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Variations of aerosol optical properties during the extreme solar event in January 2005

I. A. Mironova,[1] L. Desorgher,[2,4] I. G. Usoskin,[3] E. O. Flückiger,[2] and R. Bütikofer[2]

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[1] We present the results of analysis of the aerosol optical depth variations for January 2005 when an extreme solar energetic particle event occurred leading to a greatly enhanced flux of energetic particles penetrating into the atmosphere. An increase of the concentration of sulfate or nitrate aerosol was found on the second day after the solar energetic particle event in the south magnetic pole region with the maximum penetration of anisotropic solar cosmic rays. This suggests that an enhanced flux of solar energetic particles can lead to notable changes in the chemical and physical properties of the polar troposphere. A statistical test confirms that the observed change of the aerosol index is significant and is unlikely to be related to a spatial or temporal independent fluctuation of the aerosol content. Thus, the results of the present work provide evidence of a direct influence of cosmic rays on physical-chemical properties of the atmosphere. **Citation:** Mironova, I. A., L. Desorgher, I. G. Usoskin, E. O. Flückiger, and R. Bütikofer (2008), Variations of aerosol optical properties during the extreme solar event in January 2005, *Geophys. Res. Lett.*, *35*, L18610, doi:10.1029/2008GL035120.

1. Introduction

[2] Cosmic rays (CR) are energetic particles of galactic or solar origin continuously bombarding the Earth's atmosphere. They penetrate deep into the atmosphere and initiate complicated nucleonic-muon-electromagnetic cascades, ionizing the ambient air [*Dorman*, 2004]. While the direct energy input of cosmic rays into the atmosphere is minor, they form the main source of ionization (cosmic ray induced ionization – CRII) of the low and middle atmosphere. Therefore, cosmic rays may, via CRII, play a role in physical-chemical processes in the atmosphere. However, such possible cosmic ray induced changes of the atmospheric properties are still far from being understood. In particular, theoretical modelling of such processes is extremely difficult and includes a still missing link between micro- and macro-physics. Phenomenological correlative studies are limited in interpretation, especially on an inter-annual time scale, since the CR-atmosphere relations, if existent, may be masked by other concurrent processes of external (solar total/spectral irradiance variations, geomagnetic activity) [*Voiculescu et al.*, 2006; *Haigh*, 2007] or internal (Quasi-Biennial Oscillations (QBO), North Atlantic Oscillations (NAO), El Niño Southern Oscillations (ENSO), volcanic activity etc.) origin [*Benestadt*, 2002; *Dorman*, 2004; *Voiculescu et al.*, 2007]. Promising in disentangling different effects is the use of strong sporadic events rapidly changing the CR flux, such as Forbush decreases (a sudden suppression of galactic CR flux by 5–25% due to passage of an interplanetary transient) or solar energetic particle (SEP) events (a short increase of CR flux up to several orders of magnitude due to the arrival of solar energetic particles). A special case of the latter is a ground level enhancement (GLE) of the count rate of ground-based neutron monitors, implying that some of the solar energetic particles are energetic enough to undergo nuclear reactions and produce a flux of neutrons detectable by ground-based neutron monitors. Some earlier studies reported casual statistical relations between such sporadic events (e.g., Forbush decreases, SEP events and heliospheric current sheet (HCS) crossing) and various atmospheric parameters, e.g., cloud formation [*Pudovkin and Veretenenko*, 1995], atmospheric transparency [*Roldugin and Tinsley*, 2004], vorticity [*Tinsley et al.*, 1989; *Veretenenko and Thejll*, 2004]. Most of the earlier phenomenological studies declared a statistical relation based on the superposed epoch analysis, while the effect of single events was barely visible. A clear case study was still missing [*Usoskin and Kovaltsov*, 2008].

[3] An extreme and one of the strongest ever observed SEP events occurred on 20 January 2005. Because of the very high anisotropy during the maximum phase of the event, the strongest ionization effect was limited to a relatively small region on Earth in the Antarctic region (see detailed description of the event in section 2). Thus, a unique opportunity exists to perform a detailed phenomenological study of whether such an extreme event can produce a notable effect in the observed atmospheric parameters.

