Near real-time determination of ionization and radiation dose rates induced by cosmic rays in the Earth's atmosphere – a NMDB application

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Abstract. **A real-time database for high resolution neutron monitor data is being developed within the Neutron Monitor Database (NMDB) project funded by the European Union's 7th Framework Programme (www.nmdb.eu). In addition to the database, the NMDB project will provide different data products. One of the applications is the near real-time determination of ionization and radiation dose rates induced by cosmic rays in the Earth's atmosphere. The procedure of this application has four steps. In the first step, the near-Earth cosmic ray flux outside the geomagnetosphere is computed based on the NMDB. This flux is the basis for the next step, which is computing the cosmic ray flux at the top of the Earth's atmosphere for a 5°x5° grid in geographic coordinates. In the third step, at each grid point the secondary cosmic ray flux and the ionization of the atoms and molecules in the atmosphere at selected altitudes are processed with the Geant4 software package PLANETOCOSMICS developed at the University of Bern. Finally, the radiation dose rates at typical aircraft altitude are evaluated by using published flux to dose conversion factors. The paper presents the procedure and compares first computed radiation dose values with other theoretical results.**

Keywords**: effective radiation dose rate, ionization rate, NMDB**

I. INTRODUCTION

The cosmic ray (CR) variability and its possible connection to the physics and chemistry of the Earth's atmosphere as well as the radiation exposure of aircrew and frequent flyers due to CRs have become issues of increasing interest in recent years.

A. Ionization in the atmosphere

CR shower particles are the main source of ionization in the lower and middle atmosphere. Based on this fact, Ney [1] pointed out as early as 1959 that if the climate on Earth is sensitive to the amount of tropospheric ionization, then the climate is sensitive to the CR flux. The ideas by Ney were revived in 1997 by Svensmark and Friis-Christensen [2], who report a correlation between the CR intensity and the global cloud coverage during the 11-year solar cycle from an analysis of satellite and neutron monitor (NM) data for the time period 1980–1995. The paper by Svensmark and Friis-Christensen caused a controversial discussion in the last few years about a possible correlation between the ionization in the atmosphere caused by CRs and climate on Earth. In the last decennium many papers pro and contra this hypothesis have been published, see e.g. [3] and references therein. In this context, an increasing need for detailed information on the CR induced ionization in the Earth's atmosphere is apparent.

B. Radiation exposure at flight altitudes

The typical total effective dose due to galactic cosmic rays (GCRs) for a transatlantic flight, i.e. between Europe and North America, is of the order of about 50 μSv. Aircrew and frequent flyers may accumulate annual effective doses of a few mSv. This value is above the international dose limit for artificial exposure of 1 mSv per year for the normal population, but well below the average annual dose limit for radiological workers of 20 mSv/a as specified by the European Council Directive [4]. In 1996 the recommendations worked out by the International Commission on radiation Protection (ICRP) were adopted into European law. They require assessment of the radiation exposure of air crews. Currently there are a number of radiation transport codes and programs in use to compute dose rates and route doses by GCR. In these codes the relevant modulation of the GCR flux level is usually characterized by a monthly parameter based on data of one or several NM stations. Not considered are short term changes in the intensity of GCR near Earth or transient, increased radiation dose rates caused by solar cosmic ray (SCR) events that are observed at Earth, so-called ground level enhancements (GLEs). Two examples demonstrate the possible effect of SCR on radiation exposure. An increased dose rate for a period of more than one hour was observed during the GLE on 15 April 2001. During this GLE, Spurný and Dachev [5] reported a maximum dose rate of about double that for GCR from the measurements on board a flight from Prague to New York. The measurements for this flight show a total additional dose contribution from the SCR of $\sim$20 μSv. For the GLE on 20 January 2005 Bütikofer et al. [6] estimate an effective dose of 550 μSv for a flight from Buenos Aires to Auckland in a worst case scenario. This additional radiation dose due to SCR makes a relative increase of $\sim$500 % compared to the level before the onset of the GLE.

