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Possible effect of extreme solar energetic particle event of 20 January 2005 on polar stratospheric aerosols: direct observational evidence

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Abstract

Energetic cosmic rays are the main source of ionization of the low-middle atmosphere, leading to associated changes in atmospheric properties. Via the hypothetical influence of ionization on aerosol growth and facilitated formation of cloud condensation nuclei, this may be an important indirect link relating solar variability to climate. This effect is highly debated, however, since the proposed theoretical mechanisms still remain illusive and qualitative, and observational evidence is inconclusive and controversial. Therefore, important questions regarding the existence and magnitude of the effect, and particularly the fraction of aerosol particles that can be formed and grow large enough to influence cloud condensation nuclei (CCN), are still open. Here we present empirical evidence of the possible effect caused by cosmic rays upon polar stratospheric aerosols, based on a case study of an extreme solar energetic particle (SEP) event of 20 January 2005. Using aerosol data obtained over polar regions from different satellites with optical instruments that were operating during January 2005, such as the Stratospheric Aerosol and Gas Experiment III (SAGE III), and Optical Spectrograph and Infrared Imaging System (OSIRIS), we found a significant simultaneous change in aerosol properties in both the southern and northern polar regions in temporal association with the SEP event. We speculate that ionization of the atmosphere, which was abnormally high during this extreme SEP event, might have led to formation of new particles and/or growth of preexisting ultrafine particles up to the size of CCN. However, a detailed interpretation of the effect is left for subsequent studies. This is the first time high vertical resolution measurements have been used to provide evidence for the probable production of stratospheric CCN from cosmic ray induced ionization.

1 Introduction

Cosmic rays are energetic particles (mostly protons and α−particles) of extra-terrestrial origin impinging upon the Earth's atmosphere. They are categorized according to their origin as either galactic cosmic rays (GCRs) or solar cosmic rays, the latter more conventionally referred to as solar energetic particles (SEPs). The third category, anomalous cosmic rays, has too low energy to ionize the lower atmosphere and is not considered here. The primary effect of cosmic rays in the atmosphere is ionization of the ambient air (see, e.g., a review by Bazilevskaya et al., 2008), and this is the main source of ionization in the low and middle atmosphere. GCRs are always present in the Earth's vicinity, and their atmospheric effect is roughly constant, with the range of variations being within 10–20 %. SEPs occur sporadically, usually in conjunction with giant eruptive events (solar flares or coronal mass ejections) at the Sun. SEPs are less energetic (typically protons with energy below 1 GeV) than GCRs but may produce fluxes exceeding those of GCRs by orders of magnitude during hours–days. Because of their lower energy SEPs can penetrate into the Earth's atmosphere only in the polar regions, where there is no shielding of the geomagnetic field; and they generally affect only the mesosphere and stratosphere above about 20 km (Vitt and Jackman, 1996). However, there is a special class of SEP events, called Ground Level Enhancements (GLEs), which are characterized by the presence of very energetic particles (up to several GeV) that can cause a noticeable effect at the ground level as observed by neutron monitors (e.g., Shea and Smart, 1990). Because the energetic particle flux varies greatly during short time intervals, GLEs provide a good opportunity for case studies of atmospheric effects.

Many studies have been done on the SEP influence on such atmospheric constituents as HO_x, NO_x and O_3 in the polar mesosphere and stratosphere (e.g., Randel and Wu, 1999; Krivolutsky et al., 2003; Semeniuk et al., 2005; Jackman et al., 2005; Randall et al., 2007; Seppälä et al., 2008). Such chemical changes are usually reasonably parameterized by semi-empirical models (e.g., Semeniuk et al., 2005; Krivo-

lutsky et al., 2006; Jackman et al., 2008). However, the issue of a possible influence of energetic particles, mostly GCR, on cloud and aerosol properties in the lower atmosphere (lower stratosphere and troposphere) is still debated (e.g., Kulmala et al., 2010). Although there are some hints that atmospheric ionization due to cosmic rays may affect aerosol particles and/or clouds in the troposphere and stratosphere (e.g., Carslaw et al., 2002; Arnold, 2006; Curtius et al., 2006; Kazil et al., 2008; Harrison and Tammet, 2008), it is difficult to get clear experimental evidence. Comparisons of interannual variability in solar activity or cosmic rays and cloud data (e.g., Pallé et al., 2004; Usoskin et al., 2006; Voiculescu et al., 2006; Kulmala et al., 2010) lead to ambiguous interpretations because of the natural climate variability modes operating on the same time scales (e.g., Voiculescu et al., 2007). It is common to study the relation between aerosols or different types of clouds and short-term suppressions of GCR flux during Forbush decreases caused by strong interplanetary transients. Such studies are numerous (e.g., Kniveton, 2004; Kristjánsson et al., 2008; Pierce and Adams, 2009; Svensmark et al., 2009; Laken et al., 2009; Calogovic et al., 2010) but also highly controversial and inconclusive. Moreover, they are looking for a possible disappearance of existing aerosols or cloud condensation nuclei (CCN) associated with a reduction in the GCR flux, which may be quite different from production of new particles by enhanced flux. In this sense it is more promising to perform a case study of the potential atmospheric response to a strong GLE event. For a detailed analysis we have chosen the time period of January 2005, which is characterized by a strong burst of solar activity, including an extreme GLE/SEP event of 20 January 2005. That event was analyzed earlier by Mironova et al. (2008) who found, using the Total Ozone Mapping Spectrometer (TOMS) data obtained by the Earth Probe Satellite, an increase in the overall aerosol optical depth in the southern polar region associated with the event. The observed changes could not be explained by modeled downward propagation of the chemical changes induced by the same GLE in the mesosphere (Seppälä et al., 2008), and thus were thought to be associated with the direct additional ionization of the stratosphere by SEP. The analysis by Mironova et al. (2008) was however limited to only the southern polar region and provided no altitudinal information, therefore precise attribution of the aerosol changes to enhanced GLE-induced ionization in the lower stratosphere was not possible.