[4] One of the atmospheric characteristics that can respond to rapid changes in CRII is the atmospheric aerosol content. However, an increase in atmospheric aerosols can only occur in regions where both ions produced by CR and trace gases with a possibility to attach to atmospheric ions are present. The maximum CRII rate occurs in the stratospheric layers at about 15–20 km. This corresponds to the altitudes of maximum of sulphuric and nitric acid vapor concentrations and where the formation of stratospheric clouds takes place. It can be supposed that the aerosol particles can be involved in the ion induced aerosol formation scheme [*Kazil et al.*, 2006; *Arnold*, 2006; *Tinsley and Zhou*, 2006; *Svensmark et al.*, 2007; *Yu*, 2004] and thus be sensitive to variations of CRII.

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[1] Institute of Physics, Saint-Petersburg State University, St. Petersburg, Russia.

[2] Cosmic Ray Group, Physikalisches Institut, University of Bern, Bern, Switzerland.

[3] Sodankylä Geophysical Observatory, University of Oulu, Oulu, Finland.

[4] Also at SpaceIT GmbH, Bern, Switzerland.

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[5] On the other hand, aerosol particles scatter and absorb solar and terrestrial radiations depending on their microphysical and optical characteristics. This makes them not only an important player in the Earth's radiation budget, but also allows their measurement from satellites. In the present Letter we aim to perform a statistical analysis of a possible response of the satellite-based atmospheric aerosol index to the extreme SEP event in January 2005.

2. Data and Analysis Methods

2.1. Aerosol Optical Depth

[6] The TOMS (Total Ozone Mapping Spectrometer onboard NASA spacecraft) is an instrument that makes precise observations of the aerosol content in the atmosphere. TOMS aerosol data is quantified in units of the aerosol index (AI). The TOMS aerosol index (collected by NASA on http://toms.gsfc.nasa.gov/) is related to the aerosol optical depth. The relationship between the aerosol index and the optical depth depends on the altitude. Aerosols at low altitudes lead to a lower TOMS aerosol index than an equivalent amount of aerosols at a higher altitude. Data from TOMS can be used to detect the presence of both UV absorbing aerosols and non-absorbing aerosols. AI has a positive sign for UV-absorbing aerosols, such as smoke produced by biomass burning, black carbon from urban and industrial activities, and a negative sign for non-UV absorbing aerosols, which are primarily sulfate (H_2SO_4) or nitrate (HNO_3) aerosols.

[7] The TOMS aerosol index is defined as the difference between the observations and model calculations from a pure molecular atmosphere with the same surface reflectivity and measurement conditions. Quantitatively, the aerosol index AI is defined as [e.g., *Hsu et al.*, 1999]:

$$\mathrm{AI} = -100 \cdot \left[\log_{10}\left(\frac{I_{360}}{I_{331}}\right)_{\mathrm{meas}} - \log_{10}\left(\frac{I_{360}}{I_{331}}\right)_{\mathrm{calc}} \right], \qquad (1)$$

where I_{360} (or I_{331}) corresponds to the backscattered radiance at the 360 nm (or 331 nm) wavelength, and subscript *meas* or *calc* denotes that the values are measured or calculated, assuming a measured atmosphere of non-absorbing aerosols plus pure molecular scatterers, and a calculated atmosphere of pure molecular scatterers, respectively. When UV absorbing aerosols are present in the atmosphere, the spectral contrast (I_{360}/I_{331}) is smaller than predicted by the calculation model, and positive residues are produced by equation (1). Non-absorbing aerosols produce greater spectral contrast, and thus result in a negative AI. Absolute value of AI correspond to the content of aerosol particles in the atmosphere.

2.2. Model of Cosmic Ray Induced Ionization of the Atmosphere

[8] When energetic CR particles enter the atmosphere, they initiate a nucleonic-muon-electromagnetic cascade. Development of the atmospheric cascade leads, in particular, to ionization of the ambient air in the troposphere. The CR particles with energies below 1 GeV produce ionization and large amounts of NO_x in the lower stratosphere without nuclear reactions. It is a complicated task to model the CRII process, which requires massive numerical Monte-Carlo simulations of the atmospheric cascade [*Usoskin and Kovaltsov*, 2006]. The Bern model [*Desorgher et al.*, 2005; *Desorgher*, 2007] called PLANETOCOSMICS, based on the GEANT4 simulation package [*Agostinelli et al.*, 2003] are used for CRII computations. Only energetic CR particles with rigidity above about 1 GV can penetrate down to the troposphere to ionize it. Moreover, additional shielding due to the geomagnetic field requires particles to have more energy to penetrate the atmosphere at lower latitudes.

