We thank the reviewers and the editors for their time and comments that have significantly improved the manuscript. Below we list our responses to the reviewers' comments. The reviewers' comments are in blue font, and our responses are in normal font.

Replies to Reviewer RC1

RC1: This paper appears to have been written by the corresponding author, and not have been edited by the native English-speaking co-authors. There are several English grammar errors, which are annoying to this reviewers. Reviewers should not be expected to edit the paper. And every author is required to agree to submission before a paper is submitted. Why did they not read it and correct the grammar? Languages like Russian and Chinese do not have articles, and so it is obvious when the paper is missing articles that the author did not learn English well enough to use them correctly.

We acknowledge the comments provided. As noted by the Executive Editor, the remarks above were inappropriate. In accordance with the editor's guidance, we will not be responding to those specific comments.

We remain committed to constructive scientific dialogue and appreciate the opportunity to address the remaining points raised during the review process.

RC1: This paper is about health effects of volcanic emissions, looking at SO_2 and PM.

While we appreciate the reviewer's interest in the broader implications of our findings, we would like to respectfully clarify that it is somewhat misleading to characterise the main focus of our manuscript being "about health effects." Our study presents observational data on ground-level concentrations of particulate and gaseous air pollutants associated with volcanic activity. At no point do we present, or claim to present, data on health outcomes.

We acknowledge the importance of understanding health impacts; however, such assessments require clinical or epidemiological methodologies, which are beyond the scope of this study and the remit of ACP.

RC1: But adverse health effects depend on exposure, which includes not just concentration of the pollutants but on how long a person is exposed. There was no discussion of this in the paper.

We understand the reviewer's comment to suggest that the manuscript lacks a discussion of how long a person is exposed to volcanic air pollutants. We respectfully disagree with this interpretation.

Our analysis explicitly compares observed concentrations of SO_2 and particulate matter (PM_1, $PM_{2.5}$, PM_{10}) against both international and national air quality thresholds. These thresholds are inherently time-based: for example, the SO_2 threshold is based on a 60-minute averaging period, while the PM thresholds are based on 24-hour averages. By definition, these thresholds incorporate both concentration and duration of exposure.

Figures 3, 4, 5, and 6 present pollutant concentrations alongside the relevant exposure thresholds and show the total number of exceedances for each time-based standard. These figures, and their accompanying discussion in the manuscript, directly address the duration and frequency of exposure to above-threshold pollutant levels.

We hope this clarifies that the temporal dimension of exposure is indeed a central part of our analysis.

RC1: How dangerous are these pollutants? Is SO_2 or PM more dangerous? And I have never heard of PM_1 before. Is it more or less dangerous than $PM_{2.5}$?

We have restructured the Introduction to improve clarity and provide additional context. Specifically, we have added a new subsection titled 1.1. Volcanic Air Pollutants and Associated Health Impacts, which offers a more detailed overview of the respective health effects of SO_2 and particulate matter (PM), including PM_1, $PM_{2.5}$, and PM_{10}. This new section also addresses the limited but emerging evidence on the combined effects of SO_2 and PM in volcanic plumes, and highlights the growing body of research on the health impacts of PM_1, particularly in comparison to $PM_{2.5}$. We believe this addition strengthens the manuscript by better contextualizing the relevance of our observational data to public health.

Furthermore, we would like to respectfully point out that, as of the date the reviewer submitted their comments, there were 1,367 articles in ACP and ACPD on PM_1. Of these, 56 had been published since the beginning of 2025. This underscores that PM_1 is an active and growing area of research that is highly relevant to the scope of ACP.

RC1: The paper needs a discussion of these issues, and the conclusions need to frame the results in terms of short or long-term health impacts. Were the lifespans of visitors or Icelandic residents really affected by this eruption?

We thank the reviewer for their helpful suggestion. In response, we have expanded the discussion of the potential health impacts on the Icelandic population in Section 3.5.1. This addition provides further context for the observed pollutant concentrations and highlights the relevance of our findings for public health considerations in the affected regions. We also added an explicit mention of the potential health impacts to the Conclusions.

Revised text from section 3.5.1 ‘Exposure of residents’:

“<...>Based on the available evidence, it is likely that the 2021 eruption may have resulted in adverse health impacts among exposed populations. Epidemiological studies by Carlsen et al. (2021a, b) on the 2014–2015 Holuhraun eruption demonstrated a measurable increase in healthcare utilisation for respiratory conditions in the Reykjavík capital area, associated with the presence of the volcanic plume. Exposure to above-threshold SO_2 concentrations was linked to approximately 20% increase in asthma medication dispensations and primary care visits. Furthermore, even modest increases in SO_2 levels were associated with small but statistically significant rises in healthcare usage—approximately a 1% increase per 10 $\mu g/m^3$ SO_2—suggesting the absence of a safe lower threshold. During the Fagradalsfjall eruption, SO_2 concentrations in populated areas reached levels broadly comparable to those observed during the larger but more distal Holuhraun eruption. Consequently, similar health impacts may be expected, as inferred from the findings of Carlsen et al. (2021a, b). Holuhraun emissions led to 33 exceedances of the SO_2 air quality threshold in Reykjavík, with hourly-mean concentrations peaking at 1400 $\mu g/m^3$ (Ilyinskaya et al., 2017). In comparison, the Fagradalsfjall eruption caused 31 exceedances, with a maximum of 2400 $\mu g/m^3$ SO_2 recorded in the community of Vogar (station G2-F). Additionally, Fagradalsfjall caused SO_2 threshold exceedances across all monitored areas within approximately 50 km of the eruption site (areas G1–G5). By definition, there is no safe lower limit for the number of air quality exceedance events. Therefore, all areas that recorded above-threshold pollutant concentrations may have experienced adverse health effects. Furthermore, although the monitored regions in North and East Iceland (areas G6 and G7) did not register threshold exceedances, potential health impacts in these areas cannot be ruled out. As reported by Carlsen et al. (2021b), even relatively small, above-background increases in SO_2 concentrations during the Holuhraun eruption were associated with measurable health effects.

Given the limited number and scope of health impact studies on previous volcanic eruptions, the potential health implications discussed here should be further investigated through dedicated epidemiological and/or clinical studies focused specifically on the Fagradalsfjall event. Moreover, existing health studies from volcanic regions have primarily concentrated on short-term exposure (hourly and daily), with a gap in research of potential long-term effects. Since the 2021 eruption, ten additional eruptions of similar style and in the same geographic area have occurred. Although each event has been relatively short-lived—ranging from several days to several months—their cumulative impact on air quality and public health may be chronic rather than acute, and thus warrants comprehensive investigation.

