Atmos. Chem. Phys. Discuss., 13, 5411–5428, 2013
www.atmos-chem-phys-discuss.net/13/5411/2013/
doi:10.5194/acpd-13-5411-2013

Atmospheric Chemistry and Physics
Open Access
Discussions

Possible effect of extreme solar energetic particle events of September–October 1989 on polar stratospheric aerosols: a case study

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Received: 18 December 2012 – Accepted: 18 February 2013 – Published: 27 February 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The main ionization source of the middle and low Earth atmosphere is related to energetic particles coming from outer space. Usually it is ionization from cosmic rays that is always present in the atmosphere. But in a case of a very strong solar eruption some solar energetic particles (SEP) can reach middle/low atmosphere increasing the ionization rate up to some orders of magnitude at polar latitudes. We continue investigating such a special class of solar events and their possible applications for natural variations of the aerosol content. After the case study of the extreme SEP event of January 2005 and its possible effect upon polar stratospheric aerosols, here we analyze atmospheric applications of the second sequence of several events that took place over the Autumn 1989. Using aerosol data obtained over polar regions from two satellites with space-borne optical instruments SAGE II and SAM II that were operating during September–October 1989, we found that an extreme major SEP event might have led to formation of new particles and/or growth of preexisting ultrafine particles in the polar stratospheric region. However, the effect of the additional ambient air ionization on the aerosol formation is minor, in comparison with temperature effect, and can take place only in the cold polar atmospheric conditions.

1 Introduction

Natural variability of the outer space factors, in particular cosmic ray fluctuations, is important for the terrestrial environment. Cosmic rays produce direct effect on the Earth's atmosphere via ionization of the ambient air and form the main source of the atmospheric ionization for the lower and middle atmosphere (Bazilevskaya et al., 2008). There are some indications that it may affect properties of the atmospheric aerosols (Kazil et al., 2008; Mironova et al., 2008, 2012) and possibly even cloud formation (Carslaw et al., 2002; Tinsley, 2008), which may be crucially important as an indirect factor affecting the climate. However, it is still a subject of intensive debates (Pierce and Adams, 2009; Kulmala et al., 2010; Usoskin et al., 2010; Calogovic et al., 2010). Statistical correlation studies are inconclusive and lead to contradictory results largely because the contemporary fast expansion of the anthropogenic factor makes it difficult to study the natural variability of the terrestrial system, including the solar factor, by means of statistical/phenomenological methods. Direct laboratory and in-situ experiments (Kulmala et al., 2010; Kirkby et al., 2011; Enghoff et al., 2011) suggest that enhanced ionization may lead to aerosol particle formation in the realistic conditions, but this effect is small. However, a quantitative model enabling an assessment of the cosmic ray influence on the aerosol properties still does not exist, even in the form of a simple empirical parametrization.

Here we continue studying, from atmospherical point of view, major solar energetic particle (SEP) events occurring in relation to solar eruptive phenomena, when the flux of energetic particles can be enhanced by many orders of magnitude during hours-days. While the effect caused by such SEP events in the upper atmosphere is more or less known (Randall et al., 2007; Seppälä et al., 2008; Egorova et al., 2011; Rozanov et al., 2012), its possible influence on the lower atmosphere is still unclear. Previous phenomenological studies (Mironova et al., 2008, 2012) yielded that there is a small, marginally detectable effect of an extreme SEP, e.g. such as the one of 20 January 2005, on the aerosol particles in the lower-middle polar stratosphere during stable winter/summer conditions. However, an appropriate model able to explain the observed features is still missing. Here we study the series of SEP events in the Autumn 1989, which was among the largest events, aiming at providing an assessment of the possible atmospheric effect of energetic particles on stratospheric-tropospheric aerosols. We focus on short-time sporadic solar eruptive events, which can help in separating the cosmic ray effect because of its sharp temporal (duration of hours-days) and spatial (polar region) localization. It is a step forward toward a realistic consideration of the effect for forming up an empirical quantitative model, able to parameterize the atmospheric changes (ionization rate, aerosols properties, etc.) for specific conditions, such as the flux of cosmic rays of galactic/solar origin, season and location.

