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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Lidar observation and model simulation of a volcanic-ash-induced cirrus cloud during the Eyjafjallajökull eruption" *by* C. Rolf et al.

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The authors thank Referee 1 for reviewing the paper and for fruitful comments which were helpful to improve the paper. All changes of the paper are highlighted with blue and red colors. Point by point answers to your comments are reported below.

General comments

- *Abstract: I expected that the volcanic aerosol provided a high IN concentration in the upper troposphere shortly after the Eyjafjallajökull eruption in mid April*

2010, much more than just a factor of 10 compared to clean background conditions. May be the given background value (0.01 cm-3) is too high? Please check Richardson et al. (JGR 2007) and other papers dealing with particle concentration in the upper free troposphere.

You are right, the IN concentration of 0.01 cm-3 is to high for clean background conditions. But in our study we want to exclude possible impact of other IN types which are not originating from the volcano. Richardson found typical background IN values of 1-10 per std liter (0,0005 - 0,005 cm-3). But also higher values are found up to 0.01 cm-3. This is in accordance to DeMott et al. 2010 who found also higher values above 0.01 cm-3. So we changed the text from clean to normal IN conditions in the whole paper.

Specific comments

- *Page 15676, line 21: the first large eruption occurred on 14 April 2010.*
  Is changed to 14 April (see page 1, line 34).
- *Line 24: The second paragraph is a bit misleading. Seifert et al. (2011) is introduced too late. Right in the beginning of the paragraph, there should be more information regarding recent observations of clouds and Eyjafjallajökull volcanic aerosols. There are several special issues (ACP, Atmos. Environ, JGR) available.*
  We have insert a sentence in the first section documenting the observations and related publications (see page 1, lines 29 - 33).
- *Page 15677, line 29 (last line): increasing depolarization is found also by others over central Europe. However, at 355 nm, it is hard to see that based on volume depolarization ratios. Could you provide some numbers for the particle depolarization ratio (i.e., depolarization ratios after removing the dominating Rayleigh effects)?*

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Figure 1 is extended by profiles of particle depolarization before ash induced cirrus and during the first and the second half of the cirrus cloud (see page 5).

- *Page 15678, line 21: Leo-Lidar sounds like a nick name, please provide full name of the lidar type, and may be provide manufactory information. How large is the receiver telescope (primary mirror, 20cm?, 30cm?). What is the receiver field of view? Was the lidar pointing to the zenith or not? This has a strong impact on cirrus observations (backscatter, depol, because of specular reflection, multiple scattering). Should thus be mentioned.*
  More information about the lidar (i.e. telescope diameter and FOV) is provided in the text. The lidar type is Leosphere ALS 450 with telescope diameter of 15 cm and FOV of 1.5 mrad reaching a full overlap at 510 m (see page 2, lines 115-120).

- *Page 15679, lines 4-5, please check Gross et al. (Atmos. Env. 2012) for further depolarization values, and others: Miffre (GRL 2011, Atmos. Env. 2012) , Chazette (JGR 2012). Gross et al. present high quality lidar observations at 355 nm (your wavelength!). I believe, Miffre also shows observations for 355nm.*
  Depolarization values are now presented in Figure 1 and compared to values from Gross et al. 2012 and Chazette et al. 2012. (see page 4, lines 319-322)

- *Page 15679, line 6: I learned (from discussions with Chazette and Marenco, running a leosphere lidar as well) that depolarization ratio observations with this lidar type are crucial, because the calibration constant is always changing with temperature. This can be a significant source of uncertainty. What are your findings here. Please provide more information on depol. observations with the lidar, and respective uncertainties.*
  We observe a similar behavior of changing calibration constant. That is the reason for using the depolarization only for qualitative considerations and discrimination between ice and water or aerosol and water.

- *Line 24: lidar ratios can also be found in the paper of Gross et al. (Atmos. Env.*

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2012). They show observations at 355 and 532 nm!
We now cite the paper of Gross et al. 2012 in addition to Ansmann et al. 2010. (see page 2, lines 162-163)

- *Page 15680, line 8: What do you mean with 'iterative procedure'. The Wandinger MS approach is to my opinion based on approximations and straight forward computations. Iterative procedures are not used, I believe. Please check!*
  Wandinger uses model simulations to calculate Multiple-scattering for particular and molecular lidar returns. In chapter 5 in Wandinger et al. 1998 she describes the application of multiple scattering correction to lidar measurements (effective extinction coefficient) by using an iterative method with multiple scattering models which requires the single scattering extinction coefficient as an input parameter like the model used in this study.

