



## Role of centennial geomagnetic changes in local atmospheric ionization

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[1] Many studies of solar-terrestrial relation are based on globally (or hemispherically) averaged quantities, including the average cosmic ray flux. However, regional effects of cosmic ray induced ionization due to geomagnetic changes may be comparable to or even dominate over the solar signal at mid-latitudes on centennial-to-millennial time scales. We show that local changes of the tropospheric ionization due to fast migration of the geomagnetic axis are crucial on centennial time scale, and the use of global averages may smear an important effect. We conclude that changes of the regional tropospheric ionization at mid-latitudes are defined by both geomagnetic changes and solar activity, and none of the two processes can be neglected. This substantiates a necessity for a careful analysis of the regional, not global, indices at mid-latitudes and offers a new possibility to disentangle direct (solar radiation) and indirect (via cosmic rays) effects in the solar-terrestrial relations. **Citation:** Usoskin, I. G., M. Korte, and G. A. Kovaltsov (2008), Role of centennial geomagnetic changes in local atmospheric ionization, *Geophys. Res. Lett.*, 35, L05811, doi:10.1029/2007GL033040.

### 1. Introduction

[2] Despite numerous evidence of a relation between the Earth's climate and solar variability on long-term scale, the mechanism of such a link is still not clear. An apparent influence via the solar luminosity variations seems too weak [e.g., *Foukal et al.*, 2006], and either an unknown ad-hoc trend in the luminosity [*Solanki and Krivova*, 2004; *Wang et al.*, 2005] or a terrestrial amplifier of the spectral irradiance variations [e.g., *Haigh*, 1996; *Shindell et al.*, 1999] have to be assumed to explain the direct solar-terrestrial influence. Alternatively, an indirect mechanism also driven by the solar activity may play a role, e.g. via the ionization effect of cosmic rays (CR) in the atmosphere. Cosmic ray induced ionization (CRII) is the principle source of ionization of the low and middle atmosphere and can slightly modify the properties of the atmosphere–aerosol content or cloud formation (e.g., Part 3 by *Dorman* [2004]). Even a small change in the transparency/absorbtion/reflectance of the atmosphere affects the amount of solar radiation received by Earth even without changes in the solar irradiance. Since the flux of CR is modulated by the solar magnetic activity, this can provide a link between solar variability and climate [*Marsh and Svensmark*, 2003]. On the other hand, CR impinging on Earth are modulated also by the slowly

changing geomagnetic field. While terrestrial effects of the solar irradiation is strictly latitudinal, the CR effect is expected to have a complicated geographical pattern because of not-aligned rotational and geomagnetic axes.

[3] Many studies of solar influence on the terrestrial climate are dealing with global quantities, such as global surface temperature, cloud cover, etc. However, such an approach cannot distinguish between different mechanisms of the solar-terrestrial link, e.g. solar radiation, cosmic rays or solar wind–magnetosphere coupling. Though there are evidence [*Christl et al.*, 2004; *Courtilot et al.*, 2007] of a relation between the geomagnetic field strength and cold episodes in the Earth's history, recent efforts to disentangle CR and solar irradiance effects on centennial scale using variations of the geomagnetic dipole moment were inconclusive [e.g., *de Jager*, 2005; *Usoskin et al.*, 2005b]. The use of global climatic indices, e.g., global temperature, may also be misleading [*Bradley et al.*, 2003; *Jones and Mann*, 2004] and regional effects should be considered. On the other hand, a relation between CRII and cloud cover is not uniform but exists only in a few limited geographical areas at mid-latitudes, viz. Europe + N. Atlantic, S. Atlantic, and Far East [*Pallé et al.*, 2004; *Usoskin et al.*, 2004; *Voiculescu et al.*, 2006]. Such regions can be climate-defining and require special consideration. In addition, many paleoclimatic reconstructions are somewhat biased towards the Northern hemisphere and particularly European sites. This substantiates a necessity for a careful analysis of the regional (rather than global) indices, especially in these specific regions. Here we analyze long-term regional variations of CRII, with emphasis on mid-latitude regions in the Northern hemisphere.

