" eruption is. Certainly, eruptive history that is left out of the input data for hazard mapping will not be represented (e.g., lava lake activity that is not well preserved in the geologic or historical records), but it is unclear why the authors also do not feel that the map represents events that are included (e.g., recent large eruptions that end each eruptive cycle).

Indeed this part was re-written in the discussion (section 4.1) as follow:

"Because our hazard maps are computed with a database in which only four of the 137 eruptions since 1931 are high volume, source-related-cycle terminating, events (i.e. 1931, 1961, 1986 and 2007), such infrequent events have a low probability and hence may occur in low probability areas. For example, it is clearly visible that the April 2007 lava flow occurred in a low (<0.5 %) probability zone of the 1997 hazard map (Figure 7a). It is therefore important to recall that low probability does not mean that an event cannot happen, it only means that it is less probable, i.e., it is atypical if it happens in a low probability area."

If the input data are not representative, it would be helpful to offer suggestions for how they could be represented moving forward, or utilize a different methodology for the treatment of these spatiotemporal patterns. Similarly, if the results have limited utility to specific time periods or scenarios, incorporating those explicitly, such as producing different conditional probability maps for specific conditions or regimes (e.g., just the large events that occur only after smaller ones) or a map of probability of any lava inundation over a given time period (1 year, a decade, given that the recurrence rates are well characterized), would help in the discussion. Overall, it seems like the map in Fig. 6 is perhaps more representative of the current state of the volcano, and applicable on the scale of years to decades, than the text implies, because of the relatively complete recent record.

Yes exactly, this was implemented accordingly.

In terms of discussing the results, adding/reorganizing the discussion around the "Impacts of cyclicity (or spatiotemporal variability in eruptions more generally) on hazard assessment" instead of methods-based section headings (e.g., 8.1.2), would help focus discussion on a key topic that repeatedly is mentioned throughout the other sections. These cycles are introduced in the background section and talked about a lot in the discussion as changing in location and magnitude through time, but the reader is not shown what these look like or exactly how their properties evolve. This discussion should therefore be accompanied by a figure that shows this well. Maybe marking vent locations and flow extents by cycle position (in different colors) in map view and comparing this to hazard mapping results.

The effect of activity cycle is already well discussed in the discussion section 4.2 "Historical and geological records: representativeness of future eruptions".

We modified the title of a discussion section into : " Accounting for spatiotemporal volcanic activity patterns" as recommended (now section 4.3)

Adding a figure about activity cycle is not the aim of the paper and already presented in Derrien 2019. Here we only wish the alert the reader on this fact but not quantify it. For this, a new article would deserve to be written.

Methods questions

Input data for hazard mapping includes vent locations, as well as statistics on the number of lava flows, their lengths, etc. However, these are not clear in the methods given the potential for a given eruption to produce vents that are actually lengthy fissures, multiple vents, and multiple lava flows. Some clarification on how vents, flows, and locations were defined, any implications of these choices on the results, and references to literature on these challenges (e.g., Cappello et al. 2012; Runge et al. 2014), are needed. Given some uncertainty in how these may be defined, the high precision and number of significant figures in the tables seems overestimated and should be discussed.

The methodology to count vents and lava flows has now been clarified in section 2.3. And the numbers in the table were rounded.

For the application of DOWNFLOW, were these simulations run from a single vent or from all vents and/or a fissure geometry (lots of point sources along a line, say)?

From single vents as already mentioned in the methods

How were ocean- limited flows treated in defining the lava flow length distribution (line 305)?

We consider here the maximum length, therefore from the vent to where the flow ends (i.e. the coast).

The DEM resolution is very important to the performance of DOWNFLOW, and separate calibrations are appropriate, so please provide the resolutions when describing the methods (e.g., line 287) and in the discussion of the results (line 453).

Done

In Fig. 4a, it is not clear that the calibration was completed though, given the best-fit seems unconstrained in the parameter-space (Δh >5?).

There were no need to test Δh >5 because the fit was already good for Δh >4.

How do multiple vents affect DOWNFLOW modeling/misfit?

Multiple vents are not considered with this methodology.

For long flows, the fit seems much worse (Fig. 4a) - greatly overpredicting the inundated area. Would a different model work better for these?

Were other models considered?

Yes, it is quite intriguing at Piton de La Fournaise that the distal part of the flow is not well fitted by the model. We could have used two different Δh to better fit the distal part of the flow (high Δh for the proximal part and small Δh for the distal part), but here we preferred to keep the simulations straightforward and neglect this by using only one Δh and assuming an overestimation of the distal part.

No, other models were not considered. Here we aimed at applying DOWNFLOW.

Can uncertainty from this type of misfit be propagated in this methodology?

Probably but his was not tested here because the scope of the paper was not to test different methodology.