C. NMDB application: Ionization and radiation dose rates

Because of the above mentioned facts there is great interest in determining the ionization rates at altitudes relevant for atmospheric physics and chemistry as well as the radiation dose rates at typical flight altitudes with high resolution in space and in time. The new NM database that is built under the European Union's 7th Framework Programme project, *A real-time database for high resolution neutron monitor data* (NMDB), forms the basis for this mission. Beside the neutron monitor data in the data base, NMDB will provide different data products such as GCR flux near Earth but outside the geomagnetosphere, SCR flux during GLEs, different CR key parameters for space weather applications, and GLE alert systems [7]. Another application is the near real-time determination of the ionization and radiation dose rates induced by CRs in the Earth's atmosphere with software developed at the University of Bern.

II. Procedure to compute ionization and radiation dose rates

In a first step the GCR flux and the SCR flux outside the geomagnetosphere as well as the CR particle trajectories through the geomagnetosphere are calculated in parallel. In a next step the CR flux at the top of the Earth's atmosphere is determined based on the information calculated in the first step. Then the interactions of the GCR and the SCR with the Earth's atmosphere are simulated, i.e. the flux of the different secondary particle species and the resulting ionization of the atoms and molecules in the Earth's atmosphere are determined. The effective dose rates are calculated from the secondary particle flux in the atmosphere by using published flux to dose conversion factors. Finally, the information about the global ionization and radiation dose rates is fitted by spherical harmonics, and the corresponding coefficients are stored. For each selected time the procedure of the ionization and radiation dose rates computation consists of the above described steps. The flow-chart of the computation procedure is shown in Fig. 1.

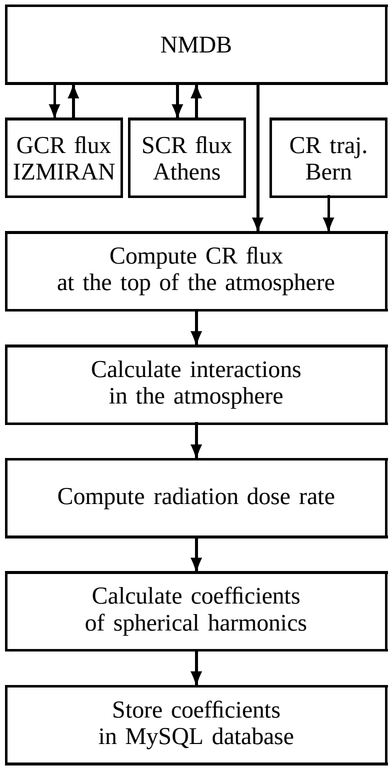

Fig. 1. Flow-chart of the computations of the ionization and radiation dose rates. For details see the text.

A. Computation of cosmic ray flux

1) GCR: An algorithm to calculate the rigidity spectrum of GCRs based on the mean daily data of the NM network was developed by the Cosmic Ray Department of the Solar-Terrestrial Division at the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences (IZMIRAN), Troitsk, Moscow region [8].

The IZMIRAN model describes the differential rigidity spectrum, $J(t, R)$, of the primary CR flux near Earth but outside the geomagnetosphere in function of the rigidity, R, and the time, t, with the following expression:

$$J(t, R) = J_0(t_0, R) \cdot (1 + \delta) \tag{1}$$

where $J_0(t_0, R)$ is the differential GCR rigidity spectrum at the reference time, t_0.

The parameter δ describes the primary variation of the GCR and is defined as:

$$\delta = a_{10} \cdot \frac{10^\gamma + b}{R^\gamma + b} \tag{2}$$

where a_{10} is the amplitude variation of the GCR density at rigidity $R = 10\,\mathrm{GV}$. Modeling the GCR intensity is reduced in this model by finding the three parameters: a_{10}, γ, and b.

No information about anisotropy is included in the IZMIRAN model, i.e. outside the geomagnetosphere an isotropic GCR flux is adopted.