3. Results and Discussion

3.1. CRII of the Low Atmosphere During GLE of 20 January 2005

[9] CRII is always present in the atmosphere due to the flux of galactic CR, which is modulated by the varying solar activity and/or interplanetary transients (shock waves, magnetic clouds, etc.). Occasionally, the flux of incoming CR particles can be greatly enhanced due to sporadic injection of energetic particles of solar or interplanetary origin. Usually, these particles are not energetic enough to produce ionization in the troposphere, but sometimes their energy can reach several GeV and thus they are able to induce enhanced ionization in the polar troposphere and stratosphere. Such events may occur several times per solar cycle, and it is of great importance to study their effect due to enhanced CRII.

[10] One of the most severe SEP events took place on 20 January 2005. The X7 flare and coronal mass ejection (CME) occurred at about 07 UT and produced the hardest and most energetic proton event in solar cycle 23 measured at or near Earth. The flare position was near the west limb (12°N, 58°W) on the Sun, implying that solar particles were directed towards Earth. This SEP led to the largest GLE measured by neutron monitors since 1956 [*Mewaldt et al.*, 2007], and had a very hard energy spectrum of SEP during the initial phase, implying a significantly increased flux of energetic particles [*Plainaki et al.*, 2007; *Bütikofer et al.*, 2008]. The GLE at ground based neutron monitors started first at Antarctic stations at about the same time as the X7 flare and CME were recorded. The duration of the GLE was a few hours. Two components can be distinguished during the event – a highly anisotropic prompt component with a hard energy spectrum and a softer prolonged component with a nearly isotropic flux of SEP [*Plainaki et al.*, 2007; *Bütikofer et al.*, 2008].

[11] Because of the highly anisotropic first component of SEP, a full 3D computation, including particle tracing in the magnetosphere, has been performed to calculate the corresponding CRII. The calculation has been done by the GEANT4 code PLANETOCOSMICS [*Desorgher*, 2007]. The resultant tropospheric CRII during the peak of the event is shown in Figure 1. One can see an increase of the ionization rate by two orders of magnitude during the very peak of the event in a limited region around 70°S 140°E. Enhanced (by an order of magnitude) ionization was expected also in the South Pole region and in a narrow belt around 65°N.

3.2. Variations of the Aerosol Optical Depth

[12] As discussed above, one of the atmospheric parameters that can be affected by CRII is the abundance of

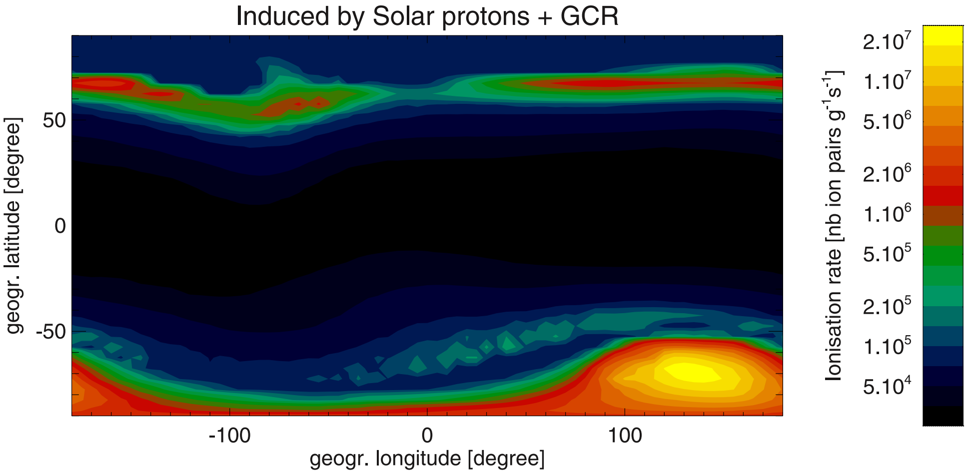

Figure 1. Cosmic rays induced ionization (CRII) rate at the atmospheric depth of 300 g/cm^2 (altitude about 9 km) computed for the peak of GLE (0655–0700 UT) 20 January 2005.

aerosol particles. Aerosol production by ion-induced nucleation is limited by the concentration of the small ions. Therefore the enhanced ion production rates (see Figure 1) associated with the SEP event, can greatly enhance the rate of formation of new particles. However, fundamental mechanisms that lead to new particle formation are still poorly understood.