### 2. Data and Methods

#### 2.1. Cosmic Ray Induced Ionization

[4] CRII is a result of the cascade induced by energetic cosmic rays in the Earth's atmosphere [e.g., *Desorgher et al.*, 2005] and thus is sensitive to the energy spectrum of incoming CR. The ionization rate at a given location and atmospheric depth (or altitude)  $h$  can be expressed as [*Usoskin and Kovaltsov*, 2006]

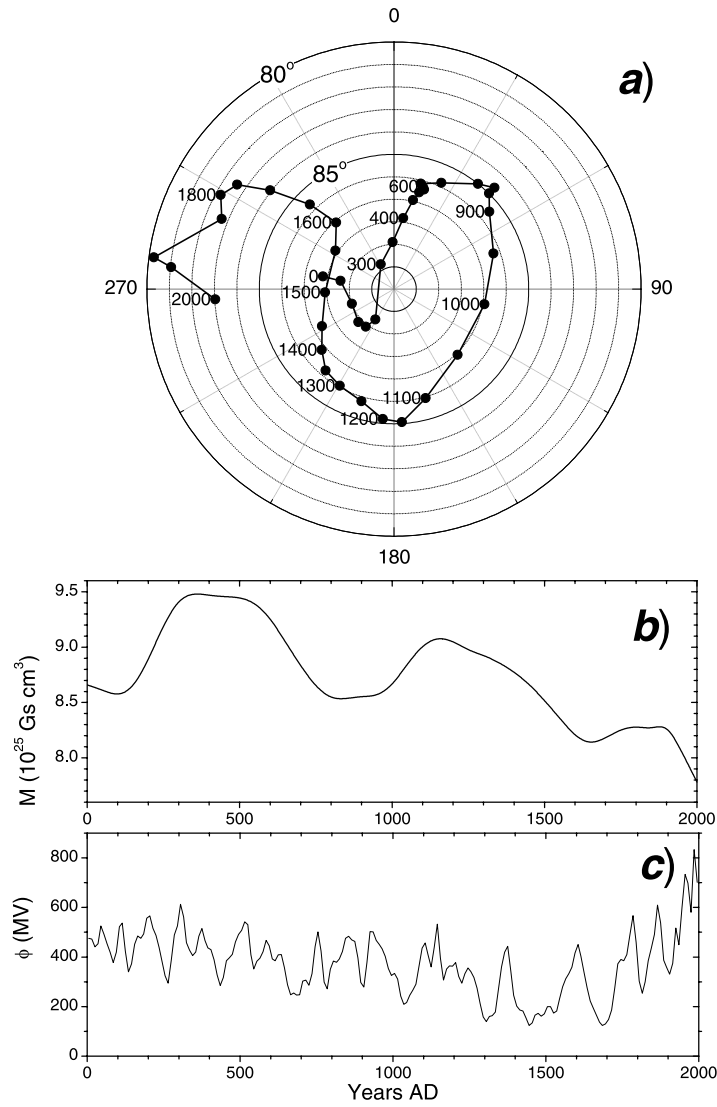
$$Q = \sum_i Q_i = \sum_i \int_{T_{c,i}}^{\infty} J_i(T, \phi) Y_i(h, T) dT, \quad (1)$$

where summation is over different species of primary CR,  $J_i$  is the differential energy spectrum of the  $i$ -th specie of CR near Earth outside the geomagnetic field, and  $Y_i(h, T)$  is the ionization yield function (number of ion pairs produced at the atmospheric depth  $h$  by a unit flux of CR particles of type  $i$  with kinetic energy  $T$ ). Integration is over the kinetic energy  $T$  above  $T_{c,i}$ , which is the kinetic energy corresponding to the local geomagnetic cutoff rigidity  $P_c$ . Therefore,

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**Figure 1.** Reconstructions of temporal changes of the geomagnetic field and solar activity over since AD: (a) Migration of the Northern (magnetically South) geomagnetic pole in geographical polar coordinates. (b) Changes of the geomagnetic dipole moment. (c) Changes in the modulation potential  $\phi$ .

the overall CRII is defined by three mutually independent components that separate pure atmospheric, solar and geomagnetic effects.

