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Cosmic rays and climate forcing

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Abstract. An important factor affecting the terrestrial environment is the flux of cosmic rays permanently impinging on Earth. Energetic cosmic rays initiate a nucleonic-electromagnetic cascade in the atmosphere, affecting its physical-chemical properties. In particular, cosmic rays form the dominant source of ionization in the lower and middle atmosphere. Therefore, a detailed knowledge of processes leading to the cosmic ray induced ionization makes a solid basis for a quantitative study of the outer space influence upon Earth. Via the variable heliospheric modulation of cosmic rays, this provides an indirect solar-terrestrial link.
We present here a review of atmospheric effects of cosmic rays, including ionization and aerosol particle formation. Both physical modeling and phenomenological relations are considered on different time scales.

1. Introduction

Cosmic ray form the main source of the ionization of the lower and middle atmosphere (e.g. Bazilevskaya et al., 2008). Although the relative ionization rate is small (10^{-18}–10^{-19} s^{-1}), and the atmosphere can be considered essentially neutral, the presence of a small amount of ions can modify physical and chemical properties of the atmosphere. Thus, the cosmic ray induced ionization (called CRII henceforth) is an important factor of the outer space influences on atmospheric properties. Since direct measurements of the atmospheric ionization are limited in time and space, they can be used for rough estimates, while an appropriate model is required for detailed studies.

In this article, we review the existing numerical models of CRII, their ranges of validity and intercalibrations, as well as the main patterns of spatial and temporal changes of CRII in the atmosphere (Section 2). In Section 3, we briefly discuss cosmic rays as a possible external forcing for the Earth climate. Conclusions are summarized in Section 4.

2. Cosmic ray induced ionization

Cosmic rays are highly energetic charged particles, consisting of about 90% protons, about 10% of $\alpha-$particles and 1% of heavier species. Energy range of primary cosmic rays is from several hundred MeV (less energetic particles cannot produce ionization in the lower-middle atmosphere) up to about 10^{20} eV (Grieder, 2001). However, high energy cosmic rays (with the energy above TeV) do not significantly contribute to the atmospheric ionization because of their low flux.

When an energetic particle enters the atmosphere, it first goes straight gradually decelerating and ionizing the ambient rarefied air along it's path. This process is quite straight-

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forward and can be modelled using a simple analytical approach (Velinov & Mateev, 1990; Vitt & Jackman, 1996) or numerical methods (Wissing & Kallenrode, 2009; Usoskin et al., 2010). Soon or later the primary particle collides with a nucleus of one of the atmospheric constituents, mostly oxygen, nitrogen and argon in the volume fractions of N_2, O_2 and Ar being 78.1%, 21% and 0.9%, respectively (see, e.g., Weast, 1986). The first collision takes place, on average, after traversing roughly 100 g/cm^2 of air, which corresponds to the height of 15–26 km depending on the location and solar activity level. A number of secondaries can be produced, which experience further collisions, leading to a complicated cascade in the atmosphere. An oversimplified scheme of the cascade (only components important to the atmospheric ionization are shown) is presented in Figure 1. The cascade can be roughly divided in three principal components: the soft or electromagnetic one (electrons, positrons and photons); the hard or muon one (muons); and the hadronic or nucleonic component (protons, neutrons and α−particles). The lower atmosphere is ionized not by the primary cosmic rays but rather by secondaries of the cascade. All the components of the cascade shown in Fig. 1 are important for the CRII, but in different energy ranges. E.g., lower energy (<1 GeV) cosmic rays produce mostly the hadronic component. For middle energies (about 10 GeV), all the three components are equally important but at different altitude ranges. Ionization form high energy cosmic rays is dominated by muon and electromagnetic components, while the contribution from hadronic component can be neglected (Usoskin & Kovaltsov, 2006). Therefore, all three components are important.

Modelling the CRII is a challenging task because of the complexity of the atmospheric cascade. Earlier models were based on analytical or semi-empirical approximation of the cascade (e.g., O'Brien, 1979), but they are not reliable in the lower atmosphere. The most appropriate method is based on the full Monte-Carlo simulation of the cascade with computation of energy deposited by secondary particles in each layer. This method was pioneered by Usoskin et al. (2004a) and Desorgher et al. (2005). The former, the CRAC:CRII model (Usoskin et al., 2004a; Usoskin & Kovaltsov, 2006; Usoskin et al., 2010) is based on the CORSIKA+FLUKA Monte-Carlo package and its look-up tables are available at http://cosmicrays.oulu.fi/CRII/CRII.html. The latter, the ATMOCOSMIC/ PLANETOCOSMIC model (Desorgher et al., 2005) is based on the GEANT-4 simulation package, and is available at http://cosray.unibe.ch/~laurent/planetocosmics/. A detailed comparison of the two model (Usoskin et al., 2009) demonstrates that the simulations agree within 10%, the difference being mainly due to the different atmospheric models used and, to a lesser extent, to different cross-section approximations in CORSIKA and GEANT-4 packages.

