Solar and galactic cosmic rays in the Earth's atmosphere

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Summary. A brief review of the research of atmospheric effects of cosmic rays is presented. Numerical models are discussed, that are capable to compute the cosmic ray induced ionization at a given location and time. Intercomparison of the models, as well as comparison with fragmentary direct measurements of the atmospheric ionization, validates their applicability for the entire atmosphere and the whole range of the solar activity level variations. The effect of sporadic solar energetic particle events is shown to be limited on the global scale, even for for the most severe event, but can be very strong locally in polar regions, affecting the physical-chemical properties of the upper atmosphere, especially at high altitudes. Thus, a new methodology is presented to study cosmic ray induced ionization of the atmosphere in full detail using realistic numerical models calibrated to direct observations.

1 Introduction

Cosmic rays (CR) form an important outer space factor affecting physics and chemistry of the entire atmosphere. In particular, they are the main ionizing agent for the lower and middle atmosphere. For many practical purposes, e.g., for the impact of cosmic rays on the ozone layer and formation of clouds in the troposphere, it is important to know precisely the cosmic ray induced ionization (CRII) and its variations with the location, time, solar and geomagnetic activity. Two main components are important for CRII: (1) high energy galactic cosmic rays that are always present in the vicinity of the Earth and are subject of the solar modulation and (2) sporadic solar energetic particles of lower energy but high peak flux. The effect of both components is quantitatively studied here. Balloon experiments have been used in the past to measure the CRII at different locations and during several solar cycles (e.g., Neher, 1971; Lowder et al., 1972; Rosen et al., 1985; Ermakov et al., 1997), but a coordinated continuous world wide measurement of CRII is still missing. On the other hand, several physical models have been developed recently to compute CRII in the full range of physical parameters. In the framework of the COST-724 action, three numerical CRII models have been developed: Sofia model (Velinov and Mateev, 2005), Bern model (Desorgher et al., 2005; Scherer et al., 2006), and Oulu model (Usoskin et al., 2004; Usoskin and Kovaltsov, 2006). Here we present these models, their validation and comparison with direct observations and other results. We also discuss effects caused by solar and galactic CR in the atmosphere.

2 Cosmic Ray Induced Ionization in the atmosphere

2.1 Galactic Cosmic Rays

The ionization due to galactic cosmic rays (GCR) is always present in the atmosphere, and it changes with the 11-year solar cycle due to the solar modulation. Primary cosmic rays initiate a nucleonic-electromagnetic cascade

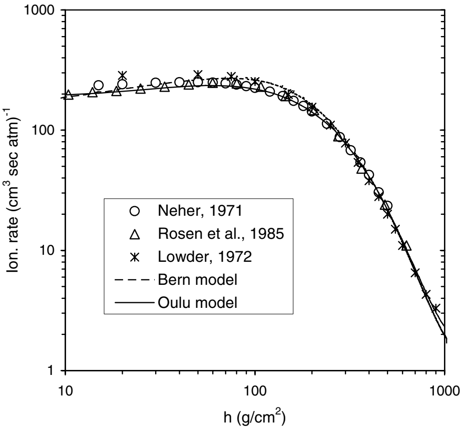

Fig. 1. Measured and calculated ionization rate in a high-latitude region during a solar maximum ($\phi \approx 1000$ MV). Symbols represent direct measurements as denoted in the legend, while curves correspond to the present calculations using the Bern (dashed) and Oulu (solid) models.

in the atmosphere, with the main energy losses at altitudes below 30 km resulting in ionization, dissociation and excitation of molecules (see, e.g., Dorman, 2004). The details of the cosmic ray initiated cascade are discussed in (Vainio et al., this volume). The CRII can be represented in numerical models in the following form:

$$Q(h, \phi, P_c) = \sum_i \int_{T_{c,i}}^{\infty} J_i(T, \phi)\, Y_i(h, T)\, dT, \tag{1}$$

