Interactive comment on "Atmospheric changes caused by galactic cosmic rays over the period 1960-2010"
by C. H. Jackman et al.

Reply to Referee #1
We thank Referee #1 for helpful comments and suggestions. The "Referee's Comments" are noted first and then we give our "Reply:" to the comment.

Referee 1: **Anonymous Referee #1**
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Referee #1 *The paper studies, in the framework of the set of models involved, the effect of GCR variability on the Earth's atmosphere. The topic is important, and the authors make a strong effort in assessing the effect. The paper would be worth publishing in ACP, but this reviewer has some specific comments on the models used. The authors use the NAIRAS model for GCR modulation, based on the Badhwar-O'Neill approach, which computes the GCR spectrum on the top of the atmosphere. This spectrum is further applied for computations of the ion-production rate (IPR) in the atmosphere, using the NZETRN code, which is based on a solution of Boltzman equations to simulate transport of the nucleonic component of the cosmic-ray induced atmospheric cascade in the atmosphere. It is noteworthy that the NZETRN code was primarily designed for computations of the radiation dose, which is mostly defined by the nucleonic component of the cascade, reasonably described by the Botlzman equation approach. However, this approach neglects muon and electromagnetic branches of the cosmic ray induced cascade, which contribute essentially to ionization, especially in the lower atmosphere: for example, the electromanetic component dominates atmospheric ionization in the range between 10 and 25 km (see Fig. 11 of Bazilevskaya et al., SSR, 2008; Mishev & Velinov, JASTP, 2010, Fig. 2). This shortcoming is well realised at NASA (see, e.g., Heinbockel et al., NASA/TP-2009-215560 report, 2009): "It should also be emphasized that HZETRN does not transport certain particles such as pions, muons, positrons, electrons, and photons. These particles are used in calculating dose and dose equivalent by HETC-HEDS and FLUKA, but not HZETRN. The contribution of these particles to dose and dose equivalent values can be significant." Accordingly, this approach may lead to significant distortion of the ionization pattern as discussed below. A modern way to calculate GCR-related ionization is based on a full Monte-Carlo simulation of the atmospheric cascade (e.g., PLANETOCOSMICS, Desorgher et al., 2005; CRAC:CRII, Usoskin et al., 2006; or similar models – Atri et al., 2010; Mishev and Velinov, 2014).*

The authors are requested either to use an appropriate model or to explain specific questions raised below about the validity of the used model:

Referee #1 *- 1) As one can see in Fig.1, the ionization maximum is modeled to occur at the height of ~5 km at the equator and ~10 km in polar regions. This is unrealistically low. The ionization maximum (related to the Pfotzer maximum) is typically at 10 (equator) to 15- 18 (polar) km heights, according to both measurements and models,* *see, e.g., Fig.2. of Bazilevskaya et al. (2008) or Fig.2 in Calogovic et al. (2010), or Fig.4 of Mishev and Velinov (2014). Interestingly, the results shown by Mertenes et al. (2013, Fig. 12) for the dose rate computed by NAIRAS/HZETRN are reasonable, suggesting that it is only IPR, which is not correct, probably because of neglecting muon and electromagnetic components.*

Authors' Reply to 1): The offset in the height of the maximum in GPIR is likely due to the lack of pion-initiated electromagnetic cascade processes in HZETRN 2010, the version currently implemented in NAIRAS. A comparison of NAIRAS GPIR with results from Usoskin et al. (2010) are now included in the manuscript (see new Figure 3, shown and described below), with a discussion of the differences. The new 2015 version of HZETRN will soon be integrated into NAIRAS, which includes the pion-initiated electromagnetic cascade processes.

Referee #1 *- 2) Another concern is about the North-South asymmetry. Figure 2 shows ionization at South and North poles. One can see that ionization at the S-pole is 15 % higher (at least at the height of 10 km) than at the N-pole. The same feature of N-S-asymmetry is observed also in Fig.1. This feature is not intuitively expected and is not shown by other models (e.g., Planetocosmics – see Calogovic et al., 2010). Moreover, dose rate profiles shown by Mertens et al. (2013) are perfectly symmetric as expected. Can the authors explain why GCR-related ionization is systematically higher in the S-hemisphere than in the N-hemisphere? Is it related to systematically different density profiles of the atmosphere?*

Authors' Reply to 2): The hemispheric asymmetry is due to a systematic North-South difference in the NCEP atmospheric profiles. This point has been added to the discussion of Figure 2 in the manuscript (see below).

