
Reviewer #1 Evaluations:
Scientific significance: Good
Scientific quality: Good
Presentation quality: Fair

Recommendation: the manuscript should be reconsidered after major revisions.

Comments of Reviewer #1:

This paper attempts to evaluate the minimum volume of a large-scale pyroclastic density current (PDC) at Aso volcano. This kind of approach is necessary for the assessment of future effects by PDCs.

Thank you.

Although, I found several crucial points to be revised in this paper.

Lines 22-24: This said, for Aso the current occurrence probability of such a colossal initiating eruption has been estimated <10-8 in the next 100 years.

>>> This sentence is the result of the reference paper (Aspinall et al., 2021). It is not suitable to include in the abstract.

OK. We deleted that sentence from the abstract. We also deleted it from the Introduction and moved discussion section 5.1 about probabilities of occurrence to the end of the discussion (section 5.4).

Lines 42-43 and 125-126: It was and responsible for the emission of about 500 km3 DRE, 90% credible interval [370, 685] km3 (Aspinall et al., 2021). Aspinall et al., (2021) reassessed the volume estimates of PDC and fallout deposits of Aso-4, through a Bayesian Belief Network approach.

>>> Aspinall et al. (2021) is just a proceeding of an international workshop. This is not a peer-reviewed publication. The evaluation of the credibility of the volume estimation method through a Belief Network approach is still needed. More detailed evidence should be shown to use these estimated values in other peer-reviewed papers or in this paper. Details on how to determine the eruptive volumes of Aso-4 tephra and PDCs based on discussions among the mainly European "Experts" should be shown. Clear evidence is not indicated in Aspinall et al. (2021).

We are sorry that you found the published data from the proceedings of an international workshop unsuitable to be referenced in this paper. Please note that Aspinall et al., (2021) has been peer reviewed; we are attaching the review report. Please also consider that a recently published paper, Rougier et al., (2022), re-evaluated the tephra fall deposit.

Therefore, about the mass estimates of Aso-4 we decided to maintain a neutral position in this manuscript. In particular, we deleted all volume and mass estimates from the introduction, and we are no more presenting conditional probability estimates in the abstract, because they would be related to specific volumes. Also, to avoid an excessive stress on constraining these volumes from very uncertain information, we deleted the volume and mass estimates made by Aspinall et al., (2021) from all figures, tables, results, and supporting material, except from Table 3, where they have been left as an illustrative example.

We extended a paragraph in section 2.2 to clarify this complex framework:

"*Takarada and Hoshizumi (2020) presented estimates of the volume and mass of PDC and fallout deposits of Aso-4, evaluating the magnitude (M8.1-8.4). They estimated a volume of Aso-4 tephra fall deposits of 240-370 km^3 DRE (6.0-9.3×10^{14} kg), while the volume of Aso-4 PDC deposits was estimated at about 225-590 km^3 DRE (5.6-14.8×10^{14} kg). These estimates implied a total volume of Aso-4 eruption of 465-960 km^3 DRE (1.2-2.4×10^{15} kg).*

Nevertheless, the volume of magma erupted in Aso-4 and the uncertainty in volume estimates remain open questions. Aspinall et al., (2021) undertook a preliminary quantification of this uncertainty by combining several different volume estimates of PDC and fallout deposits of Aso-4, through a Bayesian Belief Network approach. They defined composite volumes, determined by weighted combinations of different estimates of the various products, including those from Takarada and Hoshizumi (2020), and hypothesized a lower bulk volume for the ash fall deposit and therefore a smaller total magnitude with 90% confidence (i.e. M7.9-8.2). In a subsequent, related assessment of the Aso-4 tephra fall deposit, Rougier et al., (2022) applied advanced statistical methods and re-evaluated its bulk volume to have been in the range 220 to 370 km^3, which equates to the range 95 to 160 km^3 DRE (2.2 to 3.7×10^{14} kg). Since volumes of co-ignimbrite tephra fall deposits and PDC deposits are typically comparable to one another (Sparks and Walker 1977) the reduced estimate tephra fall deposits also suggests a somewhat reduced PDC volume.

