Production of cosmogenic $^7\text{Be}$ isotope in the atmosphere: Full 3-D modeling

Ilya G. Usoskin$^1$ and Gennady A. Kovaltsov$^2$

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[1] We present a physical model to calculate production of cosmogenic isotope $^7\text{Be}$ in the atmosphere. The model is based on a full Monte Carlo simulation of an electromagnetic-muon-nucleonic cascade in the atmosphere, using CORSIKA and FLUKA packages. The present results are in broad agreement with earlier empirical and semiempirical models but predict higher production rate than some recent theoretical models. A comparison to direct and indirect measurements of the $^7\text{Be}$ production rate in the atmosphere confirms the validity of the model in the whole range of geographical latitudes and altitudes. Results of the full Monte Carlo simulation are tabulated in a form of the yield function. These tables are given together with a detailed recipe, which allows a user to compute easily the isotope production for given location, altitude, and the spectrum of cosmic rays. An effect of a severe solar energetic particle event of January 2005 is estimated, providing a new tool for tracing of mass transport.


1. Introduction

[2] Cosmogenic isotopes with a relatively short lifetime have been long recognized as useful tools to study atmospheric transport of air masses [e.g., Lal and Peters, 1962; Raisbeck et al., 1981]. Particularly suitable for this purpose is the cosmogenic isotope $^7\text{Be}$ (the half-life time of 53.6 days), which is produced through interactions of atmospheric O and N nuclei and the nucleonic component of the atmospheric cascade induced by galactic cosmic rays (GCR) [see, e.g., Dorman, 2004, chapter 10.6]. Shortly after formation $^7\text{Be}$ atoms become attached to atmospheric aerosols and thus their fate is related to the aerosol transport. Therefore, $^7\text{Be}$ appears to be an excellent tracer for the atmospheric circulation, and is often used to constraint atmospheric circulation models [e.g., Koch et al., 1996; Liu et al., 2001; Jordan et al., 2003], when the data on measurements of the isotope concentration in stratospheric or tropospheric air is confronted with predictions of modern sophisticated 3-D models of the air mass transport.

[3] For this purpose one needs to know precisely features of its production in the atmosphere, including altitude and latitude profiles. A number of models have been developed to compute the $^7\text{Be}$ production in the atmosphere, as presented in Table 1. The first consistent model was developed by D. Lal and coworkers [Bhandari et al., 1966; Lal and Peters, 1967; Lal and Suess, 1968], called henceforth LP67. The LP67 model uses an empirical approach based on fitting simplified model calculations to measurements of the isotope concentrations and “star” (inelastic nuclear collisions) formations in the atmosphere. Accordingly, the LP67 model yields the best agreement with measurements of stratospheric $^7\text{Be}$ (see discussion by Liu et al. [2001]). Next was an analytical model by O’Brien [1979] (hereinafter referred to as OB79), who solved the problem of GCR-induced cascade in the atmosphere using an analytical stationary approximation in the form of Boltzman equation, which has been also normalized per “star” formation. Those models were based on calculating the rate of inelastic collisions or “stars” and then applied the mean spallation yield per “star.” This approach has been further developed by Nagai et al. [2000] (called N00 henceforth) who calculated the isotope production using secondary neutron spectra obtained by Armstrong et al. [1973] for the solar activity minimum conditions, and recent cross sections instead of the mean yield of a “star.” The N00 model is semiempirical and contains essential simplifications; for example, its proton spectrum was obtained by scaling from neutron spectra and applied in the same shape to all depths. Moreover, it is valid only for the solar minimum conditions. A new step in modeling of the isotope production has been made by Masarik and Beer [1999] (hereinafter referred to as MB99), who performed a full Monte Carlo simulation of the GCR-initiated cascade of the atmosphere and directly used cross sections of spallation reactions instead of the average “star” efficiency. Since Masarik and Beer [1999] were interested in the total production rather than in its altitude profile, they used an approximation of the flat atmosphere. The models described above compute isotope production by galactic cosmic rays and do not consider production by solar energetic particles (SEP). A recent model by Webber and Higbie [2003] and

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$^1$Oulu Unit, Sodankylä Geophysical Observatory, University of Oulu, Oulu, Finland.
$^2$Ioffe Physical-Technical Institute, St. Petersburg, Russia.