Carlsen et al. (2021a) found that when volcanic air pollution events from the Holuhraun eruption were successfully forecast and public advisories were issued, the associated negative health impacts were reduced compared to events that were not forecast. In Iceland, residential buildings are predominantly well-insulated concrete structures with double-glazed windows, offering substantial protection from outdoor air pollution. However, under normal conditions, windows are kept open for ventilation, facilitated by the availability of inexpensive geothermal heating. Additionally, it is common practice for infants to nap outdoors in prams, and for school-aged children to spend breaks outside. Public advisories included simple, easily implemented measures such as keeping windows closed and minimizing outdoor exposure for vulnerable individuals. Given that such basic societal actions have been shown to be effective, it is likely that further improvements in pollution detection—particularly enhancements in spatial resolution—and more effective communication strategies could provide additional protection to the population."

Revised text from the Conclusions:

"<…>These results suggest that the Fagradalsfjall eruption may have contributed to measurable adverse health effects, warranting further public health investigations. Moreover, the high frequency of eruptions in this region since 2021 raises the possibility of chronic, low-level air pollution, which should also be examined, particularly given that the ongoing 'Reykjanes Fires' eruptions may continue for several generations.<…>"

RC1: The paper analyzes concentrations of particles, but does not provide any modeling of the particles from the volcanic vents to the sensors. This could be done with various air pollution models, forced by actual meteorology, say from reanalysis, or downscaled with a local high-resolution model. This would explain the variations, and also provide a capability to predict the air pollution from future eruptions. Emissions from a fissure only get to populated places if the wind is blowing that way. Even without sophisticated models, the paper needs to explain the synoptic situation in the most polluted cases to show how the pollution gets to the people. The wind rose in Fig. B11 is not sufficient. Show the data. Provide time loops of satellite images, and show weather maps. Animations are allowed and encouraged as supplementary information.

We agree that, ideally, our high-quality observational dataset could be complemented by meaningful dispersion modelling. Prior to writing this manuscript, we carefully considered whether to include in-depth dispersion modelling and ultimately decided against it. Below, we outline the rationale for this decision and the steps we have taken in the revised manuscript to address the reviewer's suggestion as fully as possible. To enhance the manuscript, we have now included a discussion of dispersion modelling results and their limitations in the revised text. Additionally, we have added several maps and animations to the Supplementary Material to provide further context.

Rationale for not including in-depth dispersion modelling in the main manuscript:

The dispersion models that have been used for simulating the 2021 Fagradalsfjall eruption do not currently have sufficient skill to meaningfully complement our observational dataset. One of the main reasons for the relatively low level of skill is that eruptions like the 2021 event are small but highly dynamic emission sources. While the models can simulate the broad direction of the plume with approximately 80% accuracy, the fine-scale spatial (≤ a few kilometres) and temporal (≤ 6 hours) fluctuations in plume direction are not accurately reproduced, and the models particularly struggle to simulate the pollutant concentrations at ground level. For example, the most significant volcanic SO_2 pollution event in Reykjavík (18–19 July 2021, when ground-level SO_2 reached 750 μg/m^3) was not reproduced by the model. This limitation is now mentioned in the revised manuscript (the new text is copied below).

The most extensively used model for this eruption is 'CALPUFF', operated by the Icelandic Meteorological Office (IMO). CALPUFF has been used operationally by IMO since 2014 for forecasting volcanic SO_2 pollution and alerting the public to the presence of unhealthy concentrations. A recent evaluation of CALPUFF's performance during the 2021 eruption (Pfeffer et al., 2024; https://www.sciencedirect.com/science/article/pii/S0377027324000568#s0010) identified key challenges in simulating this eruption and explored improvements through varying source parameters. Furthermore, a workshop was held at IMO (organised by co-author S. Barsotti) to compare the performance of different dispersion models for this eruption. Models evaluated included CALPUFF (IMO), NAME (UK Met Office), and a WRF-based model (UK National Centre for Atmospheric Science). The consensus was that none of the models were able to simulate the dispersion of pollutants from this eruption with high skill, and that further work is needed to improve model performance. Given these limitations, we concluded that full dispersion modelling analysis is beyond the scope of this paper and warrants a full investigation of its own. Importantly, we believe that publishing the observational dataset first is essential to support future model development and validation.

We appreciate the reviewer's suggestion to include satellite imagery to illustrate the synoptic dispersion of the volcanic plume. While we agree that satellite data can be valuable for understanding the dispersion volcanic plumes, we have carefully assessed its applicability to this particular eruption and concluded that it does not meaningfully complement our high-resolution ground-based observations. Below, we outline the reasons for this decision.

The best satellite instrument for SO_2 detection available during the 2021 eruption was the TROPOMI sensor onboard Sentinel-5P, which provides daily global coverage and measures SO_2 as column-integrated Dobson Units (DU). The TROPOMI is optimised for detecting large-scale SO_2 plumes and has a spatial resolution of 5 × 12 km (with the longer axis oriented north–south), which is insufficient to resolve the fine-scale spatial variability captured by our ground-based network. The data quality is also compromised during periods of low solar angle, which is common in Iceland, particularly outside of summer months. Below is a Sentinel-5p image showing SO_2 on the 20 of April 2021. Note the area over NE Iceland. This is noise in the data, probably due to the low solar angle affecting the data capture.

Another limitation for using satellite data to explain our ground-level observations is that the TROPOMI detects SO_2 throughout the atmospheric column and cannot determine whether the plume is present at ground level ('grounding'). In a comparative analysis conducted by the lead author as part of her PhD thesis (Whitty, 2022, University of Leeds), it was found that on days when the satellite detected the volcanic plume, it was grounding in only ~36% of cases.

In summary, while satellite data can provide useful synoptic context for large eruptions, the resolution, coverage, and vertical sensitivity of the available satellite observations during the 2021 Fagradalsfjall eruption are not sufficient to contribute meaningfully to our high-resolution ground-based dataset.