Additionally, the impact of DEM resolution is worth testing with regard to varying Δh between time periods/DEMs, rather than attributing all differences to thickness changes (e.g., 455). Coarser DEMs (such as the 1997 DEM vs. the >2008 DEMs) have built-in flow spreading from pixel size, potentially greater DEM uncertainty, and significant effective smoothing, which generally seems to change the best-fit Δh significantly. If you resample the later DEMs to 25 m instead of 5 m, does the best-fit Δh change? There may be changes related to flow thickness, too, but DEM resolution should be integrated into this discussion (also in terms of validation – does the 25 m data perform worse?).
Yes, this was also pointed by reviewer 1 and it is now explicitly discussed.

Quantitative analysis of hazard probabilities
There are a number of places where results are described, but using inundation values for a given pixel, rather than integrating the results to answer the broader questions, such as "what is the probability of lava inundation in the Enclos during the next eruption?" (line 22)
Direct integration (sum) of the values of the hazard map inside the Enclos will not give the probability of lava inundation in the Enclos because a single lava flow will affect many pixels. However, the answer is actually given in Table 1 where one can read that there is 97.87% of chance that the next eruption will be in the Enclos (23.55 % in the summit crater and 74.16% in the rest of the Enclos).

or "what is the probability that the next lava flow will intersect the coastal road?" (line 339, this is written as if integrated, but it's just the probability within a given pixel, not along the whole road). The actual probabilities are possible to calculate with these data though (the first is dictated empirically, but the second could be calculated based on the model results).
We actually cannot get the result by simply integrating along the road because one single eruption does not cut the road in a single point. For this we have to identify all the possible vents that can cut the road and their probabilities to reach the road (e.g. as done in figure 12 of Favalli et al., 2012) and multiply this probability at each possible vent by the probability of having the next vent at that position (e.g. figure 3b of this article) and finally integrate over the region of the possible vents.
This would be too much to be added in this paper and we therefore rather not add this information here in order to keep a concise article.

Line-by-line comments
33 – Many lava flow hazard maps also incorporate time (probability of inundation at a location over a given time interval), as opposed to just a conditional probability on the condition of an eruption occurring (e.g., Bebbington 2013; Cappello et al. 2015). Given the known recurrence rates in this study, this extension would potentially be possible here as well, and relevant for applications to land use planning.
Yes this extension would be potentially possible. However, we do not include this is this article because it would require important lengthening of the manuscript. This will likely be presented in a future article where we will address directly risk maps for mitigation and land use planning.

64 – "complete" – that seems risky statement given how extensive burial is also described
Complete has been replaced by "large"

86 – "Morphological" – replace with "Geological"

Done

120 – Introducing these here as low frequency, high impact events will set up why they are so difficult to forecast in the discussion. They're in the data, but they are not the "most likely" event, and less spatially concentrated.
Yes, you are right. The sentence was reformulated and moved to section 1.3 .

150 – Expand this to fully introduce the spatiotemporal patterns in eruptive history. Given that episodes on the order of centuries are also later invoked for the methods of database assembly and the short/long-term applicability of the analysis, these could also be introduced here in this background section.
We believe that the spatiotemporal patterns in eruptive history is already well describe in this section.

192 – Using the longest flows only will overpredict flow length and yield higher probabilities overall. Perhaps add more explanation (as mentioned in the 'methods' questions above).
Maybe this part was not clear enough. If the fissure opens perpendicular to the slope, many little flows will propagate until the eruption concentrate on one spot. But if the fissure is parallel to the slope then where ever the lava come out, it will form only one stream (parallel to the slope). To avoid generating errors in number of lava flow, if the fissure is perpendicular and there are many little lobes, we decided to only count one flow per fissure, and to consider the longest one.
This is now rewritten as follow: "Note that in the case of a fissure opening perpendicular to the slope, the lava may erupt uniformly along the fissure to feed several lava flow units simultaneously to form a flow field of many lava fingers (Harris and Neri, 2002; Kilburn and Lopes, 1991, 1988). In such a setting we counted only the main, longest flow, and do not consider all fingers that comprise the compound lava flow field in the database (cf. Walker, 1973)."

Tables 1 and 2 – Are all flows mapped or are some flows that are unmapped (or poorly mapped) but were reported included in these counts? I think since these are directly compared to each other and they have the same rows, it would be much easier for the reader to just combine them into one table.
Table 1 reports the number of lava flows, while table 2 reports the number of scoria cones. The number of lava flows is restricted for the flows since 1931, while the number of scoria cones is unlimited in time, but consider all scoria cones found on the edifices. To avoid misunderstanding, they cannot be combined in a single table.
In contrast in Table 3, we reports counts of lava flows and scoria cones for the same period of time, in that case they are therefore in a single table.

236 - Is this every single cone, spatter rampart, and fissure? Or grouped/summarized somehow?
We do not make a difference between single cone, spatter rampart, and fissure. We counted morphologically distinguishable scoria cones as well as vent location for any lava flows.
(see section 2.3)

242 – What function is used for bandwidth, is it symmetric or asymmetric (or fissure geometries) and why?

We only considered points as possible input vents and used a 'symmetric' Gaussian smoothing function.

This because we have many different rift directions, etc., it does not make sense to use an asymmetric function as it would have to vary continuously from point to point. Also we have a great number of input data (compared to other volcanoes) and the rift pattern emerges clearly without 'forcing' them with highly-spatially-variable asymmetric smoothing functions. With the great variability in the density of cones we opted for a bandwidth that is function of the local vent density.