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Table 1. Comparison of the Parameters of Models for \(^{7}\text{Be}\) Production in the Atmosphere\(^a\)

<table>
<thead>
<tr>
<th>Model</th>
<th>LP67</th>
<th>OB79</th>
<th>MB99</th>
<th>N00</th>
<th>WH03/07</th>
<th>This Model</th>
</tr>
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<tr>
<td>Method</td>
<td>empirical</td>
<td>analytical</td>
<td>MC(^b) GEANT</td>
<td>Semiempirical</td>
<td>MC(^b) FLUKA</td>
<td>MC(^b) CORSIKA</td>
</tr>
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<td>Atmosphere</td>
<td>N/A(^c)</td>
<td>spherical shell</td>
<td>flat</td>
<td>N/A(^c)</td>
<td>flat</td>
<td>realistic curved</td>
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<td>CR flux</td>
<td>N/A(^c)</td>
<td>isotropic flux</td>
<td>isotropic flux</td>
<td>N/A(^c)</td>
<td>vertical beam</td>
<td>isotropic flux</td>
</tr>
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<td>Heavier CR</td>
<td>N/A(^c)</td>
<td>(\alpha), scaling</td>
<td>(\alpha), scaling</td>
<td>N/A(^c)</td>
<td>scaling</td>
<td>(\alpha), explicitly</td>
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<tr>
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<td>yes</td>
<td>N/A(^c)</td>
<td>N/A(^c)</td>
<td>yes</td>
<td>N/A(^c)</td>
<td>yes</td>
</tr>
<tr>
<td>Latitude profiles</td>
<td>yes</td>
<td>N/A(^c)</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Production function</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>CR type</td>
<td>GCR</td>
<td>GCR</td>
<td>GCR</td>
<td>GCR, solar min</td>
<td>GCR + SEP</td>
<td>GCR + SEP</td>
</tr>
<tr>
<td>Global production(^d)</td>
<td>0.08</td>
<td>0.063</td>
<td>0.035</td>
<td>0.055–0.062(^e)</td>
<td>0.035(^f)</td>
<td>0.062(^g)</td>
</tr>
</tbody>
</table>

\(^{a}\)LP67 [Lal and Peters, 1967; Lal and Suess, 1968], OB79 [O’Brien, 1979; O’Brien et al., 1991], MB99 [Masarik and Beer, 1999], N00 [Nagai et al., 2000], and WH03/07 [Webber and Higbie, 2003; Webber et al., 2007], as well as the present model.

\(^{b}\)Monte Carlo simulations.

\(^{c}\)Not available (N/A).

\(^{d}\)Global production (in atoms cm\(^{-2}\) s\(^{-1}\)), averaged over a solar cycle.

\(^{e}\)The value 0.068 (atoms cm\(^{-2}\) s\(^{-1}\)) originally given for the solar activity minimum has been reduced by 10–20% for the averaged solar cycle [Nagai et al., 2000].

\(^{f}\)W. R. Webber (personal communication, 2007).

\(^{g}\)Calculated for \(\phi = 0.7\) GV and geomagnetic field for the epoch 2005.

Webber et al. [2007] (hereinafter referred to as WH03/07) is also based on a full Monte Carlo simulation of the atmospheric cascade. The WH03/07 model uses improved cross sections and is advanced with respect to MB99 in the sense that it first computes the yield function (see section 2.4) for a fixed energy of GCR. This approach allows much more flexibility with the model application, in particular computing an effect of SEP, whose energy spectrum is totally different from that of GCR (see section 4). However, the WH03/07 model is simplified in the sense that it assumes a flat atmosphere and a vertical beam of primary GCR particles. With little effect on the total \(^{7}\text{Be}\) production, this assumption is crucial for the results in the stratosphere. Main properties of the earlier models have been summarized in Table 1. It is important to mention that most of the earlier models do not provide information on the altitudinal profiles of the isotope production and are not able to deal with the effect of solar energetic particles, which, as argued in section 4, can be quite important for a severe SEP event.

Accordingly, there is a need for a calibrated model that is able to compute a full 3-D pattern of the \(^{7}\text{Be}\) production in the atmosphere, including detailed simulation of the SEP effect. Here we present such a model, which can compute production of \(^{7}\text{Be}\) isotope in the atmosphere, including altitude and geographical profiles. Flexibility of the model allows a direct computation of the effect of SEP or other transient events. A special emphasis is given to comparison of the present model results with direct and indirect measurements and with other models. We provide a full numerical recipe so that everyone interested can compute the \(^{7}\text{Be}\) production in any prescribed solar and geophysical conditions.