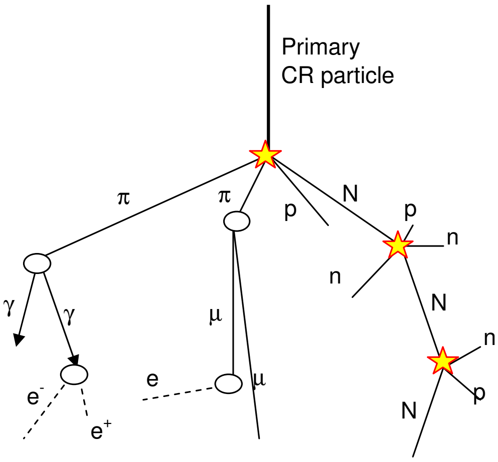

Fig. 1. A schematic sketch of a cascade induced by cosmic rays in the atmosphere. Left-hand, central and right-hand branches represents, respectively, the soft component, muon component and hadronic component of the cascade. "N" denotes nuclei, "p" and "n" protons and neutrons, "μ" muons, "π" pions, "e$^{\pm}$" electrons and positrons, and "γ" photons, respectively. Stars denote nuclear collisions, ovals - decay processes. This sketch does not represent the full development of the cascade and serves solely as an illustration for the processes discussed in the text.

Using the Monte-Carlo numerical model, the ionization yield function $Y_i(h,T)$ (the number of ion pairs produced at altitude h in the

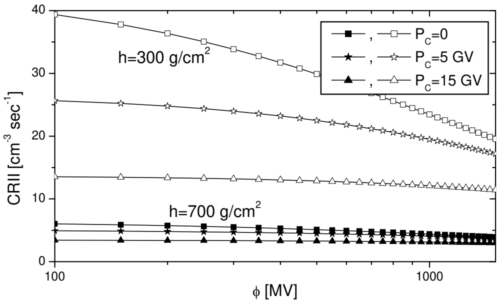

Fig. 2. Atmospheric ionization as a function of the modulation potential ϕ for several locations (pole $P_c = 0$, mid-latitude $P_c = 5$ GV and equator $P_c = 15$ GV) and heights (700 g/cm^2 and 300 g/cm^2 - about 3 km and 9 km altitude, respectively). Computations were performed by the CRAC:CRII model (Usoskin & Kovaltsov, 2006).

atmosphere by one CR particle of the i-th type with kinetic energy T) can be computed. Then the CRII can be calculated as an integral of the product of the yield function and the differential energy J_i of primary particles of type i:

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

Here the summation is performed over different i-th species of CR (protons, α-particles, heavier species); the differential energy spectrum is parameterized via the modulation potential ϕ (Usoskin et al., 2005). The integration is performed over the kinetic energy T 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. Contribution for heavier species of CR is important (Mishev & Velinov, 2011) An example of the computed CRII is shown in Fig. 2. The atmospheric ionization due to cosmic rays is maximum in the polar region, where there is no geomagnetic shielding. CRII varies over the solar cycle, in the opposite phase with the solar activity.

Ionization of the lower atmosphere by SEPs is usually small except for a few extreme GLE events that can produce some effect in the polar stratosphere and troposphere (Usoskin et al., 2011).

