Manuscript Number: acp-2016-792
Manuscript Type: research article
Title: 30-year lidar observations of the stratospheric aerosol layer state over Tomsk (Western Siberia, Russia)

We thank Referee 1 for valuable comments, questions and suggestions which will allow us to improve our manuscript.

Point-by-point response to Referee 1

2 Lidar instruments and methods

Comment: I would like to see a short description of the lidar photon-counting data acquisition electronics. Is it from a commercial vendor or built just for the lidar?

Our response: The SLS aerosol channel data acquisition electronics we used is of in-house design and manufacture. A more detailed technical description of the SLS aerosol channel and its data acquisition electronics can be found, e.g., in (Burlakov et al., 2010). We will include the reference in the final version of our manuscript.

Burlakov, V. D., Dolgii, S. I., and Nevzorov, A. V.: A three-frequency Lidar for sensing microstructure characteristics of stratospheric aerosols, Instrum. Exp. Tech., 53, 890–894, doi:10.1134/S0020441210060230, 2010.

We added the following sentence to the revised manuscript:

"A more detailed technical description of the SLS aerosol channel and its data acquisition electronics can be found, e.g., in (Burlakov et al., 2010)."
[**Page 4, lines 10 and 11, revised manuscript**]

Comment: Is signal induced noise, and counting saturation taken into account?

Response: Yes. We take into account both photomultiplier tube (PMT) afterpulses and photon-counting saturation. Furthermore, current pulses from a PMT are fed to a broadband amplifier and a differential amplitude discriminator. The latter allows controlling the lower and upper discrimination thresholds of dark-current pulses of a particular PMT specimen under the conditions of real background illumination, i.e., selection of the optimal discrimination thresholds for increasing the signal-to-noise ratio (see, please, Sect. "Technical description of the lidar" in the mentioned paper Burlakov et al., 2010).

Comment: I would like to see more about the normalization. Is only a single altitude used? Is it 30 km? Many of the Scattering Ratio profiles shown in the paper haven't decreased to 1.0 at 30 km, so higher altitude data must have been used. Is there an objective way to do this?

Response: The SLS aerosol channel makes it possible to receive almost undisturbed backscattered signals from altitudes of ~ 40–45 km. At higher altitudes, the signal-to-noise ratio is too low. Therefore, altitudes of ~30–35 km, where the stratosphere is considered to be aerosol-free, were used as the calibration altitudes.

Comment: Choosing H1 (lower attitude of the SAL) as 15 km seems reasonable, but other lidar groups have used the actual tropopause or tropopause + 1 km. Choosing this altitude can be complicated since there can be multiple tropopauses sometimes. It can also be complicated when there has been an eruption since the upper troposphere can have much more aerosol. But perhaps you can comment on how much of a difference it would make to lower the H1 altitude during background conditions.

Response: Tomsk is located near the southern boundary of subarctic latitudes, where the tropopause altitude can vary significantly (from ~11 to 13 km, depending on season), e.g., due to migration of the Arctic stratospheric jet stream within our (Tomsk) region. Sometimes one can observe a double (or even multiple) tropopause. Therefore, we consciously removed the interval of the tropopause altitude variations to observe the stratospheric perturbations only. Probably, some information about the lowermost stratospheric aerosol perturbations could be missed.

Instead of
"In our case, the tropopause altitude over Tomsk varies from ~11 to 13 km, depending on season, and therefore, we set H_1 = 15 km."

we wrote
"Tomsk is located near the southern boundary of subarctic latitudes, where the tropopause altitude can significantly vary, e.g., due to migration of the Arctic stratospheric jet stream within the Tomsk region. Sometimes one can observe a double (or even multiple) tropopause. For this reason, we consciously removed the interval of the tropopause altitude variations to observe the stratospheric perturbations only. As the tropopause altitude over Tomsk varies from ~11 to 13 km, depending on season, we set H_1 = 15 km."
[**Page 4, lines 23–26, revised manuscript**]

3 Results of the SAL lidar observations over Tomsk

3.1 Time series of the integrated stratospheric backscatter coefficient (1986–2015)

Comment: In Table 1 the maximum plume height is listed. How are these measured? The initial plume heights are not very accurate if done by naked-eye observations. Are these measured later with lidars?

Response: The maximum plume altitudes (MPAs) presented in Table 1 were taken from the Smithsonian Institution Global Volcanism Program. The Smithsonian MPA values were determined from the pooled analysis of visual and radar observations. When it was possible, the MPAs could also be determined with space-borne lidars more accurately compared to the mentioned observation methods. Considering in Sect. 3.5 the 2014 Kelut eruption as an example, we discussed the difference between MPA values determined via the space-borne lidar CALIOP and visual/radar observations.

Comment: There has been an ongoing discussion in the community about whether there is an annual cycle in SAL. Your Figure 2 shows a winter/summer ratio of about 1.35. Figure 3 is similar. This would be influenced by the choice of the H1 altitude. It would be interesting to calculate a ratio and error bar as your best estimate of an annual cycle. In Figure 2 what do the error bars represent, one sigma of the spread of the data?

Response: First of all, Figure 2 is now Figure 3 and, conversely, Figure 3 is now Figure 2 in the revised manuscript. We have extended the analyzed period of the background aerosol loading variations over Tomsk up to 16 years (1999–2015), instead of the period 2000–2006 in the old version of our manuscript. The monthly average B_π^a data for March–June 2000 (after the Hekla eruption), August–November 2008 (after the Okmok and Kasatochi eruptions), August–October 2009 (after the Sarychev Peak eruption), and also April and August–October 2011 (after the Merapi, Grimsvötn, and Nabro eruptions) were not taken into account. The exclusion of these perturbed data allowed us to extend the analyzed period of the background aerosol loading variations and, therefore, to improve the statistical reliability of the B_π^a data series. The B_π^a values were averaged separately for the westerly and easterly phases of the quasi-biennial oscillations (QBO) characterized by zonal winds in the equatorial region at 30 mbar (Fig. 3, ex-Fig. 2). Based on these 16-year averaged values of the monthly average B_π^a, we show that an annual cycle in SAL exists. Moreover, based on the inter-annual B_π^a variations (Fig. 2, ex-Fig. 3) separately averaged over the warm (April to September) and cold (October to March) half-years, we also show that aerosol loading of the mid-latitude stratosphere is maximal in the cold half-year, when the meridional air mass transport dominates (especially during the westerly phase of the QBO), and it is minimal in the warm half-year, when the zonal transport dominates. All error bars in Figs. 2 and 3 represent the standard (1–σ) deviation. As a whole, we considerably rewrote Sect 3.1. See, please, the colored version of our revised manuscript for details.

3.2.1 Okmok and Kasatochi

Comment: In Figure 5 there is a peak on September 4, 2000 at 27-30 km. Is that real?

Response: Yes, you are right. There are two small peaks of the scattering ratio profile (4 September 2000) at altitudes of 27 to 30 km in Figure 5. However, we believe that these peaks are not related to any aerosol events in the stratosphere and, therefore, they represent measurement uncertainties due to the low signal-to-noise ratio.

Comment: The altitude axis might be clearer with 1 km tic marks instead of 1.5 km.

Response: We agree. Done.

4 Discussion and conclusion

Comment: "The Happy Camp Complex fire consumed more than 134 acres (~543 km2)...". Acres are much smaller than km2, something is wrong with the areas.

Response: Thank you. We corrected the mistake: 134 acres ≈ 0.543 km^2. However, we removed the information about the Happy Camp fire from the text of our manuscript.

Comment: Figures 6 (a), 6 (b), 9, and 11. I am amazed that all four trajectories almost exactly cross over the volcanoes after so many days. Did you find an optimum altitude or something that gave you the best trajectory? Were the trajectories sensitive to the initial conditions?

Response: We usually calculate a set of the HYSPLIT backward trajectories which start from different aerosol layers detected in the stratosphere over Tomsk after a volcano eruption (See, please, Fig. 11 in our revised manuscript). A signal integration period of 20–30 min yields uncertainties in the start time and altitude (i.e. in initial conditions) of a backward trajectory. Therefore, we usually present the best trajectory to illustrate a possible way of how aerosol from an erupted volcanic plume could pass and be detected over Tomsk.

Sincerely,

Authors

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Manuscript Type: Research article
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Point-by-point response to Dr. Fromm

General comments

Comment: This manuscript gives a wide-ranging analysis of the aerosol lidar data collected at a western Siberia location. The long temporal span of this data set, for a location far removed from other ground-based lidars, is a welcome addition to the globe's sparse stratospheric aerosol archive. Considering that these data are presumably still being collected adds value for continued monitoring of the upper troposphere and lower stratosphere. Consequently this is a potentially critical work that may offer significant value to our understanding. The authors' approach is similar to many prior works that examine a particular lidar's data set in the context of other data sets and meteorological analyses. They present some individual lidar profiles, long-term time series, and annual cycle analyses. This is a very appropriate study for Atmospheric Chemistry and Physics.

Our response: We thank Dr. Fromm for his great interest in our work and comprehensive criticism, comments, questions, and suggestions which will definitely allow us to improve our manuscript.

Comment: Along with these assets, the paper has several major weaknesses. My assessment is that the weaknesses substantially limit the value of the manuscript in its present form. For the paper to merit publication, attention to these major concerns must be paid. One major concern is a significant absence of recognition of work that has direct bearing on the analyses and conclusions presented herein. The effect goes beyond that of showing insufficient background work. It extends to the realization that critical scientific aspects of stratospheric aerosol and cloud have not been taken into account in the interpretation of the Tomsk lidar data. Detailed examples are given below. Another major concern is that the Tomsk data may be biased with respect to other similar lidar data sets, as called out specifically in a comment below.

Response: We have tried to take into account all weaknesses specified by Dr. Fromm.

Comment: The manuscript offers no direct or even indirect comparisons of the Tomsk lidar data with any other aerosol data sets; hence it is not possible to assess the accuracy of the aerosol data in the full range of stratospheric aerosol loading. Another concern is that the authors utilize a local measurement data set of total ozone abundance, but without any qualification. The reader is left with great uncertainty as to the robustness of the results and certain interpretations the authors give for certain phenomena.

Response: Such data comparisons exist and were made with, e.g., data of the Minsk lidar station (Belarus) which is simultaneously incorporated in 1) the CIS-LiNet together with the Tomsk lidar station (Chaykovskii et al., 2005; Zuev et al., 2009); and 2) the EARLINET (Wandinger et al., 2016). Moreover, the Tomsk station measurement data were widely used, e.g., by Ridley et al. (2014).

Chaykovskii, A. P., Ivanov, A. P., Balin, Yu. S., El'nikov, A. V., Tulinov, G. F., Plusnin, I. I., Bukin, O. A., and Chen, B. B.: CIS-LiNet lidar network for monitoring aerosol and ozone: methodology and instrumentation, Atmos. Ocean. Opt., 18, 958–964, 2005.

Zuev, V. V., Balin, Yu. S., Bukin, O. A., Burlakov, V. D., Dolgii, S. I., Kabashnikov, V. P., Nevzorov, A. V., Osipenko, F. P., Pavlov, A. N., Penner, I. E., Samoilova, S. V., Stolyarchuk, S. Yu., Chaikovskii, A. P., and Shmirko, K. A.: Results of joint observations of aerosol perturbations of the stratosphere at the CIS-LiNet network in 2008, Atmos. Ocean. Opt., 22, 295–301, 2009.

Wandinger, U., Freudenthaler, V., Baars, H., Amodeo, A., Engelmann, R., Mattis, I., Groß, S., Pappalardo, G., Giunta, A., D'Amico, G., Chaikovsky, A., Osipenko, F., Slesar, A., Nicolae, D., Belegante, L., Talianu, C., Serikov, I., Linné, H., Jansen, F., Apituley, A., Wilson, K. M., de Graaf, M., Trickl, T., Giehl, H., Adam, M., Comerón, A., Muñoz-Porcar, C., Rocadenbosch, F., Sicard, M., Tomás, S., Lange, D., Kumar, D., Pujadas, M., Molero, F., Fernández, A. J., Alados-Arboledas, L., Bravo-Aranda, J. A., Navas-Guzmán, F., Guerrero-Rascado, J. L., Granados-Muñoz, M. J., Preißler, J., Wagner, F., Gausa, M., Grigorov, I., Stoyanov, D., Iarlori, M., Rizi, V., Spinelli, N., Boselli, A., Wang, X., Lo Feudo, T., Perrone, M. R., De Tomasi, F., and Burlizzi, P.: EARLINET instrument intercomparison campaigns: overview on strategy and results, Atmos. Meas. Tech., 9, 1001-1023, doi:10.5194/amt-9-1001-2016, 2016.

Ridley, D. A., et al. (2014), Total volcanic stratospheric aerosol optical depths and implications for global climate change, Geophys. Res. Lett., 41, 7763–7769, doi:10.1002/2014GL061541.

Specific comments

Comment: Somewhere in this paper the recent review paper by Kremser et al. should be mentioned and cited.

Kremser, S., et al. (2016), Stratospheric aerosol – Observations, processes, and impact on climate, Rev. Geophys., 54, doi:10.1002/2015RG000511.

Response: OK. We added this reference to our manuscript.

Instead of
"The volcanogenic aerosol perturbs the radiation-heat balance of the atmosphere, and thus, significantly affects the atmospheric dynamics (Timmreck, 2012; Driscoll et al., 2012)."

we wrote
"The volcanogenic aerosol perturbs the radiation-heat balance of the atmosphere, and thus, significantly affects the atmospheric dynamics and climate (Timmreck, 2012; Driscoll et al., 2012; Kremser et al., 2016)."
[**Page 2, lines 7 and 8, revised manuscript**]

Kremser, S., Thomason, L. W., von Hobe, M., Hermann, M., Deshler, T., Timmreck, C., Toohey, M., Stenke, A., Schwarz, J. P., Weigel, R., Fueglistaler, S., Prata, F. J., Vernier, J.-P., Schlager, H., Barnes, J. E., Antuña-Marrero, J.-C., Fairlie, D., Palm, M., Mahieu, E., Notholt, J., Rex, M., Bingen, C., Vanhellemont, F., Bourassa, A., Plane, J. M. C., Klocke, D., Carn, S. A., Clarisse, L., Trickl, T., Neely, R., James, A. D., Rieger, L., Wilson, J. C., and Meland, B.: Stratospheric aerosol – Observations, processes, and impact on climate, Rev. Geophys., 54, 278–335, doi:10.1002/2015RG000511, 2016.

Comment: There is no citation of Vernier et al (GRL, 2011), Ridley et al. (GRL, 2014), Santer et al. (Nature Geo., 2014) and some other very relevant recent papers on volcanoes and recent stratospheric aerosol layer trends.

Response: Thank you for these references. However, these and other very relevant recent papers were considered in Kremser et al. (2016), which we already cited.

Comment: P2, L10. Consider citing

Jäger, H. and Wege, K.: Stratospheric Ozone Depletion at Northern Midlatitudes after Major Volcanic Eruptions, J. Atmos. Chem., 10, 273-287, 1990.

Response: Thank you for the reference, but the data and results of this paper were mentioned in Trickl et al. (2013), which we also cited in our manuscript.

Comment: P2, L5. "vulcanian" refers to a specific style of eruption, the characteristics of which are not associated with stratospheric injection. Is the term even needed to make the point of this sentence?

Response: According to the Smithsonian Institution Global Volcanism Program, gas and ash plumes from some volcanic eruptions (with VEI ≥ 3) of the Vulcanian type can directly reach the stratospheric altitudes:

https://web.archive.org/web/20111110173623/http://www.volcano.si.edu/world/eruptioncriteria.cfm

(See there, please, Section "VEI (Volcanic Explosivity Index)" and Table containing the Eruption Type and Cloud Column Height).

Comment: P3, L19. How about measurement frequency? What was the lidar operation frequency and regularity? It would be important for the reader to know what is typical for the number of profiles that go into the 10-day average.

Response: The lidar operation regularity depends on the weather conditions, of course. The absence of clouds is required for stratospheric aerosol measurements. As seen in Fig. 1, the measurement frequency allows us to retrieve the 10-day average values of the integrated stratospheric backscatter coefficient, when it is possible. See, please, also the "10-day average values" file in **the Supplement** containing data for Fig. 1.

Comment: P3, L23. Consider giving the name of the PMT manufacturer.

Response: The manufacturer of PMTs "FEU-130" is the Moscow Elecro-Lamp Plant (MELZ).

http://www.melz-evp.ru/about.html

http://rutubes.com/category/melz-tube-moscow-russia/

Instead of

"The signals were registered with a vertical resolution of 374 m by a photomultiplier tube (PMT) FEU-130 operating in the photon counting mode."

we wrote

"The signals were registered with a vertical resolution of 374 m by a photomultiplier tube (PMT) FEU-130 (USSR, Moscow Elecro-Lamp Plant) operating in the photon counting mode."
[**Page 3, lines 25 and 26, revised manuscript**]

Comment: P4, L4. This statement arouses my curiosity to know if this lidar made any observations of the Chelyabinsk bolide plume in 2013. It was observed by satellite aerosol profilers above 30 km.

Gorkavyi, N., D. F. Rault, P. A. Newman, A. M. da Silva, and A. E. Dudorov (2013), New stratospheric dust belt due to the Chelyabinsk bolide, Geophys. Res. Lett., 40, 4728–4733, doi:10.1002/grl.50788.

Response: We have rechecked our lidar measurement data (both scattering ratios and integrated stratospheric backscatter coefficients). The Chelyabinsk bolide plume was not detected over Tomsk in 2013 (See, please, red lines from 977 to 992 in the "10-day average values" file in **the Supplement** to check the integrated stratospheric backscatter coefficient data). So, the belt was not over Tomsk.

Comment: P4, L10. What does the pi character refer to? Please consider stating its meaning.

Response: The π character denotes an angle of π radian (180 degrees), i.e. the angle of the backscatter lidar signal propagation.

We have added the following sentence to the revised manuscript:
"π denotes an angle of π radian, i.e. the angle of the backscatter lidar signal propagation."
[**Page 4, lines 14 and 15, revised manuscript**]

Comment: P4, L20. This is understandable and defensible. But the median tropopause at Tomsk is such that a lot of the lowermost stratosphere is not sampled with the fixed lower limit of 15 km. For instance, many volcanic plumes just above the tropopause have occurred in recent years (Kasatochi is one example). And pyrocumulonimbus smoke plumes are routine in summer, but usually between the tropopause and ~15 km. It might be worthwhile to try other lower-boundary, for instance based on potential temperature or a tropopause-relative height offset.

Response: Yes, some stratospheric aerosol events could be missed due to the lower limit of 15 km for integrated stratospheric backscatter coefficient B_π^a calculation. However, this limit definitely excludes any tropospheric aerosol events. Moreover, we usually determined the scattering ratio R(H) starting from the lower limit of 12.5 km (Figs. 5, 7, 8, 12–15), or even from 10 km in the case of Eyjafjallajökull volcano (Fig. 10).

Comment: Figure 2. The error/uncertainty bars are not defined or even mentioned. Moreover, however they are defined, the majority of them extend farther than the winter/summer range. This suggests to me that this pattern of monthly averages is not particularly repeatable. Auth should consider discussion of the robustness of this pattern in light of the relatively large uncertainty. The feature that stands out here is the March average and uncertainty. Can the authors explain why this month's aerosol amount is so large and variable?

Response: Sect 3.1 was considerably rewritten. See, please, the colored version of our revised manuscript for details. For example, we have extended the analyzed period of the background aerosol loading variations over Tomsk up to 16 years (1999–2015) and averaged the B_π^a values separately for the westerly and easterly phases of the quasi-biennial oscillations (QBO) characterized by zonal winds in the equatorial region at 30 mbar (Fig. 3, ex-Fig. 2). The monthly average B_π^a data for March–June 2000 (after the Hekla eruption), August–November 2008 (after the Okmok and Kasatochi eruptions), August–October 2009 (after the Sarychev Peak eruption), and also April and August–October 2011 (after the Merapi, Grimsvötn, and Nabro eruptions) were not taken into account. The exclusion of these perturbed data allowed us to extend the analyzed period of the background aerosol loading variations and, therefore, to improve the statistical reliability of the B_π^a data series. All error bars in Figs. 2 and 3 represent the standard (1–σ) deviation.