2. Modeling the Isotope Production in the Atmosphere

2.1. Monte Carlo Simulations of the Atmospheric Cascade

The isotope \(^{7}\text{Be}\) is produced in the atmosphere mainly as a result of spallation of oxygen and nitrogen by energetic protons, neutrons and \(\alpha\) nuclei. These energetic particles can be either primary cosmic rays in the upper atmosphere or secondary nucleonic components of the cascade initiated by interactions of cosmic rays in the atmosphere. We have modeled development of the atmospheric cascade by means of a Monte Carlo simulation tool CORSIKA (Cosmic Ray Simulations for Kascade, version 6.617, August 2007) [Heck et al., 1998]. Interactions between low-energy (below 80 GeV of total energy) hadrons were treated with the FLUKA tool (version 2006.3b, March 2007) [Fassò et al., 2001]. We used a realistic curved atmosphere, in contrast to flat atmospheres used in most earlier models, also allowing for upward moving secondary particles. Using the curved atmosphere is important for the stratosphere. The chemical composition of the atmosphere was taken as N\(_2\), O\(_2\) and Ar in the volume fractions of 78.1%, 21% and 0.9%, respectively. The atmosphere’s density profile was modeled according to the standard U.S. atmosphere parameterized by Keilhauer et al. [2004].

The flux of primary cosmic rays corresponding to their CR intensity with isotropic angular distribution, \(J\) given in (cm\(^2\) s sr GeV\(^{-1}\)), has been modeled as follows. The corresponding particle flux, \(F\) in (cm\(^2\) s GeV\(^{-1}\)) impinging on the top of the atmosphere is defined as [see, e.g., Grieder, 2001, equation (1.35)]

\[
F = 2\pi \int_{0}^{\pi} J \cos \theta \, d(\cos \theta),
\]

where \(\theta\) is the incident zenith angle. We note that the unit flux, i.e., \(F = 1\), corresponds to the CR intensity \(J = 1/\pi\). Therefore, the distribution (over the zenith angle \(\theta\)) of the primary CR particles impinging on the atmosphere is proportional to \(\cos \theta\):

\[
\frac{dF}{d\cos \theta} = 2 \cos \theta,
\]

for the unit flux. Accordingly, when simulating the cascade, we threw primary CR particles with a fixed kinetic energy on the top of the atmosphere with the zenith angle distribution proportional to cosine of the zenith angle (equation (2)) and with the even azimuthal distribution. Cascade simulations have been done separately for two
Figure 1. Efficiency of $^7$Be production in air (see text).

Types of primary cosmic rays, protons and $\alpha$ particles. The number of simulated cascades $N$ was chosen depending on the energy of primary CR particle $E_o$, so that the statistical uncertainty of the final result is below 1%, which is much better than uncertainties in the used cross sections. We have performed $3 \cdot 10^6$ cascade simulation runs for each fixed value of $E_o$ below 1 GeV/nucleon, $10^6$ runs for $1 \leq E_o < 10$ GeV/nucleon, $3 \cdot 10^5$ runs for $10 \leq E_o < 100$ GeV/nucleon, and $10^5$ runs for higher energies.

For each cascade simulation we have fixed all the secondary and primary particles of the following types (protons $p$, neutrons $n$ and $\alpha$ particles) that cross a fixed observation level $h$ in the atmosphere. For each such particle we have recorded three components of its momentum, $P_x, P_y, P_z$, in the Cartesian coordinate system with the $z$ axis pointing to nadir. Then the angle $\psi$ between the nadir and the direction of the particle’s momentum is defined as

$$\cos \psi = \frac{P_z}{\sqrt{P_x^2 + P_y^2 + P_z^2}}$$

This information has been collected over all simulation runs with a given energy $E_o$ of primary CR particles and for fixed atmospheric depth $h$, and used in forthcoming computations.

2.2. Isotope Production Function

Since the development of atmospheric cascade is defined mostly by the amount of matter traversed, we express altitude in units of the atmospheric depth, i.e., the amount of the atmospheric matter in g/cm$^2$ overburden at a given level in the atmosphere. It is directly related to the barometric pressure so that the sea level (1013 mbar barometric pressure) corresponds to the atmospheric depth of 1033 g/cm$^2$. Average (per one primary particle of type $A$ with energy $E_o$) production of $^7$Be, in units of atoms g$^{-1}$ cm$^{-2}$, at the atmospheric depth $h$ can be defined as a sum of productions by all secondaries

$$\frac{dN}{dh}(E_o, h, A) = \frac{1}{N(E_o)} \left( \frac{1}{\cos \psi_\alpha} \sum_i S_p(E_i) + \frac{1}{\cos \psi_n} \sum_i S_n(E_i) + \sum_k S_\alpha(E_k) \right),$$

where $N(E_o)$ is the number of the simulated cascades with the primary particle’s energy $E_o$ and type $A$ (protons or $\alpha$ particles), and the three items correspond to sums over all secondary protons, neutrons and $\alpha$ particles, respectively, recorded as crossing the observational level $h$. Numerators of the sums represent the efficiency of the isotope production in air by a particle ($p$, $n$ or $\alpha$) with the kinetic energy $E$:

$$S_p(E) = \kappa_O \cdot \sigma_{pO}(E) + \kappa_N \cdot \sigma_{pN}(E),$$
$$S_n(E) = \kappa_O \cdot \sigma_{nO}(E) + \kappa_N \cdot \sigma_{nN}(E),$$
$$S_\alpha(E) = \kappa_O \cdot \sigma_{\alpha O}(E) + \kappa_N \cdot \sigma_{\alpha N}(E),$$

where $\sigma_{xy}$ is the cross section of $^7$Be production by particle of type $x$ on target $Y$, $\kappa_O = 8.672 \cdot 10^{21}$ g$^{-1}$ and $\kappa_N = 3.225 \cdot 10^{22}$ g$^{-1}$ are the numbers of oxygen and nitrogen nuclei, respectively, in gram of air. Cross sections have been adopted from Lange et al. [1994], Tatischeff et al. [2006], Webber and Higbie [2003], and Webber et al. [2007]. The resultant efficiency curves are shown in Figure 1.

2.3. Production in the Upper Atmosphere

The CORSIKA code is not well suited for simulations of the upper atmosphere ($h \leq 10$ g/cm$^2$) before the first nuclear interaction. Therefore, we have also performed an analytical calculation of the $^7$Be production in the upper 10 g/cm$^2$ atmospheric layer, using a thin target approximation. In this thin layer, secondaries can be neglected, and the isotope is produced by reactions between primary CR particles and the target nuclei. Let us consider a primary proton with energy $E_o$ penetrating to the atmosphere at zenith angle $\theta$. We neglect elastic scattering and assume that the particle moves straight, but loses its energy due to ionization of the ambient air or is lost due to nuclear inelastic processes. The probability of a particle of type $A$ with initial energy $E_o$ to survive, against inelastic process, until its energy becomes $E'$ is given as

$$W(E_o, E', A) = \exp \left( - \int_{E_o}^{E'} \frac{dE}{\lambda_{id}(E, A) \cdot \lambda_{ss}(E, A)} \right).$$

where $\lambda_{id}(E, A)$ and $\lambda_{ss}(E, A)$ are the stopping power due to ionization losses and the path length for inelastic nuclear collisions, respectively, as tabulated by Janni [1982]. The energy $E'$ is related to the distance $x$ traversed by the particle along its trajectory as

$$x = R(E_o) - R(E'),$$

where $R(E)$ is the path length of a particle with energy $E$ due to ionization losses [Janni, 1982]. Then the isotope production at a distance $x$ is given as

$$\frac{dq}{dx}(x, E_o, A) = S_A(E') \cdot W(E_o, E', A),$$

where $S_A$ is taken from equation (5) and $E'$ is defined from the equation (7).
where the units of \( Y \) are atoms g^{-1} cm^{2} sr. The factor \( \pi \) appears as conversion between the flux on the top of the atmosphere and CR intensity in the interplanetary space (see equation (1)).

[17] The tabulated yield function is presented in Tables 2 and 3 for primary cosmic protons and \( \alpha \) particles, respectively. Throughout the paper we discuss the isotope production per nucleon of the incident primary particle; that is, the production by one \( \alpha \) particle is four times that shown here.

[18] As an additional test for the correctness of our computations of the nucleonic component of the cascade and the yield function, we computed the yield function of a standard NM64 sea-level neutron monitor in a way similar to equation (13), but using the NM64 efficiency \( S_{NM64} \) [Hatton, 1971; Clem and Dorman, 2000] instead of the \( ^{7}\text{Be} \) production efficiency (equation (5)). A ground-based neutron monitor detects, with the known efficiency, superthermal secondary neutrons which are also the main source of the \( ^{7}\text{Be} \) isotope in the troposphere. The neutron monitor yield function has been thoroughly studied earlier by different groups and methods, including Monte Carlo simulations and confronting the obtained results with direct measurements in a wide range of conditions [see Clem and Dorman, 2000; and references therein]. Thus computed NM yield function is shown in Figure 3 together with the yield function computed by Clem and Dorman [2000], and one can see a close agreement between them, including both the shape and the absolute values. This confirms correctness of our computations of the flux of secondary neutrons in our approach.

2.5. Galactic Cosmic Rays Spectrum

[19] The spectrum of GCR at the Earth’s orbit is often parameterized by the so-called force field model [Gleeson and Axford, 1968; Caballero-Lopez and Moraal, 2004], where the spectrum of \( i \)th specie (with the charge number \( Z_i \) and the mass number \( A_i \)) of CR at Earth’s orbit, \( J_i \), is related to an unmodulated local interstellar spectrum (LIS)
Table 3. Normalized Yield Function $Y_{9}/\pi$ of $^{7}$Be Production by Primary Cosmic Protons$^{a}$