3. Do cosmic rays affect Earth's climate?

Variability of solar activity, in particular the solar electromagnetic radiation undoubtedly affects the Earth's climate on long run in the pre-industrial epoch (see, e.g., a review by Gray et al., 2010). A schematic view of different forces affecting climate is presented in Fig. 3. The anthropogenic factor became an important player recently (IPCC, 2007). Natural forcing includes internal climate factors, such as volcanoes, chemical composition of the atmosphere, ocean circulation, etc. Orbital forcing is related to variations of the Earth's orbit around the Sun (the so-called Milankovic cycles in precession, obliquity and eccentricity) which modulate the amount of solar radiation received by Earth with a typical time scale of 40,000 years and longer (e.g., Hays et al., 1976). Changes in solar brightness lead to changes in the amount of solar energy received by Earth (solar irradiance) which directly affects climate. However, the estimated variability of the irradiance is too low in order to explain all the observed climate variability, particularly the warming since the 1970s (IPCC, 2007), although the uncertainty of different estimates are very large (e.g. Solanki & Krivova, 2004). On the other hand, in addition to direct mechanisms of solar influence on climate via the changing flux of incoming radiation, indirect mechanisms may play an important role. For example, if the Earth was a black body, its mean temperature would be 255 K, which is about 33 lower than the really observed temperature. This extra warming is due to non-black body effects and leaves a possibility for indirect mechanisms to affect climate without invoking notable changes in the solar irradiance. Several types of indirect mechanisms have been proposed, most of them include amplification of the solar signal via positive feed-back of the solar total or spectral irradiation employing non-linear dynamical coupling between different parts of the climate system (see a review by Gray et al., 2010). Of a particular emphasis for this paper is another mechanism involving ionization effect caused by cosmic rays in the atmosphere.

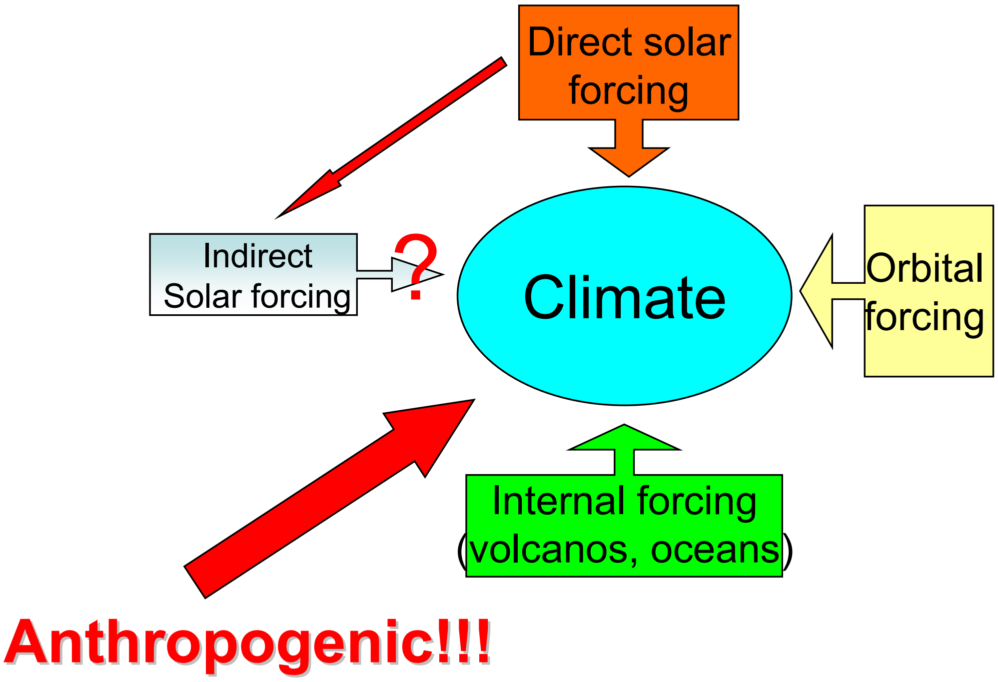

Fig. 3. A scheme of the climate forcing. The indirect solar forcing is marked by the question mark as not yet clearly understood.

As proposed initially by Ney (1959), enhanced ionization in the atmosphere may facilitate growth and life-time of clouds. Clouds play an important role in the radiation budget of the atmosphere by both trapping outgoing long wave radiation (warming effect) and reflecting incoming solar radiation (cooling). The net effect of typical low clouds is cooling. This affects the amount of absorbed radiation, even without invoking notable changes in the solar irradiance. Since the incoming flux of CR and hence the level of ionization in the atmosphere is modulated by the solar activity, this provides a potential link. We would like to note that an analogy with the Wilson cloud chamber is invalid as it requires very high supersaturation of water in air, several hundred %, which is unreachable in the atmosphere. Until recently, this mechanism has been advocated solely as a qualitative idea (e.g., Svensmark, 1998), but later two more detailed mechanisms have been proposed (Kazil et al., 2008).