Here we look for a possible influence of a sudden dramatic increase in atmospheric ionization due to the extreme SEP/GLE event of 20 January 2005 on the behavior of aerosol particles in the polar lower stratosphere. We base our analysis on satellite aerosol data that allow investigation of the behavior of aerosol components in both polar hemispheres with high vertical resolution.

2 Time interval of 20 January 2005

The SEP event of 20 January 2005 was recorded as a very high count rate at the ground-level network of neutron monitors and was one of the strongest GLE events ever observed (Mewaldt et al., 2007). This event was highly anisotropic and asymmetric in the short impulsive phase; in particular the peak enhancement was stronger in the southern polar region (almost 3500 % at the South Pole station) than in the northern one (about 300 % at the Oulu station) during the impulsive phase of the event (e.g., Plainaki et al., 2007; Bütikofer et al., 2008). During the main phase the GLE event was fairly isotropic, leading to similar enhancements in both regions. The GLE occurred on 20 January 2005, beginning at about 06:50 UTC, with the peak intensity reached at 07:00–07:10 UTC, DOY (day of year) 20.3. This was followed by a second lower peak at about 09:00 UTC and a gradual decay until about mid-day of 20 January. The very high level of neutron monitor count rate increase implies that the ionization of the polar atmosphere was dramatically increased during the event (Vainio et al., 2009). Atmospheric ionization during this event has been discussed in great detail by Usoskin et al. (2011). This is illustrated in Fig. 1,showing that the calculated ionization due to the SEP event of 20 January started dominating over the GCR ionization already at 10-km altitude and reached its maximum at about 30 km altitude. In particular, the CRAC:CRII model calculations suggest that the SEP event produced additional ioniza-

tion in the polar atmosphere in the altitude range 12–23 km, with the number of ions being greater by a factor of 3–30 than the averaged GCR-induced daily ionization in January 2005. So high level of atmospheric ionization is reached very rarely and thus makes it possible to study the proposed relation in detail. However, this enhanced ionization existed only in the polar region above ≈60° magnetic latitude. At lower latitudes and altitudes, the ionization was reduced due to the relatively strong Forbush decrease (about 15 %) that started on 17 January in association with a medium-size SEP event (Bazilevskaya et al., 2008). We note that the previous SEP event of 17 January had a much softer spectrum than that for the 20 January event, with significant ionization only down to about 20 km (see Fig. 1). Before 17 January, and after 24 January, the cosmic ray flux remained fairly stable. These computations have been performed using the CRAC:CRII (Cosmic Ray induced Atmospheric Cascade: application for Cosmic Ray Induced Ionization) model (Usoskin and Kovaltsov, 2006; Usoskin et al., 2010), energy spectra of SEP provided by Tylka and Dietrich (2009) and Usoskin et al. (2011), and GCR according to Usoskin et al. (2005). The altitude range analyzed in this study is not hatched. Ionization due to the SEP event of 20 January dominates over the GCR ionization at altitudes above 10 km.

3 Remote sensing of the atmosphere during January 2005

To complement our previous work (Mironova et al., 2008), which was based on TOMS data providing the integrated aerosol optical depth, here we analyze vertical profiles of stratospheric aerosol properties in January 2005. The analyses are based on data from the third Stratospheric Aerosol and Gas Experiment (SAGE III) and the Optical Spectrograph and Infrared Imaging System (OSIRIS). We also investigated data from the Polar Ozone and Aerosol Measurement (POAM III) instrument. However, the latter results are disregarded since POAM aerosol data were affected by a sporadic mechanical problem in the instrument during the second half of January 2005 (C. Randall and K. Hoppel, personal communication, 2010). We have checked also other data sets potentially providing data for that period and found that only the data sets discussed here can be used for our study.

