Long-term geomagnetic changes and their possible role in regional atmospheric ionization and climate

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Abstract. **Cosmic rays form the primary source of the lower atmospheres ionization, which may potentially affect the regional climate. The ionization at a given location is affected by two factors - solar magnetic activity, which modulates the flux of incoming cosmic rays, and geomagnetic field, which provides an additional shielding against cosmic rays. Here we discuss results of a study of the tropospheric cosmic ray induced ionization and its possible climate implications on the multi-millennial time scale. Spatial and temporal variations of the tropospheric ionization has been computed using the CRAC:CRII model and applying the paleomagnetic CALS7k.2 reconstruction. It has been shown that long-term trends of the tropospheric ionization are largely defined by changes of the geomagnetic field, rather than by the solar variability. This makes it possible to distinguish between direct and indirect solar-terrestrial climate effects. An analysis of spatio-temporal relation between the modelled ionization trends and some regional climate indices on the time scale of 6–7 millennia reveals a highly significant correlation between them, a feature that is difficult to model with direct general circulation models considering only the direct solar forcing. This suggests that cosmic ray induced ionization may play a role in long-term regional climate variations and needs to be properly accounted for in the models.**

Keywords: **cosmic rays, atmosphere, ionization**

I. INTRODUCTION

Cosmic rays (CR) form an important factor of the outer space influence upon the terrestrial environment (e.g., [1], [2]). CR variations on long-term scale are defined by not only heliospheric modulation, but also by changes of the geomagnetic field [3]. Accordingly, variations of CR in the Earth's atmosphere can be essentially different from solar activity on longer time scales, leading to potentially distinguishable effects on the terrestrial environment. The most important terrestrial effect of CR is related to the ionization of the ambient air [4], which is called the cosmic ray induced ionization (CRII) and may result in atmospheric changes potentially capable of affecting climate. Such potential mechanisms include enhanced aerosol and cloud formation in the troposphere, mediated by CR (e.g., [5], [6], [7], [8]). Although details of these mechanisms remain unclear, one can expected that enhanced CRII would correspond to a larger amount of tropospheric clouds, and thus to colder and wetter regional climate. Long-term (centennial) changes in CRII can be different in different regions, affected by the fast geomagnetic axis migration [3], [9]. Here we study regional changes of the tropospheric CRII over the last 6–7 millennia and show the importance of the geomagnetic field variations. We also provide, as a possible implication of the millennial CRII regional variations, a statistical comparison between some regional paleoclimatic reconstructions and the computed tropospheric CRII variations. Such a study may shed a new light on the role, if any, of cosmic rays on the long-term regional climate variations. Here we concentrate on the long-term studies for the pre-industrial epoch without essential anthropogenic factors.

II. VARIATIONS OF CRII OVER MILLENNIA

CRII is a result of the cascade induced by energetic cosmic rays in the Earth's atmosphere. The ionization rate Q at a given location and altitude h can be expressed as [10]:

$$Q = \sum_i \int_{Tc,i}^{\infty} J_i(T,\phi)\; Y_i(h,T)\; dT, \qquad (1)$$

where summation is over different species of primary CR, J_i is the differential energy spectrum of the $i^{\rm th}$ specie of CR near Earth outside the geomagnetic field, and $Y_i(h,T)$ is the ionization yield function. Integration is over the kinetic energy T above $T_{c,i}$, which is the kinetic energy corresponding to the local vertical geomagnetic cutoff rigidity P_c. The CRII temporal variations are effectively controlled by two mutually independent factors: the local geomagnetic cutoff, defined by the geomagnetic field; and the differential energy spectrum of CR outside the magnetosphere. CRII was computed using the CRAC:CRII [10] model at a given altitude as function of the CR energy spectrum, parameterized via the heliospheric modulation potential ϕ (see formalism in [11]), and the local geomagnetic rigidity cutoff P_c. We use a recent reconstruction of ϕ over the last 7000 years from the data on cosmogenic ^{14}C [12] (see Fig. 1A).