Comment: P6, L4. The minimum integrated backscatter coefficient value in Figure 1 and Trickl et al.'s background value are not equal, in contrast to the authors' claim. Figure 1's value is between 1e-4 and 2e-4. Trickl et al.'s 1979 background value is 5e-5, smaller by roughly a factor of two. Zuev et al.'s Pinatubo peak matches well with Trickl et al., but the comparable quiescent-period values are off by about a factor of 2. This sentence should be corrected. The differences in the background values should be acknowledged and discussed. Trickl integrated from a tropopause-relative altitude that probably includes more of the lowermost stratosphere than Zuev et al. yet their integral is much smaller. The wavelength difference is seemingly too small to account for the difference.

Response: Thank you for this comment. We agree that the background value of B_π^a observed in Tomsk at λ = 532 nm in 2004 was not equal to the Trickl et al.'s background value determined for Garmisch-Partenkirchen at λ = 694 nm in 1979. We corrected this sentence. However, it is not reasonable to discuss and hardly possible to intercompare the 2004 Tomsk and 1979 Garmisch-Partenkirchen B_π^a background values, because one atmospheric (air) circulation epoch was replaced by another one during 25 years (e.g., Chu, 2002; Chernavskaya et al., 2006). Therefore, the sources and type of the background aerosol were also changed.

Instead of

"The thin horizontal line in Fig. 1 indicates the minimum value of the annual average B_π^a reached in 2004. This value equals to that determined in 1979 and considered as the background one (Trickl et al., 2013)."

we wrote

"Note that taking into account the spectral dependence of B_π^a, its minimum annual average value observed in Tomsk at λ = 532 nm in 2004 was close to that determined for Garmisch-Partenkirchen at λ = 694 nm in 1979 and considered as the background by Trickl et al. (2013)."

[**Page 7, line 20 and Page 8, lines 1 and 2, revised manuscript**]

Chu, P.-S.: Large-Scale Circulation Features Associated with Decadal Variations of Tropical Cyclone Activity over the Central North Pacific, Journal of Climate, 15, 2678–2689, doi:10.1175/1520-0442(2002)015<2678:LSCFAW>2.0.CO;2, 2002.

Chernavskaya, M. M., Kononova, N. K., and Val'Chuk, T. E.: Correlation between atmospheric circulation processes over the Northern Hemisphere and parameter of solar variability during 1899–2003, Adv. Space Res., 37, 1640–1645, doi:10.1016/j.asr.2005.06.022, 2006.

Trickl, T., Giehl, H., Jäger, H., and Vogelmann, H.: 35 yr of stratospheric aerosol measurements at Garmisch-Partenkirchen: from Fuego to Eyjafjallajökull, and beyond, Atmos. Chem. Phys., 13, 5205–5225, doi:10.5194/acp-13-5205-2013, 2013.

Comment: P7, L14-19. Discussion of the Brewer Dobson circulation and its impact on the extratropical SAL. Presumably the point here is that the pattern shown by Fig. 2 is consistent with the generalizations here such that a citation is needed for work(s) that show this intra-annual tendency.

Response: There is no need for a reference to any other work, because we can show the intra-annual tendency (an annual cycle in the mid-latitude SAL via the Brewer-Dobson circulation) based on our 16-year averaged values of the monthly average B_π^a (Fig. 3, ex-Fig. 2). See, please, the rewritten Sect. 3.1 for details.

Comment: Figure 3. What is the averaging period of the data points?

Response: (Figure 3 is now Fig. 2). The averaging period for each **red** point (warm half-year) is from April to September of the corresponding year. The averaging period for each **blue** point (cold half-year) is from October of the current year to March of the next year. The "warm" and "cold" average points are assigned to 1 June of the current year and 1 January of the next year, respectively. Black and red vertical bars at the bottom of the figure indicate volcanic eruptions as in Fig. 1 (see also Table 1).

Comment: Since error bars were shown for Figure 2, they should also be shown here, and the implications discussed.

Response: Done. All error bars represent the standard deviation.

Comment: P8, L17-18. This statement does not reconcile with VEI=4. I recognize that VEI=4 is in the GVP database. So this sentence probably should call out the apparent discrepancy.

Response: Well, both VEI and the maximum plume altitude of the Eyjafjallajökull volcano eruption were taken from the GVP database, as it is noted in Table 1 caption. The VEI coefficient is responsible for the volcanic gas and ash volume, rather than for their rise altitude.

Comment: P10, L3. The trajectory analysis is largely unnecessary. There is no need to run trajectories for the 8 Aug observation; it's obvious that layer can't be from Kasatochi (and there is no other plausible source). For the September observation (and latter ones), the stratosphere at that time had Okmok and Kasatochi aerosols distributed all over. If the Tomsk back trajectory intersected with any of the Okmok layers prior to its pass over the Kasatochi volcano, that is a more plausible attribution than a 3.5 week trajectory connection.

Response: Well, we agree that the sentence "In the August of 2008, the detected aerosol layers were related only to the Okmok plume, but in the September of 2008, there was observed a superposition of plumes from both volcanoes." declares the obvious fact. The mentioned sentence was removed from the text. Regarding the usage of the trajectory analysis, we can say that all HYSPLIT trajectories were used only to illustrate and not to prove the results of our lidar observation. We noted in several places in our manuscript (including Sect. "Discussion and conclusion") that all the trajectories longer than 2 weeks can be considered only as probable ones. We also compared our vertical profiles of the scattering ratio $R(H)$ with the Minsk CIS-LiNet lidar station profiles (Zuev et al., 2009) and revealed the similar SAL perturbations over Minsk. As a whole, we considerably rewrote Sect 3.2.1. See, please, the colored revised version of our manuscript for details.

Zuev, V. V., Balin, Yu. S., Bukin, O. A., Burlakov, V. D., Dolgii, S. I., Kabashnikov, V. P., Nevzorov, A. V., Osipenko, F. P., Pavlov, A. N., Penner, I. E., Samoilova, S. V., Stolyarchuk, S. Yu., Chaikovskii, A. P., and Shmirko, K. A.: Results of joint observations of aerosol perturbations of the stratosphere at the CIS-LiNet network in 2008, Atmos. Ocean. Opt., 22, 295–301, 2009.

Comment: P10. The impression I got from reading this analysis was that Zuev et al. are attempting to draw general conclusions about the Kasatochi and Okmok plumes and the SAL. If they are instead limiting their assessment of the SAL to just where the Tomsk observations are, they should make that explicit. The more general SAL analysis of these plumes is already published but not cited in this manuscript. E.g. Bourassa et al., Anderssen et al., Kravitz et al. These make clear that the Kasatochi and Okmok plumes were observed at all altitudes from the tropopause to nearly 19 km.

Andersson et al. (2015), Significant radiative impact of volcanic aerosol in the lowermost stratosphere, DOI: 10.1038/ncomms8692.

Bourassa, A., D. Degenstein, B. Elash, and E. Llewellyn (2010), Evolution of the stratospheric aerosol enhancement following the eruptions of Okmok and Kasatochi: Odin-OSIRIS measurements, J. Geophys. Res., 115, D00L03, doi:10.1029/2009JD013274.

Kravitz, B., A. Robock, and A. Bourassa (2010), Negligible climatic effects from the 2008 Okmok and Kasatochi volcanic eruptions, J. Geophys. Res., 115, D00L05, doi:10.1029/2009JD013525.

Response: As we already pointed out above, we deeply rewrote Sect 3.2.1. to clarify the situation. First, our conclusion (based on the HYSPLIT trajectories), that the plumes from both Okmok and Kasatochi volcanoes reached altitudes of ≥16 km, is consistent with different satellite observation data, including the CALIOP data (Yang et al., 2010; Kristiansen et al., 2010; Prata et al., 2010). Second, the more general SAL analysis of these plumes was already published by Zuev et al. (2009) but not cited in the works published later by, e.g., Bourassa et al. (2010), Kravitz et al. (2010), and Anderssen et al. (2015). Nevertheless, we included Bourassa et al. (2010) and Andersson et al. (2015) to our manuscript as an example. See, please, the colored revised version of our manuscript for details.

Yang, K., Liu, X., Bhartia, P. K., Krotkov, N. A., Carn, S. A., Hughes, E. J., Krueger, A. J., Spurr, R. J. D., and Trahan, S. G.: Direct retrieval of sulfur dioxide amount and altitude from spaceborne hyperspectral UV measurements: Theory and application, J. Geophys. Res., 115, D00L09, doi:10.1029/2010JD013982, 2010.

Kristiansen, N. I., Stohl, A., Prata, A. J., Richter, A., Eckhardt, S., Seibert, P., Hoffmann, A., Ritter, C., Bitar, L., Duck, T. J., and Stebel, K.: Remote sensing and inverse transport modeling of the Kasatochi eruption sulfur dioxide cloud, J. Geophys. Res., 115, D00L16, doi:10.1029/2009JD013286, 2010.

Prata, A. J., Gangale, G., Clarisse, L., and Karagulian, F.: Ash and sulfur dioxide in the 2008 eruptions of Okmok and Kasatochi: Insights from high spectral resolution satellite measurements, J. Geophys. Res., 115, D00L18, doi:10.1029/2009JD013556, 2010.

Comment: P10, L12. My impression is that Zuev et al. are attempting to assess the accuracy of the injection height as reported by the GVP. The point made here, and below, regarding the accuracy of the Hmpa for the two eruptions, is of little consequence. I also get the impression that they are using the altitude of the back trajectory endpoint over the volcano as a point of comparison with Hmpa. If I have the wrong impression, perhaps other readers will be similarly affected. So I ask the authors to clarify the wording here. Otherwise, giving the precise altitude of a 3-4 week old trajectory much weight asks more of the trajectory model and the weather analyses than they can promise. Secondly, the Hmpa data in the GVP database is neither tightly constrained. Thirdly, it can be shown easily with CALIOP data that the Hmpa for these two eruptions is even farther off the mark than this analysis suggests. CALIOP data within a few days of each eruption shows that the injection altitude was at least 17 km (Okmok) and 18 km (Kasatochi). These data would offer a much more compelling analysis for this argument than the Tomsk data.

Response: We have rested on our experimental results obtained with the SLS lidar, not on the CALIOP data. We calculated a lot of trajectories and showed only several ones as an example. Note that our HYSPLIT trajectories in cases of Okmok and Kasatochi eruptions (started from Tomsk) definitely ended within their plumes over the volcanoes. Thus, these results of the trajectory analysis made are also in agreement with the CALIOP data (see, please, our response for your previous comment). We never claimed that HYSPLIT trajectories are able to determine the maximum plume altitudes of any volcanic eruptions. No essential conclusions were made on the basis of the HYSPLIT trajectories.

Comment: P11, L15. This is way too precise and exclusive. The Sarychev Peak eruption spanned several days, as shown in their table. The time of a 3+ week back trajectory is by its nature too uncertain to permit such a definitive connection.

Response: The trajectory (presented in Fig. 9 and started from one of the detected aerosol layers over Tomsk) shows a possible way how aerosol from the Sarychev Peak volcanic plume erupted in one of the eruption days (e.g. 15 June) could pass and be detected over Tomsk on 7 July. We consider that the trajectory also shows that the detected aerosol layer is not associated with the after-effect of the 2009 Redoubt eruption.

Instead of

"As seen in Fig. 9, this layer is associated with the backward trajectory passed over Sarychev Peak volcano at an altitude of ~13.8 km on 15 June at the moment of the eruption, 17:30 UTC."

we wrote

"This layer is seen in Fig. 9 to be: 1) associated with the backward trajectory passed over Sarychev Peak volcano at an altitude of ~13.8 km on 15 June at the moment of the eruption, 17:30 UTC; and 2) not associated with the after-effect of the Redoubt eruption."

[**Page 13, lines 13–16, revised manuscript**]

Comment: Figure 10. These strong stratospheric layers at 15 km and their source are not subjected to a back trajectory test. Given that they are a much shorter time post eruption than the prior examples, it would critical to show if they connect to the volcano. If Eyja did not inject material this far above the tropopause, where did this material come from?

Response: Now we present in Fig. 11 an ensemble of the air-mass backward trajectories started from altitudes (~11.1–14.6 km a.s.l.) of strong stratospheric layers over Tomsk (Fig. 10) on 21 April 2010 at 00:00 LT (20 April, 17:00 UTC). Only one trajectory started from an altitude of ~11.6 km a.s.l. directly passed over Eyjafjallajökull volcano. The other trajectories passed south of the volcano.

Instead of

"Figure 11 shows the HYSPLIT air-mass backward trajectory started from an altitude of the detected aerosol layers (~11.6 km a.s.l.) over Tomsk on 21 April at 00:00 LT (20 April, 17:00 UTC). The trajectory passed over Eyjafjallajökull volcano on one of the eruption days, 16 April at 13:00 UTC, at the altitude $H_{\text{traj.}}^{\text{back.}} \approx 10.7$ km that is clearly higher than $H_{\text{MPA}} \le 9$ km. This inconsistency between the altitudes $H_{\text{traj.}}^{\text{back.}}$ and H_{MPA} ($H_{\text{traj.}}^{\text{back.}}$ should normally be equal to or lower than H_{MPA}) is discussed in Sect. 4."

we wrote

"Figure 11 shows the HYSPLIT air-mass backward ensemble trajectories started from altitudes of the detected aerosol layers (~11.1–14.6 km a.s.l.) over Tomsk on 21 April at 00:00 LT (20 April, 17:00 UTC). Only one trajectory (started from an altitude of ~11.6 km) directly passed over Eyjafjallajökull volcano on one of the eruption days, 16 April at 13:00 UTC, at the altitude $H_{\text{traj.}}^{\text{back.}} \approx 10.7$ km that is clearly higher than $H_{\text{MPA}} \le 9$ km. The inconsistency between the HYSPLIT $H_{\text{traj.}}^{\text{back.}}$ and GVP H_{MPA} altitudes is discussed in Sect. 4. The other trajectories passed south of the volcano."

[Page 15, lines 9–13, revised manuscript]

Comment: P15, L13. Regarding the connection between the weak layer in Figure 12, localized reduced total ozone, and Merapi, a stronger candidate would be Arctic O3 depletion. See Manney et al., (Nature, 2011) "Unprecedented Arctic Ozone Loss in 2011" doi:10.1038/nature10556.

Response: We agree with Dr. Fromm that the degree of ozone depletion in April 2011 was greater than it could be due to the influence on ozone of volcanic aerosol plumes. As the purpose of our research was to study aerosol perturbations of the stratosphere over Tomsk and was not to study the ozone depletion, here and elsewhere all information and discussions about ozone depletion and mini-holes were removed from the manuscript, without prejudice to the generality of the foregoing. We substituted Fig. 12 by a new one with additional perturbed scattering ratio profiles to make it clearer and informative.

Instead of
"As an example, Fig. 12 presents an aerosol layer observed over Tomsk at an altitude of ~18 km on 18 April 2011."

we wrote
"Figure 12 presents the observed after-effect of the Merapi eruption, i.e. several perturbed scattering ratio profiles retrieved from the SLS aerosol lidar measurements between 28 February and 18 April 2011."
[**Page 16, lines 11 and 12, revised manuscript**]

Instead of
"**Figure 12.** Detection of the Merapi volcanic plume in the stratosphere over Tomsk. The volcano erupted in Indonesia from 4 to 5 November 2010."

we wrote
"**Figure 12.** Perturbed scattering ratio profiles retrieved from the SLS aerosol lidar measurements in the winter-spring period of 2011."
[Page 17, line 2, revised manuscript]

The sentence "Note also that a significant decrease in the total ozone content was observed over Tomsk at the same period of time (April 2011), which is evidence of stratospheric ozone depletion caused by the Merapi aerosol plume (Zuev et al., 2016)." was removed from our manuscript.
[**Page 16, line 15, revised manuscript**]

The reference Zuev et al., 2016 was removed from our manuscript too.

Zuev, V. V., Zueva, N. E., Savelieva, E. S., Bazhenov, O. E., and Nevzorov, A. V.: On the role of the eruption of the Merapi volcano in an anomalous total ozone decrease over Tomsk in April 2011, Atmos. Ocean. Opt., 29, 298–303, 2016.

Comment: P16, L4. This conclusion regarding Nabro's injection height has been exhaustively disputed. There are no citations here of the papers demonstrating the classic, direct injection of Nabro to the stratosphere. http://science.sciencemag.org/content/339/6120/647.4

http://science.sciencemag.org/content/339/6120/647.3

The Bourassa et al. scenario was shown to be improbable by Fairlie et al.(2014). Clarisse et al. (2014), Fairlie et al. (2014), and Penning de Vries et al. (2014) showed, using a variety of satellite data, that direct injection above the tropopause was more consistent with these data than the indirect path via the Monsoon. Fromm et al. (2014) established a root cause for the misattribution to the Asian Monsoon pathway and made connections with prior papers on other volcanic stratospheric aerosol discrepancies. Hence the full weight of Nabro-related papers gives a very different perspective than what is documented here. I would ask the authors to more fully capture these various works in their presentation on Nabro.

http://www.atmos-chem-phys.net/14/7045/2014/

http://www.atmos-chem-phys.net/14/3095/2014/

http://www.atmos-chem-phys.net/14/8149/2014/

http://onlinelibrary.wiley.com/doi/10.1002/2014JD021507/full.

Response: We have to agree with you. Thank you for these references. We used them all.

We revised and partially corrected Sect. 3.3.2.

Instead of
"Grimsvötn volcano erupted ash clouds and gases directly into the stratosphere at an altitude of 20 km, whereas the Nabro volcanic plume did not exceed the local tropopause altitude. Nevertheless, Bourassa et al. (2012) and Robock (2015) showed that a considerable part of the Nabro volcanic aerosol and gases, erupted into the upper troposphere, was able to enter the mid-latitude stratosphere due to deep convection and vertical air transport associated with the strong Asian summer monsoon anticyclone."

we wrote
"According to the GVP data, Grimsvötn volcano erupted ash clouds and gases directly into the stratosphere at an altitude of 20 km, whereas the Nabro volcanic plume did not exceed the local tropopause altitude. Bourassa et al. (2012) showed that a considerable part of the Nabro volcanic aerosol and gases, erupted into the upper troposphere, was able to

enter the mid-latitude stratosphere due to deep convection and vertical air transport associated with the strong Asian summer monsoon anticyclone. On the other hand, Vernier et al. (2013), Fromm et al. (2013), Fairlie et al. (2014), Clarisse et al. (2014), and Penning de Vries et al. (2014) showed that the initial Nabro plume was directly injected into the lower stratosphere at altitudes up to 18 km (Fromm eat al., 2014)."

[**Page 17, lines 5–11, revised manuscript**]

Vernier, J.-P., Thomason, L. W., Fairlie, T. D., Minnis, P., Palikonda, R., and Bedka, K. M.: Comment on "Large volcanic aerosol load in the stratosphere linked to Asian monsoon transport", Science, 339, 647-d, doi:10.1126/science.1227817, 2013.

Fromm, M., Nedoluha, G., and Charvát, Z.: Comment on "Large volcanic aerosol load in the stratosphere linked to Asian monsoon transport", Science, 339, 647-c, doi:10.1126/science.1228605, 2013.

Fairlie, T. D., Vernier, J.-P., Natarajan, M., and Bedka, K. M.: Dispersion of the Nabro volcanic plume and its relation to the Asian summer monsoon, Atmos. Chem. Phys., 14, 7045–7057, doi:10.5194/acp-14-7045-2014, 2014.

Clarisse, L., Coheur, P.-F., Theys, N., Hurtmans, D., and Clerbaux, C.: The 2011 Nabro eruption, a SO2 plume height analysis using IASI measurements, Atmos. Chem. Phys., 14, 3095-3111, doi:10.5194/acp-14-3095-2014, 2014.

Penning de Vries, M. J. M., Dörner, S., Puķīte, J., Hörmann, C., Fromm, M. D., and Wagner, T.: Characterisation of a stratospheric sulfate plume from the Nabro volcano using a combination of passive satellite measurements in nadir and limb geometry, Atmos. Chem. Phys., 14, 8149-8163, doi:10.5194/acp-14-8149-2014, 2014.