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2 Data for the time interval of September–October 1989

For our analysis we have chosen the time interval of September–October 1989, where a series of major SEP events, recorded also as ground level enhancements (GLE) of ground-based neutron monitors, took place. These SEP events were among the strongest ones in the 22nd solar cycle (Duldig et al., 1993; Lovell et al., 1998). On the other hand, the atmospheric conditions were monitored by several space-borne instruments during that period, making a detailed case study possible. While the chemistry of the upper atmosphere is known to be greatly affected by the SEP events in the Autumn of 1989 (Vitt et al., 2000; Verronen et al., 2002), a direct detailed analysis of the low and middle atmosphere data has not been done previously.

2.1 Solar energetic particles and cosmic ray induced ionization

As an index of cosmic ray variability, we show in Fig. 1 (upper panel), the count rate of the polar Oulu neutron monitor. One can see, that four GLE/SEP events took place during September–October 1989, the strongest event of the series occurred on 29 September (Day of Year, DOY 272); followed by a series of moderate events of 19, 22 and 24 October (DOY 292, 295 and 297, respectively). These events are indicated by vertical lines at this and forthcoming Figures. The lower panel of Fig. 1 depicts the corresponding cosmic ray induced ionization (CRII) of the atmosphere, calculated using the CRAC:CRII model (Usoskin and Kovaltsov, 2006; Usoskin et al., 2010). One can see that the ionization effect of the SEP events penetrated down to about 10 km for the greatest of the analyzed events of DOY 272, to about 15 km for moderate events of DOY 292 and 297 and was hardly noticeable below 18 km for the weak event of DOY 295. Atmospheric ionization during these events has been discussed in Usoskin et al. (2011). We note that GLEs of the Autumn 1989 were weaker than that of January 2005. However cosmic ray induced ionization of the stratosphere over polar regions on 29 September 1989 was at the same order of magnitude as it was on 20 January 2005

(Usoskin et al., 2011). This leads us to concentrate our analysis on the September event but also taking into account the others GLEs having place in the Autumn 1989.

2.2 Remote sensing of the atmosphere during September–October 1989

During the Autumn 1989 two satellites provided vertical profiles of aerosol extinctions over polar regions. One of them was satellites with SAGE II apparatus giving retrieval information on aerosol extinction at the 1020, 525, 453, and 385 nanometer wavelengths, the aerosol surface area density and the effective radius. Another satellite had SAM II experiment, also giving information about the aerosol extinction at only one wavelength of 1000 nm. Let us consider both satellites separately with their experiments and their capabilities of taking data for our investigation.

2.3 Latitudinal coverage of SAGE II

The Stratospheric Aerosol and Gas Experiment (SAGE) II data and all supported information were taken from the site (http://www-sage2.larc.nasa.gov/).

The SAGE II was launched aboard the Earth Radiation Budget Satellite in October 1984. The SAGE II instrument used the solar occultation technique to measure attenuated solar radiation through the Earth's limb in the channels centered at wavelengths ranging from 385 to 1020 nm. The exo-atmospheric solar irradiance is also measured in each channel during each event for the use as a reference in determining limb transmittances. The instrument provides high quality measurements of ozone, nitrogen dioxide, water vapor, and multi-wavelength aerosol extinction from the mid troposphere to as high as the lower mesosphere. The aerosol data contains profiles of aerosol extinction at 1020, 525, 453, and 385 nm, the aerosol surface area density and the effective radius at the vertical resolution of 0.5 km.