<table>
<thead>
<tr>
<th>$h/E_0$</th>
<th>0.02</th>
<th>0.03</th>
<th>0.05</th>
<th>0.1</th>
<th>0.15</th>
<th>0.4</th>
<th>0.76</th>
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<th>4.6</th>
<th>10.0</th>
<th>21.5</th>
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<td>6.0E-4</td>
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</tbody>
</table>

$^{a}$Unit of $^{7}$Be production is atoms g$^{-1}$ cm$^{-2}$. Column 1 depicts the atmospheric depth $h$ in g/cm$^2$. Columns 2–14 depict the energy in GeV/nucleon.
A product of the yield function \(Y\) and spectrum \(J\) is the differential production function of \(^{7}\text{Be}\):

\[
D(h, E_o, A) = Y(h, E_o, A) \cdot J(h, E_o, A).
\]  

An example of the production function \(D\) for protons is shown in Figure 5, for \(\phi = 0.7\) GV and several values of the atmospheric depth. One can see that the most effective energy of cosmic rays for the isotope production depends on the atmospheric depth. The maximum production in the stratosphere is due to particles with an energy of about 1 GeV/nucleon. The peak, corresponding to the effective energy, moves toward higher energies with decreasing altitude, being about 3 GeV/nucleon for lower troposphere. Once the production function \(D(E_o, h, A, \phi)\) is known, the production of the isotope at a given atmospheric level \(h\) and geomagnetic cutoff rigidity \(P_c\) can be computed as a sum (over different species of cosmic rays) of integrals of \(D\) over the energy of primary cosmic rays:

\[
Q(h, \phi, P_c) = \sum_i Q_i = \sum_i \int_{T_{c,i}}^{\infty} J_i(T, \phi)Y_i(h, T)dT,
\]

where \(Y_i\) is the yield function and \(J_i\) is the differential energy spectrum of the \(i\)th specie of GCR (protons and \(\alpha\) particles here). Integration is over the kinetic energy above \(T_{c,i}\), which is the kinetic energy corresponding to the local vertical geomagnetic rigidity cutoff \(P_c\). This cutoff energy (per nucleon) depends on the \(Z_i/A_i\) ratio of the cosmic ray specie and is given as

\[
T_{c,i} = T_r \left( \frac{Z_i/P_c}{A_i/T_r} \right)^{1/2} + 1 - 1.
\]

This implies that particles with the ratio of \(Z_i/A_i < 1\) are less deflected by the geomagnetic field, which, in combination with their weaker heliospheric modulation, makes them crucially important in the isotope production. Therefore, contribution of heavier species cannot be neglected in realistic models of the isotope production.

We note that using the vertical geomagnetic cutoff \(P_c\) does not account for realistic directional geomagnetic cutoffs but it provides a reasonable first-order approximation [e.g., Cooke, 1983; O’Brien, 2005] to the effective cutoff for isotropically impinging flux. Although this approach is supported by the agreement between our results and the measurements, it may be a source of uncertainties, and detailed computations of cosmic ray transport in the magnetosphere are planned for the future. A question of the
precise determination of $P_c$ for a given location and time is a separate problem [Cooke et al., 1991; Kudela and Bobik, 2004], which is left beyond the scope of the present study.

2.7. Recipe

By means of the above formalism one can easily compute the $^7$Be production rate for a given altitude $h$, location $P_c$ and time (or actually, the modulation potential $\phi$), using the following recipe:

1. Tabulated values of the yield function $Y(E_0, h)/\pi$ are given in Tables 2 and 3 for protons and $\alpha$ particles, respectively.

2. The value of the modulation potential $\phi$ can be obtained for a given period from Usoskin et al. [2005] or from a continuously updated list at http://cosmicrays.oulu.fi/phi. The shape of the differential energy spectrum $J(T, \phi)$ is then calculated using equations (14)–(17) for both protons and $\alpha$ particles.

3. The final production rate is computed using equation (19), where the integration bounds are different for the two species of GCR (see equation (20)).

The authors have also computed and tabulated the production rate $Q$ (equation (19)) for a 3-D grid of $h$ (0–1030 g/cm$^2$), $P_c$ (0–20 GV with the grid size of 0.5 GV) and $\phi$ (0–1.5 GV with the grid size of 0.05 GV). These digital tables are available in the auxiliary material or can be requested directly from the authors. The authors would be also happy to provide, upon requests, computation of $^7$Be production rate for any specific location and/or time, including contribution from solar energetic particles (see section 4).

2.8. Results

The main result of this model is a three-dimensional $(h, P_c$ and $\phi)$ matrix of the $^7$Be production rate $Q$, which can be found in the auxiliary material or requested from the authors. Since a 3-D function cannot be plotted, we show in Figure 6 its 2-D projection for a fixed medium cosmic ray modulation.