2) SCR: The additional SCR flux during GLEs will be determined with the NM-BANGLE model developed by the National & Kapodistrian University of Athens, Greece [9]. The NM-BANGLE model computes the evolution of the GLE parameters (SCR spectrum, anisotropy, position of the anisotropy source) from the recordings of the NM network in a trial and error procedure by minimizing the differences between the calculated and the observed NM count rate increases.

The differential primary SCR flux, $I(R, t, \theta)$, in the NM-BANGLE model is assumed by the following expression:

$$I(R, t, \theta) = b \cdot R^\gamma \cdot \Psi(\theta, t) \tag{3}$$

where $\Psi(\theta, t)$ is the anisotropy function reflecting the angular dependence of the SCR flux coming from a direction with pitch angle, θ, with respect to the anisotropy direction. The anisotropy function is chosen as:

$$\Psi(\theta, t) = \exp\left(-n_a^2 \cdot \sin^2 \frac{\theta}{2}\right) \tag{4}$$

A total of five free parameters have to be determined by the model: b, γ, n_a, geographic latitude, λ, and longitude, ϕ, of the anisotropy direction.

3) The GCR flux will be determined by the IZMIRAN group and the SCR flux by the Athens group. Both groups will insert the parameters in the NMDB database. For the further computations the program developed at the University of Bern will utilize the parameters from NMDB.

B. Transport through the geomagnetosphere

The CR trajectories through the geomagnetosphere are calculated with the Geant4 [10] software MAGNETOCOSMICS [11]. In the code, the Earth's magnetic field is described by the IGRF model [12] for the internal field and by the Tsyganenko89 magnetic field model [13] for the magnetic field caused by external sources. The Tsyganenko89 model includes the disturbances of the geomagnetic field by providing seven different states of the magnetosphere that are described by the geomagnetic Kp indices (0, 1, ..., $\geq$6). The estimated Kp-index of the U.S. Air Force Space Forecast Center is used for the determination of the external geomagnetic field. These data are downloaded from the U.S. Dept. of Commerce, NOAA, Space Environment Center (http://www.swpc.noaa.gov/rpc/costello/).

The calculations of the effective vertical cutoff rigidities and of the asymptotic directions are made for vertical incidence at the top of the atmosphere and at the gridpoints of a network with mesh size 5°x 5° in latitude and longitude for the rigidity range 0-20 GV with a step size of 0.01 GV.

C. Computation of the cosmic ray intensity at the top of the atmosphere

With the knowledge of the CR intensity (galactic and solar) near Earth but outside the geomagnetosphere and the CR transport through the geomagnetosphere, the CR flux at the top of the Earth's atmosphere is computed at the gridpoints of the 5°x 5° geographic network.

D. Transport in the Earth's atmosphere

At each grid point the interactions of the GCR and the SCR with the Earth's atmosphere are computed by using yield functions that were determined with the Geant4 PLANETOCOSMICS [14] code. The flux of the different secondary particle species and the resulting ionization of the atoms and molecules in the Earth's atmosphere are evaluated as a function of the atmospheric depth.

E. Computation of the effective radiation dose rate

The effective dose rates caused by CRs are calculated for selected atmospheric depths at the specified gridpoints. For these computations the flux to dose conversion factors based on FLUKA calculations by Pelliccioni [15] are applied to the computed secondary particle flux in the atmosphere.

F. Storage of computed data

Instead of storing the values at each grid point of the 5°x 5° network for each moment, the computed data are fitted by spherical harmonics. With this procedure the ionization and radiation dose rates can be described by about 100 coefficients each when spherical harmonics of degree nine are used. The spherical harmonic coefficients for ionization and effective dose rates are stored in a MySQL database. This procedure guarantees fast and easy access to the data.

III. Publication and public access of data on NMDB webpage

In the following we present the different possibilities to access the computed ionization and dose rate data:

- The current computed ionization and effective dose rates will be published as contour plots on a world map. The effective radiation dose rate will be shown at a typical aircraft altitude, and the ionization rate will be plotted for an altitude where CRs may have a relevant effect on the atmospheric physics and chemistry. In addition, an animated contour plot will show the computed values for the preceding days for times without SCRs, as the GCR flux will be computed on a daily basis. During a GLE the sampling rate will be much higher, but it will be limited by the capacity of the computers used. Figures 2 and 3 show as an example the ionization rate and the effective radiation dose rate, respectively, for the day 2 April 2009 in the form they will be published on www.nmdb.eu.
- Plots and/or ASCII tables of ionization or dose rate for a user defined position and a specific time interval in the past can be retrieved from the NMDB webpage.
- Contour plots of ionization and/or dose rate for a user defined time in the past will also be available.