Latitudinal coverage of the satellite with the SAGE II instrument, during the end of September till the end of October 1989, is presented in Fig. 2. One can see that during that period SAGE II could cover all altitudes from the equator to polar areas in both

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hemispheres. Since additional ionization effects from a GLE event will be noticed only in the polar atmosphere, we need to use for our investigation only data obtained from polar regions. On Fig. 2 these regions are shown by dashed boxes. Unfortunately in spite of the extensive data coverage of the Northern Hemisphere, we can not use it for our analysis since the highest latitude distance of the SAGE II orbit did not cover polar regions for the period of time under investigation. As one can see in Fig. 2 only during the first GLE on DOY 272, SAGE II could cover Southern Hemisphere polar regions that helps us in our study.

2.4 Latitudinal coverage of SAM II

The Stratospheric Aerosol Measurement (SAM) II data and all the supported information were taken from the site of Atmospheric Science Data Center (http://eosweb.larc.nasa.gov/).

The SAM II instrument, aboard the Earth-orbiting Nimbus-7 spacecraft, was designed to measure solar irradiance attenuated by aerosol particles in the Arctic and Antarctic stratosphere. The scientific objective of the SAM II experiment was to develop a stratospheric aerosol data base for the polar regions by measuring and mapping vertical profiles of the atmospheric extinction due to aerosols. The measurement technique is solar occultation. The latitude of the measurements was slowly changed with the season by one to two degrees per week. Therefor for our short period study of about one month the latitudinal changes could not play a big role in our case in contrast to the SAGE II measurements. The operations SAM II took place in the latitude regions about 70 degrees for both polar hemispheres. Unfortunately SAM II provides aerosol extinction data only at one wavelength of 1000 nm.

As a sub-conclusion on the satellites data over the Autumn 1998 we notice that we can use SAGE II data (see Fig. 2) only for the southern polar hemisphere and only for an analysis of the largest GLE of 29 September 1989. And SAM II aerosol information can be taken only at 1000 nm wavelength, but for both polar hemispheres for all the GLEs over the end of September till the end of October 1989.

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3 Aerosol properties associated with the GLE event

Ions play an important role in the atmospherical processes. However up to now the role of ions in the aerosol formation is still not clear. One of the proposed link mechanism (Carslaw et al., 2002) is so called "the ion-aerosol clear-air mechanism" based on the presence of ions that enhance formation and early growth of aerosol particles in the atmosphere so that such fractions may eventually grow to cloud condensation nuclei (CCN). An additional ionization sources ionization in the polar atmosphere can help to test this possible mechanism of aerosol formation in the real cold atmosphere. Such additional ionization sources can be short-time sporadic solar eruptive events, which can help in separating the effect of cosmic rays because of their sharp temporal (duration of hours-days) and spatial (polar region) localization. An analysis of vertical aerosol profiles during such sporadic events shall show the exact altitudinal regions where some changes connected with investigated increasing of ionization rate and numbers of ions in the atmosphere take place.

3.1 Aerosol properties observed by SAGE II

Altitudinal and temporal 2-D variations of the optical properties of aerosols are shown in Fig. 3. Altitudinal and temporal 2-D variations of aerosol microphysical properties such as effective aerosol radius and aerosol surface area density are shown on the upper panels of Fig. 4. Variations of the temperature for the southern polar atmosphere for the period of time under investigation can be also seen on the lower panel of Fig. 4. All the SAGE II data used in the present study are zonal averages over the appropriate longitudes in the polar region.

As mentioned in Sect. 2.2 the data from SAGE II can be used for finding atmospheric effects only from the first GLE event that took place on DOY 272. And unfortunately this data can not be compared with the SAGE II data obtained in the Northern Hemisphere. Figures 3 and 4, where altitudinal and temporal variations of aerosol optical as well as aerosol microphysical properties are shown, clearly indicate an increase of aerosol

