

Interactive comment on “Monitoring presence and streaming patterns of Icelandic volcanic ash during its arrival to Slovenia” by F. Gao et al.

F. Gao et al.

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The authors wish to thank the reviewer for extensive and valuable comments and suggestions, which were very helpful for improving the manuscript.

Comment on the Abstract: in the last sentence the authors gives the impression that the performed trajectories simulations are done by a local model, but in the 5th paragraph seem clear that this is not case: please clarify.

Response: We have changed the last sentence of the abstract into “We analyzed airflow trajectories using ECMWF model and HYSPLIT model to explain the history of the air masses bringing volcanic ash to Slovenia”.

Comment on 1. Introduction: in the last sentence: the same comment in Abstract.

Response: We have changed the last sentence of the introduction into “In this paper, we present the results of the measuring campaign, including the modeling of air-mass trajectories reaching Slovenia, using the ECMWF and HYSPLIT models.”

Comments on 2. Synoptic situation: 2.1 – Row 3, p.3866: Why from 15 April if the explosive eruption starts on 14?

Response: This is a typo, as we actually do describe the synoptic situation from 14 April on (see page 3866, line 8). We have changed the dates in the first sentence on page 3866 into “... will be focused on the days from 14 April to 20 April 2010.”

2.2 – Row 13-15, p.3866: The precise timing isn't very clear, i.e. if the arrival of the ash is between 16-17 or 17-18 April, perhaps a satellite image will be helpful.

Response: The initial precipitation in Ljubljana occurred on 17 April 2010, at 01:00 UTC. Analysis of the precipitation sample showed the presence of volcanic ash. In addition, satellite images (Meteosat 8 satellite) show the arrival of volcanic ash to Slovenia between 00:00 UTC and 06:00 UTC. The corresponding satellite images with marked ash belt are attached as Fig.1. Based on this, the text has been modified accordingly: “Based on Meteosat 8 satellite images (Meteosat Data, 2010), air masses containing volcanic ash reached the air space over Slovenia between 00:00-06:00 UTC on 17 April 2010.”

2.3 – Row 18-19, p.3866: again it's important to clarify when the precipitation occur also with the hour detail.

Response: The precipitations in Ljubljana occurred on 17 April 2010, at 01:00-02:30 UTC and on 18 April at 07:00-11:30 UTC. Analysis of the precipitation samples showed the presence of volcanic ash. The text (page 3866, row 18-19) was modified correspondingly into “On 17 April there was a local shower at Ljubljana from 01:00-02:30 UTC. Moreover, a shallow low-pressure center formed over Northern Italy and moved towards Slovenia, resulting in precipitations on 18 April 2010; at 03:20-08:20 at Nova

[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)[Discussion Paper](#)

Gorica and 07:00-11:30 UTC at Ljubljana.”

Comments on 3.1 Ground based measurements

3.1.1 – Row 21, p.3867: The PM10 measurements are performed at two different altitude but there is no evidence in the text or graphs on how and if these are combined and why. The information of the positioning of the instrument (urban area, etc...) is also omitted.

Response: There is a typo in this sentence. The measurements were performed at two different heights (1.5 m and 4.0 m above the ground). We have also modified the PM10 graph in Fig.2 (left, attached) accordingly to show both measurements. The corresponding text was changed into “Concentration of PM10 particles was continuously monitored at two different heights (1.5 m and 4.0 m above the ground) using a tampered element oscillating micro-balance.” All ground measurements including PM10, SO2 and precipitations were performed at the same site, which is located within the Ljubljana city (urban area with possible influence of traffic and heating).

3.1.2 – Row 25, p. 3867: The authors evidence an increasing value of PM10 since the 16 April, a data which is pre-ash plume and also few ashes should be present at ground level before the rain event.

Response: As explained in the answer to the question 2.2, satellite image evidenced the initial arrival of volcanic ash to Slovenia on 17 April 2010 around 00:00 UTC (Fig.1 in attachment to this reply). Due to the location of the monitoring station in urban area, the PM10 concentration on 16 April may be attributed to local particles, and was not a result of the presence of volcanic ash. In our case, the concentrations of PM10 and SO2 never significantly exceeded the average value (Fig.2 in the attachment) and was used only to show the extent of the environmental impact of the presence of volcanic ash.

3.1.3 – Row 7, p. 3867: The Nova Gorica data are not presented: why?

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8, C1872–C1892, 2011

Interactive
Comment

Full Screen / Esc

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Discussion Paper



Response: Sorry for the mistake. Actually, the weather station in Nova Gorica (operated by Slovenian Environmental Agency), which performed the measurements of SO₂ concentration from 2003 to 2009 was discontinued in 2010, as in the last 5 years SO₂ concentrations were continuously found to be below the lower assessment threshold. We have modified the text accordingly (deleted “not only in Ljubljana, but also in Nova Gorica”).