3.1 SAGE aerosol data

The NASA SAGE III instrument (hereinafter referred to as SAGE) was launched on-board the Russian Meteor-3M satellite into a sun synchronous orbit with an inclination of 99.53°) (see, e.g. Yue et al., 2005); it was terminated in March 2006. The SAGE III data have been obtained from NASA Langley Atmospheric Sciences Data Center http://www-sage3.larc.nasa.gov. SAGE is a solar occultation instrument, so aerosol properties are inferred from measurements of the spectral extinction of solar radiation as it is transmitted through the atmosphere. It makes measurements at equally spaced longitudes around a circle of approximately constant latitude in each hemisphere on each day. Measurement latitudes change slowly throughout the year, ranging from about 45°–80° N in the Northern Hemisphere and from about 35°–60° S in the Southern Hemisphere. During the month of January 2005, the measurement latitudes ranged from 66.0° to 72.8° N in the north and from 36.8° to 37.8° S in the south. Thus no observations were made at the high southern latitudes of interest for this work. The vertical profile of of SAGE aerosol extinction profiles is given in the range from 10 to 45 km height with the vertical resolution 0.5 km (Yue et al., 2005). The aerosol extinction coefficient (AEC, in km^{-1}) was obtained in nine wavelength channels, 385, 449, 521, 602, 676, 756, 869, 1020 and 1550 nm.

3.2 OSIRIS aerosol data

OSIRIS was launched onboard the Odin satellite into a sun-synchronous orbit with an inclination of 98° in February 2001. It scans the Earth's limb between 6 and 60 (or 110) km and measures the atmospheric limb-scattered sunlight (Llewellyn et al., 2004). Details of the OSIRIS aerosol retrieval algorithm are described by Bourassa et al. (2007). OSIRIS samples latitudes from 82° S to 82° N on a daily basis, but be-

cause of the satellite local time and requirement for sunlight, the latitudes of the aerosol retrievals are restricted. Thus aerosol properties at polar latitudes in January 2005 were only obtained in the Southern Hemisphere. We analyze here the OSIRIS aerosol extinction coefficient data for January 2005 from 60° S to 89° S. The AEC data are considered in the altitude range 11–28 km with a vertical resolution of 1 km (Bourassa et al., 2007). OSIRIS data on AEC are only available at the 750 nm wavelength.

We note that the OSIRIS CCD detector can potentially be affected by SEP as some energetic particles may cause temporary spikes in one, or more, of its pixels. We carefully examined the vertical profiles for Level 1 radiances that were used for aerosol extinction retrievals and found that the effect of SEP on Level 1 data below 30 km was insignificant. Namely, the additional signal caused by occasional spikes was at least 150 times smaller than signal below 30 km.

Thus the work described below uses SAGE III data for the Northern Hemisphere and OSIRIS data for the Southern Hemisphere.

3.3 Meteorological parameters

Meteorological parameters such as altitude profiles of pressure, temperature, and potential vorticity were obtained from the Met Office (MetO, http://www.metoffice.gov.uk/) meteorological assimilation data and interpolated to the measurement locations.

4 Aerosol properties associated with 20 January 2005 GLE event

4.1 Northern Hemisphere

For the Northern Hemisphere we posses data from SAGE III instrument. As an example, we show in Fig. 2 changes of the AEC in the wavelength 756 nm in the Northern polar region (longitudinal information is not considered in this plot). This wavelength is close to that of the OSIRIS discussed in Sect. 4.2. One can see a strong (up to a factor of 100) apparent increase of AEC since 20–21 January until ca. 27 January in the altitude range 10–22 km. On the other hand, one can see that the AEC increase is not uniform but seemingly intermittent. This pattern is related to the spatial inhomogeneity of the aerosol features and the fact that the satellite continuously scans different longitudes.

In order to illustrate that, we show in Fig. 3 AEC at the same wavelength (756 nm) but now fixing altitudes and considering longitudinal variability (the latitude is always in a narrow band of 66–73° N). One can see that the strong increase of AEC was detected starting day 21 but only in a limited longitudinal range from about 30° W to 90° E, while in other regions there is no notable effect. The maximum effect is observed 2–4 days after the GLE event. This longitudinal feature is quite stable, ranging from 10 to about 20–22 km in altitude and being present for a week. For further analysis, we consider this longitudinal range, viz. 30° W–90° E and 66–73° N, corresponding to NW Eurasia from Greenland to mid-Siberia.

The combined effect of the GLE event of 20 January 2005 on AEC (for the selected longitudinal region in the Northern Hemisphere) is shown in Fig. 4. The AEC spectrum at nine SAGE wavelengths is averaged over 7 days before (13–19 January) and 6 days after (21–26 January) the GLE event, which occurred on 20 January. One can see that the AEC has dramatically increased, by an order of magnitude, at all heights below 25 km. This may imply either the change of the aerosol mass or changes of its properties. Interestingly, the slope of the spectrum remains largely unmodified while the values of AEC grew up simultaneously at all wavelength. The logarithmic slope of the AEC as function of wavelength is called the Ångstrom exponent (ÅE) α and reflects the size distribution of the scattering particles. Here we computed the value of α using all the wavelength channels. Since uncertainties in AEC depend on wavelength, we used the standard weighted least squares method to calculate the best fit power-law regression and its uncertainty, using the nine SAGE wavelength channels noted above (see an example in Fig. 5). We applied this method even when data in some channels were missing. If, however, the number of available wavelengths was reduced to three or less, such a data point was discarded from further analysis.