Referee #1 *- 3) As one can see in Fig.8d, the maximum of ionization during the year 1976-77 was the highest for the entire interval (equal to that of 2009). This disagrees with observations of GCR intensities, where the 1976-77 maximum was the lowest (or equal to those in 1987 and 1997, but significantly lower than 1965 and 2009). To illustrate it, Figure A (of this report) shows the variability of the count rates of the four NMs used as an input for NAIRAS model (Mertens et al., 2013). It is unclear how the profile, shown in Fig.8d, can be obtained from this input. The authors need to explain this.*

Authors' Reply to 3): The GPIR is only slightly greater in 1977 compared to 2008, by roughly 0.03 $cm^{-3}\ s^{-1}$. This is consistent with the results shown in Mertens et al. (2013). The dose rates at zero cutoff rigidity for 2008 are still within the standard deviation of the corresponding solar minimum average dose rates (Figures 8 and 9 of Mertens et al., 2013). It was also discussed in Mertens et al. (2013) that widely accessible GCR environmental models, such as BON10 used in NAIRAS, failed to reproduce the amount of increased heavy-ion GCR flux observed during the deep minimum between solar cycle 23 and solar cycle 24. The paucity of GCR proton and alpha measurements during this period made model comparisons unreliable for these ions.

Referee #1 *- 4) The authors state (page 33935, lines 12-16) that the approach was verified against data by Neher (1967) and the PLANETOCOSMICS model (Calogovic et al. (2010) and Gronoff et al. (2015)), but this statement is confusing. First, this reviewer cannot understand how the present result was compared with the data of direct measurements by Neher (1967), since the latter depict the maximum ionization at the height of 10/15 km for equator/poles, which disagrees with Fig.1 of this work. It is unclear how the present model can be in agreement with Calogovic et al. (2010) since the present Fig.1 disagrees with Fig. 2 of Calogovic et al., which shows the maximum of ionization at ~15 km and ~10 km in polar regions and equator, respectively (see item 1 above). Comparison with Gronoff et al. cannot be applied here since that paper deals with the thin Martian atmosphere where the atmospheric cascade is not fully developed and the difference between NZETRN and appropriate models is unimportant.*

Authors' Reply to 4): The Neher data is referenced to one atmospheric density value. Scaling the Neher data to the real atmospheric density changes the altitude of the maximum ionization rate. The comparison with Calogovic et al. was with respect to qualitative features and the range in the maximum ionization rates. At any rate, this section of the manuscript has been removed. Instead, explicit comparisons of NAIRAS GPIR with the results of Usoskin et al. (2010) are shown, and the differences are discussed.

Authors' modification of Paper as a result of specific questions 1), 2), 3), and 4): The revised Section 2 of the manuscript now reads:

Section 2: NAIRAS GCR ionization rate

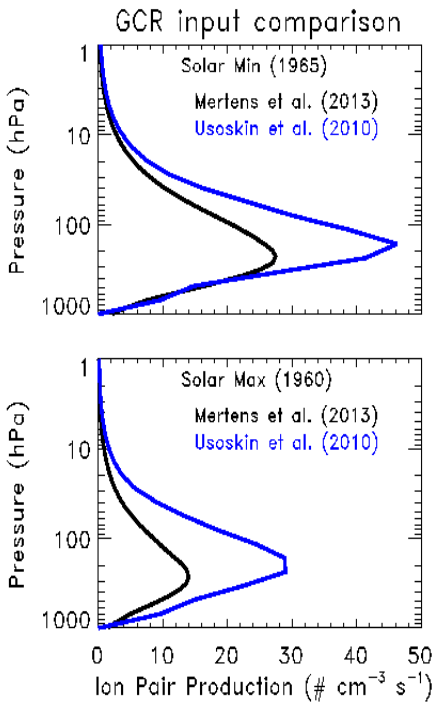
The Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) team at NASA Langley Research Center (see http://sol.spacenvironment.net/~nairas/) has developed and integrated a model to include GCRs into their ionizing radiation computation. The interplanetary magnetic field varies over a solar cycle and provides a modulation of the GCR spectral flux, which has been referred to as a solar modulation potential (e.g., Badhwar and O'Neill, 1996). For real-time application of the NAIRAS model, four high-latitude, ground-based neutron monitor count rate measurements are used to cross correlate with the solar modulation potential and provide the NAIRAS model's GCR spectral flux incident on the Earth for penetration into and through the atmosphere. NAIRAS is a physics-based model that maximizes the use of measurement input data (Mertens et al., 2013, and references therein).