Fromm, M., Kablick III, G., Nedoluha, G., Carboni, E., Grainger, R., Campbell, J., and Lewis, J.: Correcting the record of volcanic stratospheric aerosol impact: Nabro and Sarychev Peak, J. Geophys. Res., 119, 10343–10364, doi:10.1002/2014JD021507, 2014.

Comment: P16, L18. Often? I'm not aware of any literature showing any direct positive correlation between PSC formation and volcanic sulfur loading. Hence a citation is needed. Fromm et al. (2003) actually showed little (or even negative) correlation between PSC frequency and ambient aerosol loading. Hence it would be important for the authors to substantiate the claim they make here.

Fromm, M., J. Alfred, and M. Pitts, A unified, long-term, high-latitude stratospheric aerosol and cloud database using SAM II, SAGE II, and POAM II/III data: Algorithm description, database definition, and climatology, J. Geophys. Res., 108(D12), 4366, doi:10.1029/2002JD002772, 2003.

Response: The PSC formation depends on both low temperature (lower than –78 °C) and the presence of condensation nuclei. The volcanogenic aerosol also plays the role of condensation nuclei. The PSC formation is a local process and could not work on the global scale. Concerning the direct positive correlation between PSC formation and volcanic sulfur loading, see, e.g., the following reference:

Rose, W. I., Millard, G. A., Mather, T. A., Hunton, D. E., Anderson, B., Oppenheimer, C., Thornton, B. F., Gerlach, T. M., Viggiano, A. A., Kondo, Y., Miller, T. M., and Ballenthin, J. O.: Atmospheric chemistry of a 33–34 hour old volcanic cloud from Hekla Volcano (Iceland): Insights from direct sampling and the application of chemical box modeling, J. Geophys. Res., 111, D20206, doi:10.1029/2005JD006872, 2006.

We rewrote Sect. 3.4 and included Fromm et al., (2003) with appropriate comments to our manuscript.

Instead of

"Therefore, the injections of volcanogenic H_2SO_4 aerosols or/and SO_2 into the stratosphere often lead to PSC formation, if the air temperature < –78 °C."

we wrote

"Therefore, injections of volcanogenic H_2SO_4 aerosols or/and SO_2 into the stratosphere can lead to PSC formation, if the air temperature < –78 °C. The direct positive correlation between PSC formation and volcanogenic nitric and sulfur acid aerosols loading was shown, e.g., by Rose et al. (2006). However, it should be noted that, in contrast to Rose et al. (2006), Fromm et al. (2003) showed little (or even negative) correlation between PSC events and ambient aerosol loading."

[**Page 18, lines 8–11, revised manuscript**]

Comment: P17, L6. Not necessarily. In fact, spatial correlations between total-O3 minima (socalled ozone mini-holes) and PSCs are routinely attributable to synoptic-scale dynamics. See

Hood et al. and Teitelbaum et al. Exploring polar stratospheric cloud and ozone minihole formation: The primary importance of synoptic scale flow perturbations, Teitelbaum, H., M. Fromm, & M. Moustaoui, J. Geophys. Res., 106, 28173–28188, 2001.

Hood, L. L., B.E. Soukharev, M. Fromm, and J.P. McCormack, Origin of extreme ozone minima at middle to high northern latitudes, J. Geophys. Res., 106, 20925–20940, 2001.

Response: All information and discussions about ozone depletion were removed from Sect. 3.4. See, please, the colored version of our revised manuscript for details.

Instead of

"Hence, the stratospheric temperature over Tomsk can occasionally be cooled lower than –78 °C, when Tomsk is inside the polar vortex. ~~As stratospheric ozone is depleted due to heterogeneous chemical reactions, releasing chlorine on the surfaces of PSCs (Solomon, 1999), the occurrence of PSCs in the mid-latitudes should be followed by a significant decrease in the total ozone content.~~ Thus, the detection of aerosol layers in the stratosphere at extremely low temperatures ~~together with a considerable decrease in the total ozone content~~ can be indicative of the presence of PSCs."

we wrote

"Hence, the stratospheric temperature over Tomsk can occasionally be cooled lower than –78 °C, when Tomsk is inside the polar vortex. Thus, the detection of aerosol layers in the stratosphere at extremely low temperatures can be indicative of the presence of PSCs."

[Page 18, lines 14–16, revised manuscript]

The reference Solomon (1999) was removed from our manuscript.

Solomon, S.: Stratospheric ozone depletion: A review of concepts and history, Rev. Geophys., 37, 275–316, doi:10.1029/1999RG900008, 1999.

Instead of

"The first lidar PSC observations (over Tomsk) ~~that met the criteria of low temperature and total ozone content~~, were made at λ = 1064 nm on January 1995 (Zuev and Smirnov, 1997)."

we wrote

"The first lidar PSC observations over Tomsk were made at λ = 1064 nm in January 1995 (Zuev and Smirnov, 1997)."

[**Page 19, line 7, revised manuscript**]

Comment: P17, L17. This PSC is consistent with the findings of Fromm et al. (1999) who showed that the cold pool and PSC frequency in the northern winter of 1994/95 was located near the Tomsk longitude.

http://onlinelibrary.wiley.com/doi/10.1029/1999JD900273/epdf.

Response: Thank you for this reference. We added Fromm et al. (1999) with appropriate comments to our manuscript.

Instead of

"The stratospheric temperature was lower than –80 °C ~~and the total ozone content was less than 70 percent of the norm. The formation of these dense PSCs was caused by high concentrations of H_2SO_4 aerosols resulted from the eruptions of Pinatubo (1991) and Rabaul (1994) volcanoes~~."

we wrote

"The stratospheric temperature was lower than –80 °C. The cold pool presence and PSC events near the Tomsk longitude during the northern winter of 1994/95 were also reported by Fromm et al. (1999). The formation of these dense PSCs was caused by high concentrations of residual post-Pinatubo aerosols."

[**Page 19, lines 9–12, revised manuscript**]

Fromm, M. D., Bevilacqua, R. M., Hornstein, J., Shettle, E., Hoppel, K., and Lumpe, J. D.: An analysis of Polar Ozone and Aerosol Measurement (POAM) II Arctic polar stratospheric cloud observations, 1993–1996, J. Geophys. Res., 104, 24341–24357, doi:10.1029/1999JD900273, 1999.

Comment: P17, L19. Please see the prior comment regarding mini-holes.

Response: See, please, our **Response** to **Comment:** P17, L6.

Comment: P17, L20. This seems to be quite unlikely considering that PSCs are formed inside the vortex, which represents air isolated from the extratropics. Rabaul aerosols, introduced just a few months before the northern 1994/95 vortex season, would not likely have been meridionally transported that far north in time to be in place before the vortex formed and isolation was in place.

Response: Well, aerosol resulted from the 1994 Rabaul eruption could enter inside the polar vortex weakened and deformed due to a minor sudden stratospheric warming in January 1995. This is a subject for discussion and additional research. Anyway, as the main cause of PSC formation is the extremely low temperatures, we excluded the Rabaul volcanic aerosol discussion from this part of the text.

Comment: P18, L2. It seems highly unlikely (or at least hard to prove) to argue for a PSC in the northern polar vortex one season after a southern hemisphere volcanic eruption. It would be best to state this as speculative, if the statement is to remain.

Response: We agree with this comment.

Instead of
"Another event of PSCs over Tomsk was observed at λ = 532 nm on 27 January 2007 (Fig. 14) ~~as an after-effect of the Rabaul volcano eruption occurred on 7 October 2006 (Table 1)~~."

we wrote
"Another event of PSCs over Tomsk was observed at λ = 532 nm on 27 January 2007 (Fig. 14)."
[**Page 19, line 13, revised manuscript**]

Comment: P18, L6. See the prior comment about mini-holes. At this time in Jan 2007, a localized o3 minimum was at Tomsk's longitude. The ozone signature was likely an artifact of local dynamics.

http://exp-studies.tor.ec.gc.ca/cgibin/selectMap?lang=e&type1=du&day1=27&month1=01&year1=2007&howmany1=1&interval1=1&intervalunit1=d&hem1=P18.

Response: We agree with the comment. The discussion about ozone depletion was removed from the text.

Instead of
"~~Moreover, the stratospheric ozone was considerably depleted at that time and the total ozone content was 30 percent of the norm (Zuev et al., 2008)~~. Thus, PSCs were detected at least twice (in 1995 and 2007) during 30 years of stratospheric aerosol lidar measurements in Tomsk."

we wrote
"High $R(H)$ values at altitudes in the range of 13 to 17 km were probably due to the winter aerosol supplying of the SAL from the stratospheric tropical aerosol reservoir enriched by the 2006 Rabaul eruption plume (Table 1, Fig. 14). Thus, PSCs were detected at least twice (in 1995 and 2007) during 30 years of stratospheric aerosol lidar measurements in Tomsk."
[Page 19, lines 17–20, revised manuscript]

The reference Zuev et al. (2008) was removed from our manuscript.

Zuev, V. V., Bazhenov, O. E., Burlakov, V. D., Grishaev, M. V., Dolgii, S. I., and Nevzorov, A. V.: On the effect of volcanic aerosol on variations of stratospheric ozone and NO2 according to measurements at the Siberian Lidar Station, Atmos. Ocean. Opt., 21, 825–831, 2008.

We also substituted Fig. 14 by a new one and corrected its caption.

Instead of
"**Figure 14.** Detection of the Rabaul volcanic plume together with PSCs, formed at extremely low temperatures (< –78 °C), in the stratosphere over Tomsk. Rabaul volcano erupted in Papua New Guinea on 7 October 2006. Temperature profiles were retrieved from radiosondes launched on 27 January 2007 in Kolpashevo (station 29231) at 00:00 UTC and in Novosibirsk (station 29634) at 12:00 UTC (WWW, 2007)."

we wrote
"**Figure 14.** Detection of PSCs formed at extremely low temperatures (< –78 °C) in the stratosphere over Tomsk. Temperature profiles were obtained from radiosondes launched on 27 January 2007 in Kolpashevo (station 29231) at 00:00 UTC and in Novosibirsk (station 29634) at 12:00 UTC (WWW, 2007). The dashed ellipse denotes the after-effect of the Rabaul volcanic eruption occurred in Papua New Guinea on 7 October 2006."
[Page 19, lines 2–5, revised manuscript]

Comment: P18, L26. By postulating that pyroCb smoke could increase "annual average" stratospheric aerosol, it would imply that prior research has come to similar conclusions. I'm not aware of any such finding. Please modify this statement appropriately.

Response: You are probably right. We agree that extensive forest (bush) fires (and pyroCb smoke) could hardly be expected to increase the **annual average** B_π^a value. We removed discussion about forest extensive fires and pyro-cumulonimbus clouds from Sect. 3.5 (without prejudice to the foregoing) and retained it only in Sect. 4.

The following part of the Sect. 3.5 was removed:

"~~Extensive forest (bush) fires could be another cause of occasional increases of the annual average B_π^a value. Combustion products (gases and aerosol particles) can reach the stratospheric altitudes via convective ascent within pyro-cumulonimbus (pyroCb) clouds (see, e.g., Fromm et al., 2006). For example, the smoke plumes from the strong bush fire, occurred near the Australian city of Melbourne on 7 February 2009, were observed in the local stratosphere at an altitude of ~18 km (Siddaway and Petelina, 2011). In recent years, the number and intensity of massive forest fires have significantly increased (e.g., in the USA; Trickl et al., 2013) due to the climate change. The smoke-filled air masses frequently enter the stratosphere over the South of Western Siberia from North America, where extensive forest fires occur. Their smoke plumes are most likely to be detected as the SAL perturbations over Tomsk. However, more detailed information about the pyroCb events is required for their correct identification. Thus, both the Kelut plume and smoke plumes from massive forest fires in the USA and Canada, with equal probability, could be the cause of the increase of B_π^a value in the stratosphere over Tomsk during the first quarter of 2015.~~"

Comment: P19, L13. "always" was not proved or demonstrated herein. Hence a citation is needed, or this point should be restated or removed.

Response: We agree. This "always" was removed from the text. Some of plumes from the tropical volcanoes eruptions can completely be within the Southern Hemisphere stratosphere. The tropical eruptions which plumes were within the Northern Hemisphere stratosphere and passed over Tomsk are presented in our manuscript.

Instead of

"Additional aerosol loading of the tropical reservoir ~~always leads to~~ an increase in the annual average B_π^a value in the Northern Hemisphere mid-latitude stratosphere via the meridional transport in the cold seasons (October to March)."

we wrote

"Additional aerosol loading of the tropical reservoir can usually lead to an increase in the annual average B_π^a value in the Northern Hemisphere mid-latitude stratosphere via the meridional transport in the cold seasons (October to March; Hitchman et al., 1994)."

[Page 21, lines 6–8, revised manuscript]

Hitchman, M.H., McKay, M., Trepte, C.R.: A climatology of stratospheric aerosol, J. Geophys. Res., 99, 20689-20700, doi:10.1029/94JD01525,1994.

Comment: P19, L18. It's not clear what is meant here. All volcanic plumes are represented as an initial point source. Please clarify.

Response: OK. We rewrote and clarified the sentence.

Instead of

"On the other hand, by contrast to tropical volcanoes, the northern ones represent point sources of volcanic gas, aerosol, and ash plumes. Their corresponding air-mass trajectories can either pass over a lidar station or pass it by."

we wrote

"On the other hand, by contrast to tropical volcanoes, the narrow volcanic gas, aerosol, and ash plumes from northern volcanoes can either pass over a lidar station or pass it by."

[**Page 21, lines 11 and 12, revised manuscript**]

Comment: P20, L15. What is meant by "thermal speed?" Please clarify.

Response: This is the speed achieved due to heating of erupted mass in the "gas thrust" and "convective thrust" regions of an eruption column, not due to any potential (conservative) fields like magnetic, Coulomb or gravitational fields. The word "thermal" was removed from the text.

Comment: P20, L15. This is confusing. A plume is buoyant because it is less dense than the surrounding air. This makes it sound as if the surrounding umbrella region is less dense.

Response: We agree with this comment. The sentence was rewritten accordingly.

Instead of

"The most heated fraction of gas-vapor emissions from the "convective thrust region" has the high ~~thermal~~ speed and, therefore, can penetrate through the ~~lower~~-density "umbrella region" of the eruption column and reach altitudes higher than H_{MPA} (Raible et al., 2016)."

we wrote
"The most heated fraction of gas-vapor emissions from the "convective thrust region" has the highest speed and, therefore, can penetrate through the higher-density "umbrella region" of the eruption column and reach altitudes higher than H_{MPA} due to the cumulative (jet) effect (Raible et al., 2016)."
[Page 21, lines 25–27, revised manuscript]

And

Instead of
"In addition to volcanoes, PSCs also represent a cause of significant SAL perturbations ~~and, hence, marked increases in the annual average B_π^a value~~."

we wrote
"In addition to volcanoes, PSCs also represent a cause of significant SAL perturbations."
[**Page 22, line 1, revised manuscript**]

Comment: P20, L24. "drifting" needs to be clarified. It implies to me that the ozone feature is drifting with the wind, whereas the papers previously offered in these comments show that the minihole is tied to dynamics and thus move with the speed of the synoptic-scale wave, not the wind.

Response: The sentences "The possibility of PSCs to form and be detected in the mid-latitudes is usually related with the presence of "mini ozone holes" drifting over lidar measurement points. As the lifetime of these "holes" is sufficiently short in the mid-latitudes, the PSC observations can be only occasional." were removed from Sect. 4.

Comment: P20, L29. The impact of pyroCb smoke on annual average stratospheric aerosol has not been shown in the literature to my knowledge. Please cite a paper or modify this statement accordingly.

Response: Yes, we agree. See, please, our **Response** to **Comment:** P18, L26 concerning the **annual average** B_π^a value.

Comment: P20, L32. The measures in acres and square km are not equivalent. Please correct this.

Comment: P21, L2. What is the reason to call out the Happy Camp fire?

Response: Thank you. We corrected the mistake: 134 acres ≈ 0.543 km^2. However, we removed the information about the Happy Camp fire from the text of our manuscript.

We rewrote a substantial part of Sect. 4 to make it clearer.

Instead of
"Smoke plumes from strong forest (bush) fires can reach the stratospheric altitudes (Fromm et al., 2006; Siddaway and Petelina, 2011), spread out to great distances, and perturb the SAL state over different regions, including Tomsk. This is known to result in a measurable increase in the annual average B_π^a value. Due to the climate warming, the number and intensity of massive forest fires have significantly increased in the last few years (Wotton et al., 2010). For example, about 137 strong forest fires were registered in the Northwest Territories of Canada in July 2014 (CBC News, 2014), and the Happy Camp Complex fire (41.80° N, 123.37° E) eventually consumed more than 134 acres (~0.543 km^2) of forests in California in August–October 2014. According to the California Department of Forestry and Fire Protection (CAL FIRE, http://www.ca.gov/) data, the Happy Camp Complex fire is in the list of the "Top 20 Largest California Wildfires". The smoke plumes from these mentioned massive forest fires could probably cause the increase in B_π^a value in the stratosphere over Tomsk in January–March 2015. More detailed information about the pyroCb events such as precise time, place, and smoke plume altitude is required to correctly assign the pyroCb plumes to the corresponding aerosol layers over an observation point via the HYSPLIT model trajectory analysis. It is quite possible that some after-effects of strong forest fires occurred, e.g., in North America could be detected over Tomsk, but not identified during lidar observations in Tomsk (1986–2015)."

we wrote

“Extensive forest (bush) fires could be another cause of occasional increases of the B_{π}^{a} value. Combustion products (gases and aerosol particles) can reach the stratospheric altitudes via convective ascent within pyro-cumulonimbus (pyroCb) clouds (see, e.g., Fromm et al., 2006). For example, the smoke plumes from the strong bush fire, occurred near the Australian city of Melbourne on 7 February 2009, were observed in the local stratosphere at an altitude of ~18 km (Siddaway and Petelina, 2011). Due to the climate warming, the number and intensity of massive forest fires have considerably increased in the last few years (Wotton et al., 2010). For example, about 137 strong forest fires were registered in the Northwest Territories of Canada in July 2014 (CBC News, 2014). The smoke-filled air masses frequently enter the stratosphere over the South of Western Siberia from North America, where extensive forest fires occur. Their smoke plumes are most likely to be detected as the SAL perturbations over Tomsk. However, more detailed information about the pyroCb events is required for their correct identification. It is quite possible that some after-effects of strong forest fires occurred, e.g., in North America could be detected over Tomsk, but not identified during lidar observations in Tomsk (1986–2015).”
[**Page 22, lines 5–14, revised manuscript**]

Comment: P21, L4. Regarding pyroCb smoke, I believe that there would be many occasions through the years for stratospheric observations at Tomsk. But of course the frequency of such observations would decrease rapidly with altitude above the tropopause. The highest smoke layers in the northern hemisphere to my knowledge are 19 km. They are much more likely to be at 12-15 km. Perhaps it would be to your advantage to directly employ the local tropopause height in the search for pyroCb smoke instead of a fixed altitude (e.g. 15 km) that is generally 4 km above the tropopause.

Response: We agree that the lower limit of 12 km for aerosol observations is better than of 15 km. Anyway, the perturbed scattering ratio profiles were also detected at altitudes higher than 15 km.

Comment: Technical Comments See the accompanying pdf of the manuscript. Please also note the supplement to this comment:

http://www.atmos-chem-phys-discuss.net/acp-2016-792/acp-2016-792-RC2-supplement.pdf.

Response: We corrected the text in accordance with Dr. Fromm’s technical comments.

Comment: in the Technical Comments: Trickl did not conclude that the 14.3 km aerosol was from Eyja. They were more circumspect about all the aerosols above the tropopause because back trajectories did not come close to Iceland or pass near Iceland during a big eruption day.

Response: At least, Trickl noted in his article the following:

(Abstract) A key observation for judging the role of eruptions just reaching the tropopause region was that of the plume from the Icelandic volcano Eyjafjallajökull above Garmisch-Partenkirchen (April 2010) due to the proximity of that source. The top altitude of the ash above the volcano was reported just as 9.3 km, but the lidar measurements revealed enhanced stratospheric aerosol up to 14.3 km.)