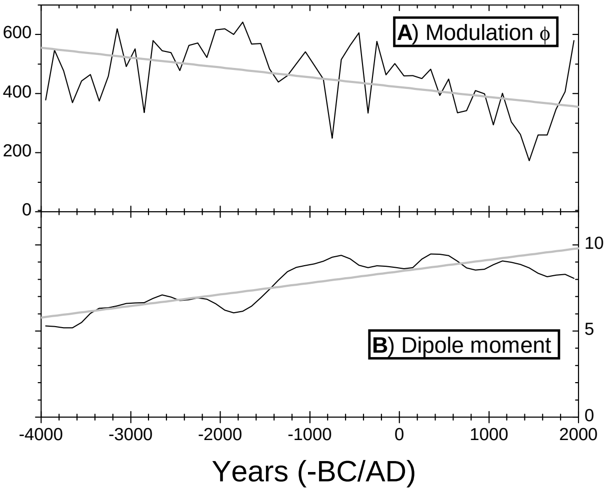

Fig. 1: Time profiles for the last 6000 years (all data are averaged over calendar centuries). A) Reconstructed modulation potential ϕ (in MV) [12]; B) Geomagnetic dipole moment M (in 10^{22} Am^2) [13]. Grey lines in each panel depict the best-fit linear trend.

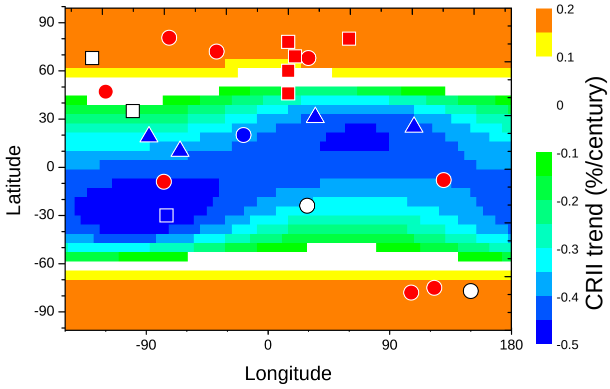

Fig. 2: Spatial pattern of the millennial trend in tropospheric cosmic ray induced ionization for the last 6000 years (see text for definition). Color scale to the right represents the slope of the trend in %/century. Symbols represent the corresponding trends in different regional paleoclimatic proxy time series (see text for references): temperature reconstructions (circles), humidity/precipitation (triangles), and glacier advances (squares). The color of the symbols represents the sign of the slope: negative (blue), positive (red), and no trend (white).

The long-term trend in the solar modulation of CR was negative, the modulation being gradually decreasing between 2000 BC and the Spörer minim of solar activity ca. 1500 AD. The modulation was quickly increasing since the Maunder minim ca. 1700 AD until present, but this plays only a little role in the multi-millennial trend.

Geomagnetic shielding of CR can be reasonably approximated via the geomagnetic vertical cutoff rigidity, computed for a shifted dipole, as

$$P_{\rm c} \approx 1.9 \cdot M \left(\frac{Ro}{R}\right)^2 \cos^4 \lambda_G, \qquad (2)$$

where M is the geomagnetic dipole moment (in 10^{22} Am^2), Ro is the Earth's mean radius, and R and λ_G are the distance from the given location to the dipole center and the angular distance to the magnetic pole (geomagnetic latitude), respectively, and $P_{\rm c}$ is expressed in GV.

Geomagnetic cutoff $P_{\rm c}$ was computed using the paleomagnetic model CALS7K.2 [13] for the same time period (Fig. 1B). One can see that the general trend in the dipole moment was increasing: it was nearly doubled during the first half of the studied period, until about 1000 BC, and remained at a high level of (8–10)$\times 10^{22}$ Am^2 after that. During that time, the magnetic axis was wandering quite essentially on the centennial scale [3] within the polar cap.

Thus, CRII at a given location and time can be affected by variations of both the solar modulation of CR and the geomagnetic field, and their relative role varies over the Globe. Since there is no geomagnetic shielding in the polar region, polar CRII is totally defined by the solar modulation and is independent of the geomagnetic field. This relation is reversed in an equatorial region, where the CR variability is mostly defined by the magnetic dipole moment. At mid-latitudes both the geomagnetic field and solar changes play a role but none of them dominates ([3], [9]). Figure 2 shows a geographical pattern of the millennial trends in CRII (defined as the slope of the best fit linear trend of the tropospheric CRII variations in each location for the past 6000 years). Since the solar activity (Fig. 1A) and geomagnetic field strength (Fig. 1B) depict opposite millennial trends, three regions can be clearly separated in the millennial scale CRII variability: Polar region, where it is totally defined by the solar activity changes – a weak positive millennial trend (about 0.2% per century), corresponding to the overall decrease of the solar activity; Tropical region, where it is mostly dominated by changes in the geomagnetic field – strong negative CRII trend (up to 0.5% per century); Mid-latitude region, where both effects are equally important – CRII remained at roughly the same level during the last millennia. The globally averaged tropospheric CRII depicts a decreasing trend (-0.2 ± 0.03%/century) over the past six millennia. Therefore, the global effect of CR upon Earth is defined, at this time scale of several millennia, largely by changes in the geomagnetic field rather than by solar variability. This effect can perturb studies of solar variability on climate (e.g., [14]). On the other hand, this may help to disentangle direct solar effects (e.g., via the irradiance) from those caused by CR via the heliospheric modulation.