[5] 1. Atmospheric properties define the integrand  $Y$ . Since chemical composition of the atmosphere is assumed constant,  $Y$  depends only on the atmospheric depth  $h$  without temporal or geographical variability.

[6] 2. CR properties are taken into account by the integrand  $J$ . Since the interstellar CR spectrum can be regarded as constant on the millennial time scale, all changes in  $J$  are defined by the solar modulation of CR in the heliosphere, quantified via the modulation potential  $\phi$  (see detailed description by *Usoskin et al.* [2005a]).

[7] 3. Shielding effect of the geomagnetic field is accounted by the variable integration limit, which can be parameterized, in a simple form well suitable for long-term studies, via the geomagnetic cutoff rigidity  $P_c$  [*Cooke et al.*, 1991].

[8] Using a full physical Monte-Carlo simulation of the CR propagation in the atmosphere [*Usoskin and Kovaltsov,*

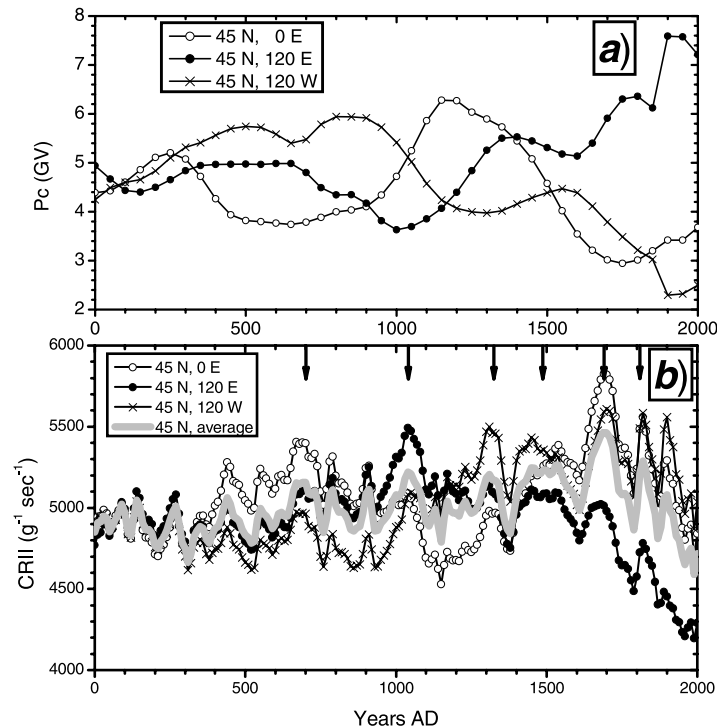
2006], we have computed CRII as a function of the atmospheric depth  $h$ , modulation potential  $\phi$  and cutoff rigidity  $P_c$ . Since we are interested in secular changes of the CRII, we suppressed the solar cycle variability by using decadal averaged data. Here we analyze CRII in the troposphere ( $h = 700 \text{ g/cm}^2$  or about 3.2 km altitude), but the results are qualitatively similar for other altitudes.