First mechanism (Marsh & Svensmark, 2003; Yu et al., 2008) assumes that CRII leads to creation of complex cluster ions which grow by ion-ion recombination or ion-aerosol attachment until they reach the size of cloud condensation nuclei (CCN). Yet a quantitative detailed model of this process does not exist, in particular a link between micro- and macro-physics is missing here, although an idealized model (Pierce & Adams, 2009) suggests that the effect is too small. Two dedicated laboratory experiments have been carried out to reproduce and measure the proposed effect of ion induced/mediated nucleation of CCN. One experiment CLOUD has been performed in CERN (Duplissy et al., 2010; Kirkby et al., 2011), the other SKY experiment in Copenhagen (Enghoff et al., 2011). In both experiment, artificial mixture and gases imitating air with controlled physical conditions and chemical composition, was exposed to a ionizing irradiation (particle beam or γ-radiation),

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and the amount of grown aerosols was measured before, during and after the exposing. The results of the two experiments agree in that there is an effect of ionization upon the CCN-size aerosol formation and growth. For example, a 10-fold increase in the ionization rate leads to a 3-fold increase in the concentration of aerosols with the size of a few nm. Note however, that the expected variability of CRII in the lower atmosphere is 10-25% (Usoskin & Kovaltsov, 2006). On the other hand, small variations of the chemical impurity of the modelled air below the measurement uncertainties lead to a factor of 3 changes in the aerosol concentration (Enghoff et al., 2011), suggesting that local physical (temperature, humidity) and chemical (admixtures like sulfur dioxide) conditions play a major role. This is confirmed also by the data from CLOUD experiment (Duplissy et al., 2010; Kirkby et al., 2011). Thus, the ion induced/mediated nucleation of CCN may play a role on the long-term scales, where the local conditions are smoothed out but is hardly relevant on short time scale.

Another potential mechanism includes the effect of the global Earth's electrical circuit, namely the vertical current, which produce charge separation in clouds and may lead to formation of ice in super-cooled water and/or enhanced precipitation (Tinsley, 2008). Although this mechanism looks promising (Harrison & Ambaum, 2009), a reliable quantitative model is still missing. A direct laboratory experiment is presently hardly possible to verify this hypothesis. Thus, it so far remains mostly a qualitative estimate. Cosmic rays can be involved here via modulation of the air conductivity (ionization), which affects the vertical current between the ionosphere and ground. On the other hand, the ionospheric potential is largely controlled by the geomagnetic activity and also solar electromagnetic radiation.

Empirical evidence for CR-cloud relation are inconclusive. First, there is no homogeneous global relation which has a clear geographical pattern (Marsh & Svensmark, 2003; Usoskin et al., 2004b; Voiculescu et al., 2006): significant correlation between cosmic rays and cloud cover exists only in North-East Atlantic and Europe, South Atlantic and East Indian, and North-West Pacific regions. Second, it is hardly possible to distinguish CR signal from solar irradiance (UVI) variability on the inter-annual time scale (Usoskin et al., 2006). Statistical studies aiming to find cloud cover response to CR variability at the daily time scale (Forbush decreases or solar energetic particle events) also did not yield a clear view. While some studies claim a statistically significant relation (Roldugin & Tinsley, 2004; Stozhkov, 2003; Svensmark et al., 2009) between Forbush decreases of cosmic rays and cloud cover, other thorough analyses do not confirm it (Kristjánsson et al., 2008; Calogovic et al., 2010). In contrast to statistical studies, a detailed case study of the atmospheric response to a major SEP/GLE event of January 20, 2005 has been performed by Mironova et al. (2008, 2011), who have shown that an increase of the density of scattering aerosols was observed at 15-20 km height in a region near the geomagnetic pole a few days after the event. However, while the SEP event of 20-Jan-2005 was extreme in its strength, one of the strongest events detected for the last 50 years (McCracken et al., 2008), the observed effect in polar atmospheric aerosols and/or polar stratospheric clouds was barely noticeable. This puts a limitation on the direct cosmic ray effect on atmospheric properties.

4. Summary

Cosmic rays form the main source of atmospheric ionization and related physical-chemical changes in the low-mid atmosphere. This process is well understood and can be properly modelled.

The direct effect of cosmic rays on clouds is unclear, most likely it is small, as follows from laboratory experiments and a case study of a severe SEP event.

An indirect effect (e.g., top-down dynamic strato-troposphere coupling) of CR on climate is possible but a reliable quantitative model is still missing.