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parameters after the GLE event. In Fig. 3 one can see that over the altitudinal range of about 13 km, after DOY 272, the aerosol extinction in the visible wavelengths increased by an order of magnitude in comparison with previous days. However, this effect is less notable for the aerosol extinction at the longest wavelengths. The variations of aerosol optical parameters are confirmed by microphysical changes of aerosol properties. In Fig. 4 (upper panel) one can also see notable increase of the aerosol surface area density on the second day after the GLE and subtle changes in the aerosol effective radius. Lower panel of Fig. 4 shows altitudinal and temporal temperature changes. Here a decrease of temperature down to 195 K is visible after DOY 272 over the altitude range from 12 to 20 km. These results let us propose two scenarios of the changes of aerosol properties. One is the homogenous theory of the new aerosol particle formation after a decrease of the temperature and another scenario is related to additional ionization that also can lead to the notable effect from the exact day of GLE. The latter can be illustrated by Fig. 3 and upper panels of Fig. 4, where one can see formation of additional small aerosol fractions and/or growth up to the CCN size exactly after the day of the GLE on 29 September 1989.

3.2 Aerosol properties observed by SAM II

Exploitation of the data from the SAM II instrument gives us a good opportunity to compare some results obtained by SAGE II over Southern Hemisphere and also to have an additional information about behavior of aerosols and temperature over the northern polar regions during the period of time needed for investigation. However here we also need to remind that the data from SAM II can be taken only at 1000 nm, and it is hard to do an approximation of microphysical changes of aerosol particles as well as of the optical properties in the visible range of wavelengths. Nevertheless after analysis of the SAM II data sets we will be able to see what happened in both southern and northern polar hemispheres for all the GLEs over September–October 1989. Here we also used SAM II data that has zonal averaged over the appropriate longitudes in the both polar region.

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Altitudinal and temporal 2-D variations of the aerosol extinction at wavelength of 1000 nm, and the temperature for the Southern and the Northern Hemispheres are presented in Fig. 5. On upper panels of Fig. 5 variations of aerosol parameters and the temperature changes are shown over the investigated period of time for the Southern Hemisphere. Low panels of Fig. 5 show behavior of aerosols and temperature changes over the investigated period of time for the Northern Hemisphere.

Let us begin our analysis with the SAM II aerosol data over the Southern Hemisphere. Here, in Fig. 5a, one can see a small increase of the aerosol extinction after DOY 272, that is in good agreement with altitudinal and temporal variations of the aerosol extinction obtained by SAGE II (Fig. 3d). However changes of temperature (Fig. 5b) began much earlier that as shown in Fig. 4 (lower panel). The decrease of the temperature down to 190 K over altitudes at about 11–20 km began in the SAM II data from DOY 270. However SAGE II data show decrease of the temperature down to 195 K over the same altitudes from DOY 272. No parallel changes are observed in the aerosol optical properties recorded by the SAGE II and the SAM II tools at the comparable wavelength of about 1000 nm (SAGE II – 1020 nm and SAM II –1000 nm). On Fig. 5a, in the altitude range of about 10–15 km, one can see a small increase of aerosol extinction on DOY 275. Nevertheless Fig. 3d, where the aerosol extinction at 1020 nm detected by SAGE II is presented, shows also a weak increase of aerosol extinction on DOY 273. However at other wavelengths of SAGE II, Fig. 3a–c, one can see some aerosol optical changes, that can be logically confirmed by the data of SAM II, see Fig. 5a.

In spite of these differences in the temperatures and the aerosol extinctions at wavelength about of 1000 nm, recorded by the SAGE II and the SAM II tools, we can confirm that both instruments show formation and/or growth of the aerosol particles after DOY 272.

The situation is completely different for the Northern Hemisphere in comparison with Southern Hemisphere, see Fig. 5 (lower panel). No notable changes are during the

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investigated period of time. However the temperature is also much higher that it can be observed in the Southern Hemisphere.

4 Conclusions

A detailed analysis of the behavior of aerosol particles and their dependence on temperature variations and increase of ionization over the end of September till the end of October 1989 for both polar hemispheres is presented. Here we found a minor possible effect from the additional ionization coming from one of the biggest GLE event in September 1989.