In the NAIRAS model, GCRs are transported from outside the heliosphere to 1 AU by the Badhwar and O'Neill (1992, 1994, 1996) and O'Neill (2010) NASA model, with the solar modulation potential determined from measurements of ground-based neutron monitor count rates. The GCR spectral flux at 1 AU travel through the magnetosphere by means of a transmission factor determined by the vertical geomagnetic cutoff rigidity computed in the International Geomagnetic Reference Field

(IGRF) model (Finlay et al., 2010). The vertical cutoff rigidities are determined by numerical solutions of charged particle trajectories in the IGRF field using the techniques advanced by Smart and Shea (1994, 2005). After transmission through the magnetosphere, the GCR spectral flux travels through the neutral atmosphere using the NASA HZETRN deterministic transport code (Mertens et al., 2012). The global distribution of atmospheric mass density is obtained from NCAR/NCEP Reanalysis 1 data at pressure levels larger than 10 hPa (Kalnay et al., 1996) and the Naval Research Laboratory Mass Spectrometer and Incoherent Scatter model atmosphere data at pressure levels less than 10 hPa (Picone et al., 2002).

The NAIRAS model has been used to compute the annual average GCR-produced ionization rates (GPIR) for the 1960–2010 time periods. For these time periods, measurements from the Thule and Izmiran neutron monitor stations were used to determine the solar modulation potential. GPIR in the NAIRAS model are computed by multiplying the dose rate in air by the atmospheric density, divided by 35 eV per ion-pair. The annual average GPIR from the NAIRAS model for two years, 2002 and 2009, are presented in Fig. 1. This shows the inverse relationship between GPIR and solar activity. Year 2002 is very close to solar maximum and shows a smaller GPIR with maximum ionization rates of nearly 15 cm^{-3} s^{-1}, whereas year 2009 is very close to solar minimum with about a factor of two larger maximum ionization rate of 30 cm^{-3} s^{-1}. The time-dependent variation in the GPIR at 90S and 90N is given in Fig. 2. Peaks in GPIR occur in 1965, 1977, 1987, 1997, and 2009, reflective of solar minimum conditions in those years. The North-South asymmetry in the GPIR is due to a systematic hemispherical asymmetry in the NCEP atmospheric density profiles.

The Mertens et al. (2013) GPIR are about a factor of two smaller than those presented in Usoskin et al. (2010), and the altitude of the maximum in the GPIR is lower in the NAIRAS results as well. A comparison of these two computations of GCR ion rates at 90 degrees N is given in Figure 3 for both solar minimum (1965) and solar maximum (1960) conditions. The underprediction of the NAIRAS GPIR and the lower altitude of its maximum is due to the lack of pion-initiated electromagnetic cascade processes in the HZETRN version 2010 currently implemented in the NAIRAS model (Mertens et al., 2013). This deficiency will soon be rectified when the 2015 version of HZETRN is integrated into the NAIRAS model (e.g., Norman et al., 2012, 2013; Slaba et al. 2013).



New Figure 3 caption:

NAIRAS model computed galactic cosmic ray annual average ionization rates (Mertens et al., 2013) compared to those given in Usoskin et al. (2010) for solar minimum (1965, top plot) and solar maximum (1960, bottom plot).

