Atmos. Chem. Phys. Discuss.,
doi:10.5194/acp-2016-846-AC2, 2017

Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Variability and evolution of mid-latitude stratospheric aerosol budget from 22 years of ground-based lidar and satellite observations" *by* Sergey M. Khaykin et al.

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Received and published: 4 January 2017

We express our gratitude to Anonymous Referee #1 for constructive remarks on the manuscript. Please check the pdf file in supplement, which contains the formatted text for easier reading.

Abstract: line 32: define post-Pinatubo era or recall date of eruption The respective sentence was modified: "…during the last two decades"

Section 1 Lines 76-80: what are "minor" eruptions in this context? How do they compare with the "strong eruptions" (line 63) of VEI >= 4? Compared to VEI≥5 eruptions, the VEI=4 ones can be termed "minor" considering their impact on stratospheric

aerosol load. However, it would be more correct to term the VEI=4 eruptions "moderate" The sentence was modified: "…the increase was primarily caused by moderate volcanic eruptions with VEI=4, whose impact…"

Lines 113-116: why mention the separate telescope and detection channel if not used for this study? Note that the Hoareau et al. (2013) reference is missing. This information is addressed to the users of NDACC aerosol data who may already be familiar with OHP aerosol data and should be aware that the present study makes use of a different measurement source. A reference to Hoareau et al. (2013) was added.

Lines 119-121: "the primary low gain channel of LTA. . ...0.03 m2 telescope": are you here describing the "primary, more powerful channel detection channel of LTA" used in this study? The collecting area seems very small. Please clarify. The LTA system features several telescopes and corresponding detection channels, including Rayleigh/Mie and Raman channels. The Rayleigh/Mie channels A (0.88 m2 telescope) and B (0.03 m2 telescope) represent the high and low gain channels of the temperature lidar. The cirrus/aerosol channel E uses a separate telescope of 0.03 m2 that is the same size as for channel B. It is thus incorrect to refer to channel B as "more powerful". However, the advantage of using channel B instead of the cirrus/aerosol channel E is that the former was more regularly maintained and has less temporal gaps in the measurements. In addition, the electronic range-gating of the photomultiplier in the B channel is set to 12 km altitude (as opposed to 5 km for channel E), which improves the signal-to-noise ratio at the calibration levels, whilst limiting the useful measurement range to altitudes above 14 km. The collecting area of the LTA low-gain B channel is not large, however this is compensated by a powerful laser (17 W, upgraded to 24 W after 2013). This translates to a total lidar power of 0.54 (0.74) WâĂćm2, which is larger than some of the NDACC aerosol lidars and comparable to CALIOP (1.73 WâĂćm2). The respective paragraph was modified as follows: "The LTA system includes a separate telescope and detection channel for clouds and aerosol (Chazette et al., 1995; Keckhut et al., 2005; Hoareau et al., 2013). In contrast to the pervious studies we use for the first time the primary low-gain detection channel of LTA system for stratospheric aerosol retrieval. This choice benefits from lesser measurement gaps thanks to a more regular maintenance and better signal-to-noise ratio of the LTA low-gain channel, which is achieved thanks to the electronic range-gating adjusted to 12 km altitude. This configuration reduces the signal-induced noise at mid-stratospheric levels whilst limiting the useful measurement range to altitudes above 14 km."

It is stated that the study is restricted to altitudes above 12-13 km due to saturation issues (lines 115-116). It seems inconsistent with lines 242-244 where it is written that LTA may be affected by incomplete desaturation below 17 km. Please explain the saturation and desaturation issues. Photon counting? Other? The last paragraph of the Section 3 is no longer valid (see. AC1 "Reprocessing of the OHP lidar data and related changes to the manuscript") and had to be revised completely. We no longer restrict to the altitudes above 15 km when using LiO3S lidar measurements since the data were reprocessed using a proper correction for signal saturation affecting the aerosol retrieval at lower levels. However, this exercise could not be applied to LTA data due to range-gating limiting the useful measurement range to altitude above 14 km. The last paragraph of Sect. 3 is updated as follows: "Figure 2 displays a comparison of aerosol extinction profiles averaged over two 20-month volcanically-quiescent periods 2002-2003 and 2013-2014 covered by time-overlapping observations by two different triplets of satellite sounders. The comparison reveals close agreement between OHP lidar, SAGE II, GOMOS and OSIRIS (Fig. 2a) above 15 km and somewhat poorer agreement below. Fig. 2b suggests a good agreement between OHP lidar and CALIOP (relative difference 5-10%) throughout the entire range of altitudes except the uppermost layer above 25 km, where OHP lidar is 15-20 % low with respect to CALIOP. This feature may be related to an error in lidar calibration, relying on the assumption of the absence of aerosol above 30 km, which – as suggested by CALIOP data calibrated at higher altitudes - may not always be the case. The other two satellite sounders covering 2013-2014 period – OSIRIS and OMPS - show somewhat larger discrepancies (reaching 30%) with OHP lidar and CALIOP in the uppermost and lowermost layers.