The value of α depends on the particle size distribution so that the larger α is, the smaller particles are. For example, for particles with the diameter larger than the maximum wavelength, the AEC does not depend on the wavelength, i.e., $\alpha \sim 0$. In the framework of standard idealistic Mie theory, some estimates on the particle size can be made. However, here we consider here only possible qualitative changes in the features of the scattering particles, since any quantitative values depend on the underlying assumptions on unknown parameters.

Figure 6 shows the temporal and latitudinal changes of ÅE α for the selected geographical region (panel A) and for the entire Northern polar region (panel B). One can see a small, but significant, increase of the α since 21–22 January in the altitude range 15–20 km. The increase of α from ≈ 1.5 to 2.5 suggests that the effective size of scattering particles somewhat decreased that can be interpreted as possible production (or growth from below detection threshold) of ultrafine particles, probably along with the simultaneous increase of the total aerosol mass. This feature was persistent for a week and then disappeared, viz. the size of particles restored to its normal value. In the selected geographical region in NW Eurasia (Fig. 6A), the pattern was different. A slight increase in α already started on 20 January, the day of the GLE event, at 15–17 km height everywhere in the Northern polar region and remained for 3–4 days. It has changed on 24–25 January, when the value of α dramatically decreased to nearly 0 with the lowering of the affected region by a few km. Such low value of α indicates a sudden increase of the effective aerosol size up to several hundred nm or more (comparable to the wavelength range of the SAGE experiment), i.e. to the CCN size. We note that such a dramatic change is observed only in the region of NW Eurasia.

We have also checked the meteorological conditions in the Northern polar region during January 2005, which was the middle of the Boreal winter. Spatial and temporal variability of the temperature is plotted in Fig. 7. First half of the month in the NW Eurasian region, between DOY 1 and 15 in the altitudes range from 14 to 25 km (see panels B, C and D), was characterized by temperatures below $\approx$200 K, that could lead to formation of PSCs (Polar Stratospheric Clouds). Another cooling by about 10 K was observed in the NW Eurasian region in the entire altitude range from 10 to 25 km a few days after the GLE event, on 23 January, when the temperature dropped again to 200 K and below. This cooling appeared slightly later than the corresponding increase in aerosol extinction (see Fig. 3), therefore we may speculate that it was triggered by the change in aerosol properties related to the GLE event. On the other hand, this cooling could provoke further growth and sedimentation of the aerosol particles ($\alpha \approx 0$) in that region after DOY 25 and could lead to the formation of PSC (Fig. 6). In order to exclude that the observed phenomenon is a typical mid-winter/summer effect due to, e.g., a change in insolation of the polar atmosphere, we have checked the period of mid-summer/winter (January and July) for other years (1998–2003) using also POAM data (Cora Randall, personal communication 2010).

We can briefly summarize the observations in the Northern polar region as follows.

- A weak increase in the Ångstrom exponent started on DOY 22, i.e. 2 days after the GLE event, in the entire Northern polar region at altitudes 15–20 km. It was accompanied by an increase of AEC, mostly in shorter wavelength, indicating a larger number of particles. Such behavior is interpreted as a possible decrease in the effective size of aerosols due to production of new ultrafine particles within 1–2 days after the GLE event in the entire Northern Hemisphere region.
- A peculiar region, NW Eurasia (30° W–90° E), can be identified, where this effect was followed by an essential growth and sedimentation of aerosols related to the cooling of that region.

4.2 Southern Hemisphere

For the Southern Hemisphere, we posses data from the OSIRIS instrument, which is only available at one wavelength. In Fig. 8, we plotted the AEC profile at 750 nm measured by OSIRIS in the Antarctic polar region (longitudinal information is not considered in this plot) for DOY 16–31. The AEC depicted an essential (nearly two orders of magnitude between 11 and 28 km) altitudinal gradient (see panel A). Consequently,

on panel B we show normalized (per the mean profile shown in panel A) daily AEC profiles. One can see a systematic increase in the AEC on the very day of 20 January with the maximum around 25 km, extended down to 12 km. However, this increase in AEC was relatively small (maximum 30 %) compared to an order of magnitude increase in the Arctic region (Sect. 4.1) and vanished within one day. This suggest that an increase in AEC (or in the particles' size/volume) could be caused by the direct effect of GLE in the lower stratosphere, but the ambient conditions were not favorable to develop the effect further at least for larger particles, as observed at 750 nm wavelength by OSIRIS. On the other hand, it was found out earlier (Mironova et al., 2008), using TOMS data, that the aerosol optical depth at the wavelength of about 360 nm increased in the Antarctic region on the second day after the GLE, i.e. on 20 January 2005, and that the increase was statistically significant. This suggests that smaller particles affecting the optical depth at 360 nm wavelength but undetectable at 750 nm, were able to develop reaching the maximum effect on the second day after the GLE event. Unfortunately, the earlier study did not provide vertical profiles of the effect, because of the method used by the TOMS instrument.