- *Page 15683, line 20: I would be interested in, at least, one height profile with the PARTICLE depolarization ratio (may be computed from mean signal profiles for the two hour period before the cirrus layer was measured, as shown in Figure 4). The volume depolarization ratio at 355 nm is dominated by Rayleigh depolarization and suppresses all the information concerning aerosol depolarization. Please mention also, the zenith pointing of the lidar. It is essential for interpreting the results (specular reflection issue).*
  In Figure 1 profiles of particle depolarization are now included. One profile before cirrus occurrence (18-19:30 UTC) show high depol. values of 32.5 % in the main volcanic ash layer and lower values of 10 % in the second layer. The depol measurements above 7 km cannot be used due to the large noise in volume depol during daytime. This is also visible in the color plot. Furthermore, two particle depol profiles of the induced cirrus are shown. The first profile cover the first part of the cirrus with the "specular reflection" issue and shows no enhanced particle depol between 19:30 and 21:30 UTC. However, the second cirrus profile show particle depol values of around 20 %. (see page 5, Figure 1 and values are

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mentioned on page 4 lines 319-322)

- *Line 21: Klett method, please specify in the text at which height the calibration height is set. Forward Klett intergration or backward Klett integration makes a strong difference. In the optimum case both solutions should match, and then you have the cirrus AOT and the cirrus lidar ratio (of course not corrected for multiple scattering).*
  The Klett methode is run with forward as well as backward integration with reference heights about 12-13 km and 7 -7.5 km for backward and forward integration, respectively. Both solutions results in nearly the same backscatter profile confirming a lidar ratio of 25 sr of induced cirrus. This is included in the text now (see page 4, lines 332-340).

- *Page 15684, line 5: The zenith pointing of the lidar is mentioned too late here.*
  The zenith pointing is now mentioned in the "Instrumentation and methodology" section of the paper (see page 2, line 116).

- *Page 15684, line 5: The discussion on specular reflection is too speculative. There may be some hints that specular reflection preferably takes place at temperatures higher then -25C, but specular reflection occurs almost always and at any time when zenith pointing is used. Ice virga form always, and they form disregarding higher or lower temperatures, and it is never very clear how large the crystals are which are detected as falls strikes. Again, without showing the particle depolarization ratio instead of the volume depolarization ratio, the discussion of polarization observations (especially at 355nm) is almost useless. Only in case of particle depolarization ratios different studies including this study can be compared (i.e., removal of the strong Rayleigh effect is a request!).*
  We agree, that the first part of the cirrus is affected by specular reflection. As mentioned above, the profiles of particle depolarization (now included in Figure 1) show low values $<$ 5 % in the first part of cirrus. The second part with higher

particle depolarizations around 20 % indicate the occurrence of ice crystals. The observations of the second cirrus part are not affected by specular reflection. The text in the paper is changed accordingly (see page 4, lines 352-400).

- *Line 18: The second paragraph is again just speculation (who knows?), and thus should be skipped.*
  We skipped the second paragraph (see page 4, lines 352-400).

- *Page 15685, line 1: The final paragraph is confusing and speculative, too, and should also be removed. The most convincing reason for low PARTICLE depolarization ratios in case of vertically pointing lidars is clearly the specular reflection effect.*
  We skipped the final paragraph (see page 4, lines 352-400).

- *Lines 13 and 25: This is confusing! Did you measure aerosol effects with the lidar or not? That must be clearly mentioned. And then one may argue why trajectories are needed in addition? So, it clear now: We need a profile of the particle backscatter coefficient (similar to the profiles in Figure 4) already here. Figure 4 is introduced too late. And we need particle depolarization ratios in addition! Longer signal periods have probably to be averaged and smoothed vertically to obtain reliable lidar products.*
  We measured aerosol effects with the lidar, but want to compare and confirm the lidar observations by a trajectory analysis. This trajectories are also used for the model simulations and reproduction of the induced cirrus cloud. We changed the text slightly, so that it is clear that we want to confirm the lidar observations (see page 5, line 411).

- *Line 26: Please check the Dacre et al. paper (JGR, Eyja. Special issue, 2012) for ash transport times as a function of height.*
  The transport times are in agreement to the ash transport times presented here

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in this study. We cite now the paper of Dacre et al. 2012 (see page 6, lines 434-436).