3.14 – Row 8, p. 3867: The increment in SO₂ start from 11 April so can be hardly attributed to the ashes.

Response: As explained in the answers to the questions 3.1.1 and 3.1.2, SO₂ measurements were performed in Ljubljana city (urban area with possible influence of traffic and heating). The increased SO₂ concentration (which is still below average, see Fig.2 (right) in the attachment) may be attributed to local effects. The purpose of the SO₂ monitoring was to detect eventual major environmental impact of the volcanic ash.

3.15 – Figure 2: Because routinely measured, some sort of average lines would have been helpful: see Flentje et al. (Atmos. Chem. Phys., 10, 10085-10092, 2010) for example.

Response: We have modified the plots accordingly (see Fig.2 in attachment).

3.16 – Figure 3: Some sort of magnification should be employed in order to better show F- bars

Response: We have modified the plots accordingly (see Fig.3 in attachment).

3.17 – Also following the authors statements about typical local concentrations, the measurements of PM₁₀ and SO₂ seems inconclusive and not very useful for the purpose detection and monitoring the ashes over Slovenia.

Response: As explained in the answers to the questions 3.1.1, 3.1.2 and 3.14, the concentrations of PM₁₀ and SO₂ never significantly exceeded the average value (Fig.2 in the attachment) and were used only to show the extent of the environmental impact

of the presence of volcanic ash (which was found to be negligible). We fully agree that the figures in the original manuscript were lacking the average concentration values and were modified accordingly. The text was also changed to make this point clear.

3.18 – The latter part of ground based measurements, involving composition analysis, it's more convincing in order to confirm and monitor the presence of the ash cloud over Slovenia, but the actual timings are not clearly in the synoptic situation: seems that the rain events starts likes the 18, but in this case the F- presence in 17 April data it's unclear.

Response: As explained in the answer to question 2.3, the precipitations in Ljubljana occurred on 17 April 2010, at 01:00-02:30 UTC and on 18 April at 07:00-11:30 UTC. Analysis of the precipitation samples showed the presence of volcanic ash. The text (page 3866, row 18-19) was modified correspondingly into “On 17 April there was a local shower at Ljubljana from 01:00-02:30 UTC. Moreover, a shallow low-pressure center formed over Northern Italy and moved towards Slovenia, resulting in precipitations on 18 April 2010; at 03:20-08:20 at Nova Gorica and 07:00-11:30 UTC at Ljubljana.”

Comments on 3.2 Lidar-based remote sensing 3.2.1 – Lidar measurements are performed by systems that should have scanning capabilities, but seems that during this campaign both are used as zenith pointing backscatter lidar. In literature you will find that backscatter is the main optical variable that generally can be extracted from signals with lidars in this configuration: all analysis and considerations should be done using this parameter, not the extinction.

Response: Both lidar systems have scanning capability and are generally used for scanning. However, as the step motor of Otlica lidar system was at the time of the campaign broken by lightning (it was fixed shortly after the campaign measurement of volcanic ash) and the Nova Gorica lidar system had at the time limited scanning sight, no scanning was performed, and we have unfortunately missed the opportunity to obtain 2D RHI scans of volcanic ash streaming over Slovenia. Based on your

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comments, we have redone all the lidar analysis and are now using the backscatter coefficient to describe the variation of the atmospheric conditions (see the attached Fig.4). To avoid cumulative plots, we presented the backscatter coefficient profiles for four different time intervals (10:10-11:10, 15:20-17:50 and 19:40-22:50 CET for Nova Gorica lidar and 20:00 – 23:55 CET for Otlica lidar), where the full black line denotes the mean backscatter coefficient for and the shaded area the the uncertainties of the measurement. The revised manuscript reflects these changes.

3.2.2 – For the inversion procedure the Klett method is adopted but it's not clear if the single component solution or the two component solution (Fernald) which seems more appropriate especially for 355 nm.

Response: We fully agree with your comments. The Fernald method for retrieving backscatter or extinction coefficient takes into account the contributions of aerosol and molecular scattering separately, while the Klett method does not, and would seem more appropriate for 355 nm. However, based on our experience with the two methods, we know that the inversion results of Klett and Fernald method differ to some extent, so, in order to make the retrievals at 1064 nm and 355 nm comparable, the same inversion procedure was adopted. In both cases the molecular component was subtracted after the inversion procedure by assuming its behavior according to the US standard atmosphere model.