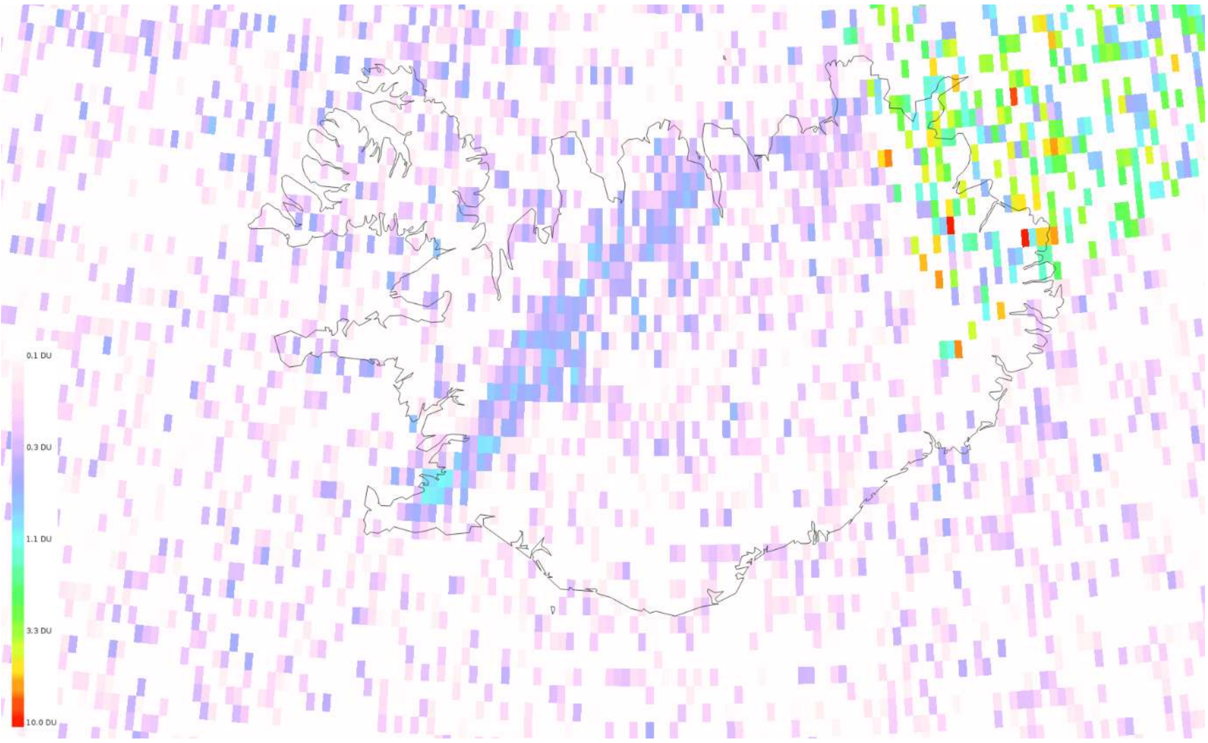

Figure: Sentinel-5p image of Iceland from 20 of April 2021 showing SO_2 in Dobson Units (DU).

Revised text discussing plume dispersion simulations and their limitations:

In section 3.4 ("Fine-scale temporal and spatial variability in SO_2 and PM_1 peaks"): "The movement and sharp boundaries of the plume during the 28–30 May episode are shown in an animation in Supplementary Figure S1, based on a dispersion model used operationally for volcanic air quality advisories during the eruption by the IMO (Barsotti, 2020; Pfeffer et al., 2024). The model results are used here for qualitative purposes—as a binary yes/no indicator of potential plume presence at ground level. This is because the model has been shown to have a reasonable skill in predicting the general plume direction but relatively low accuracy in simulating ground-level SO_2 concentrations for the 2021 eruption (Pfeffer et al., 2024)."

Also in section 3.4: "Supplementary Figure S2 shows an animation of the simulated dispersion of volcanic SO_2 at ground level during the 18–19 July episode as simulated by the IMO model (Pfeffer et al., 2024). As discussed by Pfeffer et al. (2024), the dispersion model did not accurately simulate all ground-level pollution events, including this one—the largest SO_2 pollution episode in Reykjavík during the eruption. This highlights the challenges of accurately simulating ground-level dispersion of volcanic emissions from eruptions like Fagradalsfjall 2021, as well as other small but highly dynamic natural and anthropogenic sources (Barsotti, 2020; Pfeffer et al., 2024; Sokhi et al., 2022). High-resolution observational datasets, including those presented here, can support improvements in dispersion model performance ."

In section 3.5.1: "From a nationwide public health perspective, it was fortunate that volcanic pollutants were predominantly transported to the north and northwest of the eruption site. This atmospheric transport pattern likely mitigated the frequency of SO_2 pollution episodes in the densely populated capital area, situated to the northeast of the eruption site. Supplementary Figure S3 illustrates the total probability of above-threshold SO_2 concentrations at ground level during the eruption, as simulated by the IMO dispersion model (Pfeffer et al., 2024). As outlined in Section 3.4, these simulations are used here solely to provide a qualitative indication of the broad plume direction at ground level. The modelled dispersion patterns are consistent with observational data, indicating that the plume most frequently grounded to the north and northwest of the eruption site, and more rarely in the capital area (Fig. S3)."

RC1: And just to be clear, is it correct that the wind direction is shown as the direction the wind is COMING FROM, as is the standard convention? If so, why are there so few times when the wind comes from the west and northwest?

We thank the reviewer for their observation. We have clarified in the caption of the wind rose figure that the wind direction refers to the direction *from which* the wind is blowing.

Regarding the distribution of wind directions: wind roses represent statistical summaries of wind patterns over a defined period. In this study, we analysed wind statistics over the duration of the eruption. While the jet stream generally flows from west to east, near-surface wind patterns are also influenced by local factors such as topography and proximity to the sea. These local effects can lead to more irregular wind distributions that deviate from the dominant synoptic-scale flow.

RC1: I recommend major revisions to address these issues. And the authors need to respond to the 39 comments in the attached annotated manuscript.

We have responded to the comments in the annotated manuscript and included it with this response as an attachment.

RC1: Why is there an Appendix B and not an Appendix A? Anyway, the Appendix should be supplemental material. Otherwise the paper is too long, and supplemental material should not be needed to read the gist of the paper.

We thank the reviewer for pointing out the numbering error in the Appendix. It has now been corrected to Appendix A throughout the manuscript. The figures in Appendix are in the appendix and not in the supplementary material based on the guidance from the journal:

Supplements: Supplementary material is reserved for items that cannot reasonably be included in the main text or as appendices. These may include short videos, very large images, maps, CIF files, as well as short computer codes such as matlab or python script.

RC1: There are multiple problems with the figures and tables:

The supplemental table needs a caption that can be read. Right now it is buried in Excel spreadsheet cells. The column headings in row 9 are also hard to read. Make them wide enough so the text is easy to read.

The caption for Table S1 was also in the main manuscript file, on the page after the Conclusions section, in agreement with the journal guidelines. Please note that according to the ACP journal procedures, “supplements will receive a title page added during the publication process including title”. We have made the columns in the Excel file wider to make the headings in row 9 easier to read. Please note that other users of this spreadsheet may prefer narrower columns, e.g. for comparing the quantitative values side-by-side. The width of the columns can be adjusted further by the users to suit their individual needs.