- *Page 15687, line 19: The derived particle number concentrations should be compared with other available estimations such as from Seifert et al. (2011), or from aircraft observations during the volcanic event (please check the special issues mentioned above).*
  The particle number concentrations found by Seifert et al. 2011 at cirrus level are around 3 to 5 cm-3 and similar to the aircraft observations of Schumann et al. 2011. Both measurements were taken at a later date with possible lower ash loading than on 16 April over Jülich. Nevertheless, the particle concentrations are in the same order of magnitude. The lidar observations are now also mentioned in the text (page 6, lines 518-524).

- *Line 23: The comparison with FALCON data (taken below 5 km) and the measurements presented here for the upper free troposphere makes no sense. Schumann et al analyzed the microphysical properties within a lofted pronounced ash layer. The cirrus discussed here formed in the upper troposphere at ash background conditions.*
  This is right, we now add the values of the Falkon in cirrus altitude and found the same particle concentration of 5 cm-3. Therefore, we kept the comparison (page 6, lines 518-524).

- *Page 15688, I am surprised that these ash particles are so bad IN. Just one out of hundred particles serve as IN? What would follow if you would assume that 10% are IN? Should be discussed, Note that ash particles were partly large during the first days after the eruptions, and this may not be considered in the laboratory investigations.*
  If we assume a higher IN concentration, more ice particles would evolve yielding in a higher extinction value as was observed in the cirrus (see Section 4.1.1, page

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- *Line 26: I can not be believe that such a significant disturbance of the upper free troposphere produces an aerosol concentration that is just a factor of 10 higher than for clean background conditions? Check Richardson et al. (JGR 2007).*
  See first comment (abstract).

- *Page 15689, line 10: As mentioned, one should check the literature for other ash size distribution observations (check for example all the aircraft observations in the JGR 2012 special issue). And may be there are further AERONET observations.*
  We checked Schumann et al. 2011 and Johnson et al. 2012, both found similar ash size distributions. Both papers are now referenced (see page 8, lines 582-584).

- *Page 15690, line 24: You do not know the exact extinction-to-IN relationship! Please, avoid speculations.*
  Though we do not know the exact relation of extinction-to-IN, model results (Figure 5, red dots) show increasing extinction with increasing IN. We changed the text to make that more clear now (see page 9, lines 631-632).

- *Page 15691, line 16: (1) The last paragraph is a bit confusing, please improve explanations. And what happens if the IN concentration is increased by another factor of 10 (as discussed above when 0.1 instead of 0.01 of the ash particles are IN). Would that then be in contradiction with the lidar observations?*
  (1) We shortened and rephrase the paragraph to make it clearer (see page 9-10, lines 662-693)
  (2) In this paragraph merely model studies are shown. We hope this becomes clear now.

- *Figure 1: The lowering of the base height and the diagonal structures clearly*

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indicate falling ice crystals (at least during the second half of the cirrus period). So, particles were large enough to produce coherent structures and should also be large enough to cause specular reflection. Note, that only a few aligned crystals are already sufficient to produce a significantly enhanced backscatter signal. Volume depolarization ratio is misleading, depends on particle concentration. It is impossible here to decide whether there is significantly lower depolarization during the first half of the cirrus period then during the second half. Only after correction of Rayleigh depolarization effects this can be done! And must be done! Therefore: Please show height profiles of the particle depolarization ratio for the first and second half in addition.
Figure 1 is now enhanced by profiles of backscatter coefficient and particle depolarization for the first (19:30 - 21:30 UTC) and the second part (21:30 - 000:30 UTC) of the induced cirrus cloud. The first part profile show clearly a low particle depolarization despite of a high backscatter coefficient. We agree that the first part is most likely affected by specular reflection due to few aligned ice crystals (see Section 3.1).

- *What is the temperature at 10 km before 20 UTC?*
  The temperature of -58 °C in 10 km is very similar to profile at 20 UTC. No significant deviations between both temperature profiles are visible. The structure in the relative humidity is caused by changes in water vapor.

- *Figure 2: Again, temperature scale (information) would be helpful.*
  Temperature profiles are given in Figure 3, an additional temperature scale would not provide more information relating to ice formation. Thus, we leave the Figure as is.

- *Figure 3: Please give color information in the caption: radiosonde profiles in blue, ECMWF data in red*
  The color information is now included in the caption (see page 7).

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- *Figure 4: The profiles obviously need more vertical smoothing. Most of the shown aerosol structures are caused by a low signal-to-noise ratio. Should be mentioned.*
  The profiles are now vertically smoothed with a 300 m running mean (see page 8).

- *Figure 5: Caption text must be improved.*
  Done (see page 10).

- *Figure 6: Points are too small so that colors are hard to separate*
  The points in the figure are now enlarged (see page 11).

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