(Sect. 4.2, page 5215) The upper boundary of these aerosol layers was roughly 12 km on 17 and 19 April, and 14.3 km on 20 April (Fig. 9), i.e., above the thermal tropopause that was 10.2 km on average on these days.

Sincerely,

Authors

Manuscript Number: acp-2016-792
Manuscript Type: Research article
Title: 30-year lidar observations of the stratospheric aerosol layer state over Tomsk (Western Siberia, Russia)

List of corrections made according to Referee 1 and Dr. Fromm comments

We substituted Figures 1, 2, 3, 5a, 11, 12, 13, and 14 by new ones and corrected their captions.

New Figures 5b, 6c, were added to the manuscript.

Page 1

Instead of
"We also make an assumption that both the Kelut volcano plume (Indonesia, February 2014) and smoke plumes from massive forest fires occurred in Canada (137 fires in the Northwest Territories, July 2014) and the USA (the Happy Camp Complex fire in California, August–October 2014), with equal probability, could be the cause of the SAL perturbations over Tomsk during the first quarter of 2015."

we wrote
"We also make an assumption that the Kelut volcano eruption (Indonesia, February 2014) could be the cause of the SAL perturbations over Tomsk during the first quarter of 2015."
[**Page 1, lines 27 and 28, revised manuscript**]

Page 2

Instead of
"The volcanogenic aerosol perturbs the radiation-heat balance of the atmosphere, and thus, significantly affects the atmospheric dynamics (Timmreck, 2012; Driscoll et al., 2012)."

we wrote
"The volcanogenic aerosol perturbs the radiation-heat balance of the atmosphere, and thus, significantly affects the atmospheric dynamics and climate (Timmreck, 2012; Driscoll et al., 2012; Kremser et al., 2016)."
[**Page 2, lines 7 and 8, revised manuscript**]

Page 3

Instead of
"…can be useful, e.g., in studying climate change."

we wrote
"…can be useful, e.g., in studying climate change (Mills et al., 2016)."
[**Page 3, lines 3 and 4, revised manuscript**]

The following sentence was added to the manuscript:
"Note that the CIS-LiNet station located in Minsk, Belarus, is also integrated into the European Aerosol Research Lidar Network (EARLINET; Wandinger et al., 2016)."
[**Page 3, lines 9 and 10, revised manuscript**]

Instead of
"…FEU-130 operating in the photon counting mode."

we wrote
"…FEU-130 (USSR, Moscow Elecro-Lamp Plant) operating in the photon counting mode."
[**Page 3, lines 25 and 26, revised manuscript**]

Page 4

The following sentence was added to the manuscript:
"A more detailed technical description of the SLS aerosol channel and its data acquisition electronics can be found, e.g., in (Burlakov et al., 2010)."
[**Page 4, lines 10 and 11, revised manuscript**]

The following sentence was added to the manuscript:
"π denotes an angle of π radian, i.e. the angle of the backscatter lidar signal propagation."
[**Page 4, lines 14 and 15, revised manuscript**]

Instead of
"In our case, the tropopause altitude over Tomsk varies from ~11 to 13 km, depending on season, and therefore, we set H_1 = 15 km."

we wrote
"Tomsk is located near the southern boundary of subarctic latitudes, where the tropopause altitude can significantly vary, e.g., due to migration of the Arctic stratospheric jet stream within the Tomsk region. Sometimes one can observe a double (or even multiple) tropopause. For this reason, we consciously removed the interval of the tropopause altitude variations to observe the stratospheric perturbations only. As the tropopause altitude over Tomsk varies from ~11 to 13 km, depending on season, we set H_1 = 15 km."
[**Page 4, lines 23–26, revised manuscript**]

Page 5

Instead of
"**Figure 1.** … The red bars correspond to tropical volcanic eruptions, whereas the black ones correspond to eruptions of extratropical volcanoes located in the Northern Hemisphere. PSC: polar stratospheric clouds."

we wrote
"**Figure 1.** … The red bars correspond to tropical volcanic eruptions, whereas the black ones correspond to eruptions of extratropical volcanoes located in the Northern Hemisphere. The thin horizontal line in Fig. 1 indicates the minimum value of the annual average B_π^a reached in 2004. PSC: polar stratospheric clouds."
[**Page 5, lines 16 and 17, revised manuscript**]

Page 7

Figure 2 is now Figure 3 and, conversely, Figure 3 is now Figure 2 in the revised manuscript.

Instead of
"**Figure 1.** … The red bars correspond to tropical volcanic eruptions, whereas the black ones correspond to eruptions of extratropical volcanoes located in the Northern Hemisphere. PSC: polar stratospheric clouds."

we wrote
"**Figure 2.** Inter-annual variations of B_π^a values (in the stratosphere over Tomsk) separately averaged over the warm and cold half-years. The "warm" and "cold" average points are assigned to 1 June of the current year and 1 January of the next year, respectively. Black and red vertical bars at the bottom of the figure indicate volcanic eruptions as in Fig. 1 (see also Table 1). All error bars represent the standard deviation."
[**Page 7, lines 10–13, revised manuscript**]

Instead of
"…background level of B_π^a reached after 1999. Note that only…"

we wrote
"…background level of B_π^a reached after 1998. Only…."
[**Page 7, line 16, revised manuscript**]

Instead of
"The minimum annual average B_π^a values were reached in 2003–2004."

we wrote
"The minimum annual average $B_\pi^a = 1.29 \times 10^{-4}$ sr^{-1} was reached in 2004."
[**Page 7, line 18, revised manuscript**]

Instead of
"The thin horizontal line in Fig. 1 indicates the minimum value of the annual average B_π^a reached in 2004. This value equals to that determined in 1979 and considered as the background one (Trickl et al., 2013)."

we wrote

"Note that taking into account the spectral dependence of B_{π}^{a}, its minimum annual average value observed in Tomsk at λ = 532 nm in 2004 was close to that determined for Garmisch-Partenkirchen at λ = 694 nm in 1979 and considered as the background by Trickl et al. (2013)."

[**Page 7, line 20 and Page 8, lines 1 and 2, revised manuscript**]

Pages 8 and 9

We considerably rewrote Sect 3.1. See, please, the colored version of our revised manuscript for details.

Pages 10 and 11

Section 3.2.1 was deeply revised and rewritten. Figures 5b and 6c were added.

Instead of

"In summer 2008, two Aleutian volcanoes Okmok and Kasatochi started to erupt at 19:43 UTC on 12 July and between 23:00 UTC on 7 August and 05:35 UTC on 8 August, respectively (both VEI = 4). The plumes from these volcanoes considerably perturbed the SAL over Tomsk from August to October 2008, and the after-effects of their eruptions were detected up to January 2009. Vertical profiles of the scattering ratio *R*(*H*), showing the detection of the Okmok and Kasatochi plumes over Tomsk during these months, are presented in Fig. 5 as an example. In the August of 2008, the detected aerosol layers were related only to the Okmok plume, but in the September of 2008, there was observed a superposition of plumes from both volcanoes. The trajectory analysis, made by using the NOAA HYSPLIT model, showed that the SAL perturbations at altitudes lower than 16 km were caused mostly by the Okmok plume, whereas the Kasatochi plume perturbed the SAL at altitudes higher than 16 km (Fig. 6). Figure 6a shows the air-mass backward trajectory started from the altitude of the *R*(*H*) profile maximum (~15.1 km a.s.l.) over Tomsk on 8 August at 02:00 LT (or on 7 August at 19:00 UTC). The trajectory passed over Okmok volcano on the eruption day, 12 July, at the altitude $H_{\mathrm{traj.}}^{\mathrm{back.}}$ ≈ 16 km that is 1 km higher than the official maximum plume altitude (MPA; Table 1) H_{MPA}. Furthermore, Fig. 6b shows the backward trajectory started from the altitude of the *R*(*H*) maximum (~16.3 km a.s.l.) over Tomsk on 2 September at 00:00 LT (1 September, 17:00 UTC). The trajectory passed over Kasatochi volcano on the eruption day, 7 August, at the altitude $H_{\mathrm{traj.}}^{\mathrm{back.}}$ ≈ 16.4 km that is 2.4 km higher than the official H_{MPA} (Table 1)."

we wrote

"In summer 2008, two Aleutian volcanoes Okmok and Kasatochi started to erupt at 19:43 UTC on 12 July and between 23:00 UTC on 7 August and 05:35 UTC on 8 August, respectively (both VEI = 4). The plumes from these volcanoes considerably perturbed the SAL over Tomsk from August to October 2008. Vertical profiles of the scattering ratio *R*(*H*), showing the detection of the Okmok and Kasatochi plumes over Tomsk during these months, are presented in Fig. 5a as an example. Simultaneous stratospheric aerosol observations at the Minsk CIS-LiNet station at λ = 532 nm revealed the similar SAL perturbations over Minsk from July to October (Fig. 5b; Zuev et al., 2009). The after-effects of both volcano eruptions were detected in the stratosphere over Minsk and Tomsk up to December 2008.

Figure 6a shows the HYSPLIT air-mass backward trajectory started from the altitude of the *R*(*H*) profile maximum (~15.1 km a.s.l.) over Tomsk on 8 August at 02:00 LT (or on 7 August at 19:00 UTC). The trajectory passed over Okmok volcano on the eruption day, 12 July, at the altitude $H_{\mathrm{traj.}}^{\mathrm{back.}}$ ≈ 16.0 km that is 1 km higher than the maximum plume altitude (MPA; Table 1) H_{MPA} determined by the GVP. Figure 6b shows the backward trajectory started from the altitude of the *R*(*H*) maximum (~16.3 km a.s.l.) over Tomsk on 2 September at 00:00 LT (1 September, 17:00 UTC). The trajectory passed over Kasatochi volcano on the eruption day, 7 August, at the altitude $H_{\mathrm{traj.}}^{\mathrm{back.}}$ ≈ 16.4 km that is 2.4 km higher than the GVP H_{MPA} (Table 1). Our conclusion (based on the HYSPLIT trajectories), that the plumes from both volcanoes reached altitudes of ≥16 km, is consistent with different satellite observation data (Yang et al., 2010; Kristiansen et al., 2010; Prata et al., 2010). The inconsistency between the HYSPLIT $H_{\mathrm{traj.}}^{\mathrm{back.}}$ and GVP H_{MPA} altitudes ($H_{\mathrm{traj.}}^{\mathrm{back.}}$ should normally be equal to or lower than H_{MPA}) is discussed in Sect. 4.

The HYSPLIT trajectory analysis also showed that both Okmok (Fig. 6a) and Kasatochi (Fig. 6b) plumes passed close to the Minsk lidar station. This explains the similarity of the *R*(*H*) profiles presented in Fig. 5. Owing to the westerly transport of air masses, the volcanic plumes passed over Minsk three days earlier than over Tomsk. Figure 6c shows the backward trajectories which allowed us to find the connection between two aerosol layers (thick red lines in Fig. 5) detected over Minsk and Tomsk on 1 and 4 September, respectively. The more general and detailed analysis of the Okmok and Kasatochi plumes influence on the SAL state was made by Zuev et al. (2009) and later, e.g., by Bourassa et al. (2010) and Andersson et al. (2015)."

[**Page 10, line 10 – Page 11, line 17, revised manuscript**]

Instead of

"**Figure 5.** Detection of the Okmok and Kasatochi volcanic plumes in the stratosphere over Tomsk."

we wrote

"**Figure 5.** Detection of the Okmok and Kasatochi volcanic plumes in the stratosphere over **(a)** Tomsk (Russia) and **(b)** Minsk (Belarus)."

[**Page 11, line 20, revised manuscript**]

Page 12

The following sentence was added to Figure 6 caption:

"…**(c)** Air-mass backward ensemble trajectories started from altitudes of 16.4–16.7 km a.s.l. over Tomsk on 5 September 2008 at 00:00 LT (4 September, 17:00 UTC) and passed close to Minsk"

[**Page 12, lines 7–9, revised manuscript**]

Page 13

Instead of

"It should be noted that due to the zonal transport of air masses in the Northern Hemisphere lower stratosphere during summer seasons and vast geographical distance between Tomsk and the Aleutian Islands, both backward trajectories could hardly be expected to be equal to or shorter than two weeks."

we wrote

"It should be noted that due to the westerly zonal transport of air masses in the Northern Hemisphere lower stratosphere during summer seasons and vast geographical distance between Tomsk and the Aleutian Islands, both backward trajectories (Figs. 6a and 6b) could hardly be expected to be equal to or shorter than two weeks."

[Page 13, lines 1–3, revised manuscript]

Instead of

"As seen in Fig. 9, this layer is associated with the backward trajectory passed over Sarychev Peak volcano at an altitude of ~13.8 km on 15 June at the moment of the eruption, 17:30 UTC."

we wrote

"This layer is seen in Fig. 9 to be: 1) associated with the backward trajectory passed over Sarychev Peak volcano at an altitude of ~13.8 km on 15 June at the moment of the eruption, 17:30 UTC; and 2) not associated with the after-effect of the Redoubt eruption."

[**Page 13, lines 13–16, revised manuscript**]

Page 15

Instead of

"Figure 11 shows the HYSPLIT air-mass backward trajectory started from an altitude of the detected aerosol layers (~11.6 km a.s.l.) over Tomsk on 21 April at 00:00 LT (20 April, 17:00 UTC). The trajectory passed over Eyjafjallajökull volcano on one of the eruption days, 16 April at 13:00 UTC, at the altitude $H_{\text{traj.}}^{\text{back.}} \approx 10.7$ km that is clearly higher than $H_{\text{MPA}} \leq 9$ km. This inconsistency between the altitudes $H_{\text{traj.}}^{\text{back.}}$ and H_{MPA} ($H_{\text{traj.}}^{\text{back.}}$ should normally be equal to or lower than H_{MPA}) is discussed in Sect. 4."

we wrote

"Figure 11 shows the HYSPLIT air-mass backward ensemble trajectories started from altitudes of the detected aerosol layers (~11.1–14.6 km a.s.l.) over Tomsk on 21 April at 00:00 LT (20 April, 17:00 UTC). Only one trajectory (started from an altitude of ~11.6 km) directly passed over Eyjafjallajökull volcano on one of the eruption days, 16 April at 13:00 UTC, at the altitude $H_{\text{traj.}}^{\text{back.}} \approx 10.7$ km that is clearly higher than $H_{\text{MPA}} \leq 9$ km. The inconsistency between the HYSPLIT $H_{\text{traj.}}^{\text{back.}}$ and GVP H_{MPA} altitudes is discussed in Sect. 4. The other trajectories passed south of the volcano."

[Page 15, lines 9–13, revised manuscript]

Page 16

Instead of

"**Figure 11.** Air-mass backward trajectory started from an altitude of ~11.6 km a.s.l. over Tomsk on 21 April 2010 at 00:00 LT (20 April, 17:00 UTC) and passed over Eyjafjallajökull volcano."

we wrote

"**Figure 11.** Air-mass backward ensemble trajectories started from altitudes of ~11.1–14.6 km a.s.l. over Tomsk on 21 April 2010 at 00:00 LT (20 April, 17:00 UTC) and passed over or south of Eyjafjallajökull volcano."

[Page 16, lines 2 and 3, revised manuscript]

Instead of

"As an example, Fig. 12 presents an aerosol layer observed over Tomsk at an altitude of ~18 km on 18 April 2011."

we wrote

"Figure 12 presents the observed after-effect of the Merapi eruption, i.e. several perturbed scattering ratio profiles retrieved from the SLS aerosol lidar measurements between 28 February and 18 April 2011."

[**Page 16, lines 11 and 12, revised manuscript**]

Page 17

Instead of

"**Figure 12.** Detection of the Merapi volcanic plume in the stratosphere over Tomsk. The volcano erupted in Indonesia from 4 to 5 November 2010."

we wrote

"**Figure 12.** Perturbed scattering ratio profiles retrieved from the SLS aerosol lidar measurements in the winter-spring period of 2011."

[Page 17, line 2, revised manuscript]

Instead of

"Grimsvötn volcano erupted ash clouds and gases directly into the stratosphere at an altitude of 20 km, whereas the Nabro volcanic plume did not exceed the local tropopause altitude. Nevertheless, Bourassa et al. (2012) and Robock (2015) showed that a considerable part of the Nabro volcanic aerosol and gases, erupted into the upper troposphere, was able to enter the mid-latitude stratosphere due to deep convection and vertical air transport associated with the strong Asian summer monsoon anticyclone."

we wrote

"According to the GVP data, Grimsvötn volcano erupted ash clouds and gases directly into the stratosphere at an altitude of 20 km, whereas the Nabro volcanic plume did not exceed the local tropopause altitude. Bourassa et al. (2012) showed that a considerable part of the Nabro volcanic aerosol and gases, erupted into the upper troposphere, was able to enter the mid-latitude stratosphere due to deep convection and vertical air transport associated with the strong Asian summer monsoon anticyclone. On the other hand, Vernier et al. (2013), Fromm et al. (2013), Fairlie et al. (2014), Clarisse et al. (2014), and Penning de Vries et al. (2014) showed that the initial Nabro plume was directly injected into the lower stratosphere at altitudes up to 18 km (Fromm eat al., 2014)."

[**Page 17, lines 5–11, revised manuscript**]

Page 18

Instead of

"**3.4 Polar stratospheric clouds**"

we wrote

"**3.4 Polar stratospheric clouds and the after-effect of the 2006 Rabaul eruption**"

[Page 18, line 4, revised manuscript]

Instead of

"Therefore, the injections of volcanogenic H_2SO_4 aerosols or/and SO_2 into the stratosphere often lead to PSC formation, if the air temperature < –78 °C."

we wrote

"Therefore, injections of volcanogenic H_2SO_4 aerosols or/and SO_2 into the stratosphere can lead to PSC formation, if the air temperature < –78 °C. The direct positive correlation between PSC formation and volcanogenic nitric and sulfur acid aerosols loading was shown, e.g., by Rose et al. (2006). However, it should be noted that, in contrast to Rose et al. (2006), Fromm et al. (2003) showed little (or even negative) correlation between PSC events and ambient aerosol loading."

[**Page 18, lines 8–11, revised manuscript**]

Instead of

"As stratospheric ozone is depleted due to heterogeneous chemical reactions, releasing chlorine on the surfaces of PSCs (Solomon, 1999), the occurrence of PSCs in the mid-latitudes should be followed by a significant decrease in the total ozone content. Thus, the detection of aerosol layers in the stratosphere at extremely low temperatures together with a considerable decrease in the total ozone content can be indicative of the presence of PSCs."

we wrote

"Thus, the detection of aerosol layers in the stratosphere at extremely low temperatures can be indicative of the presence of PSCs."

[Page 18, lines 15 and 16, revised manuscript]

Page 19

Instead of

"**Figure 14.** Detection of the Rabaul volcanic plume together with PSCs, formed at extremely low temperatures (< –78 °C), in the stratosphere over Tomsk. Rabaul volcano erupted in Papua New Guinea on 7 October 2006. Temperature profiles were retrieved from radiosondes launched on 27 January 2007 in Kolpashevo (station 29231) at 00:00 UTC and in Novosibirsk (station 29634) at 12:00 UTC (WWW, 2007)."

we wrote

"**Figure 14.** Detection of PSCs formed at extremely low temperatures (< –78 °C) in the stratosphere over Tomsk. Temperature profiles were obtained from radiosondes launched on 27 January 2007 in Kolpashevo (station 29231) at 00:00 UTC and in Novosibirsk (station 29634) at 12:00 UTC (WWW, 2007). The dashed ellipse denotes the after-effect of the Rabaul volcanic eruption occurred in Papua New Guinea on 7 October 2006."

[Page 19, lines 2–5, revised manuscript]

Instead of

"The first lidar PSC observations (over Tomsk) that met the criteria of low temperature and total ozone content, were made at λ = 1064 nm on January 1995 (Zuev and Smirnov, 1997). More precisely, some dense aerosol layers were detected at altitudes in the range of 15 to 19 km on 24 and 26 January. The maximum scattering ratio $R(H)$ was more than 14 at an altitude of 18.1 km. The stratospheric temperature was lower than –80 °C and the total ozone content was less than 70 percent of the norm. The formation of these dense PSCs was caused by high concentrations of H_2SO_4 aerosols resulted from the eruptions of Pinatubo (1991) and Rabaul (1994) volcanoes.