## 2.2. Geomagnetic Changes

[9] The geomagnetic shielding is dominated by the large-scale magnetic field, as smaller scale contributions decay more rapidly with distance from the source. For a dipole approximation the geomagnetic vertical cutoff rigidity is evaluated using Störmer's equation [*Cooke et al.*, 1991]:

$$P_c \approx (1.9 \text{ GV}) \cdot M(R_o/R)^2 \cos^4 \lambda_G, \quad (2)$$

where  $M$  is the geomagnetic dipole moment (in  $10^{25}$  Gs  $\cdot$   $\text{cm}^3$ ),  $R_o$  is the Earth's mean radius,  $R$  is the distance from



**Figure 2.** (a) Temporal changes of the geomagnetic cutoff rigidity  $P_c$  in three geographical sites at  $45^\circ\text{N}$  (see text). (b) Temporal changes of the CR11 at  $h = 700 \text{ g/cm}^2$  (about 3.2 km altitude) in some geographical sites at  $45^\circ\text{N}$ , corresponding to Europe, Far East and USA Western coast. The thick grey line depicts CR11 averaged over all longitudes at  $45^\circ\text{N}$ . Arrows indicate historical Grand minima of solar activity.

the given location to the dipole center, and  $\lambda_G$  is the geomagnetic latitude, respectively. Although precise computations of the cutoff rigidity require complicated back-tracing of particles' trajectories [e.g., *Smart et al.*, 2000; *Kudela and Bobik*, 2004], the eccentric dipole approximation provides a good compromise between simplicity and reality [*Fraser-Smith*, 1987]. The eccentric dipole has the same dipole moment and orientation as the centered dipole, but the dipole's center and consequently the poles, defined as crossings of the axis with the surface, are shifted with respect to geographical ones. The first eight Gauss coefficients of a geomagnetic field model totally define the eccentric dipole, viz. the dipole moment  $M$ , geographical coordinates of the dipole center and the magnetic poles, and thus allow computation of  $P_c$  using equation (2).

[10] A paleomagnetic reconstruction allowing to compute variation of  $P_c$  over several millennia is the CALS7K.2 model by *Korte and Constable* [2006, 2008]. Using that model for the time interval 0 AD to 1850 AD extended by the IGRF (<http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html>) model after 1900, we have calculated the eccentric dipole for the past 2000 years. Figure 1 depicts the corresponding migration of the magnetic pole (panel A) and temporal changes of the dipole moment (panel B) since AD. One can see fast wandering of the magnetic pole with characteristic time of a few centuries and a slow consistent decreasing trend in the magnetic dipole moment on which smaller variations at a millennium time scale are superimposed. The corresponding changes of the computed value of  $P_c$  for mid-latitudes are shown in Figure 2a. One can see that the centennial-millennial changes of  $P_c$  at mid-latitudes

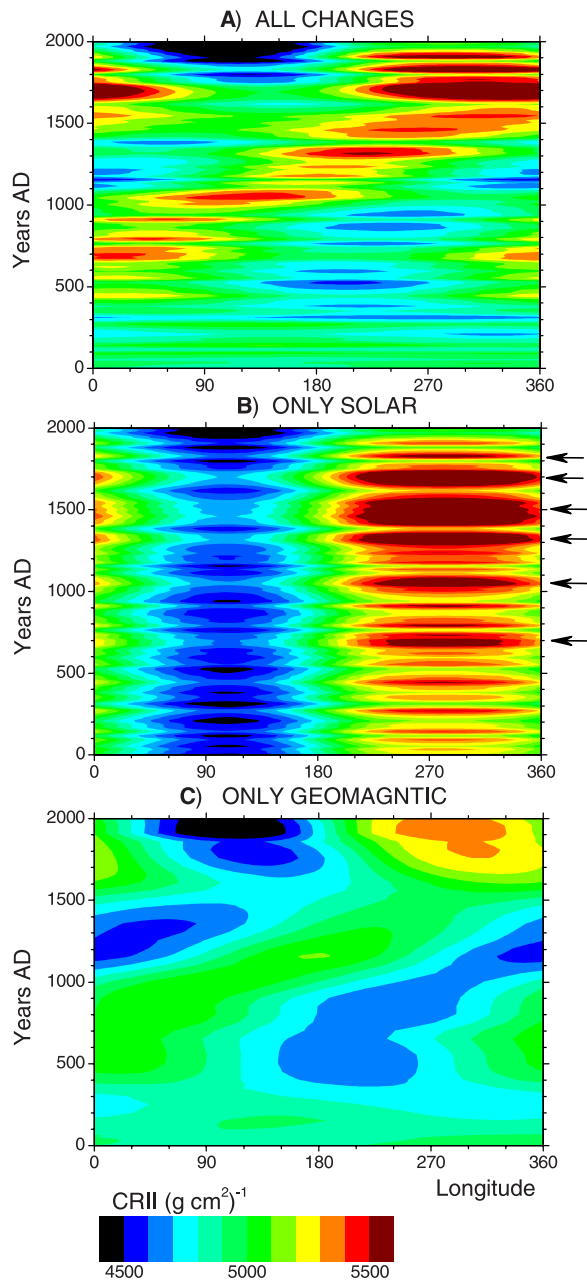
are mostly defined by the fast geomagnetic pole migration, and not by changes of the dipole moment.