where the summation is performed over different i-th species of CR (protons, $\alpha-$particles, heavier species), $Y_i(h, T)$ is the ionization yield function (the number of ion pairs produced at altitude h in the atmosphere by one CR particle of the i-th type with kinetic energy T). The differential energy spectrum $J_i(T, \phi)$ of the i-th specie of GCR in space near Earth depends on solar activity and is often parameterized via the modulation potential ϕ (see, e.g., Usoskin et al., 2005). Integration is performed above $T_{c,i}$, which is the kinetic energy of a particle of $i-$th type, corresponding to the local geomagnetic rigidity cutoff P_c. Numerical CRII models presented here are based on detailed computations of $Y_i(h, T)$ by Monte-Carlo simulations of the nucleonic-electromagnetic cascade initiated by cosmic rays in the atmosphere. The Bern model (ATMOCOSMIC/PLANETOCOSMIC code - see Desorgher et al., 2005) is based on the GEANT-4 Monte-Carlo simulation package. The PLANETOCOSMIC code is available at http://cosray.unibe.ch/~laurent/planetocosmics/. The Oulu model is based on the CORSIKA Monte-Carlo package extended by FLUKA package to simulate the low-energy nuclear interactions, and explicitly accounting for direct ionization by primary CR particles. A full numerical recipe along with the tabulated values of Y are given by Usoskin and Kovaltsov (2006). The Sofia model includes an analytical approximation of the direct ionization by CR primaries (Velinov et al., 2001) as well as CORSIKA/FLUKA Monte-Carlo simulations (Velinov and Mishev, 2007). Fig. 1 shows comparison of the CRII simulation results for Bern and Oulu model with fragmentary direct balloon-borne measurements of the ionization rate in a high latitude region (P_c <1.5 GV). Taking into account different location and dates of individual measurements, the agreement between calculated and measured CRII is pretty good (Scherer et al., 2006; Usoskin and Kovaltsov, 2006). Results of the simulations agree with each other within 10%, which is mainly attributed to the different atmospheric models used and, to a less extent, to different cross-section approximations in CORSIKA and GEANT-4 packages. The results of the CORSIKA-based Sofia model are very close to those of the Oulu model. Note that an analytical approximation model of CRII by O'Brien (2005) also shows a reasonable agreement with the present models.

Equation 1 separates the temporal variability of the cosmic ray flux impinging on the Earth (the $J(T, \phi)$ term) and local parameters (altitude and geomagnetic cutoff rigidity) via Y and P_c. The CRII strongly depends on the altitude and geographical location, the latter via the geomagnetic rigidity cutoff P_c. The CRII dependence on the

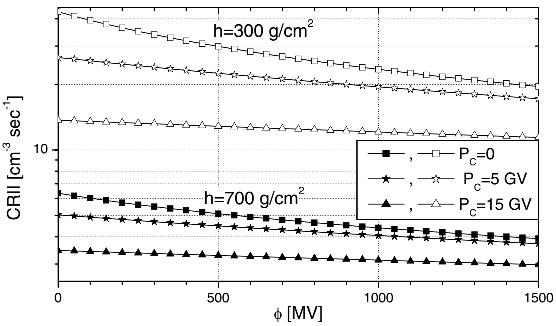

Fig. 2. CRII as a function of the modulation potential ϕ for different locations and altitudes (computations by Usoskin and Kovaltsov, 2006). Lower curves with solid symbols and upper curves with open symbols correspond to the atmospheric depths of 700 g/cm^2 (about 3 km altitude) and 300 g/cm^2 (about 9km), respectively. The results are shown for the geomagnetic pole (P_c=0), mid-latitude (P_c=5 GV, about 40° geomagnetic latitude) and equator ($P_c = 15$ GV).

solar modulation (ϕ) is relatively weak (10–50%), but it is responsible for the observed temporal variations. Some examples of the CRII at different altitudes and locations are shown in Fig. 2, while the lower panel of Fig. 4 depicts the geographical distribution of CRII for the atmospheric depth $h = 300$ g/cm^2.