Another event of PSCs over Tomsk was observed at λ = 532 nm on 27 January 2007 (Fig. 14) as an after-effect of the Rabaul volcano eruption occurred on 7 October 2006 (Table 1). As seen in Fig. 14, the maximum scattering ratio $R(H)$ was more than 1.55 at an altitude of 19.3 km. According to the data of the two nearest to Tomsk meteorological stations, launching radiosondes twice a day and situated in Novosibirsk (55.02° N, 82.92° E) and Kolpashevo (58.32° N, 82.92° E), the stratospheric temperature was lower than –78 °C at altitudes between 19 and 21.5 km (WWW, 2007) during the lidar measurements. Moreover, the stratospheric ozone was considerably depleted at that time and the total ozone content was 30 percent of the norm (Zuev et al., 2008)."

we wrote

"The first lidar PSC observations over Tomsk were made at λ = 1064 nm in January 1995 (Zuev and Smirnov, 1997). More precisely, some dense aerosol layers were detected at altitudes in the range of 15 to 19 km on 24 and 26 January. The maximum scattering ratio $R(H)$ was more than 14 at an altitude of 18.1 km. The stratospheric temperature was lower than –80 °C. The cold pool presence and PSC events near the Tomsk longitude during the northern winter of 1994/95 were also reported by Fromm et al. (1999). The formation of these dense PSCs was caused by high concentrations of residual post-Pinatubo aerosols.

Another event of PSCs over Tomsk was observed at λ = 532 nm on 27 January 2007 (Fig. 14). As seen in Fig. 14, the maximum scattering ratio $R(H)$ was more than 1.55 at an altitude of 19.3 km. According to the data of the two nearest to Tomsk meteorological stations, launching radiosondes twice a day and situated in Novosibirsk (55.02° N, 82.92° E) and Kolpashevo (58.32° N, 82.92° E), the stratospheric temperature was lower than –78 °C at altitudes between 19 and 21.5 km (WWW, 2007) during the lidar measurements. High $R(H)$ values at altitudes in the range of 13 to 17 km were probably due to the winter aerosol supplying of the SAL from the stratospheric tropical aerosol reservoir enriched by the 2006 Rabaul eruption plume (Table 1, Fig. 14)."

[**Page 19, lines 7–19, revised manuscript**]

Page 21

Instead of

"Additional aerosol loading of the tropical reservoir always leads to an increase in the annual average B_π^a value in the Northern Hemisphere mid-latitude stratosphere via the meridional transport in the cold seasons (October to March)."

we wrote

"Additional aerosol loading of the tropical reservoir can usually lead to an increase in the annual average B_{π}^{a} value in the Northern Hemisphere mid-latitude stratosphere via the meridional transport in the cold seasons (October to March; Hitchman et al., 1994)."

[Page 21, lines 6–8, revised manuscript]

Instead of

"On the other hand, by contrast to tropical volcanoes, the northern ones represent point sources of volcanic gas, aerosol, and ash plumes. Their corresponding air-mass trajectories can either pass over a lidar station or pass it by."

we wrote

"On the other hand, by contrast to tropical volcanoes, the narrow volcanic gas, aerosol, and ash plumes from northern volcanoes can either pass over a lidar station or pass it by."

[**Page 21, lines 11 and 12, revised manuscript**]

Instead of

"The most heated fraction of gas-vapor emissions from the "convective thrust region" has the high thermal speed and, therefore, can penetrate through the lower-density "umbrella region" of the eruption column and reach altitudes higher than H_{MPA} (Raible et al., 2016)."

we wrote

"The most heated fraction of gas-vapor emissions from the "convective thrust region" has the highest speed and, therefore, can penetrate through the higher-density "umbrella region" of the eruption column and reach altitudes higher than H_{MPA} due to the cumulative (jet) effect (Raible et al., 2016)."

[Page 21, lines 25–27, revised manuscript]

Page 22

Instead of

"In addition to volcanoes, PSCs also represent a cause of significant SAL perturbations ~~and, hence, marked increases in the annual average B_{π}^{a} value~~. However, the temperature condition required for PSC formation (air temperature should be < –78 °C) rarely holds in the mid-latitude stratosphere. ~~The possibility of PSCs to form and be detected in the mid-latitudes is usually related with the presence of "mini ozone holes" drifting over lidar measurement points. As the lifetime of these "holes" is sufficiently short in the mid-latitudes, the PSC observations can be only occasional~~. Only two PSC events in January 1995 and January 2007 were observed over Tomsk during the 30-year period of lidar observations in Tomsk."

we wrote

"In addition to volcanoes, PSCs also represent a cause of significant SAL perturbations. However, the temperature condition required for PSC formation (air temperature should be < –78 °C) rarely holds in the mid-latitude stratosphere. Only two PSC events in January 1995 and January 2007 were observed over Tomsk during the 30-year period of lidar observations in Tomsk."

[Page 22, lines 1–4, revised manuscript]

Instead of

"Smoke plumes from strong forest (bush) fires can reach the stratospheric altitudes (Fromm et al., 2006; Siddaway and Petelina, 2011), spread out to great distances, and perturb the SAL state over different regions, including Tomsk. This is known to result in a measurable increase in the annual average B_{π}^{a} value. Due to the climate warming, the number and intensity of massive forest fires have significantly increased in the last few years (Wotton et al., 2010). For example, about 137 strong forest fires were registered in the Northwest Territories of Canada in July 2014 (CBC News, 2014), and the Happy Camp Complex fire (41.80° N, 123.37° E) eventually consumed more than 134 acres (~543 km^2) of forests in California in August–October 2014. According to the California Department of Forestry and Fire Protection (CAL FIRE, http://www.ca.gov/) data, the Happy Camp Complex fire is in the list of the "Top 20 Largest California Wildfires". The smoke plumes from these mentioned massive forest fires could probably cause the increase in B_{π}^{a} value in the stratosphere over Tomsk in January–March 2015. More detailed information about the pyroCb events such as precise time, place, and smoke plume altitude is required to correctly assign the pyroCb plumes to the corresponding aerosol layers over an observation point via the HYSPLIT model trajectory analysis."

we wrote

"Extensive forest (bush) fires could be another cause of occasional increases of the B_π^a value. Combustion products (gases and aerosol particles) can reach the stratospheric altitudes via convective ascent within pyro-cumulonimbus (pyroCb) clouds (see, e.g., Fromm et al., 2006). For example, the smoke plumes from the strong bush fire, occurred near the Australian city of Melbourne on 7 February 2009, were observed in the local stratosphere at an altitude of ~18 km (Siddaway and Petelina, 2011). Due to the climate warming, the number and intensity of massive forest fires have considerably increased in the last few years (Wotton et al., 2010). For example, about 137 strong forest fires were registered in the Northwest Territories of Canada in July 2014 (CBC News, 2014). The smoke-filled air masses frequently enter the stratosphere over the South of Western Siberia from North America, where extensive forest fires occur. Their smoke plumes are most likely to be detected as the SAL perturbations over Tomsk. However, more detailed information about the pyroCb events is required for their correct identification."

[**Page 22, lines 5–14, revised manuscript**]

Pages 22–28 (References)

The following three references were removed from the manuscript:

Solomon, S.: Stratospheric ozone depletion: A review of concepts and history, Rev. Geophys., 37, 275–316, doi:10.1029/1999RG900008, 1999.

Zuev, V. V., Zueva, N. E., Savelieva, E. S., Bazhenov, O. E., and Nevzorov, A. V.: On the role of the eruption of the Merapi volcano in an anomalous total ozone decrease over Tomsk in April 2011, Atmos. Ocean. Opt., 29, 298–303, 2016.

Zuev, V. V., Bazhenov, O. E., Burlakov, V. D., Grishaev, M. V., Dolgii, S. I., and Nevzorov, A. V.: On the effect of volcanic aerosol on variations of stratospheric ozone and NO_2 according to measurements at the Siberian Lidar Station, Atmos. Ocean. Opt., 21, 825–831, 2008.

Nineteen new papers were cited. See, please, the colored version of our revised manuscript.

Sincerely,

Authors

30-year lidar observations of the stratospheric aerosol layer state over Tomsk (Western Siberia, Russia)

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Abstract. There are only four lidar stations in the world which have almost continuously performed observations of the stratospheric aerosol layer (SAL) state for over the last 30 years. The longest time series of the SAL lidar measurements have been accumulated at the Mauna Loa Observatory (Hawaii) since 1973, the NASA Langley Research Center (Hampton, Virginia) since 1974, and Garmisch-Partenkirchen (Germany) since 1976. The fourth lidar station we present started to perform routine observations of the SAL parameters in Tomsk (56.48° N, 85.05° E, Western Siberia, Russia) in 1986. In this paper, we mainly focus on and discuss the stratospheric background period from 2000 to 2005 and the causes of the SAL perturbations over Tomsk in the 2006–2015 period. During the last decade, volcanic aerosol plumes from tropical Mt. Manam, Soufriere Hills, Rabaul, Merapi, Nabro, and Kelut, and extratropical (northern) Mt. Okmok, Kasatochi, Redoubt, Sarychev Peak, Eyjafjallajökull, and Grimsvötn were detected in the stratosphere over Tomsk. When it was possible, we used the NOAA HYSPLIT trajectory model to assign aerosol layers observed over Tomsk to the corresponding volcanic eruptions. The trajectory analysis highlighted some surprising results. For example, in cases of the Okmok, Kasatochi, and Eyjafjallajökull eruptions, the HYSPLIT air-mass backward trajectories, started from altitudes of aerosol layers detected over Tomsk with a lidar, passed over these volcanoes on their eruption days at altitudes higher than the maximum plume altitudes given by the Smithsonian Institution Global Volcanism Program. An explanation of these facts is suggested. The role of both tropical and northern volcanoes eruptions in volcanogenic aerosol loading of the mid-latitude stratosphere is also discussed. In addition to volcanoes, we considered other possible causes of the SAL perturbations over Tomsk, i.e. the polar stratospheric cloud (PSC) events and smoke plumes from strong forest fires. At least two PSC events were detected in 1995 and 2007. We also make an assumption that the Kelut volcano eruption (Indonesia, February 2014) could be the cause of the SAL perturbations over Tomsk during the first quarter of 2015.

1 Introduction

Long-term studies show that the presence of various types of aerosol in the stratosphere is mainly caused by powerful volcanic eruptions (Robock, 2000; Robock and Oppenheimer, 2003). Volcanic eruptions are ranked in the volcanic explosivity index (VEI) category from 0 to 8 (Newhall and Self, 1982; Siebert et al., 2010). During Plinian or, more rarely, Vulcanian explosive eruptions with VEI ≥ 3, volcanic ejecta and gases can directly reach the stratospheric altitudes, where the volcanogenic aerosol stays for a long time. Then this aerosol spreads throughout the global stratosphere in the form of clouds. The volcanogenic aerosol perturbs the radiation-heat balance of the atmosphere, and thus, significantly affects the atmospheric dynamics and climate (Timmreck, 2012; Driscoll et al., 2012; Kremser et al., 2016). The injection of volcanogenic aerosol particles into the stratosphere leads to a considerable increase of their specific surface area and, therefore, to activation of heterogeneous chemical reactions on the surface of these particles. The reactions can result in, e.g., stratospheric ozone depletion (Hofmann and Solomon, 1989; Prather, 1992; Randel et al., 1995). Moreover, the long-term presence of volcanogenic aerosol clouds in the stratosphere also leads to cooling of the underlying surface and near-surface atmosphere due to the aerosol scattering and extinction of the direct solar radiation (Stenchikov et al., 2002). The latter effect is the basis for several geoengineering projects on artificial climate control (Crutzen, 2006; Robock et al., 2009; Kravitz and Robock, 2011; Laakso et al., 2016). These projects require information on aerosol cloud transport in the stratosphere.

Among various techniques for stratospheric aerosol measurements, the lidar remote sensing techniques are the most sensitive and have high spatial and temporal resolution. The number of lidar stations for stratospheric aerosol monitoring significantly increased throughout the world soon after the large volcanic eruption of Mt. Pinatubo (Philippines, 15 June 1991; VEI = 6), the most powerful volcanic eruption of the 20th century after the Novarupta volcano eruption (the Alaska Peninsula, 6 June 1912; VEI = 6; Fierstein and Hildreth, 1992). Some of these lidar stations formed continuous lidar observation networks, such as the Network for the Detection of Stratospheric Change (NDSC; now: NDACC, Network for the Detection of Atmospheric Composition Change; http://www.ndsc.ncep.noaa.gov), the European Aerosol Research Lidar Network (EARLINET; Bösenberg et al., 2003), and the Asian Dust and aerosol lidar observation Network (AD-Net; Murayama et al., 2000). However, before the Pinatubo eruption, only several individual lidars provided continuous monitoring of the stratosphere. The longest time series of the stratospheric aerosol layer (SAL) lidar measurements have been accumulated at the Mauna Loa Observatory (Hawaii) since 1973 (Barnes and Hofmann, 1997; Barnes and Hofmann, 2001), the NASA Langley Research Center (Hampton, Virginia) since 1974 (Woods and Osborn, 2001), and Garmisch-Partenkirchen (Germany) since 1976 (Trickl et al., 2013).

The first lidar observations of the SAL parameters in the USSR were performed at the Institute of Atmospheric Optics (IAO) of the Siberian Branch of the USSR Academy of Sciences (now: V.E. Zuev Institute of Atmospheric Optics of the Siberian Branch of the Russian Academy of Sciences), located in Tomsk, in 1975 (Zuev, 1982). A layer near 19 km altitude with increased stratospheric aerosol concentration due to the sub-Plinian eruption of Fuego volcano (Guatemala, 14 October 1974; VEI = 4) was detected at that time.

Tomsk (56.48° N, 85.05° E, Western Siberia, Russia) is located in the central part of the Eurasian continent. The information on the atmosphere over the vast area of Siberia is poorly presented in various databases. Therefore, the lidar measurements time series accumulated in Tomsk are definitely unique and can be useful, e.g., in studying climate change (Mills et al., 2016). A new lidar station was designed and implemented at the IAO in 1985 for continuous monitoring of the SAL volcanogenic perturbations and other stratospheric parameters over Tomsk. The monitoring started at the end of 1985 and is ongoing at the present time (i.e. more than 30 years). In 2004, the lidar station in Tomsk was integrated into the Lidar Network for atmospheric monitoring in the Commonwealth of Independent States (CIS-LiNet; Chaykovskii et al., 2005; Zuev et al., 2009). The CIS-LiNet has been established by six lidar teams from Belarus, Russia, and the Kyrgyz Republic. Note that the CIS-LiNet station located in Minsk, Belarus, is also integrated into the European Aerosol Research Lidar Network (EARLINET; Wandinger et al., 2016).

The detection of high aerosol concentration in the stratosphere over Tomsk after the Nevado del Ruiz volcano eruption (Colombia, 13 November 1985; VEI = 3) marked the beginning of routine lidar observations in 1986 (El'nikov et al., 1988). Definitely, the detection and subsequent monitoring of strong SAL perturbations by volcanogenic aerosol after the Pinatubo eruption were the major events during the first decade of lidar observations in Tomsk. The data of lidar measurements made in Tomsk over the 1986–2000 period were summarized and analyzed by Zuev et al. (1998) and Zuev et al. (2001).

In this paper, we mainly focus on and discuss: 1) the stratospheric background period from 2000 to 2006; 2) the SAL volcanogenic perturbations during the last decade (2006–2015); and 3) the potential detection of polar stratospheric clouds over Tomsk. The role of strong forest fires in the SAL perturbations is discussed. A brief review of previous lidar observations in Tomsk during the 1986–1999 period is also given.

2 Lidar instruments and methods

Regular monitoring of the SAL parameters over Tomsk was started at the IAO with a single-wavelength aerosol lidar in January 1986. A pulsed mode Nd:YAG laser LTI-701 operating at a wavelength of 532 nm with 1 W average power at a pulse repetition rate of 3 kHz was used as the lidar transmitter (El'nikov et al., 1988). The lidar backscattered signals were collected by a Newtonian receiving telescope with a mirror of 1 m diameter and a 2 m focal length. The signals were registered with a vertical resolution of 374 m by a photomultiplier tube (PMT) FEU-130 (USSR, Moscow Elecro-Lamp Plant) operating in the photon counting mode. The first results of stratospheric ozone measurements were obtained with a modified version of the IAO lidar in 1989 (El'nikov et al., 1989). In 1991, the IAO lidar system was updated with a receiving telescope with a mirror of 2.2 m diameter and a 10 m focal length. Note that this 2.2 m telescope can be used both as Newtonian and prime-focus depending on the remotely sensed object and selected lidar transmitter wavelength. Since 1994, the IAO lidar system has been named the Siberian Lidar Station (SLS; Zuev, 2000). Now the SLS represents a multichannel station for regular measurements of aerosol parameters, ozone content and vertical distribution, and for temperature retrievals in the troposphere and stratosphere. The receiving telescopes with the main mirror diameters of 2.2, 1, 0.5, and 0.3 m and lasers operating in the wavelength range 271–1064 nm are used at the SLS for these purposes.

The SLS aerosol channel we consider uses a Nd:YAG laser as the channel transmitter and a Newtonian telescope with a mirror diameter of 0.3 m and a focal length of 1 m as the channel receiver. The laser (LS-2132T-LBO model, LOTIS TII Co., the Republic of Belarus) can operate at wavelengths of 1064, 532, and 355 nm with 200, 100, and 40 mJ pulse energies, respectively, at a pulse repetition rate of 20 Hz. The backscattered signals from altitudes up to the stratopause (~50 km) are registered with a vertical resolution of 100 m by R7206-01 and R7207-01 PMTs (Hamamatsu Photonics, Japan) at used wavelengths of 532 and 355 nm, respectively. The PMTs operate in the photon counting mode. Two shutdown periods of the SLS aerosol channel from July 1997 to May 1999 and from February to September 2014 were due to the maintenance of the channel laser, and the rearrangement and improvement of the SLS. A more detailed technical description of the SLS aerosol channel and its data acquisition electronics can be found, e.g., in (Burlakov et al., 2010).

We use the scattering ratio $R(H)$ to describe the stratospheric aerosol vertical distribution, i.e.

$$R(H)=\frac{\beta_\pi^m(H)+\beta_\pi^a(H)}{\beta_\pi^m(H)}=1+\frac{\beta_\pi^a(H)}{\beta_\pi^m(H)}, \quad (1)$$

where $\beta_\pi^m(H)$ and $\beta_\pi^a(H)$ are the molecular (Rayleigh) and aerosol (Mie) backscatter coefficients, respectively; π denotes an angle of π radian, i.e. the angle of the backscatter lidar signal propagation. The detected lidar signals were calibrated by normalizing them to the molecular backscatter signal from aerosol-free altitudes above the SAL, i.e. $H_0 \geq 30$ km (H_0 is called the calibration altitude). The calibration method of lidar signals against the molecular backscatter coefficient $\beta_\pi^m(H)$ is described in detail by, e.g., Measures (1984).

We use the integrated aerosol backscatter coefficient B_π^a to describe the temporal dynamics (time series) of stratospheric aerosol loading over Tomsk. The coefficient is calculated for a certain range of stratospheric altitudes (H_1; H_2)

$$B_\pi^a=\int_{H_1}^{H_2}\beta_\pi^a(H)dH. \quad (2)$$

Here H_1 is the local tropopause altitude or slightly above, where upper-tropospheric aerosol does not contribute to the value of B_π^a, and H_2 corresponds to the calibration altitude H_0 = 30 km. Tomsk is located near the southern boundary of subarctic latitudes, where the tropopause altitude can significantly vary, e.g., due to migration of the Arctic stratospheric jet stream within the Tomsk region. Sometimes one can observe a double (or even multiple) tropopause. For this reason, we consciously removed the interval of the tropopause altitude variations to observe the stratospheric perturbations only. As the tropopause altitude over Tomsk varies from ~11 to 13 km, depending on season, we set H_1 = 15 km.