III. Possible Climate Implication

As an illustration of possible climate implication of long-term CRII variations we compare long-term trends

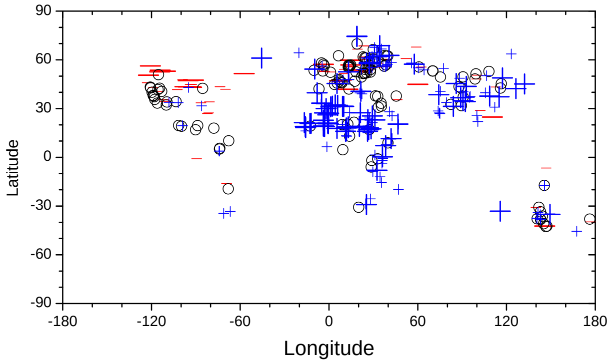

Fig. 3: Spatial pattern of the millennial trend in the lake status (see text for definition). Big and small red dashes, circles, small and big blue crosses correspond to much wetter, wetter, no change, drier and much drier present status, respectively, of the lakes compared to that 6800 BP.

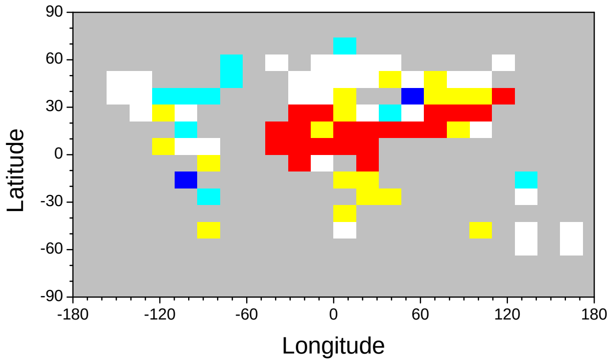

Fig. 4: The agreement P between millennial trends in the tropospheric cosmic ray induced ionization and in the lake status. Red/yellow and dark/light blue rectangles correspond to regions of high/moderate statistical significance of agreement and disagreement, respectively. White rectangles depict regions with unsettled relation ($|P| < 0.1$). Regions without data of the lake status are filled in grey.

in CRII with some paleoclimatic proxies. Since the local/regional variations are essential, we concentrate not on global indices but on regional paleoclimatic series. We also emphasize long-term multi-millennial trends in the data rather than detailed time variability of cosmic rays and terrestrial parameters. We do not pretend here to provide a comprehensive analysis of all the existing climatic data sets or study detailed mechanisms, but we want to test the hypothesis of a link by some examples.

First we studied some regional climate data sets, available for the last 6-7 millennia, as collected in [15, – see references therein]. Here we only consider the slope of linear long-term trends in the data, which were divided into three categories of their correspondence to a positive trend in CRII: positive trend in humidity/precipitation and glacier advance or cooling in temperature, no changes, and negative in humidity/precipitation/glaciers or warming in temperature. Local/regional climate trends for the last six millennia defined in this way are superposed, as colored symbols, on Fig. 2, which shows the CRII trends. One can see that trends in the temperature (dots in the Figure) depict no apparent relation with the CRII changes: they are mostly depicting a cooling. Humidity/precipitation records show formally good correlation: all the four data sets depict a negative trend (drying), in agreement with the modelled trend in CRII. However the analyzed humidity data sets are limited to the tropical regions, where the CRII changes are also dominated by the negative trend due to rising geomagnetic dipole moment. Another set of data is related to the history of glacier advances and retreats at different sites (shown as squares in Fig. 2). There is a general agreement between the glacier data and CRII trends: The only systematically shrinking glacier in South-West Cordillera corresponds to a region of strongly decreasing CRII; most high-latitude glaciers were expanding, in accord with the CRII increase in polar/subpolar regions; and the behavior of mid-latitude glaciers is not well-pronounced. Based on this limited data we are not able to conclude wether the relation between CRII and local climate trends is real or due to a coincidence.