RC1: Table 1 should be all on one page. Why are you making it so hard for the reviewers to read it, with the column headers split over two pages? This is especially true, since there is empty space after the table on that page?

We thank the reviewer for pointing out this formatting issue. We have amended the tables to make them more readable. In particular, we have made sure that tables and individual words are not split across different lines, and changed shortened words like “erupt.” to full words like “eruptions”, where possible. The font sized has reduced somewhat because of this but we believe it is still legible. We could not put tables into landscape page orientation by the copy-editing rules of the journal.

RC1: For Fig. 3, the colors of the eruption and background plots are very similar. Make one red so they can be distinguished. And the diagrams show empty boxes, but I don’t see any on the plots. However, the same type plots in Fig. 4 are easy to see. Why don’t you make the ones in Fig. 3 the same?

We have changed the dark blue colour of the background data in Fig. 3 to the same colour as on Fig. 4. This gives a high contrast to the black colour of the eruption data, more so than could be achieved with a red/black colour combination. Regarding the ‘diagrams’ we assume the reviewer is referring to the box-and-whiskers symbol in the figure legend. The boxes represent the interquartile ranges of the data and are not visible on the SO_2 plot because the interquartile range of SO_2 has very low values (a few μg/m^3). This is because the SO_2 concentrations in the local background atmosphere are virtually zero, and most of the time the background is ‘clear’ of volcanic air pollution; but when the volcanic plume is advected into the area, the concentrations become very high. The boxes are more easy to see on Figure 4 because the interquartile range of PM concentrations is relatively high. We have clarified this in the Figure 3 caption:

“The data are presented as box-and-whisker plots: boxes represent the interquartile range (IQR), the whiskers extend to +/–2.7σ from the mean, and crosses represent very high values (statistical outliers beyond +/–2.7σ from the mean). Note that the IQR is very low in most cases due to the negligible SO_2 concentrations in the clean local background; as a result, most of the SO_2 pollution episodes are statistical outliers”. We have also added the crosses to the figure legend.

RC1: Fig. 4: Why are some stars red and some orange?

There were no red stars on Figure 4, but there were orange stars that were filled in with solid colour, and orange stars that were not filled in. We have clarified the meaning of each star type in the figure caption:

"Stars with solid orange fill represent the normalised number of times PM_{10} and $PM_{2.5}$ concentrations at each station exceeded the Icelandic Directive (ID) air quality thresholds of 50 $\mu g/m^3$ and 15 $\mu g/m^3$ (24-hour mean), respectively. For PM_1, non-filled stars indicate the number of times concentrations during the eruption exceeded the Environmental Agency of Iceland (EAI) threshold of 13 $\mu g/m^3$(24-hour mean). Different symbols (filled vs. non-filled stars) are used to distinguish between internationally accepted, evidence-based ID thresholds (PM_{10} and $PM_{2.5}$) and the locally applied EAI threshold for PM_1, which is not internationally standardized."

RC1: Table 2 is very poorly done. Because of the large cell margins, Erupt. goes over two lines, and does 0.2 on one line and 5 on the next line mean 0.25? Make the left and right cell margins smaller and use no indentation, and the table will be possible to understand.

Please see the reply to the comment about Table 1.

RC1: Shouldn't Table 2 be in the supplemental, and have it replaced with a figure? That would make it much easier to compare the numbers in each cell.

The data in Table 2 are already visualised in Figures 4, 5 and 6. Table 2 is supporting the figures because the large dynamic range in PM concentrations makes it hard to read the exact values directly from the figures.

RC1: Table 3 is also faulty. The caption mentions orange and green rows, but the text is all black. And the ratios written in the headers and the years on the side span two rows and are very hard to understand. This needs to be fixed.

We thank the reviewer for pointing this out. The green and orange colours were in the originally submitted manuscript but were removed prior to review based on the copy-editing rules of the journal. The caption has been amended in the revised manuscript, copied here:

"Table 3. Concentration ratios of PM size fractions (hourly-means, $\mu g/m^3$) associated with different pollution sources in the Reykjavík capital area. Rows 1 and 2 represent periods considered typical of Reykjavík background conditions: the 'Summer period', when studded tyres are not in use (banned between April and November), and a period during the 2021 eruption when the volcanic plume was advected away from Reykjavík. Rows 3–6 show ratios during the 2021 eruption when the plume was advected toward Reykjavík. For definitions of 'fresh' and 'mature' plume, see Section 3.4. Rows 7 and 8, labelled 'Desert dust', correspond to pollution episodes caused by Icelandic highland desert storms (source area ~200 km from Reykjavík), confirmed by meteorological and visual observations from the Icelandic Meteorological Office (IMO). Station G3-G is listed first, as it is considered the most sensitive to the presence of volcanic plume due to its low background concentrations from local sources."

Please also see our reply related to Tables 1 and 2 regarding changes to the readability of the tables.

RC1: Hint: If a table will not fit in a portrait orientation page, use landscape mode!

We could not put tables into landscape page orientation due to the copy-editing rules of the journal. Please see the previous reply on how the readability of the tables has been improved.

RC1: Fig. 9 should plot population density (by area), not by municipality.

We have amended the figure to show the population density. Please note that it is now Figure 10 in the new manuscript version.

RC1: Fig. 10a is so tiny with miniscule fonts that it cannot be read. Enlarge it and put it on its own separate page.

We thank the reviewer for pointing this out. The low resolution was an error when the file was converted to a pdf. We have fixed it and increased the font size on the figure. Please note that it is now Figure 11 in the new manuscript version.

Replies to Reviewer RC2

RC2: The article investigates the impact of the 2021 Fagradalsfjall volcanic eruption on air quality in the most densely populated region of Iceland. Using one of the densest reference-grade air quality monitoring networks in the world, the study finds statistically significant increases in SO_2 and particulate matter (PM_1, $PM_{2 \cdot 5}$, PM_{10}) concentrations, particularly PM_1. These findings have important implications for assessing population exposure and public health risks associated with volcanic air pollution in inhabited areas.

We thank the reviewer for their time and constructive comments.

RC2: In the reviewers opinion, a major limitation of the study is the lack of calibration for the low-cost sensors.

We wholeheartedly agree that, ideally, the low-cost sensors (LCS) would have been calibrated against reference-grade instruments. The reasons for the lack of calibration are outlined below and have also been added to the revised manuscript (Section 2.2). However, we respectfully disagree that this constitutes a major limitation of the overall study. The LCS dataset represents a relatively small component of the work. The primary focus of the study is on populated areas, where data were collected using regulatory-grade instruments. The LCS were deployed only at the eruption site to provide short-term guidance to visitors within a limited area (0–5 km from the vent).