Various data on volcanic eruptions were taken from the Smithsonian Institution Global Volcanism Program (GVP; http://volcano.si.edu/; Section: Reports; Subsections: Smithsonian/USGS Weekly Volcanic Activity Report and Bulletin of the Global Volcanism Network). To study the SAL volcanogenic perturbations, we also analyze air-mass backward trajectories started from aerosol layers observed over Tomsk. All the trajectories were calculated by using the NOAA's Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT; Stein et al., 2015; http://ready.arl.noaa.gov/HYSPLIT.php) and the HYSPLIT-compatible NOAA meteorological data from the Global Data Assimilation System (GDAS) one-degree archive.

3 Results of the SAL lidar observations over Tomsk

3.1 Time series of the integrated stratospheric backscatter coefficient (1986–2015)

The 30-year time series of the integrated stratospheric backscatter coefficient B_π^a, obtained from the SAL lidar observations performed at λ = 532 nm in Tomsk from 1986 to 2015, is presented in Fig. 1. The backscatter coefficients are integrated over the 15–30 km stratospheric layer described above.

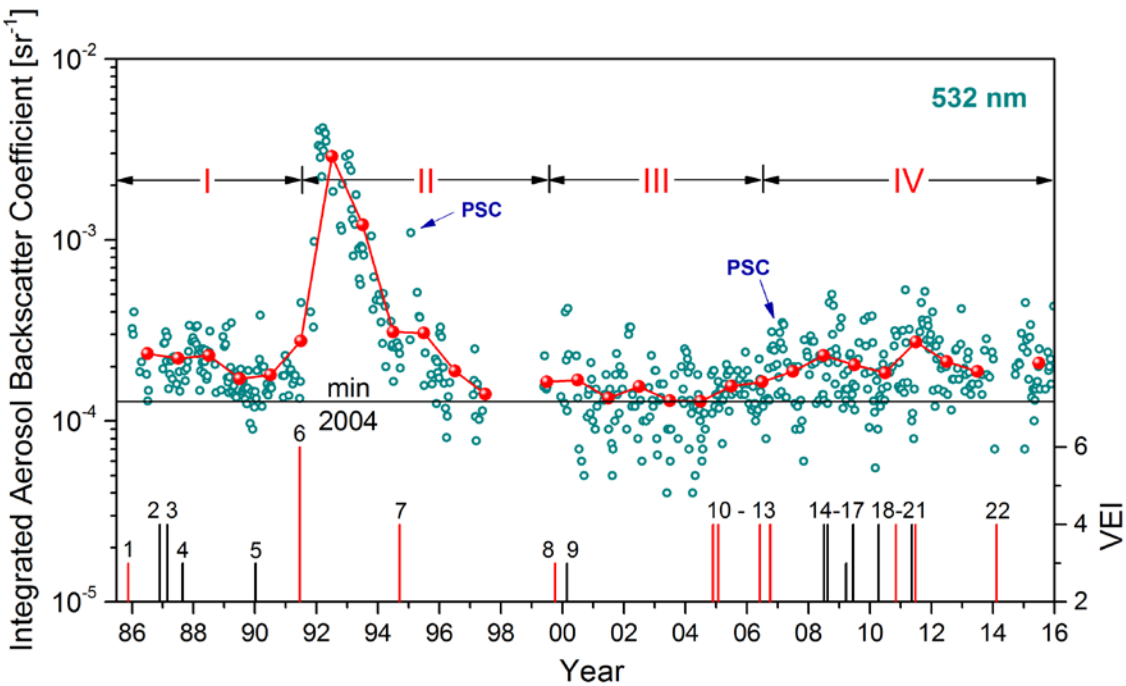


Figure 1. 30-year time series of the integrated stratospheric backscatter coefficient at λ = 532 nm over Tomsk between 15 and 30 km. Open dark-green circles denote the 10-day average B_π^a values. Solid red circles show the annual average B_π^a values assigned to 1 July of each year. Black and red vertical bars at the bottom of the figure indicate volcanic eruptions (ranked on VEI) which caused the SAL volcanogenic perturbations over Tomsk from 1986 to the present day (see also Table 1). The red bars correspond to tropical volcanic eruptions, whereas the black ones correspond to eruptions of extratropical volcanoes located in the Northern Hemisphere. The thin horizontal line in Fig. 1 indicates the minimum value of the annual average B_π^a reached in 2004. PSC: polar stratospheric clouds.

We divided the time series into the following four intervals. The 1986–1991 period (I) reflects the final SAL relaxation after the explosive eruption of El Chichon volcano (Mexico, 29 March 1982, VEI = 5) together with small SAL perturbations after several less powerful volcanic eruptions during the period (see Table 1). The next 1991–1999 period (II) is mainly determined by the strong perturbation and subsequent long-term relaxation of the SAL after the Pinatubo eruption.

Table 1. List of volcanic eruptions that have caused the SAL volcanogenic perturbations detected over Tomsk from 1986 to the present day. The list was retrieved from the GVP data. H_{MPA}: maximum plume altitude.

N	Date/Period	Volcano	Location	H_{MPA}, km	VEI
1	13 Nov. 1985	Nevado del Ruiz	Colombia (4.9° N, 75.3° W)	31	3
2	20 Nov. 1986	Chikurachki	Kuril Islands (50.3° N, 155.5° E)	14	4
3	23 Feb. 1987	Kliuchevskoi	Kamchatka (56.0° N, 160.6° E)	13.7	4
4	28 Aug. 1987	Cleveland	Alaska (52.8° N, 169.9° W)	10.6	3
5	2 Jan. 1990	Redoubt	Alaska (60. 5° N, 152.7° W)	13.5	3
6	15 Jun. 1991	Pinatubo	Philippines (15.1° N, 120.3° E)	35	**6**
7	19 Sep. 1994	Rabaul	Papua New Guinea (4.3° S, 152.2° E)	21	4
8	5 Oct. 1999	Guagua Pichincha	Ecuador (0.2° S, 78.6° W)	20	3
9	26 Feb. 2000	Hekla	Iceland (64.0° N, 19.7° W)	15	3
10	24 Nov. 2004	Manam	Papua New Guinea (4.1° S, 145.0° E)	18	4
11	27 Jan. 2005	Manam	Papua New Guinea (4.1° S, 145.0° E)	24	4
12	20 May 2006	Soufriere Hills	West Indies (16.7° N, 62.2° W)	17	4
13	7 Oct. 2006	Rabaul	Papua New Guinea (4.3° S, 152.2° E)	18	4
14	12 Jul. 2008	Okmok	Aleutian Islands (53.4° N, 168.1° W)	15	4
15	7 Aug. 2008	Kasatochi	Aleutian Islands (52.2° N, 175.5° W)	14	4
16	22 Mar. 2009	Redoubt	Alaska (60. 5° N, 152.7° W)	20	3
17	11–16 Jun. 2009	Sarychev Peak	Kuril Islands (48.1° N, 153.2° E)	21	4
18	14–17 Apr. 2010	Eyjafjallajökull	Iceland (63.6° N, 19.6° W)	9	4
19	4–5 Nov. 2010	Merapi	Indonesia (7.5° S, 110.4° E)	18.3	4
20	21 May 2011	Grimsvötn	Iceland (64.4° N, 17.3° W)	20	4
21	13 Jun. 2011	Nabro	Eritrea (13.4° N, 41.7° E)	13.7	4
22	13 Feb. 2014	Kelut	Indonesia (7.9° S, 112.3° W)	17	4

The 1999–2006 period (III) is marked by reaching the background level of B_π^a under comparatively small SAL volcanogenic perturbations. The last 2006–2015 period (IV) reflects an increase in B_π^a (i.e. in stratospheric aerosol loading) due to an increase in volcanic activity. Table 1 contains all volcanic eruptions that have caused the SAL perturbations detected over Tomsk since 1986.

As noted above, the results of aerosol lidar observations at the SLS during the periods I and II were described by Zuev et al. (1998) and Zuev et al. (2001). Next, we consider the temporal dynamics of stratospheric aerosol loading over Tomsk during the periods III and IV.

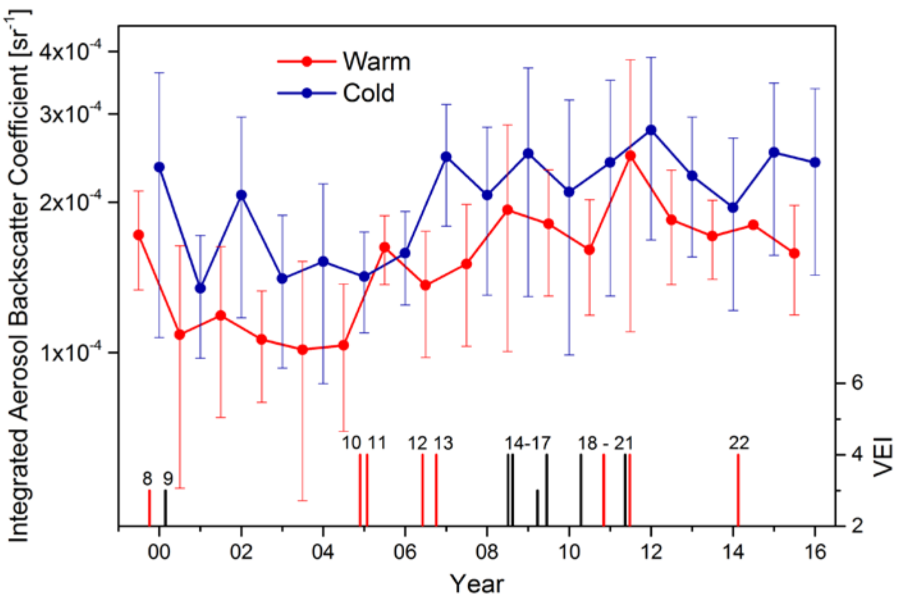


Figure 2. Inter-annual variations of B_π^a values (in the stratosphere over Tomsk) separately averaged over the warm and cold half-years. The "warm" and "cold" average points are assigned to 1 June of the current year and 1 January of the next year, respectively. Black and red vertical bars at the bottom of the figure indicate volcanic eruptions as in Fig. 1 (see also Table 1). All error bars represent the standard deviation.

Low explosive volcanic activity during the comparatively long post-Pinatubo period led to a gradual reduction in volcanogenic aerosol loading of the stratosphere down to the background level of B_π^a reached after 1998. Only the after-effect of the Rabaul volcano eruption (Papua New Guinea, 19 September 1994; VEI = 4) was definitely detected over Tomsk in the post-Pinatubo period (II). The minimum annual average $B_\pi^a = 1.29\times10^{-4}$ sr^{-1} was reached in 2004. Thus, we can consider the state of the SAL over Tomsk as background during the period III, when the annual average B_π^a values were less than those in the pre-Pinatubo period (1989–1991). Note that taking into account the spectral dependence of B_π^a, its minimum annual average value observed in Tomsk at λ = 532 nm in 2004 was close to that determined for Garmisch-Partenkirchen at λ = 694 nm in 1979 and considered as the background by Trickl et al. (2013).

Both inter- and intra-annual variations of B_π^a values in the stratosphere over Tomsk during the periods III and IV are presented in Figs. 2 and 3. Figure 2 shows the inter-annual B_π^a variations separately averaged over the warm (April to September) and cold (October to March) half-years. The B_π^a values are mostly higher in the cold half-year than those in the warm one. Furthermore, these "cold" and "warm" average B_π^a values are modulated by the quasi-biennial oscillations (QBO; http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/). The behavior of both B_π^a curves is seen in Fig. 2 to clearly demonstrate the influence of the Brewer-Dobson circulation on the aerosol state of the mid-latitude stratosphere. Stratospheric aerosol loading is minimal in the warm half-year, when the zonal air mass transport dominates. On the other hand, the meridional air mass transport from tropical into extratropical (middle) latitudes intensifies in the cold half-year and, therefore, it provides the mid-latitude stratosphere with additional aerosol mass from the stratospheric tropical aerosol reservoir (Hitchman et al., 1994). Note that the minimum "warm" average $B_\pi^a = 1.01 \times 10^{-4}$ sr^{-1} was reached in 2003 (Fig. 2).

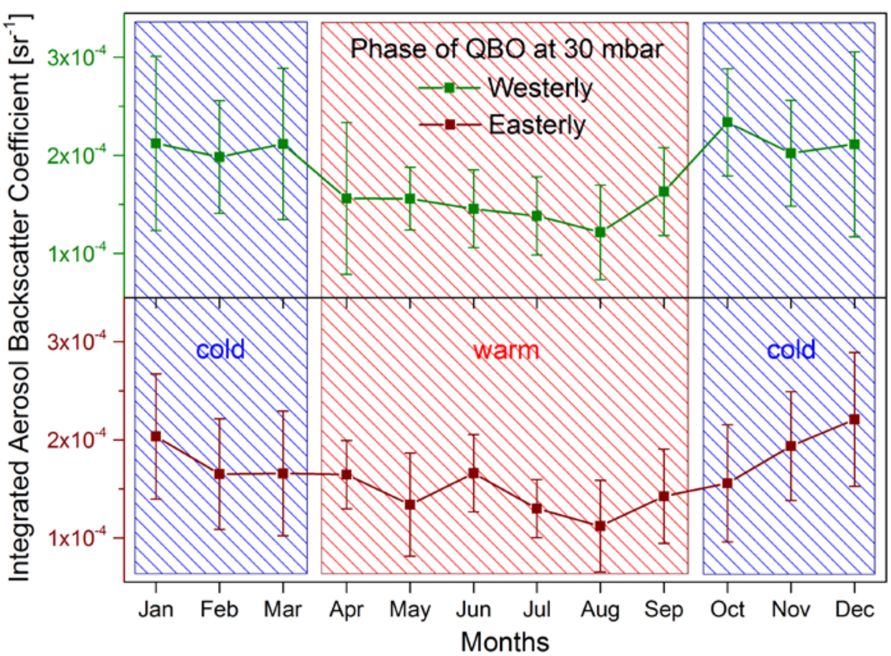


Figure 3. Intra-annual variation of the background monthly average B_π^a values averaged over sixteen years (1999–2015) of the SAL lidar observations, excluding after-effects of volcanic eruptions during the period. The B_π^a values were averaged separately for the westerly and easterly phases of the QBO characterized by zonal winds in the equatorial region at 30 mbar. All error bars represent the standard deviation.

The influence of the Brewer-Dobson circulation on background aerosol loading in the stratosphere over Tomsk can also be discovered by analyzing the intra-annual variations of the monthly average B_π^a values. For example, Fig. 3 shows the B_π^a values averaged over the period 1999–2015, separately for the westerly and easterly phases of the QBO (excluding after-effects of volcanic eruptions during the period). The monthly average B_π^a data for March–June 2000 (after the Hekla eruption), August–November 2008 (after the Okmok and Kasatochi eruptions), August–October 2009 (after the Sarychev Peak eruption), and also April and August–October 2011 (after the Merapi, Grimsvötn, and Nabro eruptions) were not taken into account. The exclusion of these perturbed data allowed us to extend the analyzed period of the background aerosol loading variations up to 16 years and, therefore, to improve the statistical reliability of the B_π^a data series. As seen in Fig. 3, aerosol loading of the mid-latitude stratosphere is maximal in the cold half-year, when the meridional air mass transport dominates (especially during the westerly phase of the QBO). Thus, both types of B_π^a variation (Figs. 2 and 3) lead us to the same conclusion.

Turning to Fig. 1, one can see that there is a positive trend in stratospheric aerosol loading over Tomsk caused by an increase in the number of explosive volcanic eruptions with VEI = 4 during the last decade. A small increase in the B_π^a value started in 2005 due to two Manam volcano eruptions occurred in Papua New Guinea closely spaced in time (Table 1). Soon after, in 2006, two relatively strong eruptions of the Soufriere Hills and Rabaul tropical volcanoes (Table 1) additionally enriched the stratospheric tropical aerosol reservoir. As a result, two corresponding volcanic aerosol peaks were observed in the stratosphere over Tomsk in October–December 2006 and January–March 2007 due to the meridional transport intensified in the cold period (Fig. 4). These peaks determined the increase of the annual average B_π^a values in 2006 and 2007.

The further increase of the annual average B_π^a value in 2008 was due to explosive eruptions of two northern volcanoes located in the Aleutian Islands: Okmok and Kasatochi (Table 1; Schmale et al., 2010). In the following two years, 2009–2010, there were only two eruptions of northern volcanoes with VEI = 4, namely Sarychev Peak (the Kuril Islands, 11 June 2009) and Eyjafjallajökull (Iceland, 14 April 2010). Note that the eruption plumes of Eyjafjallajökull mostly did not exceed the tropopause altitude over the volcano. This can explain a gradual decrease in stratospheric aerosol loading from 2008 to 2010 (see Fig. 1). However, a new increase in the annual average B_π^a value was observed in 2011. This increase resulted from aerosol perturbations of the northern mid-latitude stratosphere after the explosive eruptions of Merapi, Grimsvötn, and Nabro volcanoes (all VEI = 4, Table 1). In the next sections we consider contributions of plumes from the volcanoes erupted in the period IV to the SAL volcanogenic perturbations over Tomsk, and also discuss other possible sources of the SAL perturbations.

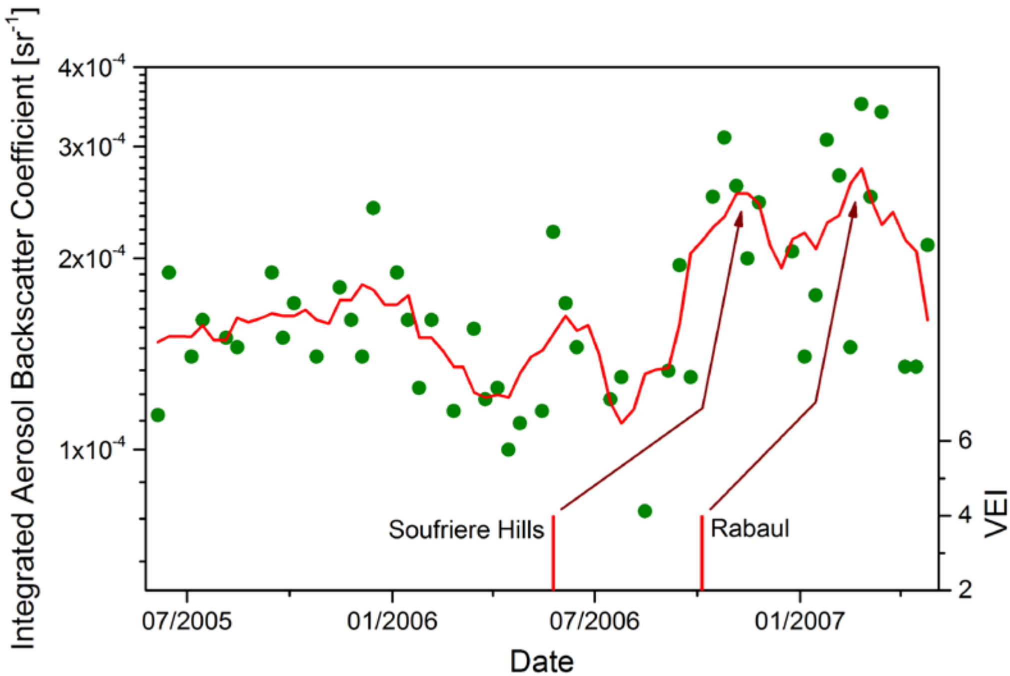


Figure 4. Two B_{π}^{a} value peaks observed in the stratosphere over Tomsk in October–December 2006 and January–March 2007 after the Soufriere Hills and Rabaul eruptions, respectively (Table 1). Solid green circles denote the 10-day average B_{π}^{a} values. The red curve denotes the B_{π}^{a} values smoothed by five-point averaging.