We conclude that the present results show variations of the aerosol optical and microphysical parameters (in the cold polar stratosphere) that are similar to the aerosol variations detected after the GLE in January 2005 (Mironova et al., 2012). The recognized effect, during these two GLEs (20 January 2005 and 29 September 1989), is found at the same altitude range 10–20 km. However, during September 1989 the effect penetrated deeper into the lower stratosphere. No effects was found at other altitudes. The maximum effect was observed some days after the GLE. Based on the present investigation we conclude that ionization plays a role additional to the temperature in formation of clouds over the polar stratosphere. No observable effect in formation and/or growth of preexisting ultrafine particles in the polar stratospheric region was found for the weaker GLEs during October 1998.

Acknowledgements. The SAGE II data is provided by the NASA Langley Research Center (NASA-LaRC) and the NASA Langley Radiation and Aerosols Branch. The SAM II data is provided also by the NASA Langley Research Center and obtained from the Langley DAAC User and Data Services Office. Data of Oulu neutron monitor are available at http://cosmicrays.oulu.fi. Supports from the Academy of Finland and Suomalainen Tiedeakatemia are acknowledged. IM acknowledges support from St. Petersburg State University grant 11.42.503.2011. The present work was performed in relation with the following international programmes: CAWSES-II and COST ES0803 and ES1005. Part of this work was supported by the COST Action

ES1005 “Toward a more complete assessment of the impact of solar variability on the Earth’s climate”. IM and IU acknowledge useful discussions within the ISSI Team on Study of Cosmic Ray Influence upon Atmospheric Processes.

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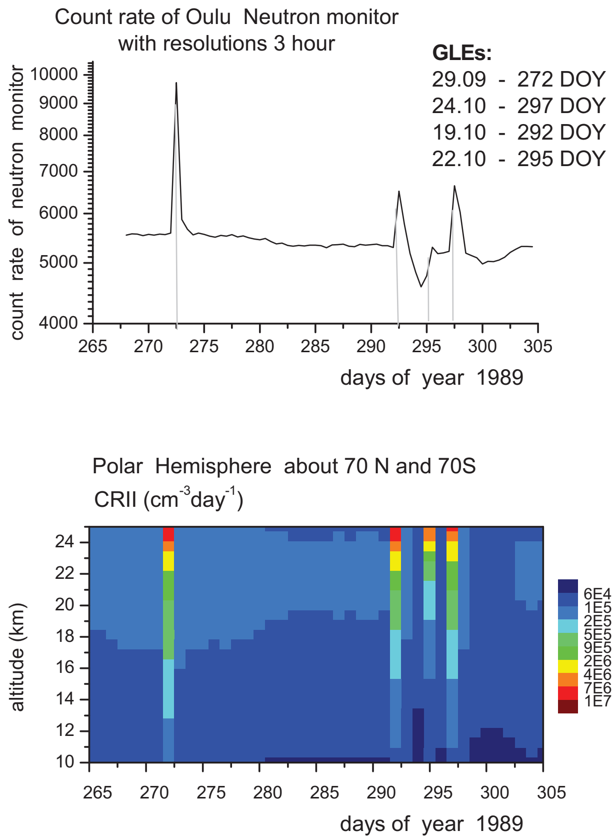

Fig. 1. Cosmic rays and atmospheric ionization variability during the period of September–October 1989. Upper panel: daily averaged count rate of the Oulu polar neutron monitor, four GLE/SEP events are indicated by the vertical lines. Lower panel: calculated corresponding cosmic ray induced ionization rate in the polar atmosphere. Logarithmic color scale is shown on the right panel.