Authors now add several papers to the Reference list as a result of the Paper modifications:

Finlay, C. C., Maus, S., Beggan, C. D., Bondar, T. N., Chambodut, A., Chernova, T. A.,Chulliat, A., Golovkov, V. P., Hamilton, B., Hamoudi, M., Holme, R., Hulot, G., Kuang, W., Langlais, B., Lesur, V., Lowes, F. J., Lühr, H., Macmillan, S., Mandea, M., McLean, S., Manoj, C., Menvielle, M., Michaelis, I., Olsen, N., Rauberg, J., Rother, M., Sabaka, T. J., Tangborn, A.,Tøffner-Clausen, L.,Thébault, E.,Thomson, A. W. P., Wardinski, I., Wei, Z., and Zvereva, T. I., International Geomagnetic Reference Field: the eleventh generation, Geophysical Journal International, 183, 1216-1230, doi10.1111/j.1365-246X.2010.04804, 2010

Mertens, C. J., Kress, B. T., Wiltberger, M., Tobiska, W. K., Grajewski, B., and Xu, X., Atmospheric ionizing radiation from galactic and solar cosmic rays, Current Topics in Ionizing Radiation Research, Edited by Mitsuru Nenoi, InTech Publisher (ISBN 978-953-51-0196-3), 2012.

Norman, R. B., Blattnig, S. R., De Angelis, G., Badavi, F. F., and Norbury, J. W., Deterministic pion and muon tranport in Earth's atmosphere, Adv. Space Res., 50, 146-155, 2012.

Norman, R. B., Slaba, T. C., and Blattnig, S. R., An extension of HZETRN for cosmic ray initiated electromagnetic cascades, Adv. Space Res., 51, 2251-2260, 2013.

Picone, J. M., Hedin, A. E., Drob, D. P., and Aikin, A. C., NRLMSIS-00 empirical model of the atmosphere: Statistical comparisons and scientific issues, J. Geophys. Res., 107(A12), 1468, 10/1029/2002JA009430, 2002.

Slaba, T. C., Blattnig, S. R., Reddell, B., Bahadori, A., Norman, R. B., and Badavi, F. F., Pion and electromagnetic contribution to dose: Comparisons of HZETRN to Monte Carlo results and ISS data, Adv. Space Res., 52, 62-78, 2013.
Smart, D. F. and Shea, M. A., Geomagnetic cutoffs: A review for space dosimetry calculations, Adv. Space Res., 14(10), 10,787-10,796, 1994.
Smart, D. F. and Shea, M. A., A review of geomagnetic cutoff rigidities for earth-orbiting spacecraft, Adv. Space Res., 36, 2012-2020, 2005.

***Referee #1** - Accordingly, the validity of the GCR-induced cascade modelling in theNAIRAS/NZETRN model is not verified against full Montre-Carlo models and rises several questions. Unless the authors can prove that the computations of ionization are correct, the result cannot be trusted.*

Authors' Reply: See discussion above regarding these issues

Other minor comments:
***Referee #1** - 1) A brief summary is needed in the end of the abstract – are these changes important or not?*

Authors' Reply to 1): We think this issue was raised when the paper was first submitted and before it was available online. There is presently a sentence at the end of the abstract, which does indicate the importance of these atmospheric impacts. It reads "*Although these computed ozone impacts are small, GCRs provide a natural influence on ozone and need to be quantified over long time periods.*"

***Referee #1** - 2) page 33935, line 6: Please give some detail how the cutoff rigidity was calculated* from the IGRF model and please add a reference to IGRF.

Authors' Reply to 2): We now provide some information about this in the second paragraph of Section 2 of the revised paper.

Authors' modification of Paper as a result of 2): Two sentences were added to the second paragraph of Section 2 that read:

The GCR spectral flux at 1 AU travel through the magnetosphere by means of a transmission factor determined by the vertical geomagnetic cutoff rigidity computed in the International Geomagnetic Reference Field (IGRF) model (Finlay et al., 2010). The vertical cutoff rigidities are determined by numerical solutions of charged particle trajectories in the IGRF field using the techniques advanced by Smart and Shea (1994, 2005).

***Referee #1** - 3) page, line 3: "primarily protons" is not exactly correct. While protons form 90% in the particle number, heavier species constitute ~30% in the nucleon number and may contribute up to 50% in the ionization rate.*

Authors' Reply to 3): We think this issue was raised when the paper was first submitted and before it was available online. The first sentence of the Introduction had the phrase "extremely energetic charged particles (primarily protons)". As a result of the preliminary review, we removed "(primarily protons)" from that sentence.

Authors' modification of Paper as a result of 3): The first sentence of the Section 1 Introduction reads:

Galactic cosmic rays (GCRs) from outside the solar system are comprised of highly energetic charged particles and are believed to be the result of supernovae events and other high energy astrophysical processes. GCRs contain a wide range of energetic particles, which are also influenced by the Earth's magnetosphere.