

## Reply to Reviewer 1:

We thank the reviewer for the insightful comments, and we agree that the paper is mostly composed of two main sections: the first one on the critical description of observations found in technical reports and newspapers and the second one on the comparison with other eruptions and considerations on the potential hazard associated with a future eruption of similar size. However, we feel that the first section is as important as the second in order to better appreciate the whole impact. In particular, most of the technical reports and newspapers used for this manuscript are not available anymore and, therefore, are not accessible to the international community. Considering the general lack of direct information on impact from eruptions, we believe that this section is crucial to make a better link between natural phenomena and impact on society.

Main comments are reported in red and our reply is reported in black.

1) It is not entirely clear how the authors “study the local impact of the 2011 eruption of Cordón Caulle volcano (Chile)”. The paper would benefit from more detail on whether any fieldwork or personal experience was incorporated, or whether this is simply a compilation of impacts from reading other’s reports and looking at local media and satellite images. More interpretation of the data sources in the main body of the paper would also be valuable. How reliable are the sources? For example, are media sources taken as definitive? Were any sources found to be contradictory?

As stated at page 2: “In this study, we compile data from the newspapers, scientific reports and satellite images (see Appendix A for more details) mainly to reconstruct a precise chronology of events and the local and regional impact of the 2011 CC eruption, as well as the management of the crisis at different localities in Argentina, where ash dispersal and deposition strongly impacted environment, population and various economic sectors.”

We have also added to the text (section 1.1):

“The large variety of sources used in this study and described in Appendix A was considered with various degrees of confidence, amongst which technical reports were judged the most reliable. Newspaper articles were used mostly to constrain the chronology of events (e.g. date and duration of tephra fallouts in various localities) and assess the impact on the aviation sector (e.g. dates, duration and location of ground traffic interruption, services interruption, flight cancellations and airports closure). It must be noted that the data published in the newspapers about the characteristic of the tephra deposit was not considered reliable as large discrepancies were observed between deposit thickness measured in the field versus those reported in the media (see Section 7.1). When possible, newspaper articles were corroborated with MODIS and/or GOES satellite images.”

2) Much of the listing of impacts appears to be an amalgamation of previous information, e.g. technical reports and information from the media. The reader needs to be clear where the new content in these sections is. For example, how does this build upon the technical reports on ‘Impacts of the June 2011 Puyehue-Cordón Caulle volcanic complex eruption on urban infrastructure, agriculture and public health’ by Wilson et al., 2013?

As mentioned above, the manuscript includes a collection of information taken from reports that are difficult to access or that are no longer available in order to make these precious observations

available to the international community. The report of Wilson et al. 2013 is also part of this collection and is quoted in various parts of the manuscript. In particular, Wilson et al. (2013) studied the impact of CC eruption and although the thematic is the same, they analyzed it in a different manner. In their report, they provide a brief description of the deposit and the remobilization of ash. They describe the impact on public health, pastoral farming and critical infrastructure, adding recommendations for each topic. They also analyzed the crisis management and give recommendations to improve it. In a few words, our approach is oriented to identify the relation between the impact and the tephra deposit, while Wilson et al. (2013) give recommendations to better manage the crisis and recovery.

3) Many of the impacts are listed without clear reference to the ash thickness or characteristics at that site, or a description of the fragility of the component, system or network. Most, if not all, of the impacts have been recognised in previous eruptions and so to better constrain the relationship between natural phenomena and society response there needs to be a discussion within the paper of how the tephra characteristics or asset in question are influencing the level of impact. Figure 9 goes some way towards this but the analysis and extra information would be better expanded and discussed throughout the paper to avoid the feeling of reading a list of impacts, with no analysis or commentary on the data quality. A few non-exhaustive examples:

a) page 5402 clearly states that the production of wool and animal loss is related to the amount of accumulated ash – this is really valuable information if quantified, but Figure 5 is a photo of a sheep. Could the authors not provide quantitative relationships? If not, why not? Lack of observations? Lack of accessibility? Too late or little fieldwork? Weather problems?

b) Page 5405 and 5406: Steppes showed initial impact proportional to the amount of ash deposited. This is also interesting and potentially valuable but it is difficult to identify a clear relationship in the text that could be used to “better constrain the relationship between natural phenomena and society response”.