[...]As discussed above, there is much uncertainty about the total PDC volume and consequently the volumes of individual PDCs generated by the Aso-4 eruption. However, from the perspective of our study these uncertainties are not important as all studies agree that the total PDC volume is likely to significantly exceed 100 km^3, while the volume of the largest and most extensive individual PDC emplacement units is also likely to be a significant fraction of the total volume. "

Finally, in section 4.1 we clarified that the volume was varied in a wide range: "*Note that volume is not considered an input parameter but it is varied to calculate the probability of any volume chosen in a wide range to reach the distance of each marker site.*"

Line 45: Aso caldera is located in the densely populated Kyushu Island (~14M people),

>>> 14 M people including the population in Okinawa Prefecture. The total population of Kyushu Island is about 12.7 M people (Oct. 2021).

OK. We corrected that number. Thank you.

Line 82-83: The PDCs generated from these eruptions reached runout distances from the caldera of ~30 km for Aso-1, ~30 km for Aso-2, ~70 km for Aso-3, and ~166 km for Aso-4 (Ono and Watanabe, 1983; Takarada and Hoshizumi, 2020).

>>> As written here, the maximum runout distance of Aso-3 PDC is about 70 km. Therefore, it is unlikely the Aso-3 class PDC will affect the 3 target sites (130-145 km). Also, the estimated volume of Aso-3 PDC still contains large uncertainties. I think that the discussion on the assessment of Aso-3 PDC should be deleted.

Recommendation accepted. We deleted the discussion on the assessment of Aso-3 from figures, tables, and results, and supporting material.

Lines 87-88: deeply dissected stratovolcano Nakadake (see Fig. 1),

>>> Nakadake is the youngest and most active post-caldera volcano within the Aso central cones. Not intera-caldera volcanoes. Please see Miyabuchi (2009) Sedimentary Geology. Probably, this is Nekodake. Although, recent work suggests that the Nekodake volcano formed after Aso-4 eruption (50-82 ka; Shinmura et al., 2021).

https://www.jstage.jst.go.jp/article/vsj/2021/0/2021_51/_article/-char/ja/

Thank you for the clarification. We corrected the misspelling and added the references suggested.

Lines 140-141: Our first-order integral PDC models aim at characterizing the potential distal impact of these flows, if any, at distances in the range 130 – 145 km.

>>> Please describe why these three nuclear power plants have to be evaluated in this paper. The evaluation of TS1 (Ikata), TS2 (Genkai), TS3 (Sendai) nuclear power plants in Kyushu and Shikoku areas are quite sensitive matters in Japan. Still, a lot of debases including lawsuits after the Fukushima nuclear power plant event due to the 2011 Tohoku Earthquake. The description should be included why the evaluation of these three nuclear power plants is needed in this paper. Currently, the Japanese government NRA (Nuclear Regulation Agency), which handles the nuclear operation evaluations, does not use probability methods to assess the nuclear power plants in Japan. Other more important evaluation targets such as Fukuoka City, Kumamoto City, Saga City, Miyazaki City, and major airports in Kyushu are also possible candidates. If the next Aso-5 eruption occurs in Aso, most of the northern part of Kyushu area will be destroyed. I think that the evaluation of the effects on the largely populated cities is much more important.

We are not specifically mentioning any nuclear power plant in the manuscript, but, simply for illustrative purposes, we evaluated the sites of some critical infrastructures facilities within 160 km from the caldera. Please note that we did not seek to define the most important sites potentially exposed, but we selected a number of manageable sites located at similar distance from the Aso caldera and in well-separated directions. To improve clarity we now call them “marker sites” (MS), instead of “target sites” (TS), throughout the manuscript. Risk analysis was outside the purpose of this study, and we avoided any discussion on nuclear plant safety regulations in Japan.