3.2.3 – Even if the used lidar ratio came from measurement of aerosols with the same origin (Ansmann, 2010), these have been done hundreds kilometer away, before the Alps and only a couple of days after the main explosive event.

Response: Thank you for your comment. Lidar ratio, needed for the retrieval of optical variables using zenith pointing backscatter lidar, can only be obtained using a Raman lidar or high spectral resolution lidar [Ansmann, 1992; Imaki, 2005], which we do not have, but was available in Germany, and was used to measure the properties of air masses carrying the same volcanic ash that eventually reached Slovenia. In order to

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be able to retrieve the optical variables, we made the assumption for the lidar ratio based on the EARLINET measurement result (55 sr), which is our best estimate. We fully agree that the lidar ratio priorly obtained in Germany can not be adopted as a high precision value, therefore, an error of ± 5 (10%) was set and the uncertainty was taken into account in the calculation of optical variables.

3.2.4 – The cited paper also claim the presence of a considerable amount of large and very large particles in the measured layer, but these particles shouldn't be efficiently present six days after the explosion. In that respect, the difference from the measurements reported in the cited paper can be seen directly: Ansmann find low dependence on lambda values for the optical parameters (AE), but the author's data would exhibits (more or less) a color ratio not far from 1, for any reasonable choice of lidar ratio values.

Response: We thank the reviewer for this observation. We fully agree that in general, the majority of large particles deposits on the ground in a few days after the emission into upper troposphere and that this could have influenced different dependence between wavelengths and optical parameters in the two measurement campaigns (Germany and Slovenia).

3.2.5 – The presence of turbulence (Row 20-21, p.3870), especially in the low level layer, should have also caused the mixing with local aerosols.

Response: We fully agree with your comment. We have modified the manuscript to clarify this.

3.2.6 – Because the small signature of molecular scattering in 1064nm signal, a time series (although not very extended) of the range corrected signal (RCS), would clearly show the presence and evolution of the ash layer (with a proper cloud screening).

Response: The time series of RCS of the Nova Gorica lidar, 1064 nm (for the night of 20 April 2010) is attached as Fig.5. Two elevated aerosol layers can be clearly seen from the THI diagram.

[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)[Discussion Paper](#)

3.2.7 – Figures with lidar vertical profiles, shouldn't contain data before the complete overlap and so those have to be modified accordingly. In that respect, the lower aerosol layer can't be visualized in Otlica because the first useful altitude will be around 2km a.s.l.

Response: We fully agree that the Otlica data below 2 km a.s.l. is not credible for the description of the accurate information of the ash layer due to partial overlap, however, we believe it can still be used as a qualitative indicator of the presence of ash layer at this height. We have clarified this in the "Discussion and conclusions" section of the revised manuscript and modified the attached Fig.4 accordingly (BS values for Otlica below 2 km a.s.l. are omitted), as well as the attached Fig.6 showing the peak positions of the aerosol layers.

3.2.8 – Figure 4 and 6: Both should evidence the reference value zone used for inversion: for example for 355 nm at the end-altitude, the extinction value is 0.1 km⁻¹, so probably extinction will reach a background value at an altitude higher than that. The ever growing x-axis isn't the best solution to clearly present data and should be avoided.

Response: Based on your comments, we have redone all the lidar analysis and are now using the backscatter coefficient to describe the variation of the atmospheric conditions (see the attached Fig.4). To avoid cumulative plots (ever growing x axis), we presented the backscatter coefficient profiles for four different time intervals (10:10-11:10, 15:20-17:50 and 19:40-22:50 CET for Nova Gorica lidar and 20:00 – 23:55 CET for Otlica lidar), where the full black line denotes the mean backscatter coefficient for and the shaded area the the uncertainties of the measurement. The height of the reference zone for Klett inversion was about 5-6 km above sea level for both Nova Gorica and Otlica (the height where just pure molecular attenuation took place was used) and will be denoted in the figure caption of the revised manuscript.

3.2.9 – No information is given about the range resolution and molecular data used of

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both lidars.

Response: The range resolution of the Licel TR TR-40-160 transient recorder used in both cases is 3.75 meters. In our case, we merged 3 consecutive bins to improve the signal to noise ratio, which resulted in the range resolution of 11.25 m. The molecular contribution (assuming the US standard atmosphere model) was subtracted after the Klett inversion. We have clarified these issues in the revised manuscript.

3.2.10 – Uncertainties in data reflects the lidar ratio variation only: are you sure that this is the dominant one? What about the magnitude of statistical errors and other systematic errors?

Response: As each of our lidar profiles is an average result of 6000 laser shots (the variance of the trace within the maximum detectable range is below the percent level), we believe that the 10% uncertainty in the LR is the dominant source of uncertainties. Other systematic errors of the system were not taken into account.

