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Calculation of the cosmic ray induced ionization for the region of Athens

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Abstract. A complete study of ionization induced by cosmic rays, both solar and galactic, in the atmosphere, is presented. For the computation of the cosmic ray induced ionization, the CRII model was used [1] as well its new version [2] which is extended to the upper atmosphere. In this work, this model has been applied to the entire atmosphere, i.e. from atmospheric depth 0 g/cm^2, which corresponds to the upper limit of the atmosphere, to 1025 g/cm^2, which corresponds to the surface. Moreover, an application has been made as a function of rigidity and latitude, from 0GV or 90^o which corresponds to Polar regions, to 15GV or 0^o which corresponds to Equator. Athens corresponds to 8.53GV rigidity and 38^{o}N latitude. An application has, also, been made for the different phases of the solar cycle (maximum at the year 2000 and minimum at the year 2010), which coincides with the operational period of the cosmic ray station of the University of Athens.

1. Introduction

Ionization is a very important factor of climate modulation, as it affects different climate parameters, such as cloud cover, precipitation, cyclogenesis in mid- to high-latitude regions, atmospheric transparency and aerosol formation [3]. Cosmic rays form the main source of ionization of the Earth's atmosphere leading to substantial physical-chemical changes in the ambient air [4], [5]. The cosmic ray induced ionization (CRII) depends on two main causes: the solar activity, which modulates the intensity of the cosmic ray flux, and the geomagnetic field, which acts as a charged particle discriminator and determines which particles arrive at the Earth at different latitudes.

In this work, the CRII model [1], [2] is applied to the entire atmosphere and all over the Globe, as well as for different time periods and solar cycle phases.

2. The CRII model

The CRII model is a full numerical model, which computes the cosmic ray induced ionization in the entire atmosphere, all over the Globe. The model computations reproduce actual measurements of the atmospheric ionization in the full range of parameters, from Equatorial to Polar Regions and from the solar minimum to solar maximum.

Roughly, the CRII rate expressed as the number of ion pairs produced in one gram of the ambient air per second (ion pairs/gr. sec) at a given atmospheric depth *x* can be represented in as follows:

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

where the summation is performed over different *i-th* species of cosmic rays (protons, α-particles, heavier species), Y_i (x,T) is the ionization yield function (the number of ion pairs produced at atmospheric depth x by one primary CR particle of the i-th type, isotropically impinging on the Earth's magnetosphere with kinetic energy T), $Ji(T,\varphi)$ is the differential energy spectrum of galactic cosmic rays in the Earth's vicinity (given in units of [cm^2 sec sr (GeV/nuc)]$^{-1}$). Integration is performed above $T_{c,i}$, which is the kinetic energy of a particle of i-th type, corresponding to the local geomagnetic cut-off rigidity R_c. Full details of the CRII computations, including a detailed numerical procedure and tabulated Y, are given in [1].

3. Results

Using the CRII model [1], [2] a study of the distribution of ionization during the solar cycle 23 on a monthly and yearly basis was performed. A gradual increase of the ionization rate from the solar maximum to the solar minimum was observed.

The results at the solar maximum (year 2000) and minimum (year 2010), for a Polar region (R_c=0.1 GV), an Equatorial region (R_c=14.9 GV) and a middle latitude region (Athens, R_c=8.53 GV), as a function of the atmospheric depth, are presented in Figure 1. It is obvious that during the solar maximum (2000), the ionization has minimum values, while during the solar minimum (2010), the ionization is maximum. This indicates that the ionization follows the behavior of the cosmic rays, which is negatively correlated with the solar activity. It is important to mention that during the solar maximum, the ionization is almost two times greater at the Poles than in Athens, while during the solar minimum, it is almost three and a half times greater. In all cases, the ionization rate is maximum at the atmospheric depth x=100 g/cm^2, with a shift to lower atmospheric depths in the Polar regions. This atmospheric depth corresponds to the altitude of 18-20 km, where the secondary energetic particles are generated. Thus, as we go toward the Poles, maximum ionization CRII is found in