5 Discussion and conclusions

We have analyzed available data of the aerosol properties in the two polar regions for the period of January 2005 when an extreme GLE event of solar energetic particles took place.

We found a change in the aerosol optical properties and Ångstrom exponent α and try to speculate on its possible implications. First, smaller particles have formed leading to a seemingly decreasing in the value of aerosol effective size after the SEP event. Several days later, the effect was also observed for larger particles. This was accompanied by the growth by an order of magnitude of the AEC in all wavelengths. A possible explanation for the observed "downsizing" of aerosol particles, based on the increasing Ångstrom exponent, is one, or a combination, of the following: (1) break-up of large particles into smaller ones; (2) formation of new (small) particles; (3) growth of pre-existing particles, whose size was below the satellite-based instruments detection threshold, before SEP. Explanations (2) and/or (3) look more likely for the following reasons. First, it is known that atmospheric ions can grow efficiently into stable aerosol particles (Arnold, 2008), and the SEP provided the required ionization. Second, the observed effects on the SAGE III and OSIRIS data were similar and took place concurrently in both polar regions, despite quite different meteorological conditions.

Timing of the aerosol response deserves a separate discussion. In our earlier study (Mironova et al., 2008), we found that a decrease in aerosol index (increase in the number of small particles, like sulfates) over places with the maximum ionization rate reached its maximum on the second day after GLE. However, in that work we studied the entire aerosol optical depth, corresponding mainly to the troposphere, while here we focus on the aerosol response to increasing cosmic ray induced ionization (CRII) in the lower and middle stratosphere. In the present study, we observed the aerosol response within one day of the GLE. There is also a tendency for the maximum effect to be observed with a few days delay at lower altitudes below 23 km for Northern polar Hemisphere, especially in the Ångstrom exponent (see Fig. 6). The exact time of the maximum response of aerosols to GLE is, however, difficult to derive. According to some numerical simulations (e.g., Arnold, 2008) for the upper troposphere, the CRII rate of about 30–40 $cm^{-3} s^{-1}$ would lead to a possible reaction of aerosol particles delayed by 1–6 days depending on the size of fractions. This is consistent with a 2–3 days delay observe here.

In conclusion, we have presented an empirical evidence for a direct influence of the extreme SEP/GLE event of 20 January 2005 on aerosol parameters in the polar stratosphere (altitudes between 11 and 25 km). In the framework of the simple theory this may be speculated as a possible nearly simultaneous growth, in both polar regions, of ultrafine particles, potentially up to the size of CNN. This aerosol response was under stable atmospherical conditions and associated with the extreme event, when the ionization due to SEP was several orders of magnitude greater than usual values

due to galactic cosmic rays (see Fig. 1). Although a detailed mechanism of such effects is not well understood yet, there are some theoretical (i.e., Kazil et al., 2008) and also empirical (Duplissy et al., 2009; Nieminen et al., 2010) evidences that an enhanced ionization may facilitate growth of ultrafine aerosols if the meteorological conditions remain constant. We note that, while the observational result is novel and robust, the possible explanation proposed here is only a qualitative speculation, based on an oversimplified theory. More detailed modeling is required in order to fully understand the found effect.

We would like also to emphasize that the observed atmospheric effect for this extreme GLE event was barely significant. No clear atmospheric effect was found beyond statistical fluctuations for the weaker SEP event of 17 January 2005, which is a typical SEP event. This implies that only extremely hard-spectrum (high energy) GLE/SEP events can produce a noticeable direct effect on aerosols in the polar low-middle stratosphere.

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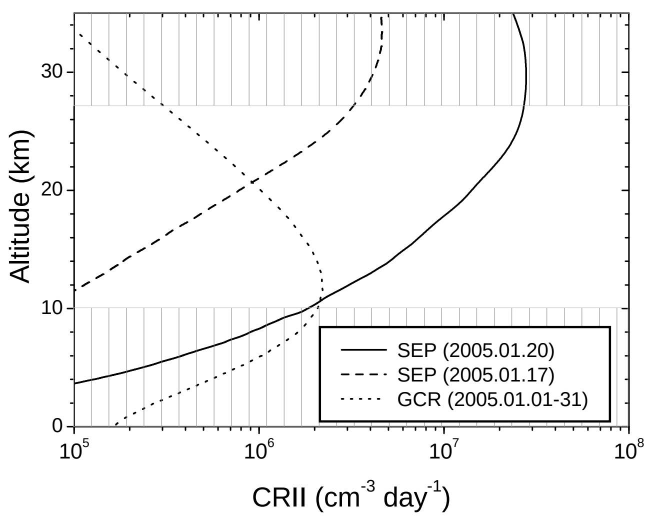

Fig. 1. Daily integrated cosmic ray induced ionization (CRII) of the polar atmosphere in January 2005. Solid and dashed curves depict the net ionization due to two SEP events, of 17 and 20 January (a typical event), respectively. The dotted curve depicts the average ionization rate due to galactic cosmic rays in January 2005.