This discrepancy may be due to the use of a fixed lidar ratio and wavelength exponents, which may vary with height depending on the size distribution of aerosol."

Section 2.2: should the title be "OHP lidars aerosol retrieval"? The title was modified as advised.

Lines 130-133: Please clarify the use of Kb and/or Ke for OHP LiO3S retrievals. Equations would be very helpful, and would clarify the presentation and discussions in Section 2.3 and Section 3. Four equations defining the scattering ratio and the wavelength conversion for backscatter, extinction and scattering ratio have been added. The text was modified accordingly.

Lines 141-148: An important source of uncertainty is indeed the actual aerosol loading in the 30-33 km reference region. This is mentioned later (lines 233-234), but could be discussed in more details here. Could CALIOP V4.00 measurements at 30-33 km be used to estimate OHP calibration biases? The assumption on the zero aerosol loading above 30 km (at least in the absence of major eruptions of VEI$\geq$5) is a commonly used approach for aerosol retrieval using ground-based lidars. In principle, CALIOP measurements above 30 km could be used to recalibrate the ground-based lidar retrieval, however we prefer to follow the traditional approach in the context of this study, in which the ground-based data are obtained in an independent way and are then used to identify the discrepancies with satellite data and to discuss their possible sources. As follows from the comparison in Sect. 3, the effect of the possible calibration bias is limited to altitudes above 25 km and the associated bias in the extinction profile does not exceed 15%. For the integrated values of extinction (sAOD) the calibration bias has a negligible effect.

Lines 149-156: this discussion is important and could/should be developed. For instance, the sensitivity to the assumed lidar ratio (line 154) should depend on the optical depth? Indeed, the sensitivity of scattering ratio and backscatter coefficient depend on the optical depth. However, even under high aerosol load conditions (e.g. peak of Nabro signal in sAOD), this sensitivity is still very low. The text was modified as follows: “We note that the uncertainty in the assumed lidar ratio has a limited effect on the derived values of backscatter coefficient and scattering ratio. For example, the sensitivity of the stratospheric mean βaero to the assumed lidar ratio was estimated at ~0.15 %/sr under background aerosol conditions (September 2005) and ~0.23 %/sr under volcanically-perturbed conditions (September 2011). Our estimates are compatible with those provided by Sakai et al. (2016). It should be noted that the error in lidar ratio has a larger effect on aerosol extinction and optical depth, whose uncertainty may thus be somewhat larger.“

Section 2.3 Satellite aerosol sounders It could be interesting to comment on the fact that some instruments measure a backscatter further converted to extinction whereas other measure directly an extinction. What is the rationale for the selection of the various values of Ke? No conversion to 532 nm is mentioned for GOMOS retrievals. Are they directly at 532 nm? Adding a table summarizing all the conversions applied to the various data sets could be useful. The value of wavelength (Angstrom) exponent depends on the wavelength pair. For the 355 nm -532 nm pair ke value was adapted from Jager and Deshler (2002; 2003). The same value (ke=-1.6) was used for SAGE II (525 nm) and GOMOS (550 nm), for which the wavelength conversion means multiplying the extinction by a factor of 0.979 and 1.055 respectively. For OSIRIS (750 nm) and OMPS (675 nm) the wavelength exponents were suggested by the instrument PIs. The following paragraph was added in the beginning of Sect. 2.3: “Over the course of the last two decades stratospheric aerosol observations from space were conducted by various satellite missions, exploiting different measurement techniques: solar and stellar occultation, limb scattering as well as nadir-viewing lidar. We use five satellite-based datasets, altogether covering the time span of OHP lidar observations. “ The following paragraph was added in the end of Sect. 2.3: “It should be noted that among the passive satellite sounders SAGE II and GOMOS measure aerosol extinction, whereas OSIRIS and OMPS measure limb-scattered radiation, from which aerosol extinction is then retrieved. In contrast, CALIOP instrument, based on active sounding