Cosmic rays may play a role in climate variability on long-term scale.

It is not cosmic ray per se but its variability that may affect climate.

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References

Bazilevskaya, G. A., et al. 2008, Space Sci. Rev., 137, 149
Calogovic, J., et al. 2010, Geophys. Res. Lett., 370, L03802
Desorgher, L., et al. 2005, Intern. J. Modern Phys. A, 20, 6802
Duplissy, J., et al. 2010, Atmos. Chem. Phys., 10, 1635
Enghoff, M. B., et al. 2011, Geophys. Res. Lett., 380,L09805
Gray, L. J., et al. 2010, Rev. Geophys., 48, RG4001
Grieder, P. 2001, Cosmic Rays at Earth (Amsterdam: Elsevier Science)
Harrison, R. G. & Ambaum, M. H. P. 2009, Envir. Res. Lett., 4, 014003
Hays, J. D., Imbrie, J., & Shackleton, N. J. 1976, Science, 194, 1121
Kazil, J., Harrison, R. G., & Lovejoy, E. R. 2008, Space Sci. Rev., 137, 241
Kirkby, J., et al. 2011, Nature, 476, 429
Kristjánsson, J. E., et al. 2008, Atmos. Chem. Phys., 8, 7373
Marsh, N. & Svensmark, H. 2003, Space Sci. Rev., 107, 317
McCracken, K. G., Moraal, H., & Stoker, P. H. 2008, J. Geophys. Res., 113,A12101
Mironova, I. A., et al. 2008, Geophys. Res. Lett., 35, L18610
Mironova, I. A., Usoskin, I. G., Kovaltsov, G. A., & Petelina, S. V. 2011, Atmos. Chem. Phys. Disc., 111, 14003
Mishev, A. L. & Velinov, P. I. Y. 2011, Adv. Space Res., 48, 19
Ney, E. 1959, Nature, 183, 451
O'Brien, K. 1979, J. Geophys. Res., 84, 423
Pierce, J. R. & Adams, P. J. 2009, Geophys. Res. Lett., 360,L09820
Roldugin, V. C. & Tinsley, B. A. 2004, J. Atmos. Solar-Terrest. Phys., 66, 1143
Solanki, S. & Krivova, N. 2004, Solar Phys., 224, 197
Stozhkov, Y. I. 2003, J. Phys. G (Nucl. Phys.), 29, 913
Svensmark, H. 1998, Phys. Rev. Lett., 81, 5027
Svensmark, H., Bondo, T., & Svensmark, J. 2009, Geophys. Res. Lett., 361, L15101
Tinsley, B. A. 2008, Rep. Prog. Phys., 71, 066801
Usoskin, I. G., Alanko-Huotari, K., Kovaltsov, G. A., & Mursula, K. 2005, J. Geophys. Res., 110, A12108
Usoskin, I. G., et al. 2009, Acta Geophys., 57, 88
Usoskin, I. G., Gladysheva, O. G., & Kovaltsov, G. A. 2004a, J. Atmos. Solar-Terr. Phys., 66, 1791
Usoskin, I. G. & Kovaltsov, G. A. 2006, J. Geophys. Res., 111, D21206
Usoskin, I. G., Kovaltsov, G. A., & Mironova, I. A. 2010, J. Geophys. Res., 115, D10302
Usoskin, I. G., et al. 2011, Atmos. Chem. Phys., 11, 1979
Usoskin, I. G., Marsh, N., Kovaltsov, G. A., Mursula, K., & Gladysheva, O. G. 2004b, Geophys. Res. Lett., 31, L16109
Usoskin, I. G., Voiculescu, M., Kovaltsov, G. A., & Mursula, K. 2006, J. Atmosph. Sol.-Terr. Phys., 68, 2164
Velinov, P. I. & Mateev, L. N. 1990, Geomagn. Aeronom., 30, 593
Vitt, F. M. & Jackman, C. H. 1996, J. Geophys. Res., 101, 6729
Voiculescu, M., Usoskin, I. G., & Mursula, K. 2006, Geophys. Res. Lett., 33, L21802
Weast, R., ed. 1986, Handbook of Chemistry and Physics, 67th edition (Cleveland: The Chemical Rubber Co)
Wissing, J. M. & Kallenrode, M.-B. 2009, J. Geophys. Res., 114, A06104
Yu, F., et al. 2008, Atmos. Chem. Phys., 8, 2537