Reasons for the lack of calibration of LCS in this study (also detailed in Section 2.2):

- **Crisis-response context:** The LCS were installed as part of an emergency response by the volcano observatory. The crisis was twofold: the eruption itself, and the unexpected and unprecedented influx of visitors to the eruption site. The primary purpose of the LCS deployment was to provide real-time alerts for very high SO_2 concentrations, not to generate a dataset with precise concentration values.
- **COVID-19 lockdown constraints:** The eruption occurred during national and international COVID-19 lockdowns, which significantly limited the capacity of observatory staff to conduct fieldwork and prevented international collaborators from assisting with sensor deployment and calibration.

While we fully acknowledge that the eruption-site data are not as robust as they could have been with proper calibration, we maintain that they provide valuable context and contribute meaningfully to the overall narrative of the study. Importantly, we use the LCS data only to identify whether SO_2 concentrations exceeded or remained below established thresholds. We do not use these data to draw conclusions about absolute concentration values. This limitation is clearly stated in the manuscript (Sections 2.2 and 3.5.2).

RC2: Below you will find my comments regarding the text.

Major Comments:

Sensor models: Please provide the specific models of the PM and SO_2 sensors used. Were these commercial low-cost sensors (e.g., Alphasense), or custom-built?

We thank the reviewer for this observation. The specific sensor models used at the eruption-site network (Alphasense SO_2-B4 and Crowcon Xgard) were already listed in Table S1, as noted in the main text, which refers readers to the table for sensor specifications and operational details.

In response to the reviewer's suggestion, we have now added to the *Methodology* section that these sensors are commercially available. We also clarify that only SO_2 was monitored at the eruption-site network; particulate matter (PM) was not measured at these locations. We have clarified this in the Methodology Section 2.2:

"At the eruption site (0.6-3 km from the active craters), the IMO installed a network of five commercially available SO_2 LCS between April and July 2021 to monitor air quality in the near-field. PM was not monitored with this network due to cost-benefit considerations as PM does not pose as acute a hazard as SO_2 for short-term exposure. The sensor specifications and operational durations are detailed in Table S1."

RC2: Air intake design: How was the air intake for the sensors constructed? Was it a prototype, experimental design, or a standardized market-available solution? This should be clearly described, ideally with a schematic or reference.

The air intake was designed in-house at the volcano observatory (Iceland Met Office or IMO) taking into account local conditions, in particular the weather and dust resuspension. We have added photographs to the appendix showing the installation in the field, and the cover of the air intake (copied below).

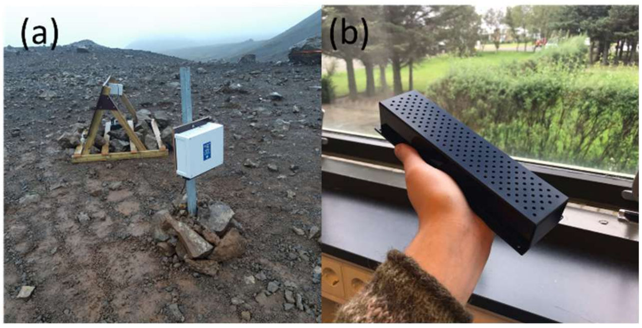

Figure A1 Lower-cost sensors used for the Fagradalsfjall 2021 eruption. Panel (a) shows the instrument installed in the field. The station was powered by a solar panel (triangular trellis at the back of the photo). The air intake was underneath the instrument (the white box at the front of the image). Panel (b) shows the air intake of the sensor. The air intake was designed in-house at the IMO taking into account local conditions, in particular the weather and dust resuspension. The cover was custom-made from Plexiglass with the sensors are recessed behind it to be protected from dust, precipitation, and other potentially damaging environmental factors.

RC2: Sensor sampling period: The manuscript lacks information on the temporal resolution or sampling interval of the sensors. This is crucial for interpreting short-term variability in pollutant concentrations and for reproducibility.

The temporal resolution for each sensor has been added to Supplementary Table S1

RC2: It may be helpful to add a dedicated supplementary table with detailed specifications for each sensor (manufacturer, model, detection range, resolution, operational dates).

This information was already available in Supplementary Table S1, with the exception of temporal resolution; this has been added to the same table.

RC2: Technical and Formatting Corrections:

Line 138 & 360: "PM2.5" → please use correct subscript formatting (e.g., $PM_{2.5}$) and apply this consistently throughout the manuscript.

We thank the reviewer for pointing this out and have correct these errors throughout.

RC2: Line 192: Correct the citation format – change "(Icelandic Directive, 2016)" to Icelandic Directive (2016).

We apologise for this recurring formatting mistake, which was introduced by our referencing software and missed during our proofreading. We have done our best to find and correct all of these mistakes in the revised version.

RC2: Line 193–194: Add space before parentheses: "15 µg/m3(World" → 15 µg/m^3 (World).

Same reply as to previous comment.

RC2: Line 119: please clarify which size fraction is being referenced here (PM_1, $PM_{2.5}$, or PM_{10}?).

PM10, this has been clarified.

RC2: Please revise the manuscript to correct improper or missing articles. Numerous instances throughout the manuscript require grammatical revision.

The revised manuscript has been proofread for English grammar and clarity by the co-authors, with additional support from Microsoft Copilot (GPT-4) as stated in the Acknowledgements.

RC2: Figures and Tables:

Figure 4: Please explain in the legend what is the meaning of full vs empty stars.

We have rephrased the caption to clarify this:

"Stars with solid orange fill represent the normalised number of times PM_{10} and $PM_{2.5}$ concentrations at each station exceeded the Icelandic Directive (ID) air quality thresholds of 50 µg/m^3 and 15 µg/m^3 (24-hour mean), respectively. For PM_1, non-filled stars indicate the number of times concentrations during the eruption exceeded the Environmental Agency of Iceland (EAI) threshold of 13 µg/m^3(24-hour mean). Different symbols (filled vs. non-filled stars) are used to distinguish between internationally accepted, evidence-based ID thresholds (PM_{10} and $PM_{2.5}$) and the locally applied EAI threshold for PM_1, which is not internationally standardized."

RC2: Table 1: The table should be kept on a single page to aid readability.

We have amended the tables to make them more readable. In particular, we have made sure that tables and individual words are not split across different lines, and changed shortened words like "erupt." to full words like "eruptions", where possible. The font sized has reduced somewhat because of this but we believe it is still legible. We could not put tables into landscape page orientation by the copy-editing rules of the journal.