However, we agree that other sites may be informative to evaluate in this context, so we added two additional “marker” sites, located near Miyazaki City and Kitakyushu City (in line with the reviewer’s suggestions). Therefore, we currently consider five indicative marker sites located at regularly spaced angular directions around Aso caldera, i.e. N, ENE, SE, SW, WNW, and at 115 to 145 km radial distance ranges from the volcano. We regard these distances as appropriate for exemplifying our PDC model-based hazard estimation: at shorter ranges, the likelihood of invasion is nearly certain, while further away the hazard is reduced (not zero, but potentially less critical). Figure 1, 2 have been modified to show the new sites, and all tables and results have been modified as well.

Lines 144-145: Our analysis relies on the implementation of four different versions of the box-model integral formulation for axisymmetric gravity-driven particle currents, based onthe pioneering work of Huppert and Simpson (1980) and with theory detailed in Bonnecaze et al. (1995) and Hallworth et al. (1998).

>>> Usually, the VEI 7-8 class eruption continues for several hours to sometimes more than several days. The mass eruption rates (MERs) fluctuate due to the change in magma and vent conditions. It is doubtful applying a simple model with constant coefficient parameters to the Aso-4 PDC. Aso-4 PDC deposits consist of several units such as Aso-4A, Aso-4B, and Aso-4T. Also, these units are composed of many flow units. Therefore, the simulations should apply to a single flow unit, not the whole Aso-4 PDC. As you already know, many previous works (such as Lipman, 1967; Watanabe, 1977; Kaneko et al., 2007 <<< please cite these papers) showed that Aso-4 PDC is composed of different units which consist of different characteristics. Therefore, one single eruption simulation model is not applicable in Aso-4 PDC.

Thank you for these thoughtful comments. We agree that it would be more appropriate to apply numerical models to single flow units. For this reason, and following your further suggestions (please see our response to your comment about Lines 299-300), we now also consider the case with $1/10^{th}$ of the total mass of PDC overflow outside of the caldera, representing the Aso-4T single unit. In particular, Figures 4 and 5, and all tables, and results, have been modified according to this condition.

Please note that the key point in the manuscript is that the furthest PDC flow unit of Aso-4 reached 166 km. We are interested in estimating the probability of a flow reaching such a distance as a function of volume or mass, and were not seeking to assess or improve mass reconstructions of past PDC. In fact, the discussion on Aso-4 volumes is not a key point in this study, beyond that everyone agrees the volumes are likely to be large (hundreds of km^3).

Line 151: Rock avalanche dynamics with constant stress over the flow basal area

>>> Careful validations are needed to apply the rock avalanche dynamics with a constant stress model to the VEI-8 class large-volume PDCs. Initially, the authors should show the validations comparing the distribution, volume, and flux of the past large-volume PDCs with the result of numerical simulations using this model.

Performing validations with any simplified model has issues and this is especially so for eruptions like Aso-4 of a scale that has never been witnessed. Validations in the laboratory scale and for much smaller PDC's in historic eruptions have been done and both the rock avalanche model and the dilute models can simulate observations with adjustments to model parameters in different kinds of PDC. However, for very large energetic low aspect ratio ignimbrites (LARIs) remains a contentious issue, although the trend in the modeling community is to consider such flows as hybrid with dense and dilute components, but research models that attempt to couple dense and dilute regions in the same flow are currently complicated and unsuitable for the probabilistic studies. At this stage in development we justified in using end member models (concentrated and dilute) that can be compared. Our study for example shows that a dense model alone struggles to reach the very long observed run-out of some Aso PDCs and this is expressed as a low probability, while a dilute model with implicitly lower friction can explain the observations.

We note here that both dense and dilute models have been applied to the Taupo AD 232 PDC. In modeling cases of this kind model parameters are adjusted to obtain a good fit so there is no strict validation beyond finding that model parameters are physically or empirically reasonable.

We have added this point to the discussion in the paper – please see next response.

Line 157: Density current dynamics with particle deposition

>>> Careful validations are needed applying density current dynamics with particle deposition model to the VEI-8 class large-volume PDCs. Initially, the authors should show the validations by comparing the distribution, volume, and flux of the past large-volume PDCs with the result of numerical simulations using this model.