[13] In our investigation we pay special attention to the regions with strongly increasing CRII (by several orders of magnitude) during the peak of the January 2005 event. Sites with available data in the TOMS aerosol index data set corresponding to these regions are presented in Figure 2. We found six data sets of AI, shown as stars in Figure 2, in a limited region around 70°S 140°E where the maximum CRII increase was expected (see Figure 1). Beyond the above six sites, another fifteen data sets of AI (denoted as polygons and squares in Figure 2) were found in the region with a moderate (more than an order of magnitude) CRII increase as shown in Figure 1. Unfortunately, no AI data sets are available for the Northern Hemisphere in the region of increasing CRII during January 2005.

[14] Normalized (i.e., the average level is subtracted and the residual is divided by the standard deviation) variations of the daily AI data during second half of January 2005 at these selected sites are presented in Figure 3. Figure 3 (top)

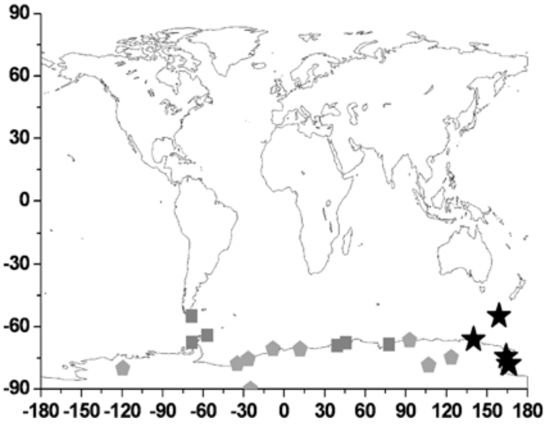

Figure 2. Sites from the TOMS aerosol index data set corresponding to enhanced CRII rate on 20 January 2005; stars, polygons and squares correspond to CRII increase by a factor of >100, 30–100 and 10–30 (yellow, red and green areas in Figure 1, respectively). Note that symbols for closely located sites may overlap, i.e., some measuring points may be not visible in Figure 2.

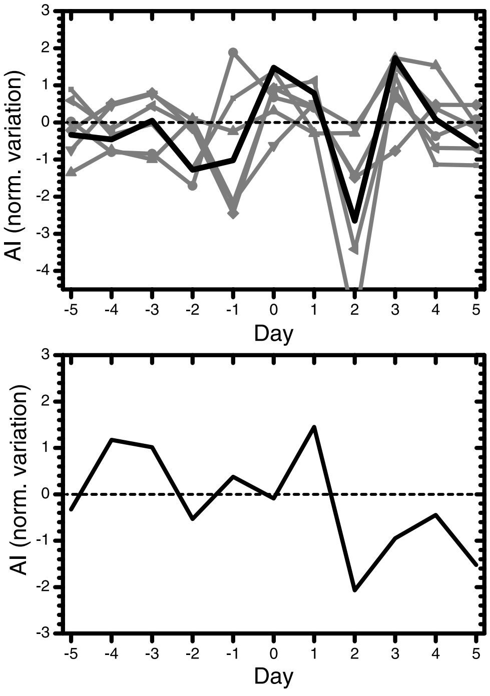

Figure 3. Normalized variations (zero mean and unity standard deviation) of the daily Aerosol Index (AI) at sites corresponding to the enhanced CRII in January 2005. X-axis gives the days with respect to 20 January 2005 (day 0). (top) Individual AI variations (grey curves) at six sites with the largest CRII increase (stars in Figure 2) as well as the average variation (thick black curve). (bottom) Mean AI variations for all the 15 sites shown as polygons and squares in Figure 2.

shows AI variations over the six sites at the maximum CRII (stars in Figure 2). One can see a simultaneous decrease of the AI on the second day after the GLE over all the six stations. The averaged curve shows that the decrease is statistically significant at a level of about 2.5σ (significance ≈ 0.01).

[15] The observed 2-day delay between the GLE event and the increase in the content of non-absorbtion aerosol particles is consistent with the time needed for the accumulation of aerosol particles in the upper troposphere [*Arnold*, 2006; *Yu*, 2004]. Note that the AI values were systematically negative during the studied period for most sites indicating that the aerosol particles in that region were mostly sulfates. From the physical point of view a further decrease of a negative value of AI means an increasing content of non-absorbing aerosols and primarily sulfates in the atmosphere. A typical altitude of this kind of aerosol particles is 10–17 km, which corresponds to the maximum CRII effect. Figure 3 (bottom) shows the normalized AI variations averaged over all the fifteen sites marked polygons and squares in Figure 2. A notable decrease in the AI on the second day after the GLE is apparent here as well. The significance level of this result is about 2σ (significance ≈ 0.05).