RC2: Table 3: The manuscript refers to "Green-coloured" and "Orange-coloured" rows, but these distinctions are not visible in black-and-white print.

We apologise for the wrong description in the caption – the green and orange colours were in the originally submitted manuscript but were removed prior to review based on the copy-editing rules of the journal. By mistake we did not update the caption accordingly. This has been amended in the revised manuscript:

"Table 3. Concentration ratios of PM size fractions (hourly-means, µg/m^3) associated with different pollution sources in the Reykjavík capital area. Rows 1 and 2 represent periods considered typical of Reykjavík background conditions: the 'Summer period', when studded tyres are not in use (banned between April and November), and a period during the 2021 eruption when the volcanic plume was advected away from Reykjavík. Rows 3–6 show ratios during the 2021 eruption when the plume was advected toward Reykjavík. For definitions of 'fresh' and 'mature' plume, see Section 3.4. Rows 7 and 8, labelled 'Desert dust', correspond to pollution episodes caused by Icelandic highland desert storms (source area ~200 km from Reykjavík), confirmed by meteorological and visual observations from the Icelandic Meteorological Office (IMO). Station G3-G is listed first, as it is considered the most sensitive to the presence of volcanic plume due to its low background concentrations from local sources."

RC2: Please make the tables more readable.

See previous reply regarding Table 1. The same reply applies to all tables.

RC2: Consider using a logarithmic scale on selected figures. This would allow better visualization of both low and high values (e.g., Figure B3).

We have introduced a logarithmic y-axis scale on Figures A3, A4 and A7 (formerly numbered B2, B3 and A6).

Replies to Reviewer RC3

RC3: General comments:

This study reports measurements of SO2 and particulate matter concentrations at several Icelandic in-situ measurement stations before and during the 2021 Fagradalsfjall fissure eruption. The study contains some novel results and is of interest to the scientific community, in my opinion. It is generally well written and I don't have any major objections to the publication of the paper. I ask the authors to consider the following general and specific comments.

We thank the reviewer for their time and constructive comments, which we have addressed as detailed below.

RC3: One general comment addressed the term „reference-grade". It is used many times throughout the manuscript and I assume most readers will understand more or less what it means. It would be good, however, to state briefly at the beginning of the paper, what the exact meaning of the term is in this study.

We have added an explanation to the Introduction (also copied below); and we changed the word 'reference-grade' to 'regulatory' throughout the manuscript because we think that a) it is more easily understood by the readers and b) it is consistent with the phrasing used in papers on similar topics, e.g. Crawford et al https://doi.org/10.1073/pnas.202554011.

Copied from the new version of the manuscript:

"Here, we use the term 'regulatory' to describe an air quality monitoring network operated by a national agency, employing certified commercial instrumentation with regulated setup and calibration protocols. These networks provide high-accuracy, high-precision measurements with high temporal resolution, but typically with low spatial resolution due to the high costs of installation (typically > € 100,000) and annual maintenance (typically > € 100,000 per annum)."

RC3: Specific comments:

Line 90: "…, locally known as Reykjanes Fires."

This is only a minor point, but from the way this is phrased, it is not entirely clear what the last part of the sentence refers to. I assume it is supposed to refer to the eruption, but linguistically it may also refer to "Reykjanes peninsula".

We have rephrased this part of the paragraph and added more explanation on what 'Reykjanes Fires' are, and why they are significant:

"This eruption is considered to mark the onset of a new period of frequent eruptions on the Reykjanes peninsula. Such periods, locally referred to as the 'Reykjanes Fires', have occurred roughly every 1000 years, each lasting for decades to centuries. The last period of Reykjanes Fires ended with an eruption in 1240 CE (Sigurgeirsson and Einarsson, 2019). Since the 2021 eruption, ten further eruptions have occurred on the Reykjanes peninsula: two within the Fagradalsfjall volcanic system (August 2022 and July 2023), and eight within the adjacent Reykjanes-Svartsengi system (December 2023 to April 2025). Volcanic unrest continues at the time of writing, and based on the eruption history of the Reykjanes peninsula, further eruptions may occur repeatedly over the coming decades or centuries."

RC3: Line 98: "and over 70% of Iceland's total population (263,000 out of 369,000 people) lived within 50 km distance, including the capital area of Reykjavík."

This has been mentioned already two times before and I'm not sure, whether it has to be repeated again.

We have removed the duplication of the number of people in Reykjavik and rephrased this to "This region is the most densely populated area of Iceland, with over 260,000 people—around 70% of the national population—residing within 50 km of the eruption site. The eruption site was 9 km from the town of Grindavík and approximately 25 km from the capital area of Reykjavík. Although the eruption took place in an uninhabited area, it attracted an estimated 300,000 visitors who observed the event at close range."

RC3: Line 132: "The sensor accuracy limits during field deployment of (Whitty et al., 2022) were significantly poorer than the detection limits reported by the manufacturer."

Something is wrong here.

Thank you for pointing out this phrasing mistake. Rephrased to "The sensor accuracy identified in the field study by Whitty et al. (2022) was significantly poorer than the detection limits reported by the manufacturer."

RC3: Line 170: "We considered whether the year 2020 had lower PM and PM concentrations"

PM10 and PM2.5?

Yes, we thank the reviewer for pointing out this unfortunate error. Corrected to PM_{10} and $PM_{2.5}$

RC3: Line 192: "by the (Icelandic Directive, 2016)."

Opening parenthesis in the wrong place.

We apologise for this recurring formatting mistake, which was introduced by the referencing software and missed during the proofreading. We have done our best to find and correct all of these mistakes in the revised version.

RC3: Lines 193 and 194: missing spaces before citations.

Corrected, thank you.

RC3: Figure 2, G3-A: an increase von 14% to 21% is not that large. It would be good to know what the standard deviation of the PM1 fraction before the eruption is.

We have added text to explain that even a small increase in the PM_1/PM_{10} mass ratio is important for potential health impacts:

"Emerging studies of the links between PM_1 and health impacts in urban air pollution have shown that even small increases in the PM_1 proportion within PM_{10} can be associated with increasingly worse outcomes; e.g. liver cancer mortalities in China were found to increase for every 1% increase in the proportion of PM_1 within PM_{10} (Gan et al., 2025). "

We have added standard deviation to Figure 2, as well as to Table S1. Please note that the % values shown on Figure 2 for the background period have changed slightly from the previous manuscript version because we discovered an error in our data processing script. The error was that the % contribution of the size fractions $PM_{2.5-1}$ and $PM_{10-2.5}$ were calculated based on a much longer timeseries than for PM_1, which has only been measured since 2020. We have updated the related discussion accordingly.