3.2.11 – Considerations and related figures about both lidar data peaks, appears to be not very useful to the discussion because the evolution of the layer is enough evidenced by vertical profiles (and time series of RCS, if inserted).

Response: We agree with the reviewer's suggestion. We have inserted the THI plot of the RCS (attached Fig.5) in the manuscript and omitted the mentioned discussion part.

Comments on 3.3 Airborne measurement 3.3.1 – The 3016 IAQ seems not specifically designed for airborne operation (IAQ stand for Indoor Air Quality) and the instrument datasheet report that aerosol mass concentration (AMC) can only measure approximately: are you sure that in the ash layer can be correctly sampled with this instrument at aircraft speed. PTU operational conditions and for this kind of aerosol?

Response: Although the 3016 IAQ is not specifically designed for airborne operation, it is a high accuracy instrument widely used for measuring particle concentration in the air. The device is widely used to monitor environment as specified in the US Federal

Full Screen / Esc

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Interactive Discussion

Discussion Paper



Standard 209E and ISO 14644-1 and its measurement range is from 10 particles of 0.1 micron size per cubic meter to 35.2×10^6 particles of 0.5 micron size per cubic meter. Mass concentration mode of the device meets the standards for EPA particulate matter. The air intake pump allows an accurate flow measurements. In our configuration, the outer air collected at the intake on the aircraft wing was conducted into an expansion box, where it was strongly decelerated to make the measurements with 3016 IAQ possible. We verified that the flux of air at the intake tube was high enough to avoid deposition in the box where the air was constantly in a turbulent state (no deposition of particles was found). We have previous experience with this setup from successful airborne sampling of particle matter from cast iron furnaces and power plants. Based on the past experience with the instrument, we also believe the adopted vertical sampling interval and the ascent/descent speed of 2.5m/s guarantees the detection of the ash layer, should one exist.

3.3.2 – How about the hypothesis on particle density to determine the AMC? Probably only particles number density should be shown and commented?

Response: 3016 IAQ operation is based on Fraunhofer scattering, which can not measure AMC directly, but it can measure the number of particles per volume for any given aerodynamic equivalent diameter (particle density). In order to determine the AMC, we adopted the following assumptions: 1. particle shape was taken to be spherical, 2. constant density of the solid matter (of which the particles are made) was assumed and in our case set to 2500 kg/m^3 . We modified the manuscript to explain this.

3.3.3 – In general in order to have a reliable and effective quantitative analysis, dedicated instruments and peculiar analysis are employed for airborne measurements: see for example Schumann et al., Atmos. Chem. Phys., 11, 2245-2279, 2011.

Response: We fully agree with your comment. However, in this case we did not have such dedicated devices as you refer to, and, as the volcanic eruption was an unforeseen and unique event, we used the instruments we had at hand. For this purpose,

[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)[Discussion Paper](#)

the air intake part including the expansion box (see answer to question 3.3.1) was designed and tested by INOGS, Trieste.

3.3.4 – Could you give more information on adhesive tape used? It's a special one? It appears a non conventional one to me: usually some kind of filters are employed.

Response: The adhesive tape we used was a standard double sided tape, and we employed no filters. The adhesive tape pads (exposed to unfiltered stream of outer air, which was divided into two branches before the expansion box) were used with the purpose to sample air layers - collect aerosols for subsequent chemical and petrographic analysis, while the mass concentration profile was measured by 3016 IAQ.

3.3.5 – Row 17-18, p.3872: “Every 300m...”: unclear.

Response: The sampling procedure by double sided adhesive tape pads yielded 9 samples during the ascent of the aircraft (the tape pads were exchanged 9 times during the ascent), which represent the cumulative effect of aerosols in the elevation intervals of 550-640m, 850-940m, ... and 2950-3040m. We have modified the manuscript to clarify this point: “The sampling procedure by double sided adhesive tape pads yielded 9 samples during the ascent of the aircraft which represent the cumulative effect of aerosols in the elevation intervals of 550-640m, 850-940m, ... and 2950-3040m.”

3.3.6 – Row 4, p.3873: wrong unit.

Response: This is a typo. We corrected “..exceeding 1.0 μm in each layer.” into “...exceeding 7.0 $\mu\text{g}/\text{m}^3$ in each layer.”

3.3.7 – Any visual proof (i.e. a photo) of the ash layer is available? For similar concentration the plume was found to be visible (see again Schumann et al.)

Response: The aircraft crew (pilot and dr. Coren from INOGS, Trieste) confirmed visual observation of the ash layer when passing through it. After the aircraft rose above 3 km, the air became visually much cleaner. General impression when looking down was that underneath was a layer of dark fine dust. Unfortunately, no photograph was taken,

so we have no material visual evidence.