[16] The above formal significance estimates are based on an assumption that all the station signals are independent, which may be not exactly true for adjoining stations, leading to a possible overestimate of the significance level. Accordingly, in order to check the geographical consistency of the obtained effect, we performed the following analysis. We have divided the Earth surface into 36 regions, each occupying a 30°-by-60° area in latitude-longitude. In each such defined region we calculated the average (of all stations that are available in the TOMS data set, located in the corresponding region) normalized variations of AI during 14–26 January 2005. We found that 27 (out of the total 36) regions are covered by reliable observations for the period under investigation. Significant variations (either increase or decrease exceeding the 2σ level) of AI was found on the second day (22 January 2005) only in one region 60°–90°S 120°–180°E, exactly where it is expected from the model (see the yellow region on Figure 1). A marginally significant ($1-2\sigma$) response was found in three more regions, two also in Antarctica (60°–90°S 60°–120°W; and 60°–90°S 0°–60°E) and one in the tropics (0°–30°N 120°–180°E). The aerosol index does not depict significant consistent variations in other regions. We can not conclude anything about possible variations of AI in the northern high latitude region, because of the absence of TOMS data. Thus, the observed geographical pattern in the AI index variations is consistent with the modeled CRII – the strongest effect in eastern Antarctica, and a weak marginally observable effect in the rest of Antarctica.

[17] We also performed an additional statistical check to exclude the possibility that a strong deviation of the AI index is a typical feature for eastern Antarctica in January. We have analyzed, in a similar manner, variations of the AI at the same six stations, shown as stars in Figure 2, for the same period of 10–30 January but for different years, 1996 through 2004. We did not find any statistically significant variations comparable to that of 22 January 2005. Therefore, we can conclude that the observed increase of the non-absorbing aerosol particles on 22 January 2005 is probably not the result of a regional character that is typical for the local (Austral) summer, but is most probably related to the SEP event on 20 January 2005. A conservative estimate of the significance of the effect is mostly defined by the possibility that it could be caused not by the SEP event but accidentally by a local cause. The chance of such a random occurrence can be roughly estimated as ≈10%, since no other comparable effect was found in the same region and same season over 10 years.

4. Conclusion

[18] The analysis of variations of the daily aerosol optical depth for January 2005 is presented. A significant increase of the content of non-absorbtion (sulfate or nitric) aerosol particles in the atmosphere was observed in the Antarctic region on the second day after an extreme solar energetic particle event of 20 January 2005. This increase is associated with the greatly enhanced (by several orders of magnitude) cosmic ray induced ionization in that region during the event. A statistical test confirms that the observed change of the aerosol index is significant and is unlikely to be related to a spatial or temporal independent fluctuation of the aerosol content.

[19] Thus, the results of the present work provide evidence of a possible influence of cosmic rays on physical-chemical properties of the atmosphere.

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References

Agostinelli, S., et al. (2003), GEANT4—A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A*, *506*, 250–303.

Arnold, F. (2006), Atmospheric aerosol and cloud condensation nuclei formation: A possible influence of cosmic rays?, *Space Sci. Rev.*, *123*, 169–186, doi:10.1007/s11214-006-9055-4.

Benestadt, R. E. (2002), *Solar Activity and Earth Climate*, Praxis, Chichester, U. K.

Bütikofer, R., E. O. Flückiger, L. Desorgher, and M. R. Moser (2008), The extreme solar cosmic ray particle event on 20 January 2005 and its influence on the radiation dose rate at aircraft altitude, *Sci. Total Environ.*, *391*, 177–183.

Desorgher, L. (2007), User guide of the PLANETOCOSMICS code, University of Bern, Bern, Switzerland. (Available at http://cosray.unibe.ch/~laurent/planetocosmics)

Desorgher, L., E. O. Flückiger, M. Gurtner, M. R. Moser, and R. Bütikofer (2005), Atmocosmics: A GEANT4 code for computing the interaction of cosmic rays with the Earth's atmosphere, *Int. J. Mod. Phys. A*, *20*, 6802–6804.