RC3: Line 230: "This is a novel result showing that volcanic plumes contribute a significantly higher proportion of 230 PM1 relative to both PM10 and PM2.5"

Without the standard deviation etc. one cannot really tell, whether the PM1 proportion is significantly enhanced, right?

See the reply to the previous comment, standard deviation has been added to Figure 2 and the related text.

RC3: Table 1: It would be very useful for the reader to add the standard deviation of the SO2 hourly means for the background conditions, to judge how large the variability is.

We have added standard deviation to Table 1 (and to Table S1 for individual air quality stations)

RC3: Figure 3: I don't fully understand what the red asterisks show? The legend states: "The figure also shows whether the number of threshold exceedances at each station exceeded the recommended annual total (n=24, orange horizontal line" and I understand what the horizontal orange line means. But the red asterisks also appear below the line? Sorry, I think, I didn't get the point here.

We have rephrased the figure caption to clarify this:

"The ID air quality threshold of 350 µg/m^3 (hourly-mean) is indicated by a black horizontal line in all panels. Red stars represent the number of times this threshold was exceeded at each station ('exceedance events'). The annual limit for cumulative hourly exceedance events is 24, shown by an orange horizontal line. Stations with red stars above the orange line exceeded the annual threshold."

RC3: Also: because of the large dynamic range of the SO2 values a logarithmic y-axis would be useful here. At the moment it is impossible to tell, whether the values in Table 1 are consistent with the figures. And the boxes and whiskers are not really visible.

We understand this comment and we have experimented with a logarithmic scale (figure version shown below); however, we believe that a linear scale is more suitable to display and discuss our data due to the following reasons:

1. The box and whiskers are not visible on the plot because the median value and the interquartile range are very low values (a few µg/m^3). This is because the SO_2 concentrations in the local background atmosphere are virtually zero, and most of the time the background is 'clear' of volcanic air pollution; but when the volcanic plume is advected into the area, the concentrations become very high. One of the key findings in our study is that the average values of SO_2 are not significantly affected by the volcanic eruption, but the SO_2 pollution peaks (i.e. the statistical 'outliers') are much higher during the eruption than during the background period. We have clarified this in the Figure 3 caption "Please note that the interquartile range is very low in most cases because SO_2 concentrations are virtually negligible in the clean local background; most of the SO_2 pollution episodes are therefore statistical outliers."
2. A logarithmic y-axis scale does not make it easier to see the median and the interquartile range as shown on the figure below (because, as explained in the previous paragraph, these values are very small compared to the statistical outliers). The logarithmic scale also has the well-known problem of visually inflating smaller values, meaning that in this case, the difference in the peak SO_2 values between the background

and the eruption periods is represented as being relatively small but in reality it was large. Given that the aim with this figure is to illustrate the large difference in the peak values we argue that using a logarithmic scale would be counterproductive for this reason.

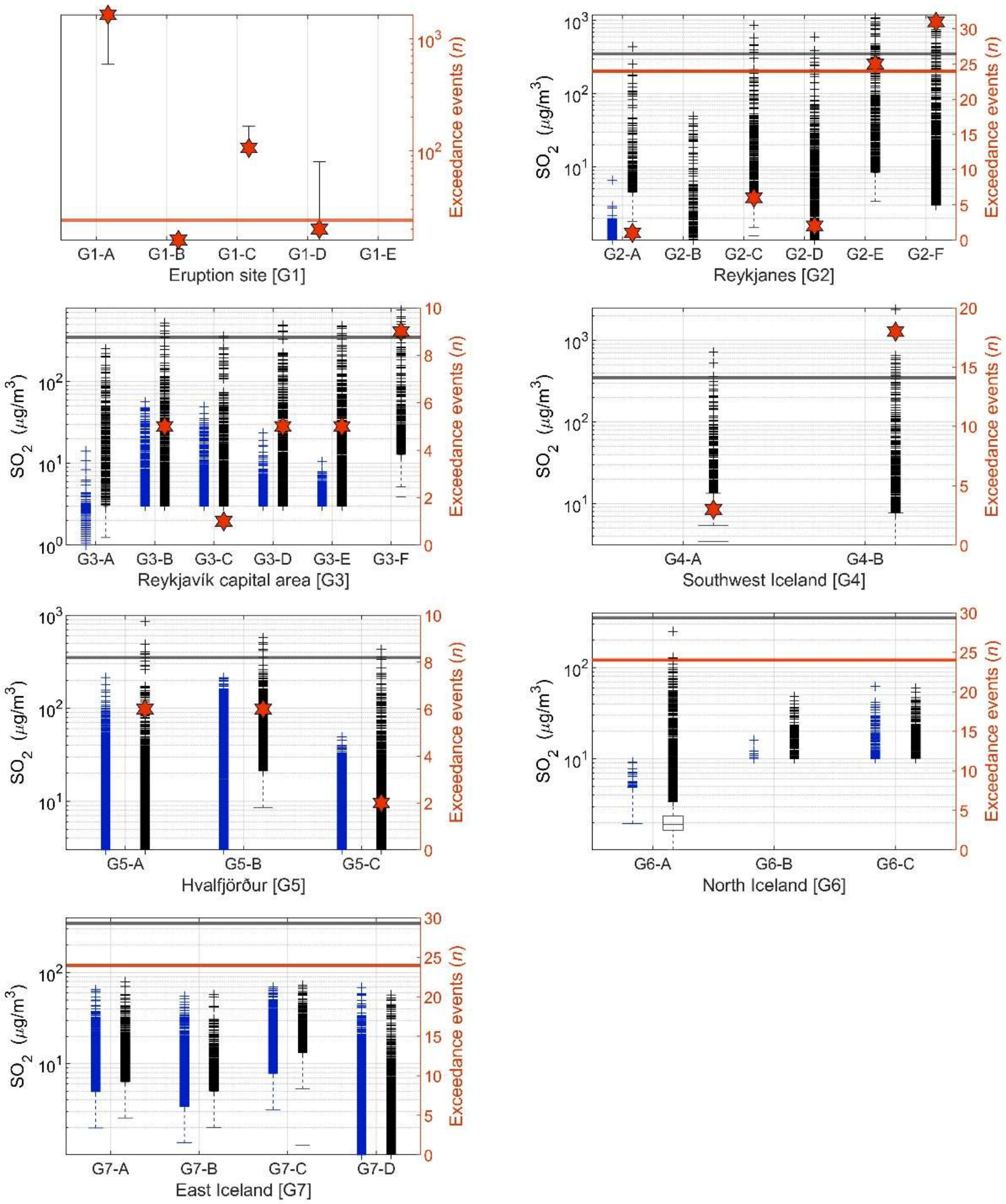

Figure: Figure 3 with y-axis logarithmic scale

RC3: Another question about the box and whisker plots: What percentiles do you assume for the whiskers? It cannot be the 0th and 100th percentiles, because you show outliers.