technique, measures aerosol backscatter. In order to compare OHP lidars and satellite instruments all data sets were converted to extinction at a common wavelength of 532 nm. Table 1 summarizes the wavelength exponents κe used for conversion (eq. 3) and the time spans of data sets involved in the present analysis.” A new table was added: “Table 1. Stratospheric aerosol sensors exploited: (columns, left to right) name of instrument, operating wavelength, wavelength exponent for extinction κe used for conversion to 532 nm, conversion factor (see eq. 3), time span of available data.”

Lines 184-186: I think that it is important to explain in the text that in Level 1 V4.00 CALIOP products, the nighttime 532 nm channel is calibrated between 36 and 39 km using GMAO Met data. Please explain how the (nonattenuated) backscatter profiles are obtained from CALIOP V4.00 Level 1 data. Because CALIOP is a lidar instrument operating at the same wavelength as LTA, it could make sense to have a dedicated section for CALIOP. Since the paper is focused on the observations by OHP lidars whereas the information on CALIOP and stratospheric aerosol retrieval is readily available in various articles by J.-P. Vernier et al. cited throughout this manuscript, we prefer to avoid dedicating a separate section to CALIOP. However the respective paragraph was updated with more details as follows: “CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) onboard CALIPSO satellite platform is a nadir-viewing active sounder (Winker et al., 2010). Operational since June 2006, CALIOP provides range-resolved measurements of elastic backscatter at 532 nm and 1064 nm with a vertical resolution of around 200 m in the stratosphere. CALIOP lidar makes use of a Nd:Yag laser operating at 20.2 Hz with a 110 mJ/pulse power and a 0.78 m2 telescope. The data used here are based on night-time 532 nm level 1B version 4.00 product, post-processed using a treatment described by Vernier et al. (2009). The total attenuated backscatter profiles from CALIOP are corrected for molecular attenuation and ozone absorption after adjusting the calibration altitude to 36-39 km. The attenuation by aerosol, constituting less than 1% at 15 km during background aerosol conditions, is neglected. Data below clouds are removed from the analysis. The scattering ratio profiles are obtained using molecular backscatter computed using NASA Global Modeling and Assimilation Office

(GMAO) data. The backscatter data of CALIOP are cloud-cleared in the upper troposphere using a depolarization ratio threshold of 5%. The conversion of backscatter to extinction is done using lidar ratio of 50 sr."

Section 3 Line 200: "zonally averaged"...I suggest to say here " over a 10âŮę latitude belt centered at OHP latitude" (line 217). The respective sentence has been modified: "…whereas the satellite values (monthly- and zonally-averaged over a 10° latitude belt centered at OHP latitude) contain…"

Line 204: Can you clarify whether the differences reported in Table 1 are computed for different time periods, depending on the availability of the 2 instruments that are being compared? If yes, these time periods could be specified. I could not find the definition of the differences reported in the table (column – row or the opposite?). The following sentence has been added at the end of the first paragraph of Sect. 3: "Note that the differences reported are computed for different time periods, depending on the availability of the data of each instrument ." The caption of Tab. 2 (former Tab.1) is updated as follows: Table 2. Intercomparison of stratospheric Aerosol Optical Depth between 17 and 30 km (sAOD1730) series displayed in Fig. 1. Mean relative difference Δmean ± 2 standard errors (top) and correlation coefficient R (bottom). Relative difference in the top panel is calculated as where X is the sAOD1730 value averaged over the entire observation time span of the respective instrument (see Tab. 1) or the mean of all satellite instruments (last column). Please note that the values in Tab. 2, computation of which involved OHP data, have been updated after OHP data reprocessing (see. AC1 "Reprocessing of the OHP lidar data and related changes to the manuscript"). The associated text in the beginning of Sect. 3 has been updated accordingly.

Line 229: "quiescent periods": please explain, because the careful selection of the quiescent periods is presented later in the paper. The beginning of last paragraph in Sect. 3 has been modified as follows: "Figure 2 displays a comparison of aerosol extinction profiles averaged over two 20-month periods 2002-2003 and 2013-2014 covered by time-overlapping observations by two different triplets of satellite sounders. These periods are also characterized by a stable aerosol load that is without strong enhancements due to volcanic eruption."