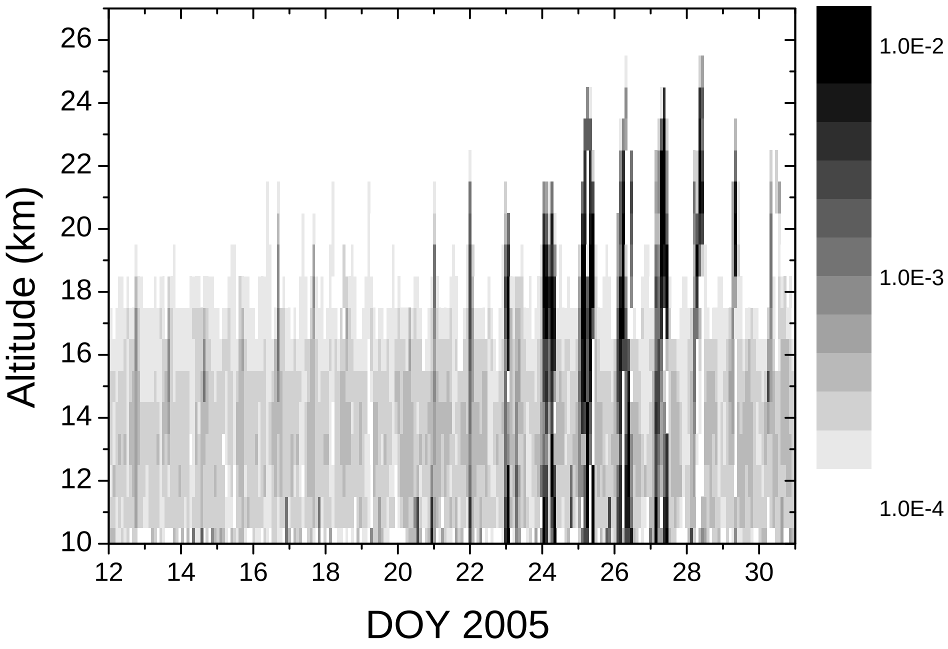

Fig. 2. Vertical profiles of aerosol extinction coefficient (in km^{-1}) at the 756 nm wavelength measured by SAGE III in the northern polar region during 13–30 January 2005. Logarithmic grey scale is shown on the right panel.

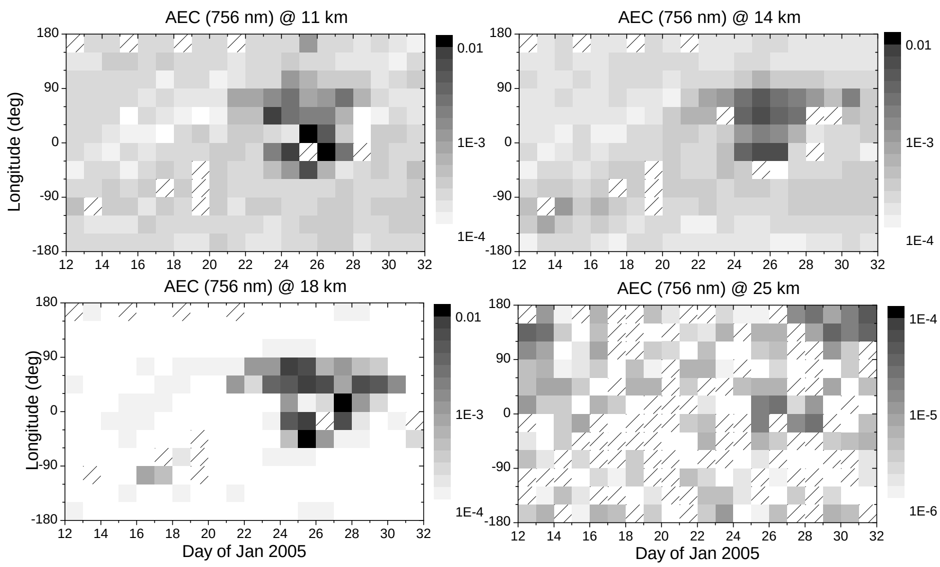

Fig. 3. Daily averaged aerosol extinction coefficient (in km^{-1}) at the 756 nm wavelength measured by SAGE III instrument at fixed altitudes (as denoted on top of each panel) as function of geographical longitude. Logarithmic grey scale is shown on the right of each panel.