One can see that the strongest dependence is over the atmospheric depth (altitude), being two–three orders of magnitude between the maximum at 20–30 km and the minimum at the sea level. Dependence on the geomagnetic cutoff rigidity is moderate, being a factor of 3–20 (depending on the altitude) between geomagnetic poles and equator. The range of production variations due to the 11-year solar cycle is from 15% (sea level at the equator) to a factor of 3 (polar upper stratosphere). Four curves bounding geographical (between the geomagnetic pole and equator) and solar cycle variations of the production rate are shown in Figure 7.

We note that the total or column production (i.e., production within the atmospheric column of unit area) of $^7$Be is not representative because of the isotope’s short lifetime, comparable to or shorter than the residence time. Therefore, a more local production should be considered, especially in the stratosphere. However, for the sake of comparison with other models, we have computed the column production as a function of the geomagnetic latitude as shown in Figure 8. The global average production of $^7$Be in the atmosphere is evaluated as 0.078 and 0.05 (at cm$^{-2}$ s$^{-1}$) for the solar minimum ($\phi$ = 0.4 GV) and maximum ($\phi$ = 1.2 GV), respectively. The global production for the medium solar activity ($\phi$ = 0.7 GV) is 0.062 (at cm$^{-2}$ s$^{-1}$), which can be compared with the results of other models in Table 1. These values are computed for the geomagnetic field, corresponding to the epoch 2005. Keeping in mind that the geomagnetic field strength keeps steadily decreasing.
during the last centuries, the estimated $^7$Be global production was about 0.067 (at cm$^{-2}$s$^{-1}$), i.e., 8% higher, for the epoch 1955.

3. Testing the Model

3.1. Comparison With $^7$Be Measurements

[34] Because of the wide diversity of model results (as discussed in the forthcoming subsection), we first compare our simulation results with direct measurements as the most robust test.

3.1.1. Production Rate

[35] The most direct comparison would be with measurements of the production rate of the isotope in the atmosphere. We know one such experiment [Lal et al., 1960], when a sealed tank filled with oxygen target was exposed during two months (July–August 1959) at Echo Lake (Colorado) site at the atmospheric depth 685 g/cm$^2$. The average (corrected for decay) production rate of $^7$Be in this oxygen tank was $9 \times 10^{-6}$ at [g target O]$^{-1}$s$^{-1}$. Using the appropriate parameters (only oxygen target, $h = 685$ g/cm$^2$, $P_c = 3$ GV, $\phi \approx 1.3$ GV for July–August 1959 [Usoskin et al., 2005]) we have obtained the expected production rate of $8 \times 10^{-6}$ at [g target O]$^{-1}$s$^{-1}$. Thus, the model result agrees well with the direct measurement of $^7$Be production rate in the troposphere.

3.1.2. Concentration in Stratospheric Air

[36] There have been numerous measurements of the $^7$Be concentration in the atmosphere, from surface to the stratosphere. We show in Figure 9 some results of airborne measurements of the $^7$Be concentrations compared with the model prediction for the same conditions ($h$, $P_c$, and $\phi$) taken individually for each measurement. The measured concentrations have been converted into the production rate assuming equilibrium between decay and production. The agreement is quite good (within 20%) in the stratosphere (values above $10^{-4}$ at g$^{-1}$s$^{-1}$), but a large disagreement is observed in the troposphere. Such a pattern is quite clear since the concentration of $^7$Be is expected to be close to the equilibrium one in the stratosphere, where the isotope’s residence time is longer than the decay time. In the troposphere, however, $^7$Be is quickly washed out leading to the residence time shorter than the decay time. Accordingly, the measured concentration is different from the equilibrium one, and the difference depends on location and season [e.g., Kulan et al., 2006].

[37] Thus, our model depicts a fairly good agreement with fragmentary data on stratospheric measurements of $^7$Be concentration, assuming equilibrium conditions. This is a rough method, and a detailed comparison can be performed only taking into account realistic 3-D transport of air masses [e.g., Koch et al., 1996; Liu et al., 2001; Field et al., 2006]. Such a comparison is beyond the scope of this study, but is planned for further work.