3.2 Detection of plumes from northern volcanoes in the stratosphere over Tomsk in 2008–2010

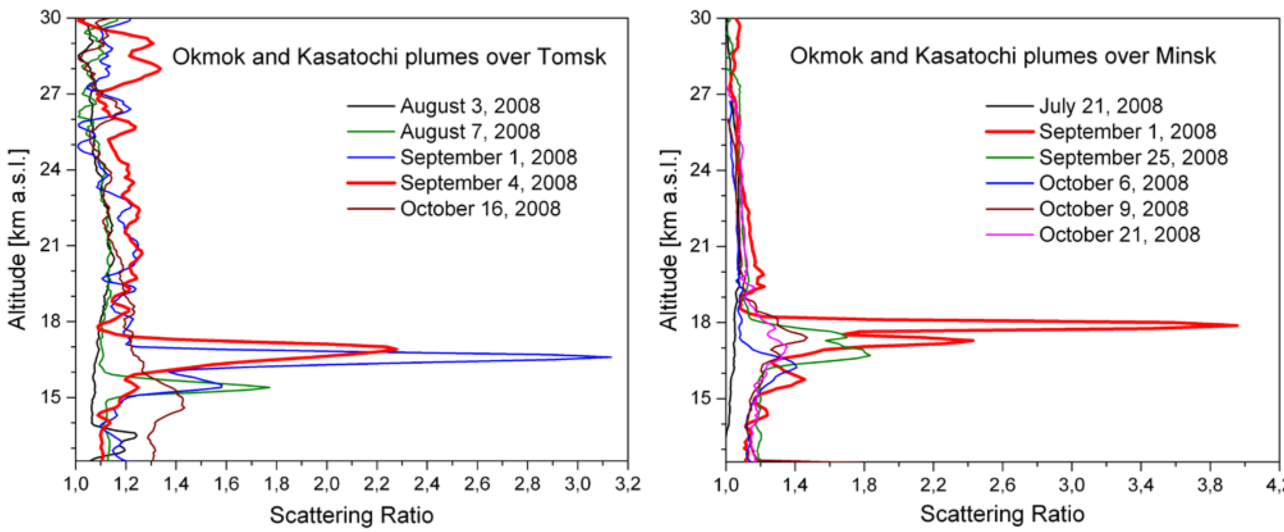
Detection of volcanic plumes over Tomsk is based on: 1) the use of the scattering ratio $R(H)$ profiles retrieved from the lidar measurements between 12.5 and 30 km and 2) the assignment of observed aerosol layers to volcanic eruptions via the HYSPLIT model trajectory analysis, when possible.

3.2.1 Okmok and Kasatochi

In summer 2008, two Aleutian volcanoes Okmok and Kasatochi started to erupt at 19:43 UTC on 12 July and between 23:00 UTC on 7 August and 05:35 UTC on 8 August, respectively (both VEI = 4). The plumes from these volcanoes considerably perturbed the SAL over Tomsk from August to October 2008. Vertical profiles of the scattering ratio $R(H)$, showing the detection of the Okmok and Kasatochi plumes over Tomsk during these months, are presented in Fig. 5a as an example. Simultaneous stratospheric aerosol observations at the Minsk CIS-LiNet station at λ = 532 nm revealed the similar SAL perturbations over Minsk from July to October (Fig. 5b; Zuev et al., 2009). The after-effects of both volcano eruptions were detected in the stratosphere over Minsk and Tomsk up to December 2008.

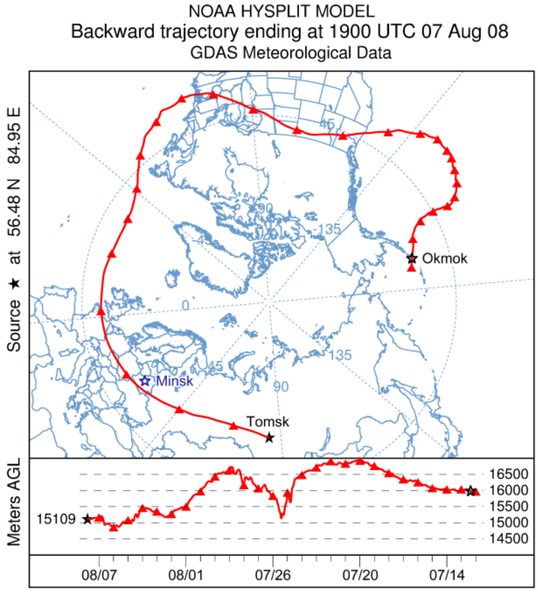
Figure 6a shows the HYSPLIT air-mass backward trajectory started from the altitude of the *R*(*H*) profile maximum (~15.1 km a.s.l.) over Tomsk on 8 August at 02:00 LT (or on 7 August at 19:00 UTC). The trajectory passed over Okmok volcano on the eruption day, 12 July, at the altitude $H^{\text{back.}}_{\text{traj.}} \approx 16.0$ km that is 1 km higher than the maximum plume altitude (MPA; Table 1) H_{MPA} determined by the GVP. Figure 6b shows the backward trajectory started from the altitude of the *R*(*H*) maximum (~16.3 km a.s.l.) over Tomsk on 2 September at 00:00 LT (1 September, 17:00 UTC). The trajectory passed over Kasatochi volcano on the eruption day, 7 August, at the altitude $H^{\text{back.}}_{\text{traj.}} \approx 16.4$ km that is 2.4 km higher than the GVP H_{MPA} (Table 1). Our conclusion (based on the HYSPLIT trajectories), that the plumes from both volcanoes reached altitudes of ≥16 km, is consistent with different satellite observation data (Yang et al., 2010; Kristiansen et al., 2010; Prata et al., 2010). The inconsistency between the HYSPLIT $H^{\text{back.}}_{\text{traj.}}$ and GVP H_{MPA} altitudes ($H^{\text{back.}}_{\text{traj.}}$ should normally be equal to or lower than H_{MPA}) is discussed in Sect. 4.

The HYSPLIT trajectory analysis also showed that both Okmok (Fig. 6a) and Kasatochi (Fig. 6b) plumes passed close to the Minsk lidar station. This explains the similarity of the *R*(*H*) profiles presented in Fig. 5. Owing to the westerly transport of air masses, the volcanic plumes passed over Minsk three days earlier than over Tomsk. Figure 6c shows the backward trajectories which allowed us to find the connection between two aerosol layers (thick red lines in Fig. 5) detected over Minsk and Tomsk on 1 and 4 September, respectively. The more general and detailed analysis of the Okmok and Kasatochi plumes influence on the SAL state was made by Zuev et al. (2009) and later, e.g., by Bourassa et al. (2010) and Andersson et al. (2015).

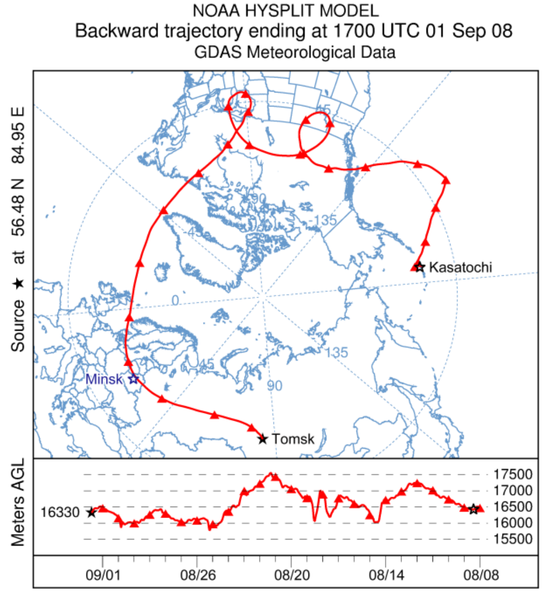


(a) **(b)**

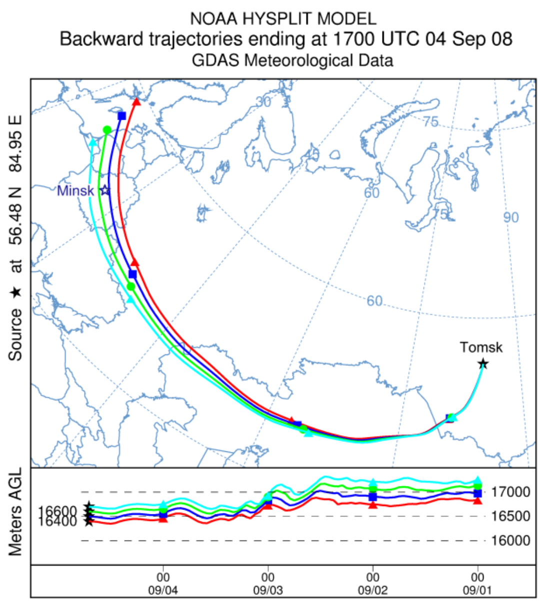
Figure 5. Detection of the Okmok and Kasatochi volcanic plumes in the stratosphere over **(a)** Tomsk (Russia) and **(b)** Minsk (Belarus). The volcanoes started to erupt in the Aleutian Islands on 12 July and 7 August 2008, respectively.



(a)



(b)



(c)

Figure 6. (a) Air-mass backward trajectory started from an altitude of ~15.1 km a.s.l. over Tomsk on 8 August 2008 at 02:00 LT (7 August, 19:00 UTC) and passed over Okmok volcano. **(b)** Air-mass backward trajectory started from an altitude of ~16.3 km a.s.l. over Tomsk on 2 September 2008 at 00:00 LT (1 September, 17:00 UTC) and passed over Kasatochi volcano. **(c)** Air-mass backward ensemble trajectories started from altitudes of 16.4–16.7 km a.s.l. over Tomsk on 5 September 2008 at 00:00 LT (4 September, 17:00 UTC) and passed close to Minsk.

It should be noted that due to the westerly zonal transport of air masses in the Northern Hemisphere lower stratosphere during summer seasons and vast geographical distance between Tomsk and the Aleutian Islands, both backward trajectories (Figs. 6a and 6b) could hardly be expected to be equal to or shorter than two weeks. Therefore, these trajectories are slightly longer than those usually used in the HYSPLIT model and, thus, can be considered only as probable ones. Nevertheless, we made the trajectory analysis to assign the observed aerosol layers to the corresponding volcanic eruptions.

3.2.2 Redoubt and Sarychev Peak

The SAL perturbations over Tomsk in 2009 were caused by the eruptions of two northern volcanoes Redoubt (Alaska, 15 March to 4 April; VEI = 3) and Sarychev Peak (the Kuril Islands, 11–16 June; VEI = 4). The Redoubt plumes caused insignificant SAL perturbations over Tomsk during the first two weeks of May 2009 (Fig. 7). Stronger and longer-lasting SAL perturbations were related to the Sarychev Peak volcano eruption. According to the GVP data, the MPA was within the range of 8–16 km or even reached 21 km (GVP, 2009). The Sarychev Peak plumes were reliably detected in the stratosphere over Tomsk during July and August (Fig. 8), and weakly observed up to November 2009. For a trajectory analysis, we considered an aerosol layer observed over Tomsk at an altitude of ~13.1 km on 7 July at 02:30 LT (6 July, 19:30 UTC). This layer is seen in Fig. 9 to be: 1) associated with the backward trajectory passed over Sarychev Peak volcano at an altitude of ~13.8 km on 15 June at the moment of the eruption, 17:30 UTC; and 2) not associated with the after-effect of the Redoubt eruption.

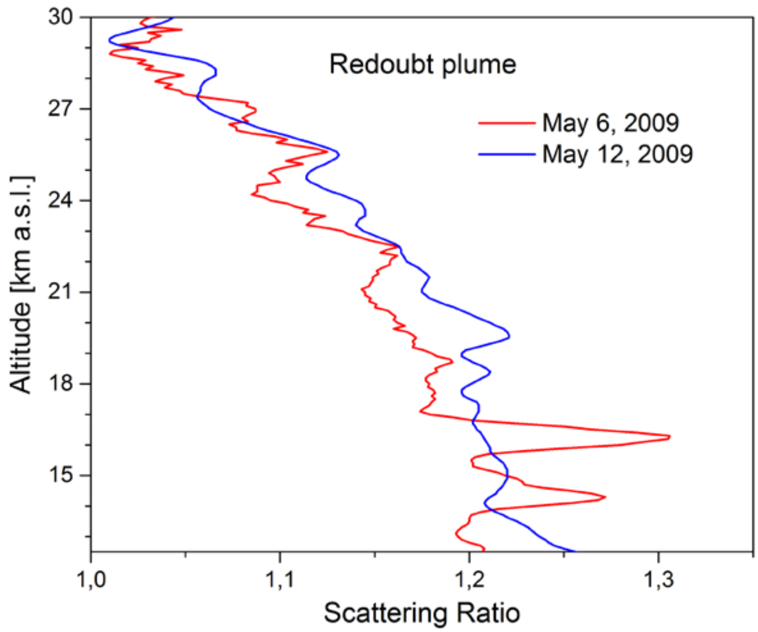


Figure 7. Detection of the Redoubt volcanic plumes in the stratosphere over Tomsk. The volcano erupted in Alaska from 15 March to 4 April 2009.

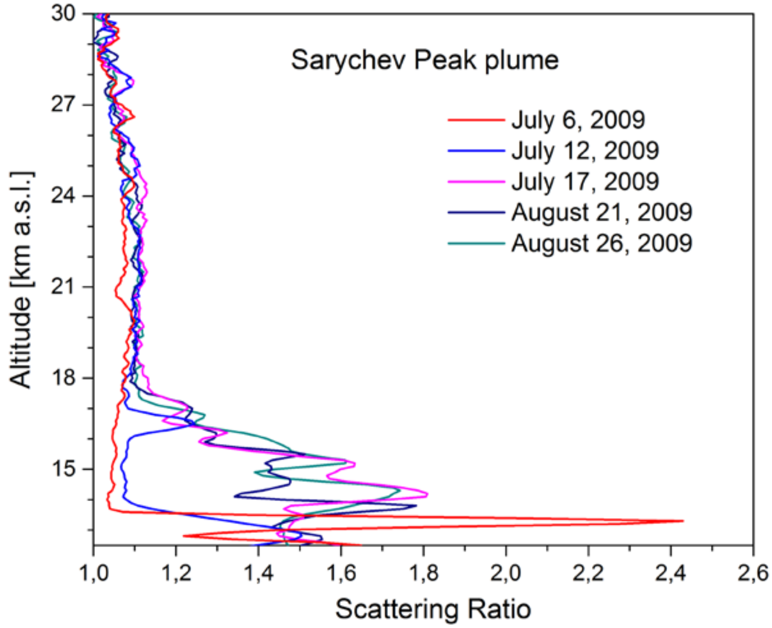


Figure 8. Detection of the Sarychev Peak volcanic plumes in the stratosphere over Tomsk. The volcano erupted in the Kuril Islands from 11 to 16 June 2009.

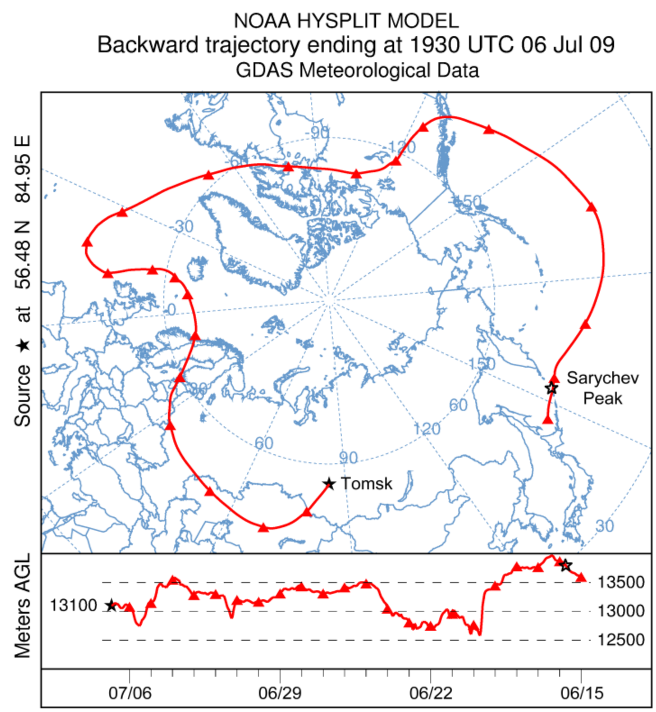


Figure 9. Air-mass backward trajectory started from an altitude of ~13.1 km a.s.l. over Tomsk on 7 July at 02:30 LT (6 July, 19:30 UTC).

3.2.3 Eyjafjallajökull

During April–May 2010, there was a series of explosive eruptions of the Icelandic volcano Eyjafjallajökull. These eruptions are noted for the subsequent extensive air travel disruption across large parts of Western Europe. According to the GVP data, the MPA occasionally reached 9 km (GVP, 2010), but did not exceed the local tropopause (GVP, 2010). However, lidar observations, performed in Tomsk on 20 and 26 April 2010, detected the presence of aerosol layers in the troposphere and lower stratosphere at altitudes up to 15 km (Fig. 10). As a comparison, aerosol lidar measurements at Garmisch-Partenkirchen revealed that the upper boundary of the observed aerosol layers from the Eyjafjallajökull volcanic plumes was ~14.3 km on 20 April, whereas the average altitude of the local tropopause was of ~10.2 km (Trickl et al., 2013).

Figure 11 shows the HYSPLIT air-mass backward ensemble trajectories started from altitudes of the detected aerosol layers (~11.1–14.6 km a.s.l.) over Tomsk on 21 April at 00:00 LT (20 April, 17:00 UTC). Only one trajectory (started from an altitude of ~11.6 km) directly passed over Eyjafjallajökull volcano on one of the eruption days, 16 April at 13:00 UTC, at the altitude $H_{\text{traj.}}^{\text{back.}} \approx 10.7$ km that is clearly higher than $H_{\text{MPA}} \leq 9$ km. The inconsistency between the HYSPLIT $H_{\text{traj.}}^{\text{back.}}$ and GVP H_{MPA} altitudes is discussed in Sect. 4. The other trajectories passed south of the volcano. Note also that, according to the Icelandic meteorological station Keflavik, the local tropopause altitude went down to ~7 km on 16 April after 12:00 UTC (Trickl et al., 2013). Hence, the Eyjafjallajökull volcanic plumes reached altitudes of 8–9 km on that day and directly entered the local lower stratosphere.

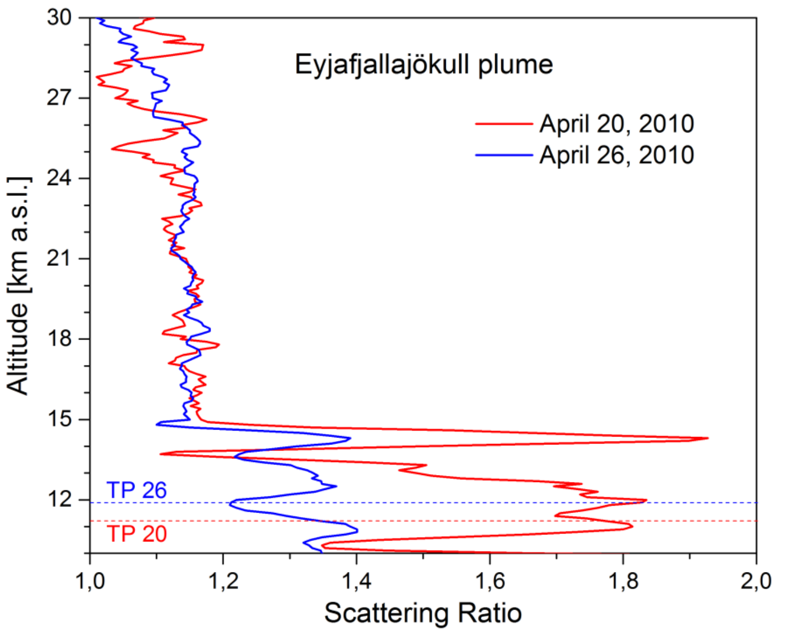


Figure 10. Detection of the Eyjafjallajökull volcanic plumes in the upper troposphere and lower stratosphere over Tomsk. The volcano erupted in Iceland from 14 to 17 April 2010. The tropopause altitude over Tomsk was of 11.2 km on 20 April and 11.9 km on 26 April.