3.3.8 – Figure 8: like the lidar ones, x-axis should be not cumulative.

Response: We replotted the profiles accordingly (Fig.7 in the attachment).

Comments on 5. Simulation of air flow trajectories 5.1 – The first important explosive activity started on 14/04 at 19:00 UTC and trajectories analysis should be done accordingly.

Response: We are aware the explosion started on 14 June, 19:00 UTC. However, after modeling all 48-hour forward trajectories (by both ECMWF and HYSPLIT) originating at Eyjafjallajökull volcano with starting times between 14 June, 19:00 UTC and 19 April, 23:00 UTC (with one hour increment of the starting time) we found that trajectories starting before 15 April 2010, 21:00 UTC do not overpass Slovenia. Forward trajectories starting at 15 April 2010, 21:00 UTC predict the transport time to Slovenia to be 30 hours, which was found to agree with the satellite images and precipitation results (first precipitation which contained volcanic ash occurred on 17 April 2010, at 01:00-02:30 UTC, see also the answers to your questions 2.2 and 2.3). The text has been modified to clarify this.

5.2 – Row 28, p.3875: “Simulation show that, occasionally, ...”: unclear.

Response: The entire paragraph was changed to clarify this. It now reads: “For the second arrival of volcanic ash on 20 April, 48-hour forward trajectories show that ash-loaded air masses did not arrive directly from Eyjafjallajökull. We checked the corresponding 48-hour backward trajectories, which were found to originate in northern and north-western Europe where ash particles were still present (Schumann, 2011 and Flentje, 2010). Backward air mass trajectories were simulated by both models, where in the case of ECMWF Ljubljana was the single endpoint and in the case of HYSPLIT multiple endpoints included Ljubljana, Nova Gorica and Divača. Simulations show that volcanic ash arriving on 20 April was brought by air masses continuously streaming for

Full Screen / Esc

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more than 15 hours from the north at altitudes below 6 km, starting on 19 April 2010 at 23:00 UTC. ”

5.3 – In general I think that back-trajectories analysis, starting at locations, time & altitudes where the measurements are done and ending where & when explosive eruption happen, should provide, within its limits, the proper information on air masses provenience: other speculations, presented in this paragraph seems to be less relevant for this purpose.

Response: We used forward trajectories for the modeling of both arrivals of volcanic ash to Slovenia (17 April and 20 April), however, as in the case of the second arrival 48-hour forward trajectories show that ash-loaded air masses did not arrive directly from Eyjafjallajökull, we checked corresponding 48-hour backward trajectories. Backward trajectories were found to originate in northern and north-western Europe, where ash particles were found to be present (Schumann, 2011 and Flentje, 2010). Please see also the answers to your questions 5.1 and 5.2.

Comments on 6. Discussion and conclusions. 6.1 – What about the linear regression with Otlica data (a location that is also nearer to the flight path)?

Response: The measurements at Otlica started from 21:00 UTC while the airborne measurement was performed from 16:00-16:38 UTC (more than 4 hours earlier), which implies that the atmospheric conditions may have changed significantly. Despite the fact that Otlica is closer to Divača (28 km) than Nova Gorica (39 km), we have chosen the Nova Gorica data for comparison as they were taken at the same time. The correlation coefficient of 0.51 shows the two data sets are correlated (Wilks, 1995), but is a bit weak due to the fact that measurements were performed at different locations and influenced by the flow of the air masses. Moreover, Otlica data is less suitable for comparison as complete overlap of the lidar is reached above 2 km above sea level, so we can only compare data between 2-3 km a.s.l. which in addition to time difference further reduces the credibility of the result.

Full Screen / Esc

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Flentje, H., Claude, H., Elste, T., Gilge, S., Köhler, U., Plass-Dülmer, C., Steinbrecht, W., Thomas, W., Werner, A., and Fricke, W.: The Eyjafjallajökull eruption in April 2010 – detection of volcanic plume using in-situ measurements, ozone sondes and lidar-ceilometer profiles, *Atmos. Chem. Phys.*, 10, 10085-10092, doi:10.5194/acp-10-10085-2010, 2010.