### 2.3. Solar Modulation of Cosmic Rays

[11] Reconstruction of solar activity over the past millennia is possible using the method of cosmogenic isotopes, in particular radiocarbon  $^{14}\text{C}$  measured in independently dated tree rings [*Stuiver and Quay*, 1980]. Here we use the most recent solar activity reconstruction [*Usoskin et al.*, 2007] from the data on cosmogenic  $^{14}\text{C}$ , that is similar to previous study [*Usoskin et al.*, 2006] but uses an updated model of the solar open magnetic flux [*Krivova et al.*, 2007]. Solar activity is considered in terms of the modulation potential  $\phi$ , whose temporal variability is shown in Figure 1c. One can see a long-term “hockey-stick” trend—a slow decrease until ca. 1400 followed by a period of low activity and a fast rise after 1700. Fast oscillations are superimposed onto this trend. Five historical grand minima of solar activity can be clearly identified (Maunder, Spörer, Wolf, Oort, and a minimum ca. 700 AD) as well as tinier Dalton minimum ca. 1800.

### 3. Results and Discussion

[12] Here we discuss variations of CR11 at mid-latitudes that are most sensitive to geomagnetic variations. Geomagnetic changes are not important at high latitudes, where  $P_c$  is small anyhow, and at low altitudes, where CR11 is low. Together with model results [*Kazil et al.*, 2006] that the strongest response of aerosol concentration to CR11 changes is expected at mid-to-high latitudes over oceans, this sug-



**Figure 3.** CRII at the atmospheric depth  $700 \text{ g/cm}^2$  (about  $3.2 \text{ km}$  altitude) at geographical latitude  $45^\circ\text{N}$  as function of the geographical longitude (X-axis) and time (Y-axis): (a) All known effects are included. (b) CRII variations as a result of only solar activity changes (the geomagnetic field is fixed as for the epoch 2000). Arrows indicated historical Grand minima of solar activity. (c) CRII variations as a result of only geomagnetic changes (solar modulation is fixed at a medium level of  $\phi = 500 \text{ MV}$ ).

gests that the possible effect of CRII on climate should be at mid-latitudes.

[13] We have computed, using the method described above, CRII in the troposphere ( $h = 700 \text{ g/cm}^2$ ) at mid-latitudes (geographical  $45^\circ\text{N}$ ), as shown in Figure 3a. In order to study it in more details we separated the geomagnetic and solar changes as follows. Figure 3b shows the expected CRII changes due to only solar variability (i.e., as

if the geomagnetic field was fixed at its present state of the epoch 2000). Since the geomagnetic dipole axis is essentially tilted now with respect to the Earth's rotational axis, there is a systematic difference in CRII between Asian region ( $70\text{--}150^\circ\text{E}$ ), where both the geomagnetic latitude and the distance to the dipole center are smaller leading to higher  $P_c$ , and N. Atlantic region ( $30\text{--}120^\circ\text{W}$ ), where values of  $P_c$  are relatively low (cf. Figure 2a). All Grand minima of solar activity, as well as the long term trend, are clearly seen. Figure 3c depicts the expected CRII changes due to only geomagnetic changes, i.e., as if the solar activity remained constant at a moderate level of  $\phi = 500 \text{ MV}$ . Apparent are changes related to the migration of the dipole axis that were mostly important around 1900 AD and a fast wandering between 600 AD and 1200 AD (cf. Figure 1a).