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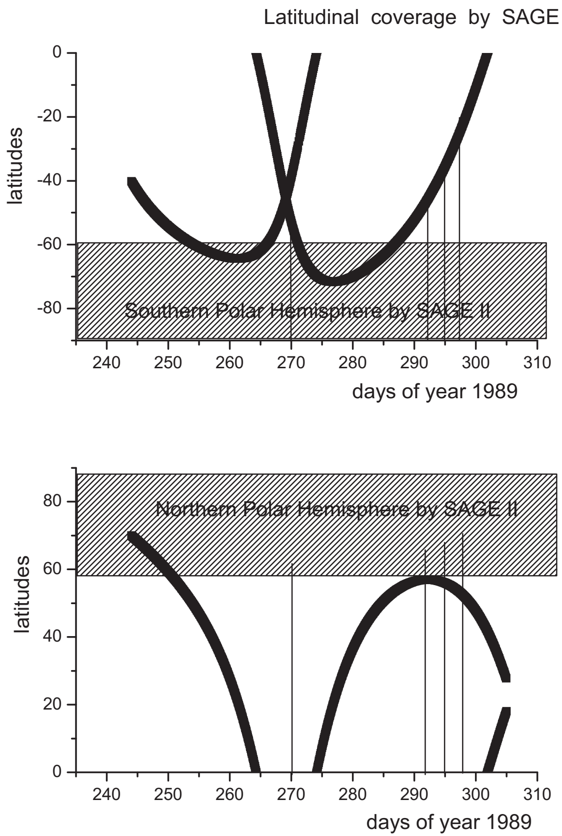

Fig. 2. Latitudes distance of SAGE II during September–October 1989. The days of GLEs mentioned by lines. Upper panel: latitudinal coverage of the satellite and operation of the instrument during each sunrise and sunset measurement over Southern Hemisphere. Lower panel: the same as for upper panel, but over Northern Hemisphere.

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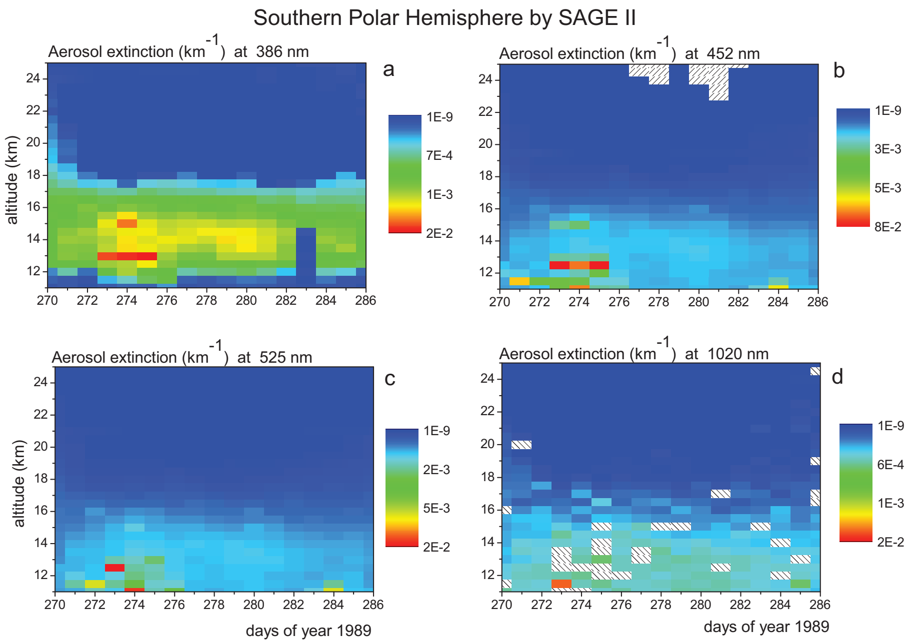

Fig. 3. SAGE II aerosol optical properties such as aerosol extinctions at four wavelengths 1020 nm, 525 nm, 453 nm and 386 nm for the southern polar hemisphere.