2.2 The effect of solar energetic particle events

In addition to the permanent flux of GCR, sporadic solar energetic particle (SEP) events occur sometimes when strong fluxes of energetic particles are produced in solar flares or CMEs. Such SEPs (mostly protons) interacting with the Earth's atmosphere can produce an important increase of the atmosphere ionization (e.g. Schröter et al., 2006). Usually SEPs are accelerated up to hundreds of MeV, and the corresponding increase of the ionization is observed only at high altitude in the polar atmosphere. However, particles can be accelerated up to higher energies (a few GeV) during strong events called GLE (Ground Level Enhancement of cosmic rays). Ionization effects due to GLEs can extend down to the lower altitude. Here we quantitatively consider the ionization effect of a severe SEP/GLE event of 20/01/2005, which was one of the strongest GLEs ever observed (nearly 5-fold increase of the ground-level CR intensity at South Pole around 06:55-07:00 UT). We have computed the ionization of the Earth's atmosphere by SEPs at the peak of the event. We have considered the spectrum and the angular distribution of solar protons outside the magnetosphere computed by Bütikofer et al. (2006) from the neutron monitor network data. In contrast to GCR which impinge on Earth nearly isotropically, SEP have an anisotropic spatial distribution, especially during the main phase of the event, propagating mostly along the IMF line. An illustration of the method to account for the anisotropic SEP propagation is shown in Fig. 3 for two high-latitude sites on Earth, site I (57.5°N 60°W) and site II (67.5° S 140° E). The asymptotic directions, representing the particle arrival directions outside the magnetosphere, depend on the paticle's rigidity and are computed using the backward trajectory technique (Smart et al., 2000) and plotted in Fig. 3A. The geomagnetic field is described by a combination of the IGRF-2005 and Tsyganenko (1989) models. The main direction of the solar proton population outside the magnetosphere, also called the apparent source, is shown in Fig. 3A by the asterisk, together with the asymptotic directions corresponding to the pitch angles of 5°, 20°, 56° and 92°. For the peak time of this GLE the pitch angle distribution of the solar protons was very narrow with the flux at 55° pitch angle being only 10% of the flux in the main direction (IMF). Knowing the asymptotic directions, the enrgy spectrum, and the angular distribution of SEPs outside the magnetosphere, one can compute the flux of SEP at the top of the atmosphere as shown in Fig. 3B. The GCR proton spectrum for this specific time is also plotted for comparison. Because of the very narrow pitch-angle distribution of SEP in the peak phase of the event, the flux at the site II in the south hemisphere is an order of magnitude higher than at the site I in the northern hemisphere, since the former is close to the IMF direction (about 20°). Using the procedure

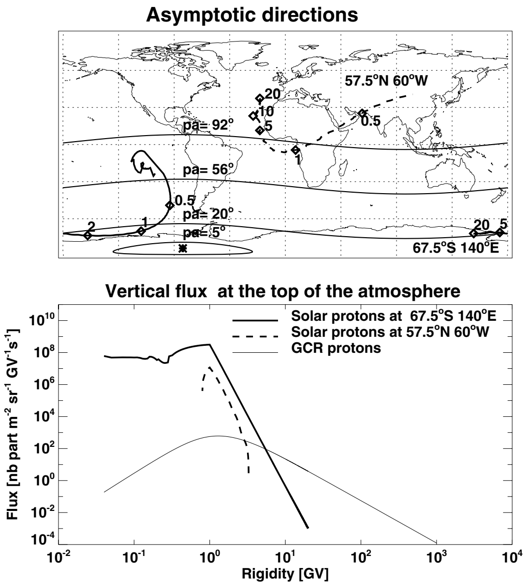

Fig. 3. Illustration of the method used for computing the solar proton flux at the top of the atmosphere from its spectrum and angular distribution outside the magnetosphere. A) Pitch angles and asymptotic directions for the two sites on Earth at 06:55 UT on 20/01/2005. The asterisk denotes the direction of the IMF. B) The corresponding flux of solar protons at the top of the atmosphere.

described above we have computed the flux of SEP at the top of the atmosphere globally in a 5°x5° geographic grid. Next, the CRII over the globe was computed for the peak of the SEP event of 20/01/2005 using the Bern model (see Sect. 2.1). The resulting CRII is shown in Fig. 4 for the upper troposphere. The top panel represents the total ionization accounting for both SEP and GCR fluxes, while in the bottom panel the ionization induced only by GCR is plotted as reference. One can see that the increase in CRII due to solar cosmic rays strongly depends on the location and, for this particular event, can be as great as a factor of 100 in a very localised region around 70°S 140°E. This is a direct consequence of the high anisotropy of the solar particles at this specific time.

Thus, the ionization effect of SEP events is local and most important in the polar atmosphere. The global effect of CRII solar particles is tiny, even for the most severe events.

