

Characterisation of a stratospheric sulphate plume from the Nabro volcano using a combination of passive satellite measurements in limb and nadir geometry

by M. Penning de Vries et al.

Authors' reply to the interactive comment by Marc von Hobe

First of all, we want to thank Marc for his very positive, detailed, and constructive review of our manuscript. We agree with all his comments and have done our best to incorporate them into the revised version of our paper. We hope the changes we have made to the manuscript improved the consistency with respect to our statements regarding the altitude and extent of the aerosol plume retrieved from limb-viewing SCIAMACHY data. Please find our replies to the specific comments below. We have colour-coded them as follows:

Green: Referee comment.

Black: Authors' reply.

Red: Modified text in manuscript.

Referee comment: 1. Page 7741, lines 18–20: '..., we find that the initial volcanic plume (...) crossed the tropopause and was located at an altitude of at least 1819 km within hours of the eruption.' If it is truly a 'we find', then the statement belongs to the results section, backed by observational or other evidence. With respect to the literature cited in the following sentence to back this statement, I think it is formulated somewhat ambiguous, because the wording implies a plume of small vertical extent situated entirely above the tropopause. This is clearly not the picture presented in the referenced literature: Clarisse et al. (2014) state that 'with respect to the Nabro eruption, we have presented evidence that the initial plume was injected at altitudes between 15 and 17 km. A smaller part was injected higher up reaching 18.5 km according to CALIOP measurements'. The trajectory analysis presented by Fairlie et al. (2013) clearly relates Sede Boker Lidar detections of aerosol between 13 and 17 km to the first Nabro eruption. I suggest rephrasing this to make clear that material from the first eruption was injected into the stratosphere, but not exclusively. The wording in Section 3 (page 7748, lines 13–16) is better in this respect.

Authors' reply: We agree with the referee that the wording was not well chosen. We meant to say that our data indicate that (part of) the plume crossed the tropopause, in contrast to the findings in the debated paper by Bourassa et al. (2012). Since the writing of the first draft of this paper, two other studies appeared that have settled the issue before us (Fairlie et al., 2013; Clarisse et al., 2013), which we acknowledged somewhat awkwardly. On account of this comment and of the first minor comment of the (anonymous) second referee, we modified the sentence on lines 15–20 to:

A large fraction of the volcanic plumes was injected below the local tropopause (dynamic tropopause at 16.8 km altitude according to ECMWF), but this was not the case for the plume from the first explosion (and possibly later plumes) from Nabro. In contrast to the analysis in (Bourassa et al., 2012), evidence has emerged that at least parts of the initial volcanic plume (emitted on 12–13 June, and here referred to as the 'first volcanic plume') were emitted at the top of or even above the tropopause and were located above 10 km, with a maximum around 18–19 km within hours of the eruption (Sawamura et al., 2012; Fromm et al., 2013; Vernier et al., 2013; Fairlie et al., 2013; Clarisse et al., 2014).

Referee comment: 2. Page 7747, lines 23–25: please explain briefly how this 'geometrical airmass factor works', or at least give a reference (and I would write 'air mass', i.e. two words).

Authors' reply: The airmass factor is a commonly used integrated weighting function of the DOAS measurement that converts the measured slant column density (along the light path) to the desired vertical column density (see, e.g. Solomon et al., J. Geophys. Res. 92, 1987). The airmass factor depends on the geometry of the measurement (viewing and solar zenith and azimuth angles), but also on the profile of the trace gas of interest and on aerosol and cloud properties. We here applied an airmass factor calculated based solely on measurement geometry: an approximation that should be adequate for our purposes. We added a short explanation of the airmass factor to the section:

The vertical column density (VCD) was calculated from the measured slant column density (SCD) by using an airmass factor (AMF) to account for the effective light path through the atmosphere (Solomon et al., 1987): $VCD = SCD/AMF$

As the volcanic SO_2 plume was located at high altitudes, the AMF was calculated based on geometrical considerations only.

Referee comment: 3. Sections 4.1 and 5.1: you should briefly discuss the implication of the large areas of deep blue color in Figures 1 and 2 (the panels showing UVAI) in Section 4.1. Can this be clear sky, or do the high positive values denote a significant load of absorbing aerosol? If the latter, can you explain it? In Section 5.1 (page 7756, lines 18–20), you state that these positive UVAI values 'could, in principle, be caused by volcanic ash'. In the following sentence (page 7756, lines 20–22), you also offer elevated dust as an explanation. But I don't really see this in Fig. 1, panels g and h. Please explain how one can identify 'elevated dust' in the MODIS images provided.