Lines 228-234: I don't see a negative bias of the OHP lidars with respect to all satellites above 25 km in Figure 2. Indeed, it seems that OSIRIS has the smallest values. Do you agree? What is the relative difference between the OHP lidars and CALIOP above 25 km? Would it be consistent with the presence of aerosols at 30-33 km, which could be further estimated from CALIOP? Could the difference be due in part to the use of different models (NCEP vs model used in CALIOP algorithm)? Please note that Figure 2 and respective discussion provided in Sect. 3 have been fully revised following the result of OHP data reprocessing. There is some negative bias of OHP LiO3S lidar compared to CALIOP above 25 km with relative difference of 15-20 %. It is hardly discernible in the plot as the extinction is very small at these altitudes. This difference may potentially be due in some part to the use of different models (NCEP and GMAO), however it is more likely that the negative bias of the OHP profile is due to higher altitude of calibration in CALIOP data retrieval. Nevertheless, given very small aerosol extinction above the Junge layer, the calibration issue has a negligible effect on the AOD values as can be concluded from the intercomparison. The discussion around Fig. 2 has been revised as follows: "OHP lidar and CALIOP capture well and agree on the main features of background aerosol annual cycle in the lower mid-stratosphere, whereas above 25 km CALIOP shows higher SR values compared to OHP lidar and somewhat less pronounced annual cycle. This may be due to higher altitude of calibration for CALIOP retrieval and the use of different atmospheric models for deriving molecular backscatter (Sect. 2.3 and 3). "

The following text was added in Sect. 5: "OHP lidar and CALIOP capture well and agree on the main features of background aerosol annual cycle in the lower mid-stratosphere, whereas above 25 km CALIOP shows higher SR values compared to OHP lidar and somewhat less pronounced annual cycle. This may be due to higher altitude of calibration for CALIOP retrieval and the use of different atmospheric models for deriving molecular backscatter (Sect. 2.3 and 3).“

Lines 236-237: I am not totally convinced by the discussion about the lidar ratio, because this issue should not introduce differences between LTA and CALIOP. The notion of desaturation is difficult to understand without specific knowledge of the instruments. I suggest describing these instrument-related difficulties in Section 2.1. Indeed, the lidar ratio has nothing to do with the positive bias in OHP lidar profiles at lower levels as was concluded in the initial version of the manuscript, i.e. before the OHP data reprocessing. The discussion of altitude limitation for LTA lidar are now restricted to Sect. 2.1. Figure 2 and respective discussion provided in Sect. 3 have been fully revised following the result of OHP data reprocessing. The plots in Fig. 2 were extended to 12 km altitude but LTA profile was removed from the plot. The text in the end of Sect. 3 has been rewritten: “Figure 2 displays a comparison of aerosol extinction profiles averaged over two 20-month periods 2002-2003 and 2013-2014 covered by time-overlapping observations by two different triplets of satellite sounders. These periods are also characterized by a stable aerosol load that is without strong enhancements due to volcanic eruption The comparison reveals close agreement between OHP lidar, SAGE II, GOMOS and OSIRIS (Fig. 2a) above 15 km and somewhat poorer agreement below. Fig. 2b suggests a good agreement between OHP lidar and CALIOP (relative difference 5-10%) throughout the entire range of altitudes except the uppermost layer above 25 km, where OHP lidar is 15-20 % low with respect to CALIOP. This feature may be related to an error in lidar calibration, relying on the assumption of the absence of aerosol above 30 km, which – as suggested by CALIOP data calibrated at higher altitudes - may not always be the case. The other two satellite sounders covering 2013-2014 period – OSIRIS and OMPS - show somewhat larger discrepancies with OHP lidar and CALIOP, reaching 30% in the uppermost and lowermost layers. This discrepancy may be due to the use of the fixed wavelength exponents, which may vary with height depending on the size distribution of aerosol.”

Section 4 Lines 251-253: Table 2 should be introduced in the text. Do you mean VEI=4 or VEI≥4? Table 3 (former Table 2) is introduced in the end of the first paragraph of Sect. 4: “The selection criteria are described hereinafter (Sect. 4.4), whereas the eruptions and periods affected are summarized in Table 3.” We meant VEI=4 eruptions, as there were no VEI>4 eruptions since Pinatubo. Putting “VEI≥4” instead may make a reader wonder if there were eruptions stronger than VEI 4 since 1994.