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[Interactive comment on Biogeosciences Discuss., 8, 3863, 2011.](#)

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8, C1872–C1892, 2011

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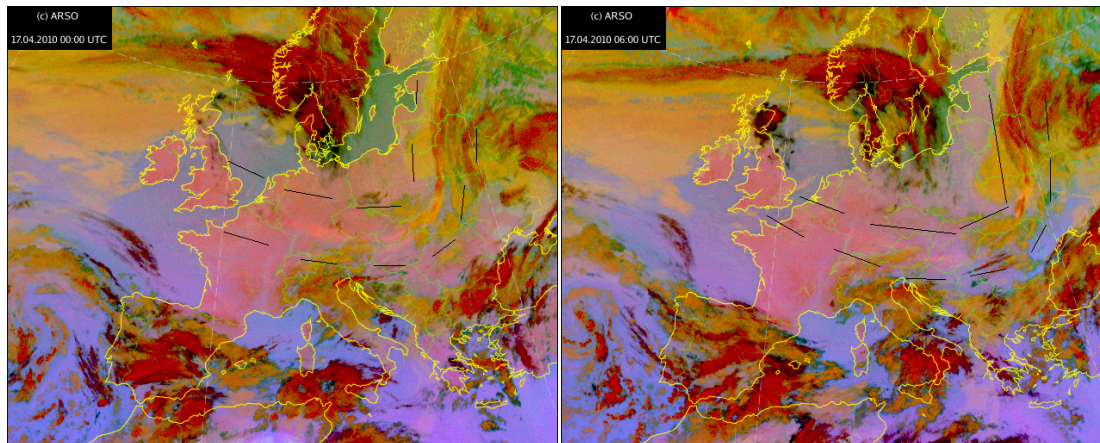


Fig. 1. Meteosat-8 satellite images for 17 April 2010, 00:00 UTC and 06:00 UTC showing the approach of the volcanic ash belt to Slovenia.

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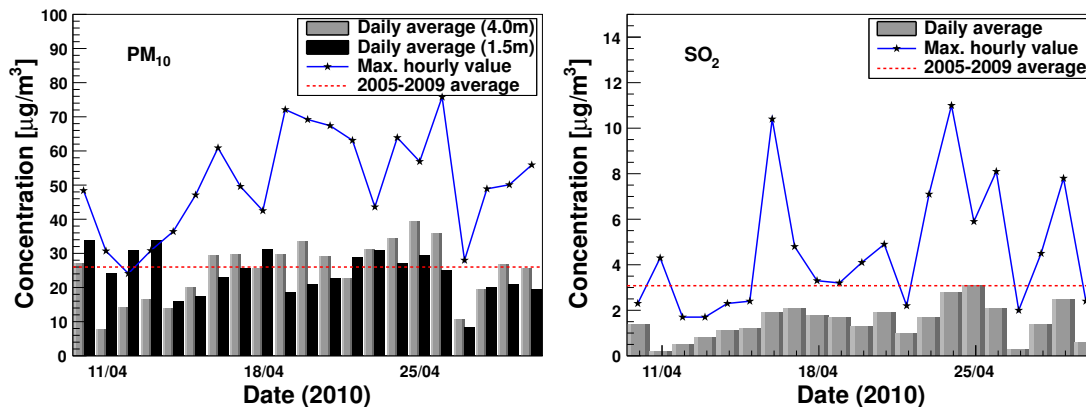


Fig. 2. Monitoring results of the concentration of solid particles (PM₁₀, left) and sulphur dioxide (SO₂, right) in the air in Ljubljana from 10 April to the end of April 2010.

Full Screen / Esc

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Interactive Discussion

Discussion Paper

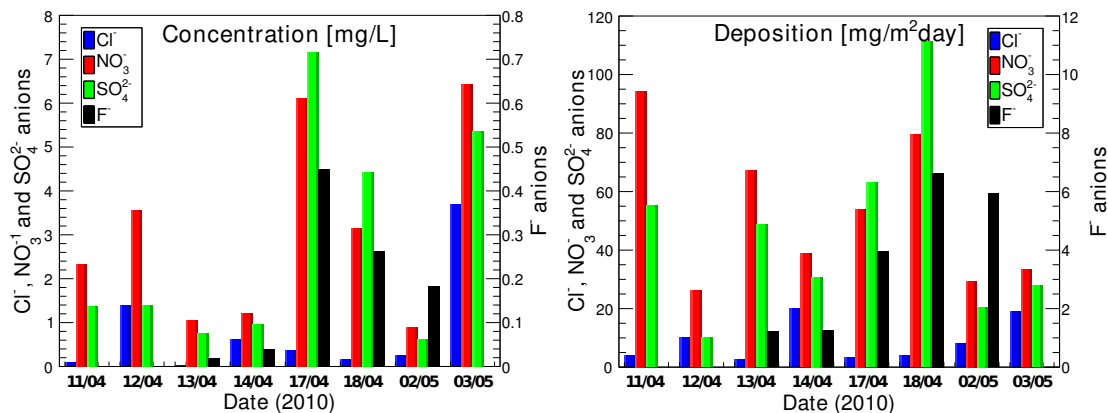


Fig. 3. Results of the composition analysis of precipitation in Ljubljana between 10 April and 3 May 2010.