2.3 CR in the upper atmosphere

In contrast to the lower atmosphere, the ionization of the upper atmosphere, where the cascade is not developed, allows a relatively simple analytical solution. This is related to the fact that the atmospheric depth at the altitude of 35 km is about 6 g/cm^2 (< 1 g/cm^2 at 50 km), which is much less than the nuclear free path of protons and $\alpha-$particles ($\approx$ 70 and 30 g/cm^2, respectively). Therefore, one can neglect nuclear interactions in the upper atmosphere (ionosphere and upper stratosphere) and consider only ionization losses of the primary CR particles. Moreover, for the altitude above 50 km, one can further neglect changes of the energy of energetic particles, thus reducing the CRII computation to an analytical *thin target* model (Velinov, 1966, 1968), where the electron production rate per g/cm^2 is computed as (cf. Eq. 1):

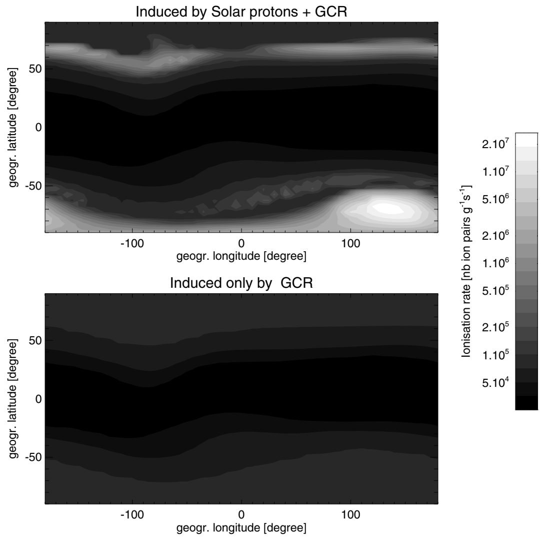

Fig. 4. Computed ionization rate of the upper troposphere (h =300 g/cm^2), at 06:55 UT on January 20, 2005: the total ionization rate (top panel) and that due to GCR only (bottom panel).

$$Q = \frac{1}{\Delta E} \sum_i \int_T \int_\Omega \left(\frac{dT}{dh} \right)_i J_i(T, \phi, \Omega) \, d\Omega \, dT, \tag{2}$$

where $\Delta E = 35$ eV is the energy required for the formation of an electron-ion pair, $(dT/dh)_i$ are the ionization losses of a particle of type i. In the altitude range from 25-30 to 50 km, an *intermediate target* model needs to be used, that accounts also for the particle's deceleration due to ionization losses (e.g. Velinov and Mateev, 1990). This model was applied for calculation of atmospheric electrical conductivities in the middle atmosphere for different cases: GCR, solar CR, Forbush decreases, day and night conditions, etc. During a strong SEP event the conductivity at altitudes of 30-80 km may increase by two orders of magnitude comparing to the background of GCR. This may affect parameters of the global atmospheric electric circuit. The intermediate target ionization model was further developed to calculate also the effect of anomalous CR (Velinov and Mateev, 1992; Velinov et al., 2001) taking into account the Chapman function values for the spherical Earth environment (Velinov et al., 2004). Anomalous CR play an important role in the maintenance of the polar ionosphere and the ionosphere at the polar cusp (Velinov and Mateev, 1992; Mateev, 1997). This model has been recently upgraded using a more precise parameterization of the ionization loss function (Velinov and Mateev, 2005) and is valid for the altitude between 25-30 km and 120 km (see Fig. 5). At its lower bound this model agrees with the full-cascade models described above but systematically underestimate the ion production for the middle and low atmosphere. It can be generalized for a 3D case for the planetary environments.

We note that ionizing agents other than cosmic rays, such as solar electromagnetic radiation, precipitation of magnetospheric and quasi-trapped particles, become progressively more important at high altitudes. These processes should be also considered by realistic ionization models for the ionosphere. Below 30 km, the nucleonic-electromagnetic cascade becomes important and CRII should be computed using Monte-Carlo models discussed in Section 2.1.