Lines 308-314: What are we learning from the fact that no plume from the Calbuco volcano (41âŮęS) is detected at OHP? Why mention this volcano specifically? Indeed, the mention of Calbuco eruption and its possible effect on stratospheric aerosol at Northern mid-latitude is beyond the scope of this paper, based on the data up to October 2015. The respective text has been removed.

Lines 316-333: are the volcanic plumes detected using global satellite coverage or by using the two conditions listed in lines 329-332? My understanding is that global satellite measurements are used to trace the origin of aerosol enhancements detected using the two conditions back to volcanic eruptions. Is it correct? Fig. 6 is complicated and described only in section 5, and introduced before Fig. 5. The detection of mid-latitude volcanic plumes (as well as Nabro) is straightforward as these eruptions left strong signatures in scattering ratio profiles and sAOD series. The detection of volcanic plumes from remote tropical eruptions using solely OHP observations is too ambiguous because the enhancements in sAOD are less pronounced and because the aerosol variability may be caused by processes other than volcanism. Therefore the plumes of tropical eruptions are first detected by visual examination of the satellite time-latitude sections and then, if a plume is found to extend Northward beyond the tropical belt, the two criteria are applied to the lidar data in order to determine the extent of a volcanically-perturbed period. In other words, the satellite data are used to detect a plume, whereas the OHP data are used to determine the duration of the respective volcanic period. The second (former first) paragraph of Sect. 4.4 (former 4.1) was revised as follows: “Volcanic plumes were detected by examining time-latitude sections of sAOD1730 and sAOD1519 from all satellite records (example for CALIOP is provided hereinafter in Sect. 5). If a plume was found to extend beyond the tropical belt towards the Northern extra-tropics, the OHP lidar monthly-mean sAOD1730 values and SR profiles posterior to the eruption were compared against those averaged over the “reference” quiescent period 1997-2003. This way, the presence of a plume at OHP and the temporal extent of the corresponding volcanic period were determined. In other words, the satellite data are used to detect a plume, whereas OHP lidar data were used to determine the duration of the respective volcanic period at OHP latitude. Thus, a period is considered as volcanically-perturbed if a plume occurs in the Northern hemisphere and if both of the following two conditions are fulfilled in OHP observation posterior to the eruption:” The introduction of Fig. 6 in this section is indeed premature, however it provides a great aid in understanding how the volcanic plumes are detected using satellite data. The sentence has been nevertheless modified : “. . .(example for CALIOP is provided hereinafter in Sect. 5).

Lines 355-356: would it be correct to say that that OHP lidars detect an increase in optical depth end 2010/early 2011, which is traced back to the Merapi volcano using CALIOP observations? As a matter of fact, it is the other way around. As explained in response to the previous remark, first the plume of Merapi is detected by CALIOP then the OHP profiles are checked to fulfil the criteria. After the OHP data reprocessing, both criteria are no longer fulfilled, thus the period in late 2010/early 2011 is no longer considered as volcanically perturbed. Indeed, as noted by Referee #3, the CALIOP data are far from supporting the suggestion that Merapi plume was transported to OHP latitude. Furthermore, the OSIRIS data suggest that Merapi plume hardly reached beyond 30° N and had an impact mainly in the Southern hemisphere. The last paragraph of Sect. 4.4 (former 4.1) describing the detection of Merapi plume detection has been removed.

Overall, I think that Section 4 is not very clear and should be reorganized. It is noted that it starts with a long introduction from lines 248 to 314, followed by only one subsection (4.1). Section 4 has been reorganized as follows: 4 Volcanic plumes and quiescent

periods 4.1 Quiescent period 1997 - 2003 4.2 Volcanically-active period 2003-2013 4.2.1 Detection of Sarychev and Nabro plumes 4.3 Post-Nabro period 4.4 Identification of volcanically-perturbed periods The text in Section 4.4 on the method for selection of volcanic periods has been revised (see above).

Section 5: Line 443: please describe Fig 7c. Second sentence in the last paragraph of Sect. 5 has been modified: “Fig. 7c shows annual cycle of water vapour vertical profile, providing further evidence to this finding.”

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/acp-2016-846/acp-2016-846-AC2-supplement.pdf

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Interactive comment on Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-846, 2016.