3.1.3. Concentration in Rain Water as Estimate for Tropospheric Production

[38] As discussed earlier, concentration of $^7$Be measured in tropospheric air cannot give an easy estimate of the production rate. However, there are measurements of $^7$Be concentration in rain water in different regions. Of special interest are regions with high level of precipitation, which washes out almost all isotope atoms produced in the troposphere. Particularly interesting is Indian region, with heavy rains during the monsoon season, where the wet deposition dominates [Field et al., 2006]. This data is not expected to be affected by the seasonal (spring and fall) breaks of $^7$Be-rich stratospheric air into the troposphere, because first the monsoon season does not usually overlap...
with the seasonal breaks and second the air mixing effect is smaller in tropics compared to the midlatitudes [Field et al., 2006]. Several measurements of $^7$Be content in the rain water have been performed during the period 1956–1959 in two Indian sites: Kodaikanal ($P_c \approx 16$ GV, about 175 cm rainfall) and Bombay ($P_c \approx 15$ GV, about 100 cm rainfall) [Rama, 1960]. The corresponding averaged measured $^7$Be flux was found to be $1 \times 10^{-2}$ and $9 \times 10^{-3}$ (at cm$^{-2}$ s$^{-1}$), respectively. These values are close to the modeled isotope’s production rate, $8.5 \times 10^{-3}$ (at cm$^{-2}$ s$^{-1}$), computed for $\phi = 1$ GV (mean modulation for 1956–1959) in the atmospheric layer 240–1030 g/cm$^2$ (0–11 km) for $P_c = 15$ GV. This assumes that all the $^7$Be atoms produced in the troposphere are quickly, within 30 days [Shapiro and Forbes-Resha, 1976] (correction for decay has been applied [see Rama, 1960]), scavenged and eventually appear in the rain water.

[39] Thus, prediction of our model is in a reasonable agreement with the $^7$Be fallout flux evaluated from measurements in rain water collected in India monsoon regions.

[40] Concluding this section we note that, while a direct comparison of model results with measurements is only indicative and cannot prove, in this simple form, the exactness of the model, it provides a solid ground to suggest that our model is broadly consistent with observations in the whole range: from ground level up to the stratosphere, and from equatorial to polar regions. Moreover, the fact that our model result agrees with an experiment of direct measurements of the cosmogenic $^7$Be production rate in oxygen target (section 3.1.1) implies the correct overall normalization of the model.

3.2. Comparison With Other Models

[41] In this subsection we make an intercomparison between different models for $^7$Be production. First we can compare the predicted total production of $^7$Be in the atmosphere. It is noteworthy that the overall global production figures for an average solar cycle are quite controversial as given by different models (see the last row in Table 1). Our present model yields the global production rate close to those given by empirical and semi empirical models (LP67, OB79, N00) but higher than other Monte Carlo models. The present results are significantly (by a factor of 2) higher than the predictions by MB99 and WH03/07 models, and this difference is too high to be ascribed to different approaches and assumptions used. The difference is most likely related to an overall normalization rather than to modeling nuances. On the contrary, Monte Carlo models (MB99, WH03/07 and the present one) operate with pure simulations without direct fitting to the observed data, and thus are not guaranteed against a normalization error.

[42] All earlier models, except of OB79 one, provide latitudinal dependence of the column isotope production, as shown in Figure 8. One can see that the latitudinal dependence is similar for all the models, implying a similar treatment of the geomagnetic shielding. The polar-to-equatorial production ratio is about 6 for most of the models, only LP67 and N00 models yield a slightly weaker latitudinal dependence, with the polar-to-equatorial production ratio being about 5.

[43] Among earlier models only the LP67 one provides altitude profiles of $^7$Be production, and we compare those for the polar and equatorial conditions, as shown in Figure 10. While the overall level is slightly different (compare Figure 8), shapes of the profiles are close to each other in the troposphere. Although MB99 model does not provide an altitudinal dependence of the isotope production, it estimates the relative stratospheric production as 53.5% of the entire atmospheric production, using a realistic latitude-dependent height of the tropopause. When using the same relative thickness of the troposphere as function of latitude (Figure 7 in MB99), we obtain with our model that 55% of the global $^7$Be production can be ascribed to stratosphere. Both LP67 and N00 models yield that about 60–70% of $^7$Be is produced in the stratosphere globally, which is consistent with the results of our model, 68%, assuming the constant heights of the tropopause at about 11 km. Note that WH03/07 model does not provide results of the relative stratospheric production.

[44] Thus, we can conclude that the present model does not contradict with earlier models in the relative variations of $^7$Be production in both latitude and altitude. However, absolute values of the production rate differ from some earlier computations:

[45] 1. Our model results broadly agree with those by the semiempirical LP67 model, yielding however slightly lower (about 25%) global production rate.

[46] 2. Our model agrees with the analytical OB79 model in the global production similar, however the latter does not provide enough results for detailed investigation.

[47] 3. Our model predicts the global production by a factor 2 higher than the results of the MB99 model. This discrepancy is too large to be ascribed to some technical
differences in the model treatment, and is most likely caused by an overall normalization.

4. Our model broadly agrees with a semiempirical N00 model, including the altitudinal profile.

5. Our model is similar to the results of a recent WH03/07 model in many respects, but predicts higher (by a factor of 2) absolute production rate. The fact that the differential column production of $^7$Be by cosmic protons, computed by the two models, is very close to each other (see Figure 2) implies that cascade simulations were done consistently in the two models. Additionally, treatment of the geomagnetic shielding was also done mutually consistently (Figure 8). Therefore, we suppose that the difference in the total production between WH03/07 and our model can be due to the different treatment of primary cosmic rays (see Table 1) or the integration.