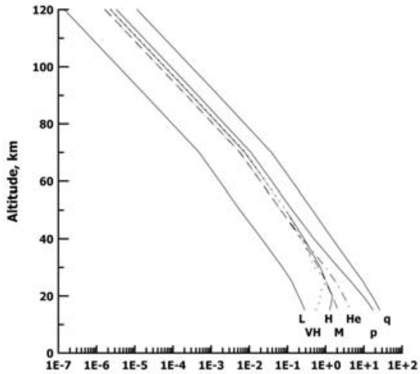

Fig. 5. Electron production rate q (cm^{-3} sec^{-1}) by cosmic rays, together with contributions from different groups of nuclei (p, He, L, M, H, VH) calculated for the solar minimum ($\phi = 400$ MV) by means of the intermediate target model (Velinov and Mateev, 2005).

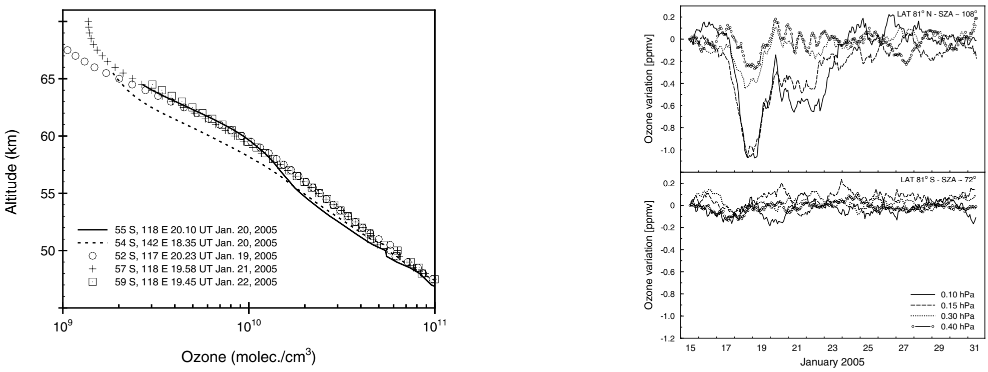

Fig. 6. Left: Atmospheric ozone profiles (SAGE II data) for similar locations during 19–22/01/2005; note the fast change during 20/01/2005 (after Damiani et al., 2006). **Right:** Ozone variability from MLS/AURA data for several atmospheric levels (after Damiani et al., 2007a).

3 CR and chemistry of the middle/upper atmosphere

Energetic CR affect chemistry of the middle/upper atmosphere, that can be both measured and modeled, e.g., SIC (Verronen et al., 2005), COMMA (Krivolutsky et al., 2006), TIME-GCM (Jackman et al., 2007). While GCR mostly affect the overall atmospheric environment, SEP result in ionizations, dissociations, etc. in the polar middle/upper atmosphere. SEP can produce minor atmospheric components (e.g., HOx and NOy) and trigger catalytic cycles with ozone destruction. Recent models and data show that: (i) SEPs deposit their energy in the Polar Cap regions; (ii) relevant O_3 depletions take place only after large SEP events; (iii) the day/night difference occurs in the chemical features, due to the different solar illumination, and (iv) SEPs can be related also to atmospheric dynamical changes, such as those involving temperature and wind. In the framework of the COST 724 action a number of SEP events were studied in details: 17/01/2005, 20/01/2005, 15/05/2005, 08/09/2005, 21/04/2002, and 14/07/2000. We used atmospheric data from satellite instruments: SAGE II (NASA Langley Atmospheric Sciences Data Center), POAM III (http://eosweb.larc.nasa.gov/PRODOCS/poam3/table_poam3.html), HALOE (http://haloedata.larc.nasa.gov/download/index.php) and MLS/EOS/AURA (http://mls.jpl.nasa.gov/data/). Proton fluxes were taken from the GOES satellite (http://www.ngdc.noaa.gov/stp/GOES/).

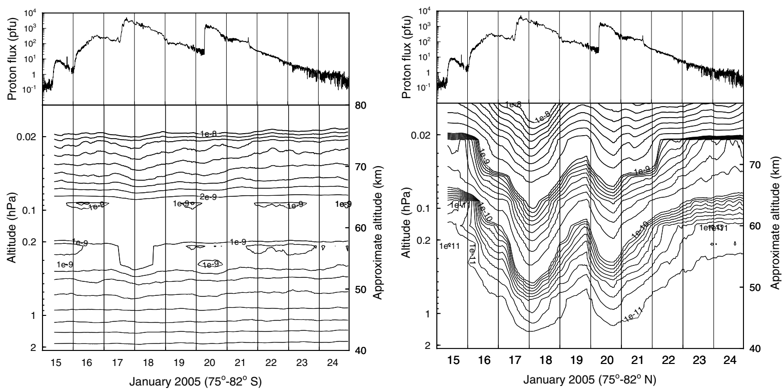

Fig. 7. Upper panels: Solar proton flux (E > 10 MeV) from GOES. **Lower panels:** Contours of the OH increase (in volume mixing ratio) from MLS/EOS data for 75°-82° S (**left**) and 75°-82° N (**right**). (after Storini & Damiani, 2007).