We have clarified this in the Figure 3 caption (as well as for other figures showing same type of plots):

"The data are presented as box-and-whisker plots: boxes represent the interquartile range (IQR), the whiskers extend to +/–2.7σ from the mean, and crosses represent very high values (statistical outliers beyond +/–2.7σ from the mean). Note that the IQR is very low in most cases due to the negligible SO_2 concentrations in the clean local background; as a result, most of the SO_2 pollution episodes are statistical outliers."

RC3: Figure 4: What is the difference between solid and open asterisks? This doesn't seem to be explicitly mentioned?

We have rephrased the caption to clarify this:

"Stars with solid orange fill represent the normalised number of times PM_{10} and $PM_{2.5}$ concentrations at each station exceeded the Icelandic Directive (ID) air quality thresholds of 50 μg/m^3 and 15 μg/m^3 (24-hour mean), respectively. For PM_1, non-filled stars indicate the number of times concentrations during the eruption exceeded the Environmental Agency of Iceland (EAI) threshold of 13 μg/m^3(24-hour mean). Different symbols (filled vs. non-filled stars) are used to distinguish between internationally accepted, evidence-based ID thresholds (PM_{10} and $PM_{2.5}$) and the locally applied EAI threshold for PM_1, which is not internationally standardized."

RC3: Figure 5: In some of the boxes the median seems to be missing? Why?

In these cases the median is zero and therefore overlaps with the lower limit of the box. We have clarified this in the figure caption.

RC3: Table 2: The standard deviation would also be useful here.

We have added standard deviation to Table 2.

RC3: Line 411: "Figures 7a-7d show the spatio-temporal resolution and ratios of SO2 and PM"

Why "resolution"? Perhaps "variation"?

Variation is a good suggestion, we have amended the text accordingly. Please note that in the revised version the old Figure 7 is now Figure 8.

RC3: And the plots don't really show ratios of SO2 and PM. Do you mean the scatter plots here?

We have rephrased the text to clarify this: "Figure 8 illustrates the variation in SO_2 and PM_1 abundances during this episode, shown as time series (Figs. 8a–8b) and as concentration ratios (Figs. 8c–8d)." Please note that in the revised version the old Figure 7 is now Figure 8.

RC3: Figure 10a: The text in figure and legend is barely legible.

We apologise for the low resolution which was an unfortunate error introduced by the pdf conversion. We have improved the resolution and also increased the font size on the figure. Please note that in the revised version the old Figure 10 is now Figure 11.

RC3: Section 3.5.2: This section only contains quite general and somewhat vague considerations with little quantitative results? What are the main conclusions of section 3.5.2?

In the Introduction we have clarified the main objective of analysing the lower-cost sensor (LCS) data:

"We present and discuss the use of LCS in a crisis mitigation context, which has broader relevance for other high-concentration, rapid-onset air pollution events, such as wildfires."

Section 3.5.2 has also been rewritten to make the aims and the conclusions clear. The whole section is too long to be copied into this response (but is available in the revised manuscript file) so we copied just the main conclusion here:

"In conclusion, we suggest that the deployment of the LCS network contributed meaningfully to reducing the SO_2 hazard at the eruption site, given the high frequency of above-threshold SO_2 concentrations and the high number of people within a small area. Such networks are recommended in comparable crisis-response scenarios, provided that careful consideration is given to how the data and resulting alerts are interpreted and communicated. However, their applicability may be less suitable in contexts where chronic exposure among permanent residents is the primary concern."

RC3: There is probably (?) no lower threshold for the harmful consequences of air pollution and it may also be of interest to consider periods with SO2 levels below the assumed threshold.

We agree that lower concentrations of SO_2 may still be associated with adverse health impacts, and we acknowledge that this is an important area for future epidemiological research. In response, we have added a discussion of this point to Section 3.5.1 (copied below). Our full dataset includes measurements across a wide range of concentrations, including lower levels of SO_2, and is therefore well-suited to support follow-on epidemiological investigations.

"Based on the available evidence, it is likely that the 2021 eruption may have resulted in adverse health impacts among exposed populations. Epidemiological studies by Carlsen et al. (2021a, b) on the 2014–2015 Holuhraun eruption demonstrated a measurable increase in healthcare utilisation for respiratory conditions in the Reykjavík capital area, associated with the presence of the volcanic plume. Exposure to above-threshold SO_2 concentrations was linked to approximately 20% increase in asthma medication dispensations and primary care visits. Furthermore, even modest increases in SO_2 levels were associated with small but statistically significant rises in healthcare usage—approximately a 1% increase per 10 μg/m^3 SO_2—suggesting the absence of a safe lower threshold. During the Fagradalsfjall eruption, SO_2 concentrations in populated areas reached levels broadly comparable to those observed during the larger but more distal Holuhraun eruption. Consequently, similar health impacts may be expected, as inferred from the findings of Carlsen et al. (2021a, b). Holuhraun emissions led to 33 exceedances of the SO_2 air quality threshold in Reykjavík, with hourly-mean concentrations peaking at 1400 μg/m^3 (Ilyinskaya et al., 2017). In comparison, the Fagradalsfjall eruption caused 31 exceedances, with a maximum of 2400 μg/m^3 SO_2 recorded in the community of Vogar (station G2-F). Additionally, Fagradalsfjall caused SO_2 threshold exceedances across all monitored areas within approximately 50 km of the eruption site (areas G1–G5). By definition, there is no safe lower limit for the number of air quality exceedance events. Therefore, all areas that recorded above-threshold pollutant concentrations may have experienced adverse health effects. Furthermore, although the monitored regions in North and East Iceland (areas G6 and G7) did not register threshold exceedances, potential health impacts in these areas cannot be ruled out. As reported by Carlsen et al. (2021b), even relatively small, above-background increases in SO_2 concentrations during the Holuhraun eruption were associated with measurable health effects.

Given the limited number and scope of health impact studies on previous volcanic eruptions, the potential health implications discussed here should be further investigated through dedicated epidemiological and/or clinical studies focused specifically on the Fagradalsfjall event. Moreover, existing health studies from volcanic regions have primarily concentrated on short-term exposure (hourly and daily), with a gap in research of potential long-term effects. Since the 2021 eruption, ten additional eruptions of similar style and in the same geographic area have occurred. Although each event has been relatively short-lived—ranging from several days to several months—their cumulative impact on air quality and public health may be chronic rather than acute, and thus warrants comprehensive investigation."