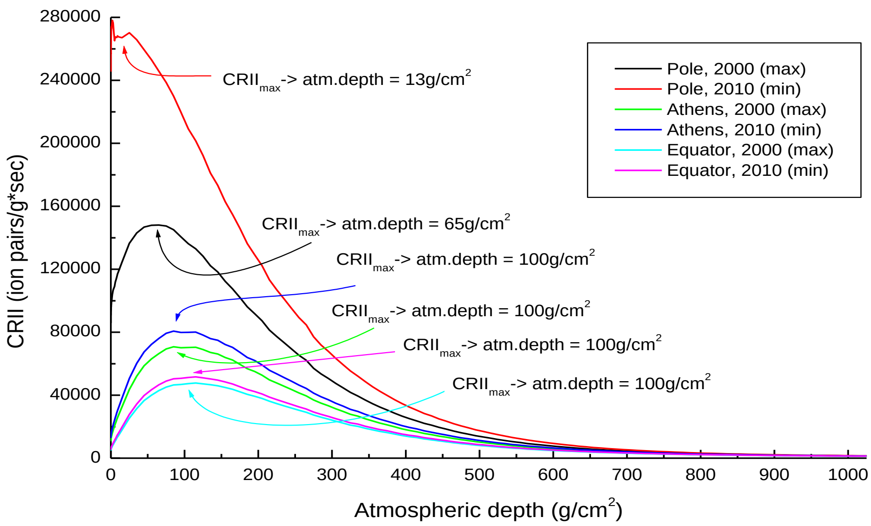

Figure 1. Yearly distribution of the CRI ionization as a function of the atmospheric depth at Athens (8.5 GV), at a Polar (0.1 GV) and an Equatorial region (14.9 GV), for the solar maximum (year 2000) and minimum (year 2010) of the solar cycle

atmospheric depths, i.e. higher in the atmosphere, and at the minimum of the solar cycle (year 2010), the ionization rate is growing, and the difference between the ionization rate at the maximum and the minimum of solar cycle in one location, is significantly increased.

The aforementioned behavior is due to the geomagnetic cut-off rigidity of each location (R_c), as the lower it is, the more cosmic rays enter the atmosphere, which then ionize it.

The time profiles of the monthly CRII from 1937 to 2010 (~7 solar cycles), at the atmospheric depth $x = 700\,\text{g/cm}^2$ (~3km altitude), which is useful for the comparison with the formation of low clouds, are illustrated in Figure 2. More to that, a possible comparison of the actual calculated ionization for the Poles, the Equator and Athens to the lack of solar activity period (i.e. φ = 0, “Maunder Minimum”) is presented [1], [6].

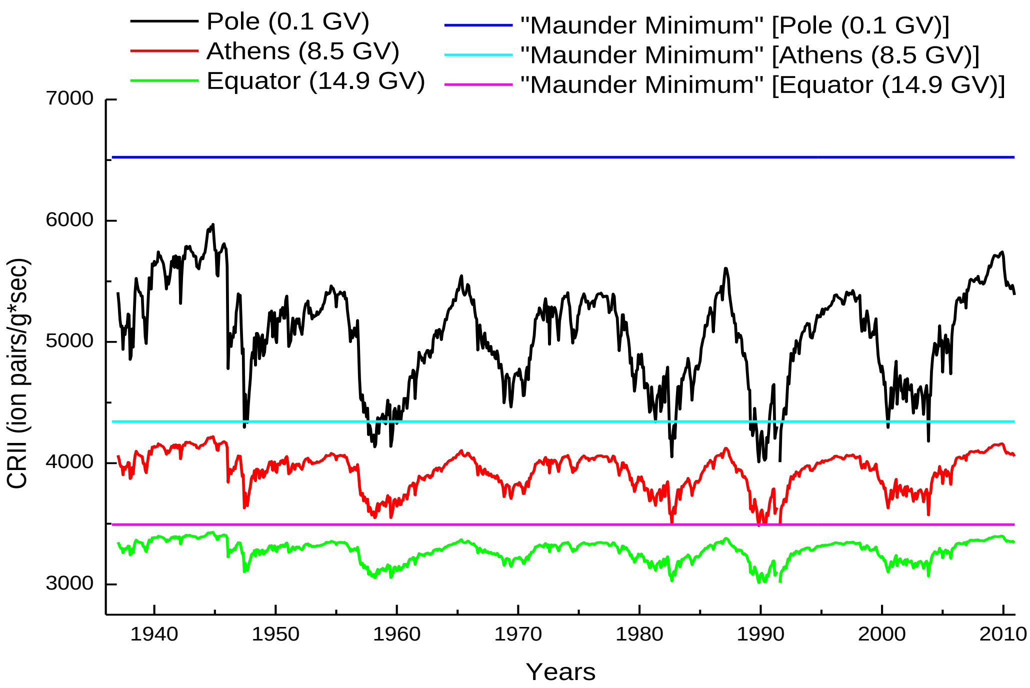

Figure 2. Monthly distribution of ionization CRII at the atmospheric depth $x = 700\,\text{g/cm}^2$, at Athens (8.5 GV), the Polar (0.1 GV) and the Equator region (14.9 GV), for the time period 1937-2010 and the illustration of the ionization effect of CRs if there was no solar modulation, i.e. $\phi = 0$, which would roughly correspond to the Maunder minimum of solar activity.