Please see our response to the previous comment. The best we could do with density current models is comparing parameters with the AD 232 Taupo eruption, which was already modeled with a similar approach in the 1990s. To clarify we added the following paragraph in section 5.3:
"*For example, the initial solid fraction of the PDC of Taupo, 232 CE, was estimated as 0.3% by Dade and Huppert, (1996), by model fitting. Nevertheless, while discussing density above the ground, Wilson, (1995) observed tens percentage solid. Although they both do not consider that column collapse creates highly variable solid fractions, these differences outline the dissimilar conditions ranging from density current dynamics with particle deposition, to one possibly similar to a rock avalanche with constant friction.*"

We note that one of the Aso 4 flows reached 166 km and our modeling is mainly addressing what plausible volumes and physical properties of PDC can reach such a distance.

Lines 299-300: Note that our models assume that that 300 total volume of the long runout PDC is the same as the volume estimates for the total outflow PDCs of the eruption.

>>> The Aso-4 PDC is composed of several units (Aso-4A, Aso-4T and Aso-4B), and these units are composed of more than 10-20 flow units in total. Therefore, this estimation is not realistic. The volume of a single flow unit of Aso-4 should be much smaller on a scale of 1/10 to 1/20. Aso-4T (Tosu unit) is the most widely distributed low-aspect-ratio ignimbrite (LARI) unit within Aso PDCs (Suzuki-Kamata and Kamata, 1990 <<< This paper should be cited). The Tosu unit reached as far as 166 km within

Yamaguchi Prefecture. Therefore, if the authors would like to access the possibility of reaching the target site, the assessment of LARI is necessary. Therefore, the stochastic discussions based on the assumption using the total volume of PDC with constant parameters are not acceptable. Please remove repeated “that”.

We are grateful for this constructive comment. We have modified all results and tables and figures, including abstract and conclusions, to test with Aso-4/10, representing a plausible mass for Aso-4T. We also amended the repeated “that”.

We added the following sentence in section 4.3 to reflect this point:
“*Since the mass of the longest runout PDC of Aso-4 may have been a significant fraction of the PDC flows outside of the caldera, we first assume that the total volume of the long runout PDC is equal to the total outflow PDCs of the eruption. In fact, by considering the entire Aso-4 mass we assume that a single flow contains most of the erupted mass of the outflow deposits, and that this mass was erupted within a time scale less than the PDC emplacement time. This assumption is further discussed in Subsection 5.1.*

However, Aso-4 contained several emplacement units and the longest runout PDC could be only one of these, e.g. Aso-4A, Aso-4B, and Aso-4T (Lipman, 1967; Watanabe, 1979; Kaneko et al., 2007). These units contain evidences of at least 10-20 PDCs in total (Takarada and Hoshizumi, 2020). In particular, Aso-4T (Tosu unit) is the most widely distributed low-aspect-ratio ignimbrite unit within Aso PDCs, but its mass remains unknown (Suzuki-Kamata and Kamata, 1990). Therefore, we tentatively tested also a mass of 1/10 of the total PDC overflow outside the caldera, i.e. 42-78-118 $\times 10^{12}$ kg (17-31-47 km^3 DRE), plausibly representative of Aso-4T mass. Note that this assumption is not aimed at constraining the actual mass of Aso-4T, but it provides an illustrative example of a PDC that does not contain most of the erupted mass of the outflow deposits.”

We also added this sentence to the Introduction:
“*Our study is not dependent on knowing the volumes of the Aso-4 or its individual flow units accurately. Indeed the volumes have large uncertainties so we can use such estimates to constrain the range of volumes of interest in the modeling and then back check that the volumes with high likelihood of reaching the observed distances are consistent with the known facts.”*

Lines 695-696: Ono, K., Matsumoto, Y., Miyahisa, M., Teraoka, Y., and Kambe, N.: Geology of the Taketa District. Quadrangle Series, 1:50,000. Kawasaki: Geological Survey of Japan, 1997.