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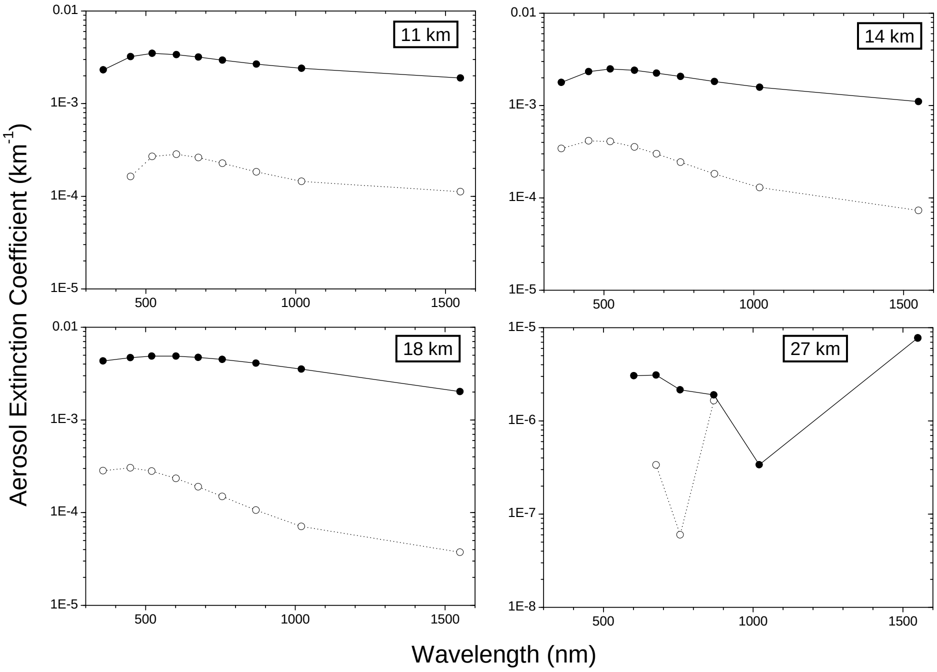

Fig. 4. Aerosol extinction coefficient measured by SAGE III in the selected NW Eurasian region (see text) at four altitudes. Dotted line with open circles and solid line with filled circles correspond to the time-averaged aerosol extinction before (13–19 January) and after (21–27 January) GLE event, respectively.

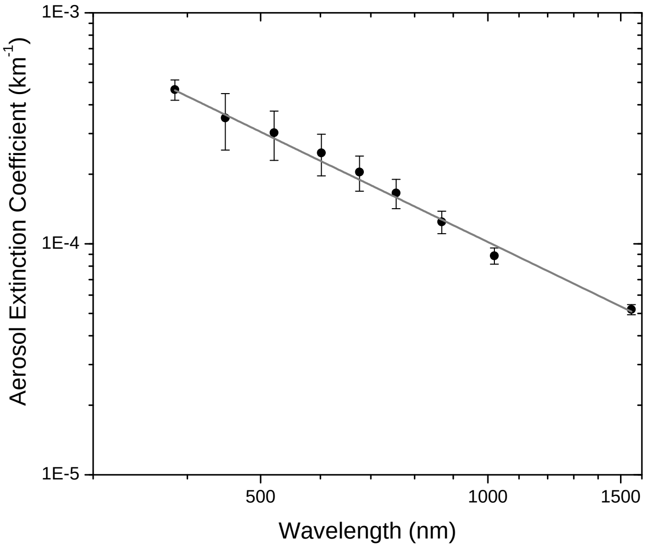

Fig. 5. An example of wavelength dependence of SAGE aerosol extinction coefficients (1 January 2005 at height 15.25 km). Solid line corresponds to the best power law fit (Ångstrom exponent) $\alpha = -1.58 \pm 0.05$.

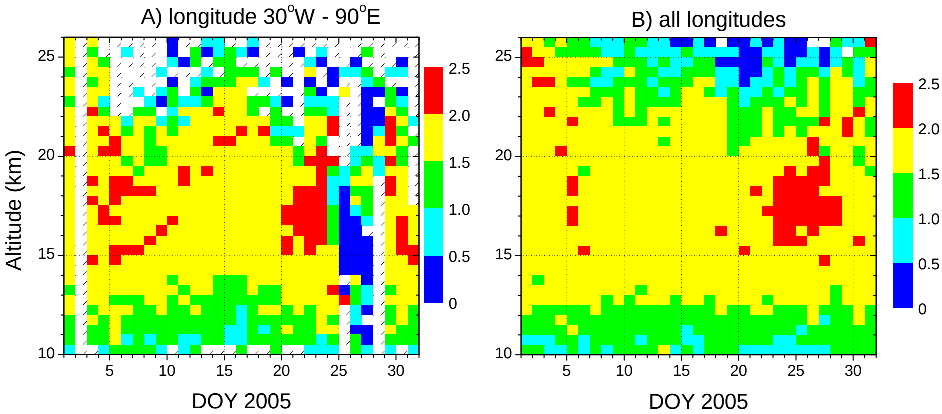

Fig. 6. Ångstrom exponent α calculated from SAGE III aerosol extinction as function of altitude and time. Data were averaged over the longitudinal region 30° W–90° E (panel **A**) and all longitudes (panel **B**) in the Northern polar region (latitude 66–73°).