IV. Comparison of different radiation dose models

A comparison of the PLANETOCOSMICS model, i.e. the model used in NMDB, with the models CARI-6 [16] and EPCARD [17] is summarized in Fig. 4 as latitude profile at geographic longitude 0° for 15 December 2007, 1200 UT. At high latitudes the resulting effective dose rates computed by PLANETOCOSMICS are $\sim$6 % higher than those determined by EPCARD and $\sim$17 % higher than those by CARI-6. However, at low latitudes the PLANETOCOSMICS model produces values that are lower than the EPCARD (22 %) and

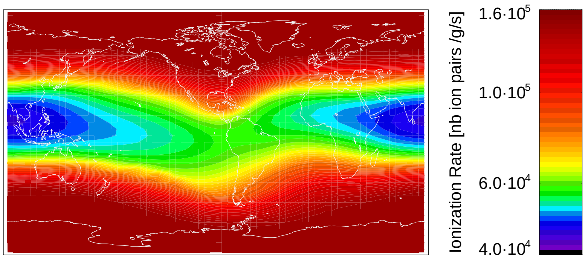

Fig. 2. Contour plot of computed ionization rates at an atmospheric depth of 700 g/cm^2 ($\sim$3.2 km asl) due to galactic cosmic ray conditions on 2 April 2009.

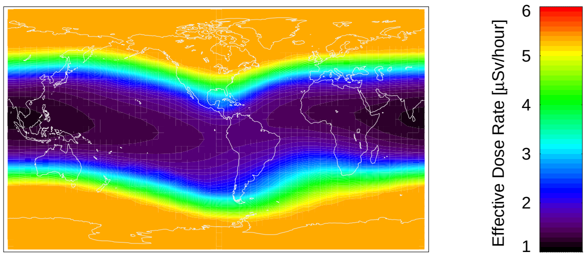

Fig. 3. Contour plot of computed effective radiation dose rates at an atmospheric depth of 250 g/cm^2 ($\sim$10.5 km asl) due to galactic cosmic ray conditions on 2 April 2009.

CARI-6 (36 %) values. The comparison of the different methods to determine the radiation dose rates has shown that the reasons for the differences in the results must be checked and that a fine tuning is needed.

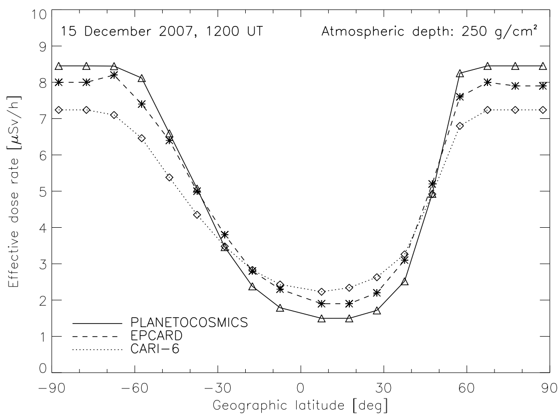

Fig. 4. Computed effective dose rates versus geographic latitude at geographic longitude 0° on 15 December 2007, 1200 UT with the models PLANETOCOSMICS, CARI-6, and EPCARD.

V. Conclusions

NMDB as a neutron monitor database and its applications will provide a comprehensive resource not only for CR scientists, but also for scientists who investigate terrestrial effects of CR, as well as for interested citizens. The published effective radiation dose rates will be of interest to airline companies and airline passengers who want to get an idea about the radiation exposure. In particular, the computation of radiation dose rates based on real-time NM data will provide rapid and more detailed information about short-time variations to a degree not previously achieved.

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