>>> 1997>>1977

We have amended that reference. Thank you.

Table 1 model 1: Flow density 992 (50%) and 1511 (95%) kg/m3.

>>> These values are too high for PDC (These values are the density of debris avalanche or landslide).

Please see, from Figure 6, that the value of flow density is not having any effect on the minMass estimates, because it cancels out from the equations.

Moreover, the distributions of input parameters for the models were determined by expert judgement, i.e. by statistically combining the opinion of several people. Changing a model input distribution could compromise the overall consistency of our method. Because such a catastrophic eruption has never been observed, we tested several models and a wide range of input parameters. Please note that the values that you comment on are from the upper half (50%) of the flow density uncertainty distribution; the full distribution also includes significantly lower density values than the pair of values cited here.

We added the following sentence in section 5.3, to clarify:
"*Since the emplacement of a low-aspect-ratio ignimbrite has never been observed, we tested several models and a wide range of input parameters. Our purpose was to capture the uncertainty affecting the plausible dynamics of similar flows, and constrain the minimum mass required to reach marker site distances; we did not endeavour to produce an optimized reconstruction of parameters for a flow identical to Aso-4 PDCs, as such.*"

Table 1 model 2: Density of solid particles 1814 (50%) and 2357 (95%) kg/m3.

>>> These values (1814 and 2357 kg/m3) are too high for the pumice rich PDC. The density of pumices is about between 800-1300 kg/m3 in Aso PDC deposit.

Please see the response to your previous comment. Also, please consider that, from Figure 6, slightly changing the density of solid particles is not having a strong effect on the results of the model, which is dominated by the effects of the settling velocity and the initial solid fraction.

Figure 1:

>>> The DEM used in this map should be cited. Probably GSI in Japan?
We clarified about the provenance of the STRM DEM that we utilized, i.e.: SRTM 1 Arc-Second 30m (NASA, 2013). We have added it in the reference section.

Figure 2:

>>> The DEM resolution for simulation should be indicated.
Thank you; as just noted, we have clarified the STRM DEM and its resolution: SRTM 1 Arc-Second 30m (NASA, 2013).

Figure 3 and Figure 4:

>>> The evaluation of Aso-3 PDC should be removed.

Accepted. We have removed it as per our earlier responses, above.

Reviewer #2 Evaluations:
Scientific significance: Good
Scientific quality: Excellent
Presentation quality: Good

Recommendation: the manuscript should be accepted subject to minor revisions.

Comments of Reviewer #2:

The manuscript presents a probabilistic approach to estimate the mass of pyroclastic density current needed to impact three different targets in the Aso Caldera, in Japan, adopting different approaches. The reviewer considers the aim of the paper well stated, and appreciates the deep insight into the state of the art of the different models.

Thank you.

Though, some concerns arise about the proposed simulations:

While model 1 is sufficiently clear to the reviewer, the way of using model 2 (in its variants 2a, 2b and 2c) is not so easy to understand. Which kind of simulation has been performed? Which are the characteristics of the models that have been run? Fluid dynamic simulations? Something like a black box? The authors are required to provide more information about this point.

We are sorry if you found that part of the narrative unclear. Most of the points raised are detailed subsequently in section 3 and in Supporting Information S1. We hope this will be sufficient to offset the suggestion that more information is required.

The mode of application of Model 2 is the same as Model 1. They are not used a black boxes, but their fluid dynamics equations are solved to define an analytic expression of reduced gravity and kinetic energy as a function of the radial distance from the source. In absence of topography, the flow stops when kinetic energy becomes zero, or when the flow becomes buoyant because solid fraction is sufficiently depleted to allow lift-off.

If fluid dynamic models have been run, please add some information about the adopted method, the governing equations, and eventually, the computational cost, the number of required simulations to build the probabilistic approach.