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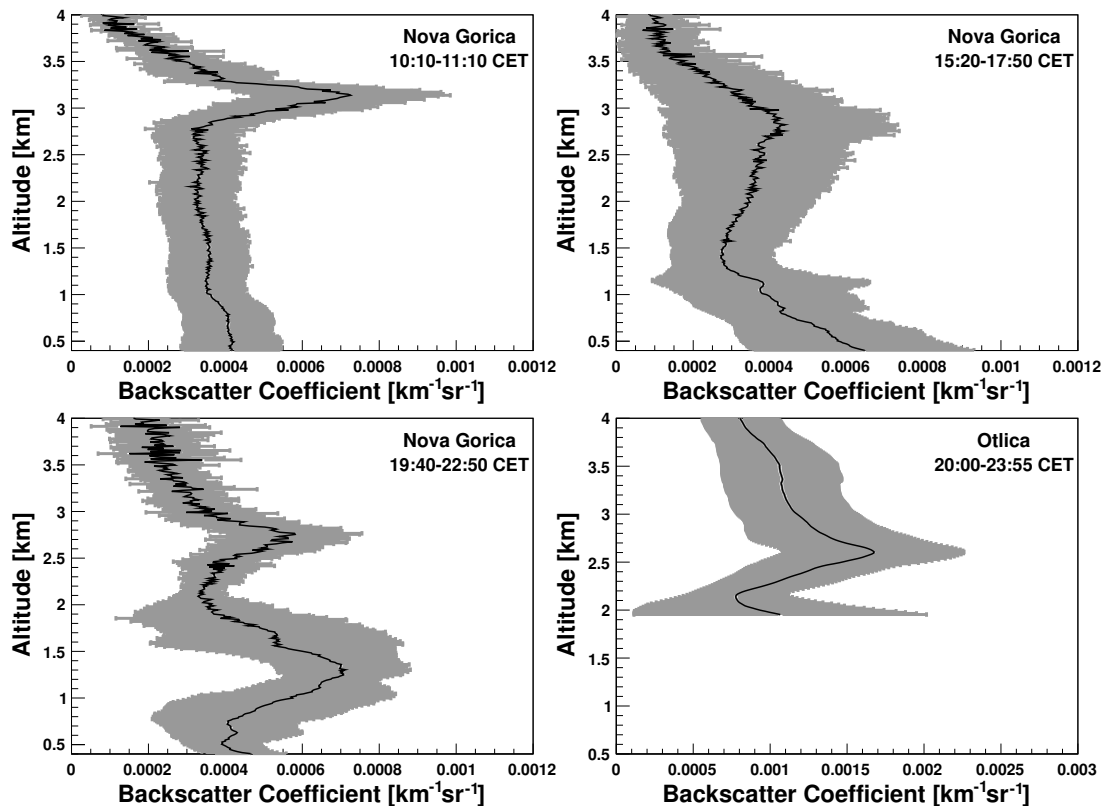
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Fig. 4. Atmospheric backscatter profiles with uncertainties (grey), obtained from measurements by the Nova Gorica and Otlica lidars on 20 April 2010.

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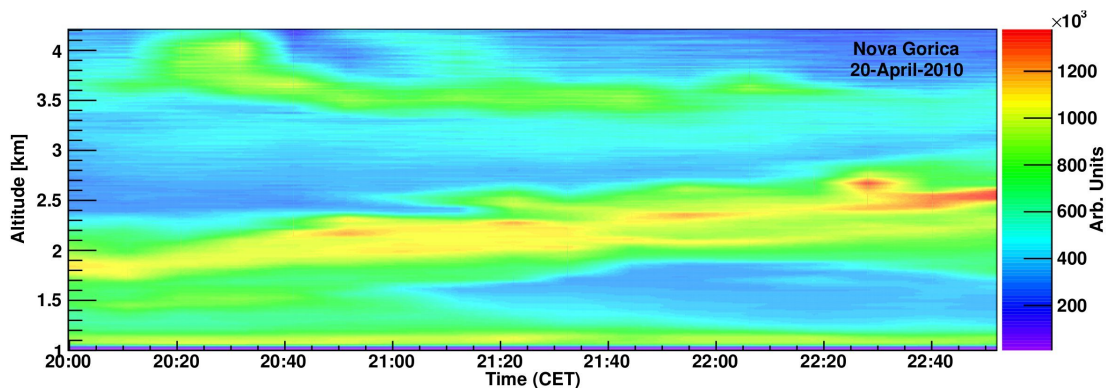


Fig. 5. Time-height-indicator of range corrected signal to describe the temporal development of aerosol loading above Nova Gorica during the night of 20 April 2010.