Authors' reply: We should indeed have discussed all of the features seen in the UVAI panels. We inserted the following lines to Section 4.1.:

As UVAI is most sensitive to UV-absorbing aerosols, panels D-F are dominated by $UVAI > 0$, indicating the presence of elevated mineral dust. It is difficult to visually confirm elevated dust over the desert, but similar patches of positive UVAI over this same domain were a common feature on several days before the eruption (not shown here, but available on www.temis.nl/absaai). Plumes of (reddish) dust can also be seen crossing the Red Sea by close inspection of the MODIS images. In the northwest corner and over the Mediterranean Sea $UVAI < 0$ can be seen that originate from broken cloud scenes (compare panels G-H) and presumably from non-absorbing pollution aerosols.

Referee comment: 4. Page 7751, line 13: different people will interpret 'high altitude' in different ways. For example, if you discuss whether the plume reached the stratosphere or not, then 11 km is not high altitude! I suggest rewording to 'the volcanic plume must be above 11 km' (an exact, quantitative statement), or, even better, to 'the bulk of the volcanic plume must be situated above 11 km' (I don't think that you can completely and quantitatively rule out any presence of volcanic aerosol below 11 km).

Authors' reply: We thank the referee for the suggestion; we changed the phrase to:
the bulk of the volcanic plume must be situated above approximately 11 km.

Referee comment: 5. Page 7753, lines 14–16: this seems a reasonable explanation, but another explanation for the extinction increasing towards the surface (i.e. to the lowest TA, correct?) could be that there is more aerosol at the lower boundary of your vertical measurement range than above. Or can you rule that possibility out based on your observations?

Authors' reply: In principle, this is true: we cannot obtain this information from the SCIAMACHY measurements alone, even if we take into account the nadir UVAI. However, the MPLNET lidar at Sede Boker shows aerosol layers between 13-18 km altitude. To address this remark and the comment raised by an anonymous referee, this section was changed to:

The SCIAMACHY limb retrieval detects the ice cloud at slightly lower altitude (possibly due to the fact that the cloud is not centred at the TP) and is of such high optical density that the limb retrievals below the maximum (at 16.5 km) are affected and probably yield extinctions that are unrealistically high. Only for optically very thin aerosol layers, such as the volcanic plume shown in panel 5B, both plume top and bottom can be retrieved. On the other hand, lower-lying aerosols (such as those detected by the MPLNET lidar at Sede Boker) may also be the cause of the increased extinction at 13.5 km in panel A.

Referee comment: 6. Page 7754, lines 26–27: I suggest replacing 'are underestimated' by 'might be underestimated'. To be absolutely sure of a factual underestimation (that is significant in the light of the 3 km vertical resolution) would require a more quantitative analysis of this particular profile.

Authors' reply: That is true; the phrase was replaced by:
we expect the extinction and altitude to be underestimated.

Referee comment: 7. Page 7758, lines 7–9: the AOT of 0.17 seen by the ground based lidar seems rather high. Please provide a reference for this number.

Authors' reply: This value is given in Sawamura et al., 2012. We added the reference to the text (see also

the referee comment by Simon Carn).

Technical corrections:

Referee comment: In all multi-panel figures, you use capital letters in the panels and captions as panel identifiers, while in the text, you always refer to the panels using small letters. Please use either small or capital letters consistently!

Authors' reply: This discrepancy appeared during copy-editing. We will revert to capital letters throughout the text.

Referee comment: Page 7741, line 13: should be Theys et al., 2013 (not 2012)

Authors' reply: Done.

Referee comment: Page 7746, line 9: insert a comma before 'in which'

Authors' reply: We do not believe that a comma should be placed here. Instead, to improve readability, we changed the sentence to:

The retrieval consists of online radiative transfer calculations at every TH. In each calculation step the extinction is varied iteratively until the simulated intensity matches the measurement.

Referee comment: Page 7751, line 28: replace 'found' by 'shown'

Authors' reply: Done.

Referee comment: Figure 5: use x-axis units consistently, either km⁻¹ or 10⁻³ km⁻¹. And as you use two different ranges for the two SCIAMACHY states anyway, you may use 2.5 x 10⁻³ as the x-axis maximum in panel B (and in all the panels in Figure 9).

Authors' reply: Done.

Referee comment: Figure 8: Please extend the latitude range in this Figure to 10 N or even the equator! This will not cost you anything in terms of resolution, but show the volcano and probably the plumes from later eruptions, for which you make claims for overlap/no overlap with the first plume at several places in the text.

Authors' reply: Done.

Referee comment: Figure 9, panel F: should be June 17, not June 15

Authors' reply: Done.