Next we use a data set, available via the PMIP-2 Project GLSDB (http://pmip2.lsce.ipsl.fr/pmip2/-synth/lakestatus.shtml), which presents the relative status of more than 600 lakes around the world for the last 6–7 millennia ([16], [17], [18]). Since the status of a lake is defined by the balance between precipitation and evaporation, the wetter lake status generally correspond to wetter/colder climate, and according to the adopted hypothesis on CR-climate relation, to higher CRII. The geographical pattern of the lake status difference L (varying from -2, much wetter, to 2, much drier – see [15]) between present days and 6800 BP is shown in Fig. 3. The general pattern shows drying in Africa and Asia, wetting in Northern America, and unsettled situation in South America, Europe and Australia. This pattern of the relative lake status can be quantitatively compared, in a statistical manner, to the CRII pattern (Fig. 2). In each grid box of $15° \times 10°$ in longitude×latitude, we computed a product $P = S \times L$ of the lake status L (if available) and the CRII trend slope S. A map of the distribution of P, a measure of the agreement between the two indices, is shown in Fig. 4. General agreement is observed over the entire Africa and a major fraction of Asia, with a few spots in both Americas and in Australia. Disagreement is observed in a region in Northern America and a few spots in South America, Near East and Oceania. Europe, Alaska and Australia, i.e. the middle-to-high latitude regions, remain uncertain. Visual inspection of the agreement does not allow to evaluate its statistical significance.

Accordingly, we have performed a statistical test of the result. The global average value of $\langle P \rangle$ is 0.18±0.04, i.e. significantly positive, formally implying a good agreement. However, this value alone can be misleading because of the uneven spatial distribution (the lakes are located at the continents, with a dominance of Africa-Eurasia, where CRII trends are mostly negative). Therefore, we estimate the significance of this result by a conservative Monte-Carlo method. First, the L values are randomly shuffled inside the existing grid boxes. Then new values of P^* are calculated, using the actual CRII trends S, and the new average value $\langle P^* \rangle$ is obtained. By repeating this procedure $N = 10000$ times, we obtained a distribution of $\langle P^* \rangle$. Finally, the number of simulations n with $|\langle P^* \rangle| > \langle P \rangle$ gives an estimate of the significance α of the agreement (the probability that this agreement is due to a random coincidence without a causal link): $\alpha \equiv n/N$. The estimated significance is $\alpha \approx 0.02$, indicating that the probability of a random occurrence of the observed agreement between lake status and CRII trends is about 2%.

Even such a formally significant agreement may be casual, not serving as an evidence for a real CRII-climate link, because different trends in regional climate between tropics and polar regions can be an intrinsic feature of the global climate system. If so, detailed models of the climate dynamics throughout the Holocene, using a general circulation model (GSM), would predict patterns comparable with the map of lake status changes [19]. However, despite several attempts ([16], [20]), results of such direct modelling, including only the direct solar forcing, did not yield sensible agreement with the observed lake status features. Therefore, it appears plausible to think that the good agreement between CRII and lake status patterns implies a real connection, viz. that changes in CRII may slightly modulate the local climate (cf., e.g., [21]). Further studies using other climate parameters are necessary to investigate particular mechanisms of the CRII climate relation, which is not attempted here.

IV. Conclusions

Long-term (multi-millennial) trends of CRII in the troposphere are defined not only by solar changes (i.e., covariant with solar irradiance), but largely by changes of the geomagnetic field. CRII variations are not spatially homogeneous but depict a clear geographical pattern. This is particularly important in tropical regions and for global averaged data. Ionization in the polar region is mostly affected by the solar variability.

An analysis of spatio-temporal relation between the modelled ionization trends and the lake level data as an example of the regional climate change on the time scale of 6–7 millennia reveals a statistically highly significant correlation between them, which appears better than the results of direct general circulation modelling considering only the direct solar forcing. This suggests that CRII may play a role in long-term regional climate variations.

Acknowledgements. Supports from the Academy of Finland, the Finnish Academy of Science and Letters (Vilho, Yrjö and Kalle Väisälä Foundation) and University of Oulu (International Short-Term Research Visits) are acknowledged. GAK was partly supported by the Program of Presidium RAS N16.

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