c) Section 8.2, and others: a discussion of the ash fall characteristics in the areas impacted would be useful, even though some information is available in the maps. This would help limit the report feeling like a listing of impacts.

d) Page 5402, lines 12-13: “The northern departments of Chubut Province were also affected with ash accumulation between 0.3–4 cm”. Does this belong with the following paragraph? Otherwise, what are we learning about the impact on livestock from this sentence?

e) Where was the 1.5 M m<sup>3</sup> of ash removed during the first 8 months (page 5409) removed to? Any problems in identifying a location, or in transporting it there? Or is there no information on that?

f) Did the crisis management (Section 12) result in any changes in strategy? How did it compare with previous eruptions in the area?

g) The authors recognise that impacts were identified qualitatively but more discussion on the limitations of this and how this could be improved in future eruptions may be useful?

*Main comment:* We completely agree with the reviewer that a relation between damage and thickness of tephra layer would be very valuable. However, this information was not available in the reports used in our collection. Nonetheless, we tried to make this relation by compiling Fig 9. Unfortunately, no more than this can be done at this stage. The reviewer also asks a more detailed description of the relation between damage and characteristics of tephra deposits, but this information is already available at page 5414-5415 when we describe Fig. 9. In this part we describe

both thickness and grainsize in relation to the impact as we could derive it based on our field observations.

*Comment 3a:* Unfortunately we cannot quantify the relation between ash accumulation and production of wool and animal loss to complement Fig. 5. The sentence “The decrease in the production of wool and the loss of animals varied according to the amount of accumulated ash” refers to the Technical Report INTA-EEA (2011), where they classified the type and degree of impact observed in the field in the different departments of Neuquén and Río Negro provinces, according to the thickness of the tephra deposit. They subdivided the areas according to the severity of the impact to water, grassland and cattle. They observed that in the departments with higher tephra accumulation the quality of wool and survival of the animals, due to burial of vegetation and water sources, was lower than in areas with thinner deposits. There is no information that quantifies loss of production with ash thickness. There are newspapers articles (2013) quoting experts from the “Argentine Rural Confederation” and “Argentine Rural Society” (groups that represent rural producers), that states that there is a loss in wool production in Patagonia. There is no quantification of the losses in different parts of Patagonia that could make possible to relate a degree of loss with the deposit thickness. Besides, there is a conjunction of factors that according to these organizations, led to the loss in wool production. These factors include the prolonged drought that affected the area since 2007, the tephra fallout, and economic factors (inflation, withholding tax on exports). A report from the Inter-American Development Bank, estimated the death of 15% of sheep and goats cattle in Northern Patagonia (total number of 2 million), with a monetary loss of US\$30 million, and a loss of US\$6 million related to the loss in wool production. However, all the information gathered is regional, preventing to generalize some conclusions about the link between losses and the tephra deposit.

*Comment 3b:* “The steppes showed initial impact proportional to the amount of ash deposited”. This sentence makes reference to the fact that in the steppe, irrespective to location and weather, the impact was directly related to ash thickness, while for other ecosystems other factors (geography, rainfall) had influence in the degree of impact.

*Comment 3d:* We agree that this sentence was confusing. We rewrote it as: “Finally, livestock in the departments located in northern sector of Chubut Province was also affected. In these areas ash accumulation varied between 0.3 and 4 cm (INTA-EEA Chubut, 2011)”.

*Comment 3e:* The removal of more than 1.5 Mm<sup>3</sup> (1.748.750. m<sup>3</sup> according to a report from Inter-American Development Bank) of ash correspond to the locality of Villa La Angostura. They removed it from the town and deposited it in an abandoned quarry in the Río Bonito Valley, close to Puerto Manzano. We have added this information to the text.

*Comment 3f:* we have added this text to the discussion: “As a direct impact of the 2011 Cerdón eruption, the Argentinean government has made several attempts to improve the management of the volcanic risk; for instance, many projects directed towards volcano monitoring have been funded at a National and Provincial level since 2011-2012. In addition, in the last couple of years, a Risk Management Commission was created by the National Ministry of Science and Technology, in order to organize the institutions involved with prevention and response. This commission is preparing Protocols to manage different types of risk.”

*Comment 3g:* We have added at the end of conclusive summary section: “These data would help the compilation of fragility curves for different systems (e.g. buildings, infrastructures, production sites, agriculture) that are necessary to link accumulation of tephra and associated impact”.