For the adopted method, please see section 3.1 and 3.2:
"*We focus on models with analytical solutions, adopting input ranges based on Expert Judgment (see Subsection 4.1). This enables us to utilize a very fast model-inversion approach in the uncertainty quantification process. We note that we are not using "reduced" models (i.e. statistical surrogates; e.g.*

Rutarindwa et al., 2019; Yang et al. 2020). […] By using the elicited probability distributions of model inputs and the analytical solutions of the kinetic energy models, for any given collapsing volume, we estimate the conditional probability for the occurrence of a PDC with runout distance on a flat topography equal or larger than the distance between the source and each marker site (i.e. ~130 km for TS1, ~135 km for TS2, ~145 km for TS3, ~115 km for TS4, and ~120 km for TS5; see Fig. 1)"

All the governing equations are fully detailed in Supporting Information S1; for easier comprehensibility, we decided not to include all this technical information within the main manuscript, also considering that these physical models are not new (they were introduced in the 1980-90s in a number of papers that are referenced: i.e. Dade and Huppert, 1996; 1998, and others). Then, the kinetic energy approach is also not new, but already adopted in a number of referenced papers (Neri et al., 2015, Bevilacqua et al., 2017; 2021; Aravena et al. 2022).

Since the model is based on the analytic function of kinetic energy, computational cost of runout calculation in absence of topography is negligible. The same is true for minMass calculation for a given runout. The number of statistical samples considered when producing estimates of MinMass and invasion probabilities is 100,000. We clarified that in all captions.

If 'reduced' models have been used, please clarify the kind of model, discussing the validity of the model itself with respect to physical based models.

We are not using 'reduced' models (i.e. statistical surrogates). We clarified that in section 3.1:
"*We note that we are not using "reduced" models (i.e. statistical surrogates; e.g. Rutarindwa et al., 2019; Yang et al. 2020).*"

With model 2 (a, b, c), how it is computed the probability of impact on the target Site.

Please see the response to the previous comment about the adopted method.

The author is required to discuss how the topographic situation is taken into account in the different adopted models.

We believe we have addressed this issue with appropriate fullness - please see section 3.2:
"*… because of the possible topographic effects in the propagation of PDCs, the simulation of 115-145 km runout in absence of topography is not a sufficient condition to assess the likelihood of marker site incursions for those distances from the source. Therefore, in a second step, we tested the inclusion of the topography in numerical simulations […]. To do this, we followed the 'energy conoid' approach, based on the assumption of nonlinear, monotonic decay of flow kinetic energy with distance adopted by Neri et al. (2015) and Bevilacqua et al. (2017). […] We compared the kinetic energy of the current front and the potential energy associated with the obstacles encountered. Our approach is mostly sensitive to the shielding effect of topography close to the target sites, and not to the large-scale topography around the source site […]. Since energy calculation is performed axi-symmetrically along every radial direction, we randomly varied the centre of propagation inside the Aso caldera (see Fig.*

1) and averaged the results to include uncertainty related to the geographical coordinates of the source."

We note that the energy conoid approach enables us to define increased values of runout distance, which then we input into the analytical solutions of kinetic energy, as explained in section 4.2:
"Tables 2, S3, S5, S7, S9 also include the results based on larger values of runout distance, i.e. 195 km, 235 km, 225 km, 155 km and 170 km for MS1, MS2, MS3, MS4 and MS5 respectively, obtained by using again the analytical solutions of kinetic energy models <u>on a flat surface</u>. This increase in the marker runout distance is introduced so as to emulate the effect of topography, i.e., runout distance reduction derived from the effect of distal obstacles (see Subsection 3.2)."

This simplified strategy for testing topographic shielding effects on PDC flow runout, based on increased distance thresholds, enabled us to use the analytical solutions of kinetic energy models that would have been invalidated by the numerical application of the energy conoid approach in each simulation. We further clarified that, by adding a new sentence in section 4.2:
"*Otherwise, the analytical solutions of kinetic energy models would have been invalidated by numerically considering the topographic shielding effects in each simulation.*"

Also, please note there is further discussion of this aspect in section 5.2: *"Simplified testing of topographic shielding effects".*

In conclusion, the reviewer suggests a minor revision of the present manuscript, provided that the above-mentioned comments are sufficiently discussed.