We used a Gaussian smoothing function as it is stated in the previous line. *We added the word "symmetric" for clarity as follow: "The vent density distribution (number of vents per unit area) was then obtained by applying a symmetric Gaussian smoothing kernel to the map of vent locations (Bowman and Azzalini, 2003; Favalli et al., 2012; Richter et al., 2016), with a bandwidth that is a function of the local vent density (Fig. 3a).."*

Section 7 – The first sentence sets up the goal of 'the next effusive eruption", but this is also making retrospective maps for other timespans, so make sure the plan of making multiple hazard maps that represent different times to look at any changes over time is introduced at the start of section 7. (will make line 323 less confusing on the first read).

This part was re-written

Sections 7.1 and 7.2 are interpretive and should be in the discussion. 7.1 can become 8.1 and describe the results, including the integrated example probabilities mentioned above. 7.2 can be modified/replaced into the core validation exercise, comparing the maps and subsequent flows more quantitatively/explicitly to show how well the method works.

We do not completely agree, Part 7.1 (now section 3) is the core result of this article. We rather keep it into the results and have therefore re-organized the manuscript to make it clear (section 3 is dedicated to results and section 4 to discussion)

Overlaying flow outlines directly on the hazard maps may be especially helpful. Where it works/doesn't work will then set up the following existing/re-organized discussions of spatiotemporal cyclicity, short/medium/long-term applications, importance of topographic updates, etc.

Done

334 – Clearly state that these are conditional probabilities

Done. This was re-written as follow: " The map clearly shows that, for the given data set, the highest probability of lava flow inundation for the next eruption at Piton de la Fournaise is located within the Enclos."

Section 8.1.1 - Overall, a 'long-term' hazard map using present-day topography in a frequently active area is most useful on the scale of the next few decades. A short-term forecast map (hours to a month, say) should be using short-term vent opening probability map integrating monitoring data, not the whole volcano over centuries (and up-to-date topography). A century- scale map needs to incorporate the potential of the volcano to change regimes entirely (it's been stated that eruption frequency can vary spatially and temporally over centuries at Piton de la Fournaise) and the present-day topography is expected to change over time (although it will likely be similar for a long time, large-scale subsidence and such can happen in addition to lava emplacement). So maps like this are most useful in that next years-decades period mostly useful for annualized to lifetime-scale planning and risk, but not shorter or longer term. Products for these other timeframes can also be produced with the same methodology, just with different input data, and that is worth saying here.

Yes exactly, this was already stated, but it is now clarified.

425 – This contradicts line 303 (although it's broadly true of course!)

Yes indeed, this is now better explained.

429–445 – It seems like these events are represented accurately in the input data (infrequent, less spatially confined), and thus the hazard map. That they occur very sporadically at locations that erupt infrequently does not mean the map is wrong (low-likelihood, large-magnitude). Based on this work, are there recommendations for how these should be treated, or maybe presented differently (e.g., as "worst-case" scenarios or similar)? What work would be needed to include lava lake activity in a future hazard map?

Recommendation are out of the scoop of this paper but we now clearly stated that "Dedicated studies on the probability of occurrence of such high magnitude and intensity, but atypical, events need to be conducted, and a separate set of hazard maps are required to compute where and when such events are more likely to happen. Likewise, our analysis does not consider the poorly studied, but relatively recent (post-1708), long-lasting activity related to overflow from summit lava lakes, as was common between 1750 and 1800, and again around 1850 (Michon et al., 2013; Peltier et al., 2012). Our maps are, though, applicable to the most common effusive event scenario currently encountered at Piton de la Fournaise. However, they must be used and applied with the above caveats in mind regarding the type of activity and effusive event to which they apply."

471 – A good place to include some numbers of the integrated probability of trails being inundated in the next eruption, or visually showing the exposure on the map.

In this work we cannot give integrated probabilities but can only visually show the exposure on the map as we do in figure 6.

477 - Can you reconcile this? It is an aspect of drainage/integration by accumulation from many possible vents, but it's extremely nonintuitive to readers and the public. Would it be valuable to make a "proximal" hazards layer, say, using a vent opening contour to define a proximal hazard region subject to tephra, ballistics, gasses and near-vent lava flows?

Actually, there is nothing to reconcile, it is not antagonist, it is just a matter of geometry. Any pixel close to the summit (high altitude) have a contributing area (possible vent location from which the lava path would reach the pixel in question) that is much smaller (up to 1000 times) than for a pixel that is at lower altitude.

"a proximal hazard region subject to tephra, ballistics, gasses" is completely out of topic for this article.

487 - Explicitly highlight that in a short-term or atypical scenario, this framework allows

updating of the input data (DEMs, vent locations, flow properties) to quickly produce a probabilistic map or specific flow forecast scenario as needed.
Done

Fig. 6 – I don't see green or white lines. Perhaps adjust line widths and colors?
This was a mistake and it is now corrected