Minor comments:

1) Page 5386, lines 11-12: Some of the earlier studies of eruption impact should surely be referenced here as well as the Wilson papers? e.g. any of those within Blong, 1984 and those from subsequent eruptions.

We have added: (Blong 1984, 2003; Hampton et al. 2015; Jenkins et al. 2014; Johnston et al. 2000 ; Magill et al. 2013; Martin et al. 2009 ; Milazzo et al. 2013; Stewart et al. 2006; Wardman et al. 2012)

Blong, R.: Volcanic Hazards: A Sourcebook on the Effects of Eruptions. Academic Press, Australia, 424 pp. 1984.

Blong, R.: Building damage in Rabaul, Papua New Guinea, 1994. *B. Volcanol.*, 65, 43–54. 2003.

Hampton SJ, Cole JW, Wilson G, et al (2015) Volcanic ashfall accumulation and loading on gutters and pitched roofs from laboratory empirical experiments: Implications for risk assessment. *J Volcanol Geotherm Res* 304:237–252. doi: 10.1016/j.jvolgeores.2015.08.012

Jenkins SF, Spence RJS, Fonseca JFBD, et al (2014) Volcanic risk assessment: Quantifying physical vulnerability in the built environment. *J Volcanol Geotherm Res* 276:105–120. doi: 10.1016/j.jvolgeores.2014.03.002

Johnston, DM., Houghton, BF., Neall, VE., Ronan, KR. and Paton, D.: Impacts of the 1945 and 1995–1996 Ruapehu eruptions, New Zealand: An example of increasing societal vulnerability. *Geol. Soc. Am. Bull.*, 112, 720–726. 2000.

Magill C, Wilson T, Okada T (2013) Observations of tephra fall impacts from the 2011 Shinmoedake eruption, Japan. *Earth, Planets, Sp* 65:677–698. doi: 10.5047/eps.2013.05.010

Martin, R.S., Watt, S.F.L., Pyle, D.M., Mather, T.A., Matthews, N.E., Georg, R.B., Day, J.A., Fairhead, T., Witt, M.L.I. and Quayle B.M.: Environmental effects of ashfall in Argentina from the 2008 Chaitén volcanic eruption. *J. Volcanol. Geoth. Res.*, 184 (3–4), 462–472, 2009. (this is already in the references)

Milazzo M, Ancione G, Basco A, et al (2013) Potential loading damage to industrial storage tanks due to volcanic ash fallout. *Nat Hazards* 66:939–953. doi: 10.1007/s11069-012-0518-5

Stewart, C., Johnston, DM., Leonard, GS., Horwell, CJ., Thordarson, T. and Cronin, S.J.: Contamination of water supplies by volcanic ashfall: a literature review and simple impact modelling. *J. Volcanol. Geoth. Res.*, 158(3), 296-306, doi:10.1016/j.jvolgeores.2006.07.002, 2006.

Wardman J, Wilson T, Bodger P, et al (2012) Investigating the electrical conductivity of volcanic ash and its effect on HV power systems. *Phys Chem Earth, Parts A/B/C* 45--46:128–145.

2) Page 5392, line 14: evacuating 3647 people is incredibly precise, presumably this comes from a technical report that uses census data or population records. It is almost certainly incorrect and should be rounded.

The number of evacuated people is 3647 as reported by Abumohor and Díaz (2011), and comes from census data. We have rounded it to 3700.

3) Page 5397, line 3: incomplete sentence at the end of the paragraph. Should it read shops and public transport were closed?

The sentence is incomplete, we changed it to: “shops were closed and public transports were interrupted”.

4) Page 5413, line 29: for exceeding the tephra accumulation.

ok

5) Page 5416, line 5: please explain that the occurrence of fine ash on top of the deposit can form a hard crust which then promoted the high rainfall: The fine-ash layer does not need to create a crust as it can reduce the infiltration and permeability of the whole tephra deposit. In order to explain this, we have added: "This effect WHERE THE WHOLE TEPHRA DEPOSIT IS MADE IMPERMEABLE BY AN OVERLAYING FINE-ASH LAYER has been largely described for several mid- to low-intensity eruptions also at Vesuvius, Italy (Cioni et al., 2008).