Studying the SEP events of Jan. 2005, Damiani et al. (2006) found two weak and short (< 12 h) ozone depletions at the outer boundary of the Southern Polar Cap (Fig. 6- left panel). While the mesospheric ozone was greatly decreased in the Northern region (night), the ozone decrease was weak in the Southern region (day) (Damiani et al., 2007a). Furthermore, the ozone decrease in the Northern hemisphere lasted longer (several days) than in the Southern one, where only short depletions were found (Fig. 6- right panel). This is in agreement with the theoretical result based on intense photolysis processes in the summer hemisphere. Using the MLS measurements of nitric acid during January 2005, it was shown that, together with the ozone depletion, a HNO_3 increase (Damiani et al., 2007a) took place, lasting until the end of the month (Storini & Damiani, 2007). It was the first time when an increase of OH (proxy for HOx) could be highlighted. According to current models, the HOx increase during a SEP event may explain the observed mesospheric ozone depletion for the night condition. For example, the OH concentration raised by an order of magnitude in the North, whereas it remained almost constant in the South (Fig. 7). Note that the tertiary ozone peak in the winter mesosphere makes it easier to distinguish the O_3 decrease linked to the OHx component rise. The destruction of the ozone peak is clear on 18/01/2005, when the quantity of destroyed O_3 varied from $\sim$ 25% (at $\sim$ 55 km) to $\sim$ 75% (at $\sim$ 70 km) at Northern high latitudes.

Several other SEP events were similarly analyzed (Damiani et al., 2007b; Storini & Damiani, 2007). In spite of the lower SEP flux, they have also been able to produce intense variations mainly in the mesospheric chemistry. We found that SEP effects on the Earth's atmosphere are different for the night and day hemispheres at high latitudes. The response of odd hydrogen species to SEP events is very fast, almost contemporary, in both summer and winter hemispheres. However, it is difficult to separate the OH variability over the solar illumination changes since the high background concentration of hydrogen species depends on the H_2O concentration. On the other hand, reduced solar illumination facilitates highlight of atmospheric chemistry changes. We note that OH changes last longer in the winter hemisphere than in the summer one, because of the short life of OH components under solar light. This does not imply that seasons affect the possibility of odd hydrogen species to trigger catalytic cycles, but it only affects our capability to disentangle the true OH variability. In fact, the scenario of the middle/upper atmosphere response to the Sept. 2005 event reveals catalytic triggering in both hemispheres, while the slightly less illuminated condition of the Southern hemisphere favors the presence of a third ozone peak in May 2005, and its subsequent destruction during/after the 15/05/2005 SEP event. The weak SEP fluence for the 16/05/2005 event led to an O_3 depletion of 10 % up to $\sim$ 60 km and reached 45 % at $\sim$ 70 km at 75°-82° S. The ozone depletion in the summer hemisphere is negligible for this event.

Although SEP result in the dominant destruction of ozone, it is possible that at certain altitudes ozone can be created as a result of chain ion reactions taking part in the stratosphere (see Tassev et al., 1999, 2003).

4 Conclusions

In this brief review we have summarized the results of the research, carried out in the framework of the COST-724 action, to study the atmospheric effect of cosmic rays. Three numerical models (Bern, Oulu and Sofia), that are capable to compute the cosmic ray induced ionization at a given location and time, are presented. The models agree with each other and with fragmentary direct measurements of the atmospheric ionization in different conditions. The models are validated for the entire atmosphere and the whole range of the solar activity level variations. The effect of sporadic solar energetic particle events is tiny on the global scale, even for a severe event, but can be very strong locally in polar regions, especially at high altitudes, leading to significant changes of the chemical properties in the upper atmosphere.

Thus, a new opportunity is presented to study cosmic ray induced effects of the atmosphere in full detail using realistic and calibrated to direct observations numerical models.

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