[14] One can see that both solar and geomagnetic changes are equally important in the overall CRII variations on the centennial-millennial time scale. For illustration we show in Figure 2b time profiles (vertical cross-sections of Figure 3a) of CRII at three sites: European ( $45^\circ\text{N } 0^\circ\text{E}$ ), Far East ( $45^\circ\text{N } 120^\circ\text{E}$ ) and US West Coast ( $45^\circ\text{N } 120^\circ\text{W}$ ). Time profiles of CRII at these sites were nearly identical and identified mostly by the solar variations before 400 AD, when the dipole axis was nearly aligned with the Earth's rotational axis and the three values of  $P_c$  were close to each other (see Figure 2a). However, dramatic differences can be observed after 400 AD mostly due to the geomagnetic changes. Time variations of  $P_c$  values at the three sites have almost nothing in common and are defined primarily by the geomagnetic axis wandering. The difference in  $P_c$  between different longitudes can be as large as  $2.5\text{--}7.5 \text{ GV}$  in the recent epoch of 1900–1950, when the tilt of the dipole axis was largest. The corresponding changes in CRII (Figure 2b) are also significant and become dramatic after 1500 AD. The European CRII reached its maximum during the Maunder minimum and had low values, comparable to the modern epoch, ca. 1100 AD and again relatively high values in 400–800 AD. Ionization at Western USA also shows a maximum at Maunder and Dalton minima and a minimum (at the modern level) ca. 800 AD. This is consistent with the famous climate deviations like the Little Ice Age and the Medieval Warm Period [Jones and Mann, 2004]. However, CRII at the Far East region shows completely different behaviour—it reaches its maximum ca. 1000 AD, and its absolute minimum is nowadays. The longitudinally averaged CRII (grey curve in Figure 2b) is pretty stable and closely follows that of the Far East region (except of the period ca. 1000 AD) before 1600, and then lies close to the European site. It depicts the maximum during the Maunder minimum followed by a moderate decrease until present time. Therefore, changes in the regional CRII at mid-latitudes are defined by both geomagnetic changes and solar activity, and none of the two processes can be neglected relative to each other.

[15] The solar radiation and CR-related effects can be disentangled on the regional scale, since the former is totally defined by the solar variations while the latter is dominated by geomagnetic changes. Thus, a comparison of the regional CRII variations with the corresponding regional paleoclimatic data may shed new light on the mechanism of solar influence upon the Earth's climate. We note that while there are alternative reconstructions of both paleomagnetic and solar activity data that are somewhat different from those

used here, the present qualitative result on the importance of regional changes is valid also for alternative data sets.

#### 4. Concluding Remarks

[16] We have shown that changes of the geomagnetic field, especially wandering of the dipole axis, play an important role in the regional cosmic ray induced ionization on centennial-to-millennial time scale. The results presented here imply that atmospheric influence of cosmic rays should be analyzed regionally as the global averaging may smear important effects. These changes at mid-latitudes dominate over those related to the solar activity, in particular during the modern epoch with highly tilted geomagnetic dipole. However, the present situation is not exceptional, and significantly stronger tilts of the geomagnetic axis might have occurred e.g. during geomagnetic excursions and reversals, with dramatic effect on the local CRII. The geomagnetic-related changes in the ionization should be studied regionally and, by comparison with the corresponding regional climate records (precipitation, draughts, etc.), can provide a new possibility in disentangling the effects of cosmic ray and solar total/spectral irradiance changes. Such correlative studies are foreseen for further research, and the authors can provide, upon request, results for CRII computed for given location, altitude and time interval, using any existing paleo-magnetic and solar activity reconstruction.

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