It is interesting to note that the ionization in the Polar regions is significantly higher than that one in Athens and the equatorial regions, for the whole time period (1937-2010). Furthermore, we compared these distributions with the value of ionization in the case of zero solar activity, as it was during the «Maunder Minimum», and found that the ionization in the atmosphere due to cosmic rays is constant and greatest! This means that the contribution of galactic cosmic rays, even if the contribution of solar cosmic radiation is negligible, it is essential to the creation of ions in the atmosphere and with the maximum value of ionization. This may be associated with the Little Ice Age (1645-1715), during which occurred the Maunder Minimum, i.e. zero solar activity ($\varphi = 0$).

A comparison of the monthly distribution of CRII at the atmospheric depth $x = 700\,\text{g/cm}^2$, to the cosmic ray flux, recorded by the Athens Neutron Monitor, for the time period 2000-2010, is shown in Figure 3 (left panel). This period coincides with the operation period of the Cosmic Ray Station of the

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University of Athens. We observe that CRII ionization agrees well with the intensity of the cosmic ray flux, while it is in a negative correlation with solar activity expressed by the sunspot number (Fig. 3, right panel).

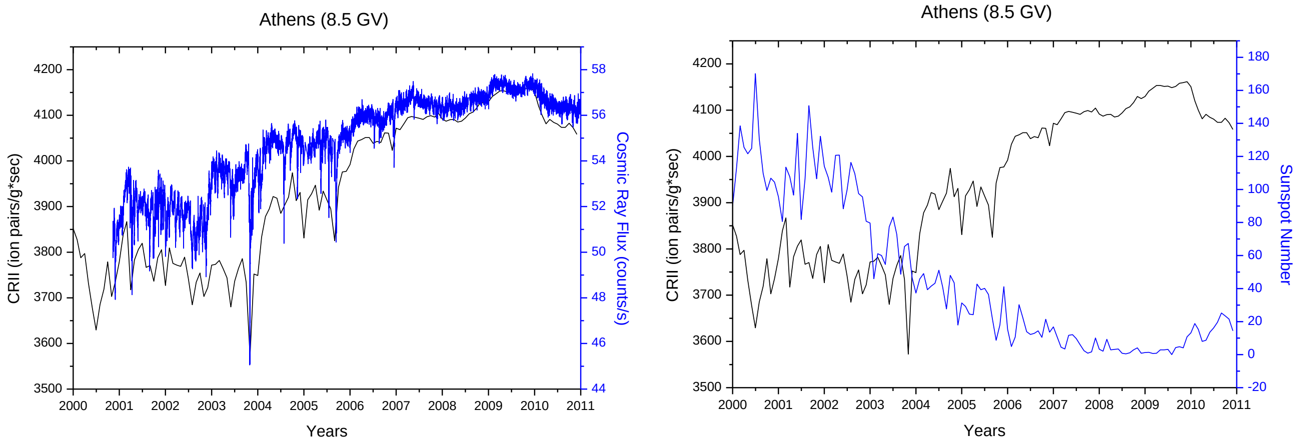

Figure 3. Comparison of the monthly distribution of CRII at the atmospheric depth $x = 700\,\mathrm{g/cm^2}$ (black line), to the cosmic ray intensity of the Athens Neutron Monitor (blue line, left panel) and sunspot number (blue line, right panel), for the time period 2000-2010.

4. Conclusions

In summary, we can say that the CRII model gives the opportunity to calculate the cosmic ray induced ionization for any desired location and for different conditions. A comparison of the CRII computations using this model with the cosmic ray intensity recorded from the Athens Neutron Monitor Station gives satisfactory results, especially during the declining phase of the solar cycle 23. Studying the distribution of the ionization at Earth for the wide range of cut-off rigidities from 0 to -15 GV, that means for latitudes 0^o-90^o, we note that the maximum ionization is found to be at Polar regions and mostly at the atmospheric depth x = 100 g/cm^2, where there is the maximum production of muons because of the interaction of the cosmic rays with the molecules of the atmosphere.

All this reinforces the belief that changes in the intensity of cosmic rays is an important factor of the ionization in the atmosphere and thus in affecting the Earth's climate.

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