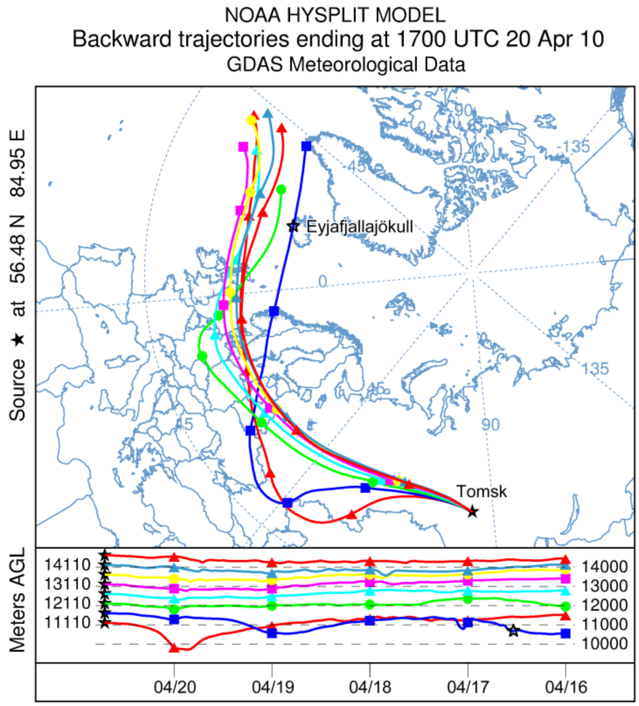


Figure 11. Air-mass backward ensemble trajectories started from altitudes of ~11.1–14.6 km a.s.l. over Tomsk on 21 April 2010 at 00:00 LT (20 April, 17:00 UTC) and passed over or south of Eyjafjallajökull volcano.

3.3 Detection of volcanic plumes in the stratosphere over Tomsk in 2011

High values of B_π^a were detected during the SAL lidar observations in Tomsk from February to April and from August to December 2011. The "first" wave of the SAL perturbations in the winter-spring period was caused by the Merapi volcano eruption (Indonesia, 4–5 November 2010; VEI = 4), whereas the "second" wave was due to the eruptions of the northern volcano Grimsvötn (Iceland, 21 May 2011; VEI = 4) and the tropical volcano Nabro (Eritrea, 13 June 2011; VEI = 4).

3.3.1 Merapi

High values of B_π^a were detected in the stratosphere over Tomsk from February to April 2011, i.e. 3–5 months after the Merapi volcano eruption. Figure 12 presents the observed after-effect of the Merapi eruption, i.e. several perturbed scattering ratio profiles retrieved from the SLS aerosol lidar measurements between 28 February and 18 April 2011. The Merapi plume (Table 1) supplied the stratospheric tropical reservoir with long-lived volcanic aerosol. The SAL perturbations, reflected by increased B_π^a and $R(H)$ values during the winter and spring of 2011, were due to the meridional air mass transport from the tropics into northern mid-latitudes in this cold period (see Sect. 3.1).

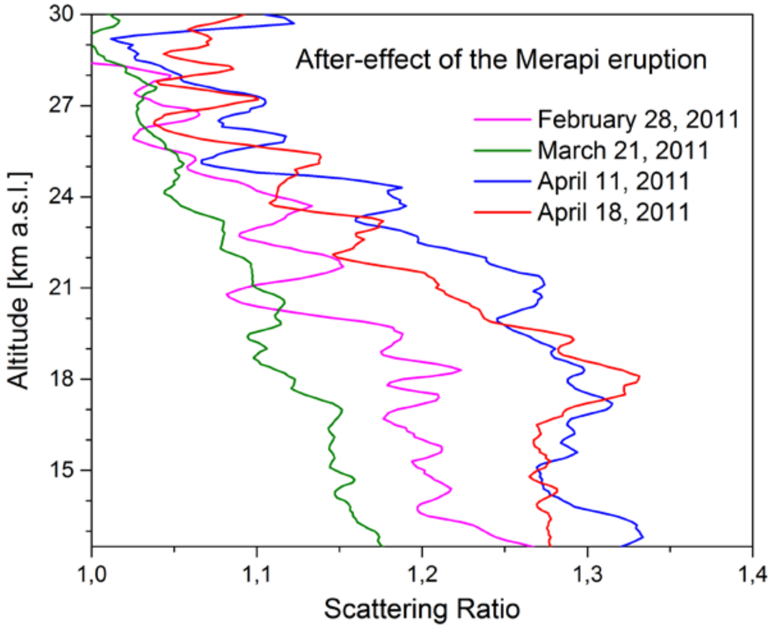


Figure 12. Perturbed scattering ratio profiles retrieved from the SLS aerosol lidar measurements in the winter-spring period of 2011.

3.3.2 Grimsvötn and Nabro

In 2011, two volcanoes with VEI = 4 Grimsvötn and Nabro started to erupt on 21 May at 19:25 UTC and 13 June after 22:00 UTC, respectively. According to the GVP data, Grimsvötn volcano erupted ash clouds and gases directly into the stratosphere at an altitude of 20 km, whereas the Nabro volcanic plume did not exceed the local tropopause altitude. Bourassa et al. (2012) showed that a considerable part of the Nabro volcanic aerosol and gases, erupted into the upper troposphere, was able to enter the mid-latitude stratosphere due to deep convection and vertical air transport associated with the strong Asian summer monsoon anticyclone. On the other hand, Vernier et al. (2013), Fromm et al. (2013), Fairlie et al. (2014), Clarisse et al. (2014), and Penning de Vries et al. (2014) showed that the initial Nabro plume was directly injected into the lower stratosphere at altitudes up to 18 km (Fromm eat al., 2014). The SAL perturbations by volcanogenic aerosol after the eruptions of both volcanoes were observed in the lower stratosphere over Tomsk from August to November 2011 (Fig. 13). All the scattering ratio profiles shown in Fig. 13, with equal probability, represent superpositions of plumes from both Grimsvötn and Nabro volcanoes.

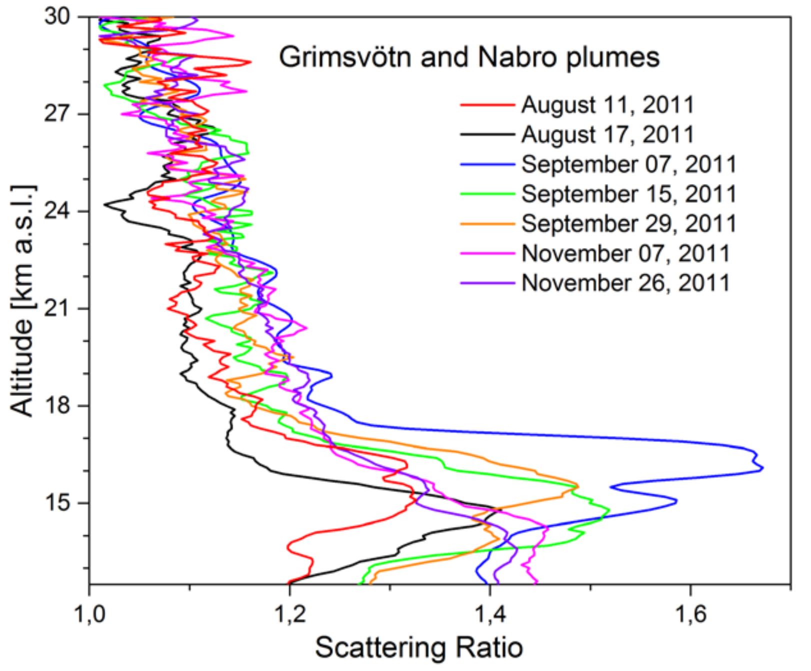


Figure 13. Detection of the Grimsvötn (Iceland) and Nabro (Eritrea) volcanic plumes in the stratosphere over Tomsk. The volcanoes started to erupt on 21 May and 13 June 2011, respectively.

3.4 Polar stratospheric clouds and the after-effect of the 2006 Rabaul eruption

Occasional perturbations of the mid-latitude SAL can also be related to the occurrence of polar stratospheric clouds (PSCs) in winter periods. PSCs are known to form at extremely low temperatures (lower than –78 °C) mainly on sulfuric acid (H_2SO_4) aerosols, acting as condensation nuclei and formed from sulfur dioxide (SO_2; Finlayson-Pitts and Pitts, 2000). Therefore, injections of volcanogenic H_2SO_4 aerosols or/and SO_2 into the stratosphere can lead to PSC formation, if the air temperature < –78 °C. The direct positive correlation between PSC formation and volcanogenic nitric and sulfur acid aerosols loading was shown, e.g., by Rose et al. (2006). However, it should be noted that, in contrast to Rose et al. (2006), Fromm et al. (2003) showed little (or even negative) correlation between PSC events and ambient aerosol loading.

The Northern Hemisphere stratosphere is usually cooled to the required low temperatures inside the Arctic stratospheric polar vortex in cold seasons (Newman, 2010). The Arctic polar vortex sometimes deforms and stretches to mid-latitudes including Siberian regions. Hence, the stratospheric temperature over Tomsk can occasionally be cooled lower than –78 °C, when Tomsk is inside the polar vortex. Thus, the detection of aerosol layers in the stratosphere at extremely low temperatures can be indicative of the presence of PSCs.

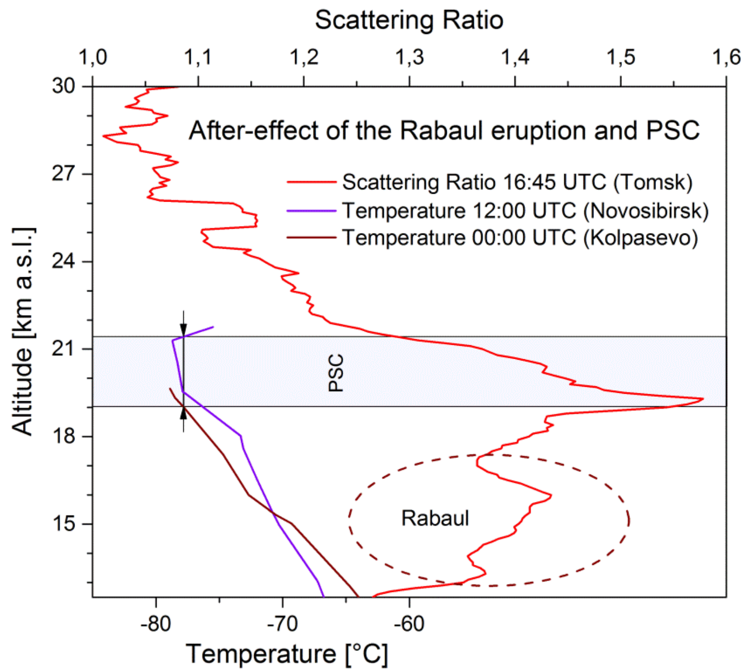


Figure 14. Detection of PSCs formed at extremely low temperatures (< –78 °C) in the stratosphere over Tomsk. Temperature profiles were obtained from radiosondes launched on 27 January 2007 in Kolpashevo (station 29231) at 00:00 UTC and in Novosibirsk (station 29634) at 12:00 UTC (WWW, 2007). The dashed ellipse denotes the after-effect of the Rabaul volcanic eruption occurred in Papua New Guinea on 7 October 2006.

The first lidar PSC observations over Tomsk were made at λ = 1064 nm in January 1995 (Zuev and Smirnov, 1997). More precisely, some dense aerosol layers were detected at altitudes in the range of 15 to 19 km on 24 and 26 January. The maximum scattering ratio $R(H)$ was more than 14 at an altitude of 18.1 km. The stratospheric temperature was lower than –80 °C. The cold pool presence and PSC events near the Tomsk longitude during the northern winter of 1994/95 were also reported by Fromm et al. (1999). The formation of these dense PSCs was caused by high concentrations of residual post-Pinatubo aerosols.

Another event of PSCs over Tomsk was observed at λ = 532 nm on 27 January 2007 (Fig. 14). As seen in Fig. 14, the maximum scattering ratio $R(H)$ was more than 1.55 at an altitude of 19.3 km. According to the data of the two nearest to Tomsk meteorological stations, launching radiosondes twice a day and situated in Novosibirsk (55.02° N, 82.92° E) and Kolpashevo (58.32° N, 82.92° E), the stratospheric temperature was lower than –78 °C at altitudes between 19 and 21.5 km (WWW, 2007) during the lidar measurements. High $R(H)$ values at altitudes in the range of 13 to 17 km were probably due to the winter aerosol supplying of the SAL from the stratospheric tropical aerosol reservoir enriched by the 2006 Rabaul eruption plume (Table 1, Fig. 14). Thus, PSCs were detected at least twice (in 1995 and 2007) during 30 years of stratospheric aerosol lidar measurements in Tomsk.

3.5 The latest SAL perturbations over Tomsk (2012–2015)

In summer 2011, the annual average B_π^a value started to decrease and the SAL state over Tomsk started to relax to its background one (Fig. 1). However, a marked increase in B_π^a value was observed in the winter of 2015. Figure 15 shows several perturbed scattering ratio profiles retrieved from the SLS aerosol lidar measurements between 29 January and 30 March, 2015. During that period of time, the Kelut volcano eruption could probably be a source of the SAL perturbations over Tomsk.

An explosive eruption of the tropical volcano Kelut occurred in East Java, Indonesia, on 13 February 2014 (Table 1). The MPA H_{MPA} value for this eruption was initially estimated by both ground and space monitoring systems to be ~17 km. On the other hand, according to the data from the space-borne lidar CALIOP (Cloud-Aerosol LIdar with Orthogonal Polarization) onboard the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) satellite (http://www.nasa.gov/mission_pages/calipso/main/index.html), a rapidly rising portion of the Kelut plume ejected material up to an altitude exceeding ~26 km, i.e. directly into the tropical stratosphere. Most of the less rapidly rising plume portions remained lower, at altitudes of 19–20 km (GVP, 2014). The Kelut plume passed over the Indian Ocean to the West, toward the African continent, with a small deviation to the South. Sandhya et al. (2015) showed that a part of this plume could turn back and pass over the South end of Hindustan. Thus, the Kelut plume enriched the stratospheric tropical aerosol reservoir at least over the Indian Ocean. This led to the increasing annual average B_π^a value in the northern mid-latitudes, including Tomsk, in 2015 (Fig. 1) due to the meridional aerosol transport.

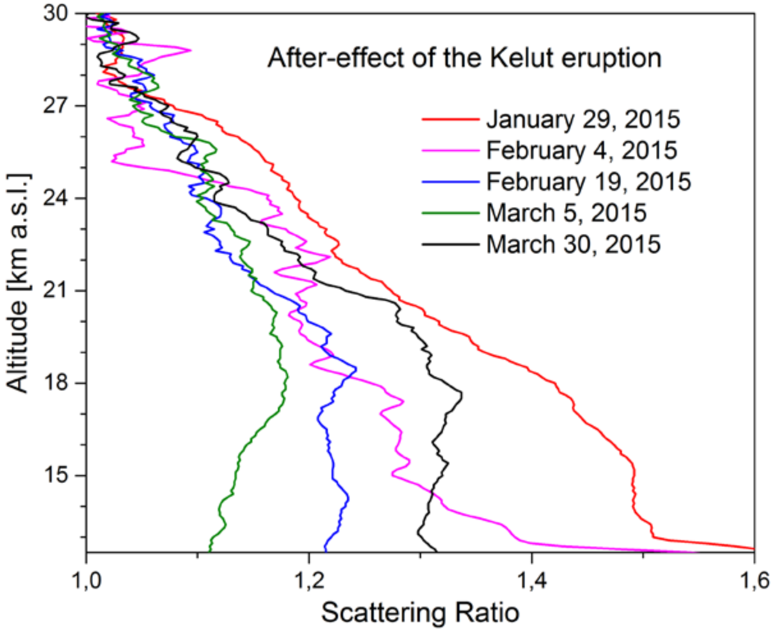


Figure 15. Perturbed scattering ratio profiles retrieved from the SLS aerosol lidar measurements between 29 January and 30 March 2015.

4 Discussion and conclusion

Thirty years (1986–2015) of lidar monitoring of the SAL state over Tomsk definitely showed that explosive eruptions with VEI ≥ 3 of both tropical and extratropical (northern) volcanoes represent the main cause of the northern mid-latitude SAL perturbations. Moreover, the tropical volcanoes, rather than the northern ones, have a dominant role in volcanogenic aerosol loading of the mid-latitude stratosphere. Indeed, major explosive eruptions of tropical volcanoes are able to enrich the stratospheric tropical reservoir with volcanogenic aerosol. Additional aerosol loading of the tropical reservoir can usually lead to an increase in the annual average B_{π}^{a} value in the Northern Hemisphere mid-latitude stratosphere via the meridional transport in the cold seasons (October to March; Hitchman et al., 1994). For example, plumes from both Merapi and Kelut volcanoes additionally supplied the stratospheric tropical reservoir with volcanic aerosol and gases (Table 1). As a result, the increased annual average B_{π}^{a} values (i.e. the SAL perturbations) were detected over Tomsk in 2011 and 2015, respectively (see Sects. 3.3.1 and 3.5). On the other hand, by contrast to tropical volcanoes, the narrow volcanic gas, aerosol, and ash plumes from northern volcanoes can either pass over a lidar station or pass it by. Owing to this, a certain part of northern volcanoes eruptions into the stratosphere did not perturb the SAL over Tomsk and, therefore, was not detected there. It is clear that an extensive network of lidar stations in the territory of the Russian Federation is required to obtain objective data on the mid-latitude stratospheric aerosol loading.

In cases of the Eyjafjallajökull and probably Okmok and Kasatochi eruptions, the HYSPLIT air-mass backward trajectories, started from the altitudes of aerosol layers detected over Tomsk with the SLS aerosol lidar, passed over these volcanoes at altitudes $H_{\text{traj.}}^{\text{back.}}$ higher than their GVP MPAs (Sects. 3.2.1 and 3.2.3). On the other hand, the initial value H_{MPA} for the Kelut volcano eruption was determined as about 17 km, but the measurements, made by the CALIOP space-borne lidar onboard the CALIPSO satellite, clearly revealed that the rapidly rising portion of the Kelut plume reached an altitude of ~26 km that is 9 km higher than H_{MPA} (GVP, 2014; Sect. 3.5). Based on these facts, we can offer the following explanation of the inconsistencies between the altitudes $H_{\text{traj.}}^{\text{back.}}$ and H_{MPA}. During Plinian explosive eruptions, solid and liquid ejecta, ash, and gas-vapor emissions intermix with each other, heat, and ascend inside the “convective thrust region” of an eruption column. Then the heated air together with erupted materials is known to expand, cool, and form the “umbrella region” of the eruption column (Woods, 1988; Scase, 2009). The most heated fraction of gas-vapor emissions from the “convective thrust region” has the highest speed and, therefore, can penetrate through the higher-density “umbrella region” of the eruption column and reach altitudes higher than H_{MPA} due to the cumulative (jet) effect (Raible et al., 2016). The secondary atmospheric H_2SO_4 aerosols are formed via oxidation of SO_2 contained in volcanic gas-vapor emissions. The currently available visual and radar methods for determining volcanic plume altitudes can detect only the large-sized volcanic ash particles. At the same time, these methods are not sensitive to the small-sized atmospheric H_2SO_4 aerosols. Nevertheless, the submicron H_2SO_4 aerosol particles can be easily detected by lidars.

In addition to volcanoes, PSCs also represent a cause of significant SAL perturbations. However, the temperature condition required for PSC formation (air temperature should be < –78 °C) rarely holds in the mid-latitude stratosphere. Only two PSC events in January 1995 and January 2007 were observed over Tomsk during the 30-year period of lidar observations in Tomsk.

Extensive forest (bush) fires could be another cause of occasional increases of the B_π^a value. Combustion products (gases and aerosol particles) can reach the stratospheric altitudes via convective ascent within pyro-cumulonimbus (pyroCb) clouds (see, e.g., Fromm et al., 2006). For example, the smoke plumes from the strong bush fire, occurred near the Australian city of Melbourne on 7 February 2009, were observed in the local stratosphere at an altitude of ~18 km (Siddaway and Petelina, 2011). Due to the climate warming, the number and intensity of massive forest fires have considerably increased in the last few years (Wotton et al., 2010). For example, about 137 strong forest fires were registered in the Northwest Territories of Canada in July 2014 (CBC News, 2014). The smoke-filled air masses frequently enter the stratosphere over the South of Western Siberia from North America, where extensive forest fires occur. Their smoke plumes are most likely to be detected as the SAL perturbations over Tomsk. However, more detailed information about the pyroCb events is required for their correct identification. It is quite possible that some after-effects of strong forest fires occurred, e.g., in North America could be detected over Tomsk, but not identified during lidar observations in Tomsk (1986–2015).

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