More important is that the results of our model are in good agreement with actual measurements, including the direct measurement of $^7$Be production rate in a special target (section 3.1.1). Because of the large diversity of the modeling results in the total production rate, we mostly rely upon comparison with measurements. Therefore, we have good reasons to believe that the overall normalization of our model is correct.

4. Effect of Solar Energetic Particles

While galactic CR are always present in the Earth’s environment, additional sporadic fluxes of solar energetic particles (SEPs) can occur related to solar eruptive phenomenon (solar flares or coronal mass ejections), leading to transient changes in the $^7$Be production in the atmosphere. As an example, we consider here the effect of a severe SEP event of 20 January 2005, which was one of the strongest events ever observed. Time profile of the neutron monitor count rate for this event is shown in Figure 11a, with a clear ground level enhancement (GLE) of a few hours duration. It is important that the GLE occurred during the continuing effect of a strong Forbush decrease caused by the interplanetary shock, when the CR level was reduced by 10–15% for a week (Figure 11a). The net effect of the sequence of events is negative in the neutron monitor count rate (i.e., the long-lasting Forbush decrease overcompensates the CR increase during the transient GLE). Figure 11b shows the calculated relative effect of the studied event, which is defined as follows. First, we have computed the production of $^7$Be by GCR during the day of 20 January 2005, when the GLE occurred, and during a quite day of 15 January, using the values of $\phi = 1.3$ and 0.69 GV, respectively (calculated using the method described by Usoskin et al. [2005]). Next we evaluated the spectrum (daily fluence) of SEP during the day of 20 January, using the spaceborne data fitted by a power law (power index $-2.15$) in energy up to 0.5 GeV [Mewaldt et al., 2005], and applying an exponential energy cutoff in higher energy range to fit the data from the world neutron monitor network. The resultant daily fluence

$$I = 6 \cdot 10^5 E_{\phi}^{-2.15} \exp \left( \frac{-E_{\phi}}{0.6} \right), \quad (21)$$

where $E_{\phi}$ and $I$ are expressed in GeV and $(cm^2 \text{ sr GeV})^{-1}$, respectively, is shown in Figure 4.

Applying this spectrum to equation (19), one can evaluate the additional production of $^7$Be due to SEPs. Let us consider the ratio of the total (GCR + SEP) production during the day of 20 January 2005 to the GCR $^7$Be production during a quite day of 15 January 2005. This ratio (or a relative effect of the SEP event in the isotope production) is shown in Figure 11 as function of geomagnetic latitude. One can see a greatly enhanced production of $^7$Be in the (geomagnetic) high-latitude region (geomagnetic latitude above 60°) at all altitudes. The enhancement of the
daily production was a factor of 2 at the sea level up to a factor of 15 in the stratosphere. On the contrary, the isotope production was reduced by 15–20% at lower geomagnetic latitudes, because of the transient GCR suppression (Forbush decrease) started 18 January. Therefore, a strong, almost instantaneous, “injection” of $^7$Be isotope took place in a limited geographical area during the extreme SEP event of January 2005. Taking into account the fact that parameters (altitude, latitude and time profiles) of this “injection” can be modeled, this provides a unique opportunity to trace the atmospheric transport on both global and local scales.

5. Conclusions

[53] We have presented a new model of production of cosmogenic $^7$Be isotope in the atmosphere. The model, based on full Monte Carlo simulation of the cosmic ray induced nucleonic cascade in the atmosphere, is able to compute 3-D (altitude and geographical location) production rate of the isotope in realistic conditions. The validity of the model has been verified by quantitative agreement with different kinds of observations, including direct measurements of $^7$Be production rate in a dedicated experiment. The present model is in qualitative agreement with earlier models, but deviates from some of them in the absolute values.

[54] We provide a detailed recipe and a set of precalculated digital tables (Tables 2 and 3 and the auxiliary material) for the yield function. Using this “do-it-yourself” kit everyone interested can compute the $^7$Be production for given location, altitude and the spectrum of cosmic rays, including solar energetic particles. This provides a new opportunity in studying details of the atmospheric transport, since it allows, e.g., computing the isotope production along the specific trajectory of a traced air volume.

[55] We have computed the effect of a severe solar energetic particle event of 20 January 2005 and shown that it resulted in greatly enhanced production of $^7$Be in (geomagnetic) polar regions, accompanied by suppression in all other regions. This very unusual distribution of the isotope production pattern provides a unique opportunity to study details of the atmospheric (particularly tropospheric) circulation and transport.

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