Full Screen / Esc

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Interactive Discussion

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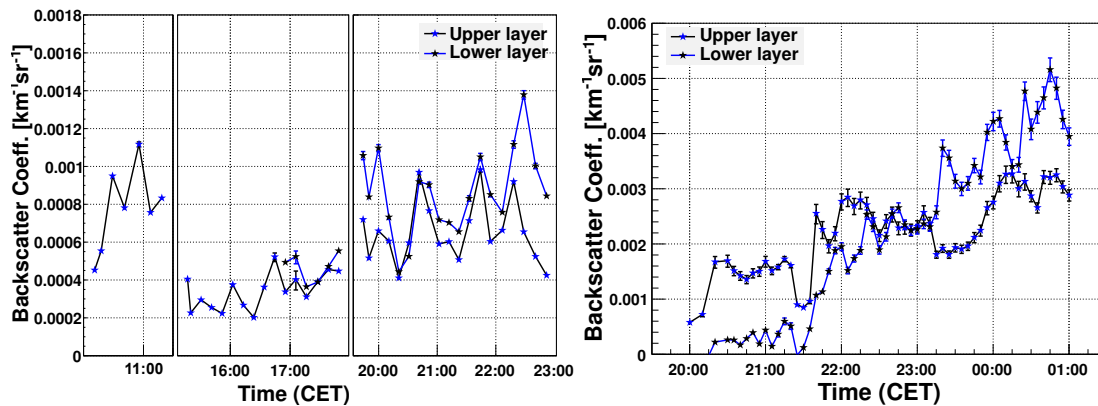


Fig. 6. Variation of the peak atmospheric backscatter coefficient in lidar profiles measured on 20 April 2010 (left: Nova Gorica, right: Otlica).

[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)[Discussion Paper](#)

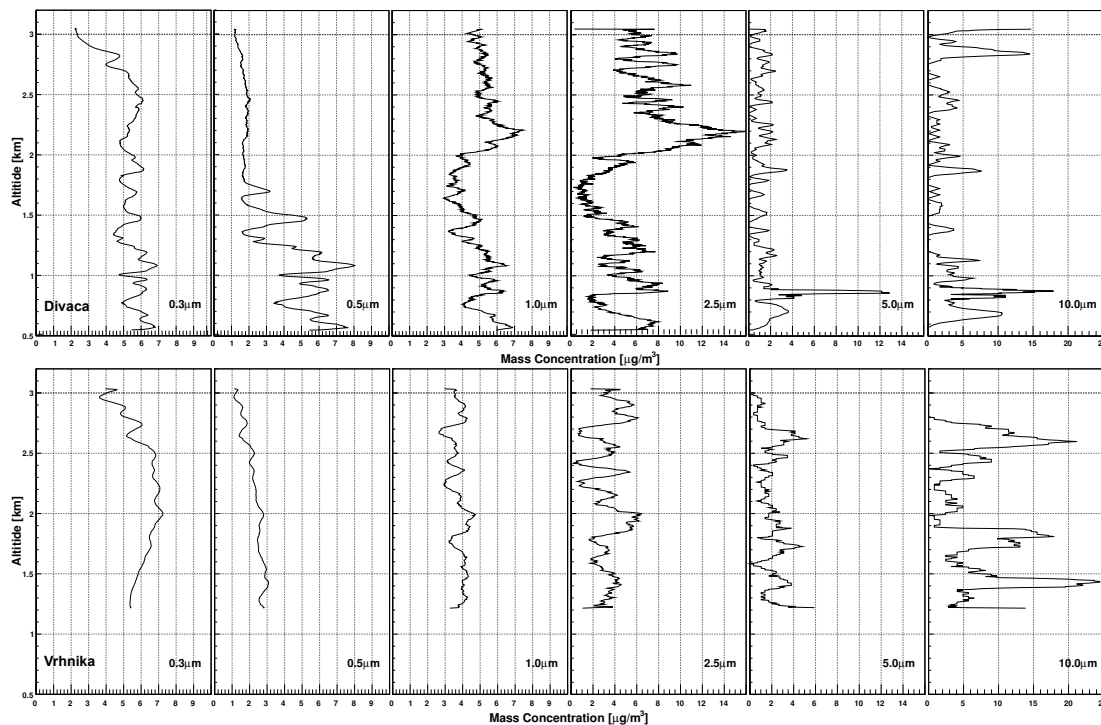
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Fig. 7. Aerosol concentration profiles for six different aerosol dynamic equivalent diameters measured on 20 April 2010 above Divača (top) and above Vrhnika (bottom).

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