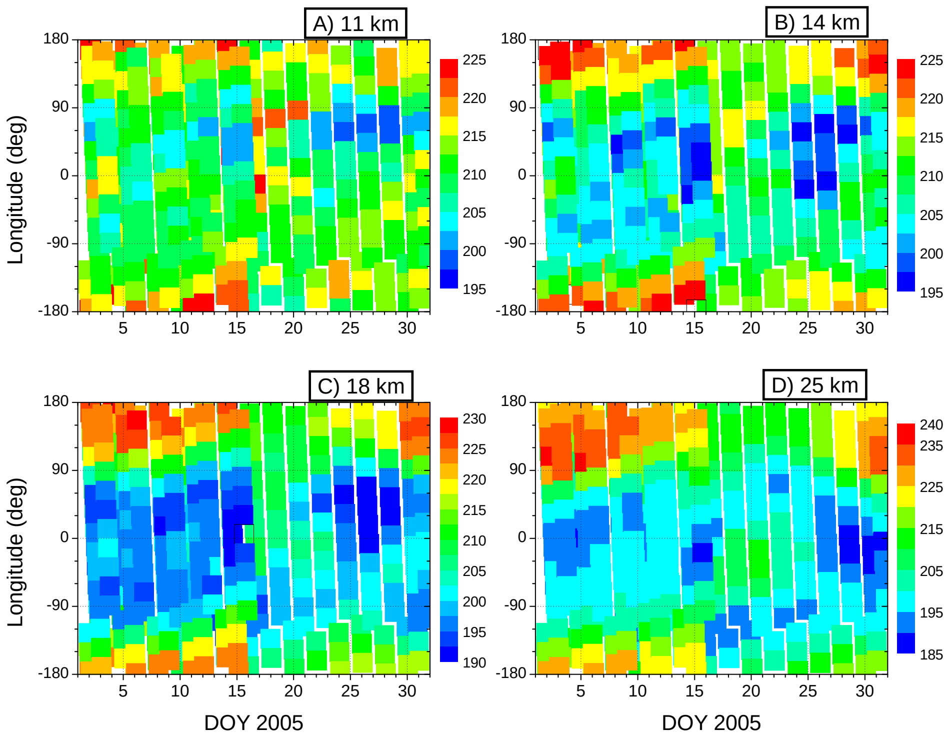

Fig. 7. Temperature distribution in the Northern polar stratosphere as a function of geographical longitude and time, for four fixed altitudes as indicated on the top of each panel. Color scale is shown on the right of each panel.

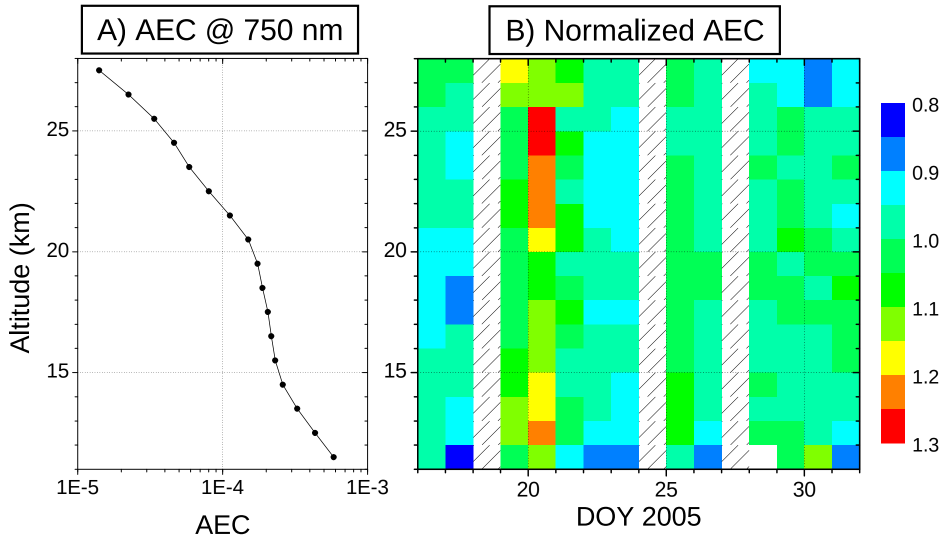

Fig. 8. Averaged OSIRIS aerosol extinction (in km^{-1}) profiles at 750 nm measured over the Antarctic region in the second half of January 2005. Panel **(A)**: The average profile for the 16–31 January 2005 period. Panel **(B)**: Normalized (per that shown in panel **A**) daily averaged AEC. Hatched area depict days with no data available.