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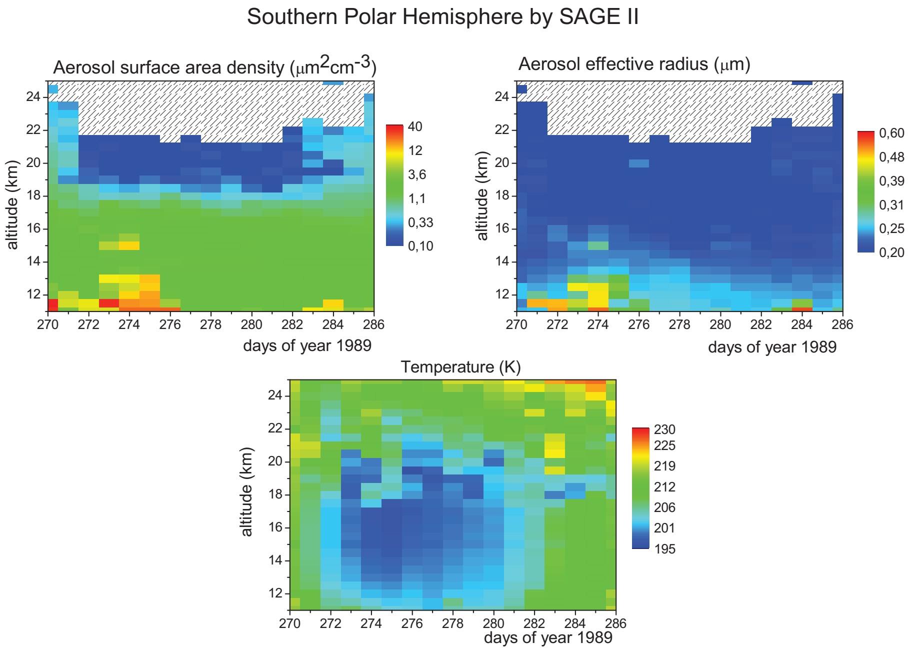

Fig. 4. Aerosol microphysical properties and temperature obtained by SAGE II data sets. Logarithmic color scale is shown on the right of each panel. Upper panel: variations of surface area density and effective aerosol radius. Lower panel: variations of temperature.

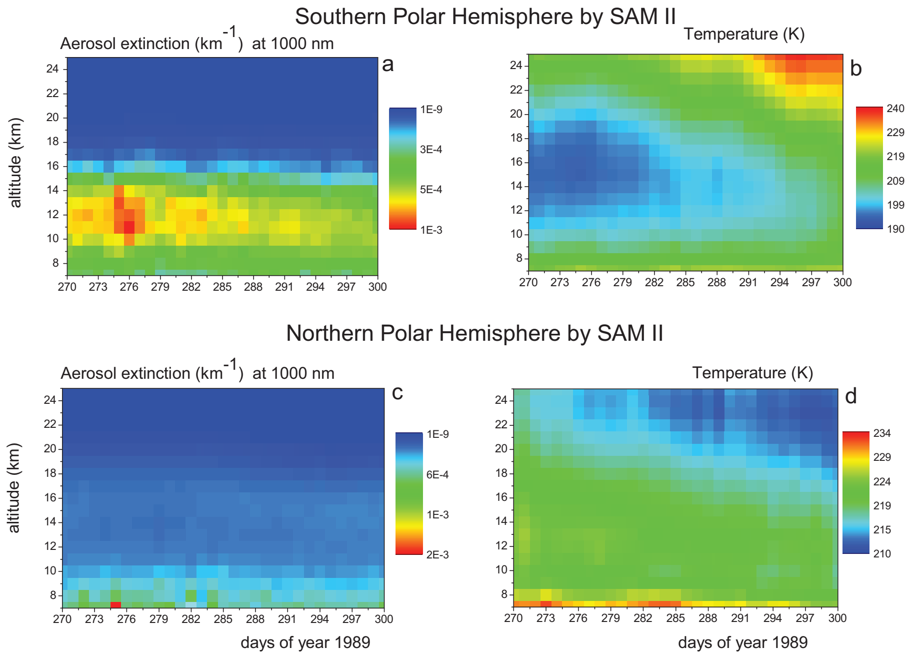

Fig. 5. Variations of the aerosol extinction at wavelength of 1000 nm and the temperature over polar hemispheres during the end of September till the end of October 1989. Upper panel: variations of atmospheric parameters over the Southern Hemisphere. Lower panel: the same but for the Northern Hemisphere. Logarithmic color scale of temperature changes is shown on the right of each panel.