Dorman, L. I. (2004), *Cosmic Rays in the Earth's Atmosphere and Underground*, 855 pp., Kluwer Acad., Dordrecht, Netherlands.

Haigh, J. D. (2007), The Sun and the Earth's climate, *Living Rev. Sol. Phys.*, *4*, 2–64.

Hsu, N. C., J. R. Herman, O. Torres, B. N. Holben, D. Tanre, T. F. Eck, A. Smirnov, B. Chatenet, and F. Lavenu (1999), Comparisons of the TOMS aerosol index with Sun-photometer aerosol optical thickness: Results and applications, *J. Geophys. Res.*, *104*, 6269–6279.

Kazil, J., E. R. Lovejoy, M. C. Barth, and K. O'Brien (2006), Aerosol nucleation over ocean and the role of galactic cosmic rays, *Atmos. Chem. Phys.*, *6*, 4905–4924.

Mewaldt, R. A., C. M. S. Cohen, G. M. Mason, D. K. Haggerty, and M. I. Desai (2007), Long-term fluences of solar energetic particles from H to Fe, *Space Sci. Rev.*, *130*, 323–328, doi:10.1007/s11214-007-9200-8.

Plainaki, C., A. Belov, E. Eroshenko, H. Mavromichalaki, and V. Yanke (2007), Modeling ground level enhancements: Event of 20 January 2005, *J. Geophys. Res.*, *112*, A04102, doi:10.1029/2006JA011926.

Pudovkin, M. I., and S. V. Veretenenko (1995), Cloudness decreases associated with Forbush-decreases of galactic cosmic rays, *J. Atmos. Terr. Phys.*, *57*, 1349–1355.

Roldugin, V. C., and B. A. Tinsley (2004), Atmospheric transparency changes associated with solar wind-induced atmospheric electricity variations, *J. Atmos. Sol. Terr. Phys.*, *66*, 1143–1149.

Svensmark, H., J. O. P. Pedersen, N. D. Marsh, M. B. Enghoff, and U. I. Uggerhøj (2007), Experimental evidence for the role of ions in particle nucleation under atmospheric conditions, *Proc. R. Soc., Ser. A*, *463*, 385–396.

Tinsley, B. A., and L. Zhou (2006), Initial results of a global circuit model with variable stratospheric and tropospheric aerosols, *J. Geophys. Res.*, *111*, D16205, doi:10.1029/2005JD006988.

Tinsley, B. A., G. M. Brown, and P. H. Scherrer (1989), Solar variability influences on weather and climate: Possible connections through cosmic ray fluxes and storm intensification, *J. Geophys. Res.*, *94*, 14,783–14,792.

Usoskin, I. G., and G. A. Kovaltsov (2006), Cosmic ray induced ionization in the atmosphere: Full modeling and practical applications, *J. Geophys. Res.*, *111*, D21206, doi:10.1029/2006JD007150.

Usoskin, I. G., and G. A. Kovaltsov (2008), Cosmic rays and climate of the Earth: Possible connection, *C. R. Geosci.*, *340*, 411–450.

Veretenenko, S., and P. Thejll (2004), Effects of energetic solar proton events on the cyclone development in the North Atlantic, *J. Atmos. Sol. Terr. Phys.*, *66*, 393–405.

Voiculescu, M., I. G. Usoskin, and K. Mursula (2006), Different response of clouds to solar input, *Geophys. Res. Lett.*, *33*, L21802, doi:10.1029/2006GL027820.

Voiculescu, M., I. G. Usoskin, and K. Mursula (2007), Effect of ENSO and volcanic events on the Sun-cloud link, *Adv. Space Res.*, *40*, 1140–1145.

Yu, F. (2004), Formation of large NAT particles and denitrification in polar stratosphere: Possible role of cosmic rays and effect of solar activity, *Atmos. Chem. Phys.*, *4*, 2273–2283.

R. Bütikofer, L. Desorgher, and E. O. Flückiger, Cosmic Ray Group, Physikalisches Institut, University of Bern, CH-3012 Bern, Switzerland.

I. A. Mironova, Institute of Physics, Saint-Petersburg State University, Ulyanovskaya 1, Petrodvorets, St. Petersburg 198504, Russia. (mironova@geo.phys.spbu.ru)

I. G. Usoskin, Sodankylä Geophysical Observatory, University of Oulu, FIN-90014 Oulu, Finland. (ilya.usoskin@oulu.fi)