JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, D11103, doi:10.1029/2008JD010557, 2009

An updated simulation of particle fluxes and cosmogenic nuclide production in the Earth's atmosphere

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Received 6 June 2008; revised 6 February 2009; accepted 23 February 2009; published 2 June 2009.

[1] Since the publication of our first paper devoted to this subject, we have extended our model, using new cosmic ray and nuclear data. Therefore, we revised particle fluxes in the atmosphere and used them in concert with experimental or evaluated cross sections to calculate the production rates of ^{3}H, ^{7}Be, ^{10}Be, ^{14}C, and ^{36}Cl. The dependencies of these production rates on solar activity and geomagnetic field intensity were investigated in detail. Our simulations cover a whole range of these two parameters observed in the past. Comparison of the production rates calculated from two of the most frequently used primary galactic cosmic ray spectra showed weak dependence on the shape of the spectra. Alpha particles were included in the simulations for the first time, and we showed that the previously used scheme for estimation of alpha particle contribution to the total production rates is more complicated and latitude dependent. The production rates obtained agree well with most published experimental values.

Citation: Masarik, J., and J. Beer (2009), An updated simulation of particle fluxes and cosmogenic nuclide production in the Earth's atmosphere, *J. Geophys. Res.*, *114*, D11103, doi:10.1029/2008JD010557.

1. Introduction

[2] The interactions of cosmic ray particles with the Earth's atmosphere produce a cascade of secondary particles and a variety of cosmogenic nuclides. Modern experimental techniques such as accelerator mass spectrometry (AMS) allow us to analyze natural archives such as ice cores with high resolution. The concentration of cosmogenic nuclides in these archives is the result of the interplay among three processes: production, transport, and deposition. In order to make full use of the information stored in these archives, a detailed knowledge of the production rates of the cosmogenic nuclides is necessary.

[3] In order to calculate the cosmogenic radionuclide production rate, models have to be developed that describe the interaction of cosmic ray particles with the main target elements of the atmosphere and their subsequent transport from the atmosphere into the various archives. A review of the most frequently used models is given by *Masarik and Beer* [1999]. The main purpose of this paper is to provide updated particle fluxes and cosmogenic nuclide production rates in the atmosphere calculated with our extended model. In addition, we want to investigate how sensitive the production of cosmogenic nuclides is to various parameters or input data that have undergone changes in the recent time.

[4] Today, instrumental developments like satellites and AMS are generating enormous amounts of new data. Among those data are fluxes of cosmic ray particles, detailed information about solar flares, energetic and isotopic composition of cosmic rays, and properties and characteristics of the Earth's atmosphere. On the basis of these data, new models and new insights into the production of cosmogenic nuclides in the Earth's atmosphere have been formulated [*Webber and Higbie*, 2003; *Usoskin et al.*, 2006].

[5] The production rate of cosmogenic nuclides depends on the flux of cosmic ray particles. Time-dependent changes in the cosmic ray flux are caused mainly by variations in both the geomagnetic field intensity and solar activity. The dependence of the production rates on these parameters is investigated.

[6] Primary cosmic rays incident at the top of the atmosphere consist mainly of protons and alpha particles with energies around 1 GeV. The characteristic features of nuclear interactions at these energies are the production of secondary particles and the gradual development of a cascade of secondary particles. To simulate the development of the cascade in detail and to calculate the corresponding production rates of cosmogenic isotopes in the atmosphere, the GEANT [*Brun et al.*, 1987] and MCNP [*Briesmeister*, 1993] code systems are applied. Our present work is an extension of previous calculations [*Masarik and Reedy*, 1995; *Masarik and Beer*, 1999].

[7] In comparison to the work of *Masarik and Beer* [1999], this paper includes several important extensions of the model.

[8] 1. Now the model doubles the range of the solar modulation function. The highest simulated value is 2000 MeV.

[9] 2. Two approximations of galactic cosmic rays [*Castagnoli and Lal*, 1980; *Webber and Lockwood*, 2001]

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0148-0227/09/2008JD010557$09.00

Table 1. Elemental Composition Adopted for Our Calculations[a]

Element	Soil	Atmosphere
H	0.002	
N		0.755
O	0.473	0.232
Na	0.025	
Mg	0.040	
Al	0.060	
Si	0.290	
Ar		0.013
Ca	0.050	
Fe	0.060	

[a]Elemental composition is in weight fraction.

are used for simulating the secondary particle fluxes in the Earth's atmosphere, and the resulting differences are discussed.

[10] 3. Interactions of alpha particles are included in our simulations. On the basis of these simulations and a simple physical model, it is shown that alpha particles have to be considered in the model separately. Latitude-dependent correction factors have to be applied to the production rates of cosmogenic nuclides induced by alpha particles.

[11] 4. Differences between our and some other models are explored, and their effect on production rates is evaluated.

2. Calculation Model

[12] The production rate of the cosmogenic nuclide j at the atmospheric position D is

$$P_j(D, M, \Phi) = \sum_i N_i \sum_k \int_0^\infty \sigma_{ijk}(E_k) J_k(E_k, D, M, \Phi) dE_k, \quad (1)$$

where N_i is the number of atoms for target element i per kilogram of material in the sample, σ_{ijk} (E_k) is the cross section for the production of the nuclide j from the target element i by particles of type k with energy E_k, and $J_k(E_k, D, M, \Phi)$ is the total flux of particles of type k with energy E_k at location D inside the atmosphere for the geomagnetic field M and the solar modulation parameter Φ. In our model, the particle fluxes $J_k(E_k, D, M, \Phi)$ are calculated using the GEANT and MCNP codes. A description of the interfacing of these two codes is given by *Masarik and Beer* [1999]. The cross sections $\sigma_{ijk}(E_k)$ were those evaluated from many measurements and used in earlier calculations [*Masarik and Beer*, 1999].

[13] Although codes like GEANT and MCNP are able to calculate production rates of nuclides directly, experience shows that these codes are better suited to calculate the particle fluxes rather than the produced nuclides. The problems related to the direct calculation of production rates are summarized by *Masarik and Reedy* [1994]. The main problem with such production rate calculations is the frequent lack of measured cross sections, especially for neutron-induced reactions. Our approach of using calculated fluxes and code-independent sets of cross sections for the particular nuclide offers the opportunity to easily implement new cross sections without having to repeat the time-consuming flux simulations. A similar approach based on a combination of thin target cross sections with calculated particle fluxes was used by *Michel et al.* [1995] and *Bhandari et al.* [1993] to calculate cosmogenic nuclide production rates in stony meteorites [*Leya et al.*, 2000].

[14] In our calculations the solid Earth was considered as a sphere with a radius of 6378 km, a surface density of 2 g cm^{-3}, and an average chemical composition as given in Table 1. The Earth's atmosphere was modeled as a spherical shell with an inner radius of 6378 km and a thickness of 100 km. The atmospheric shell was divided into 34 concentric subshells of equal thickness (30 g cm^{-2}) with the average chemical composition. Each shell was divided into nine latitudinal sections corresponding to steps of 10° in magnetic latitude. The atmospheric density and temperature were approximated by the U.S. Standard Atmosphere 1976 model [*Champion et al.*, 1985]. Small variations in temperature profile, density, and chemical composition of atmosphere produce only a negligible effect on cosmogenic nuclide production rates [*Masarik and Reedy*, 1994, 1995].

[15] The primary cosmic ray flux at the Earth's orbit has two components: galactic cosmic rays (GCR) and solar cosmic rays (SCR). The GCR particles are a mixture of ~87% protons, ~12% alpha particles, and ~1% heavier nuclei with atomic numbers from 3 to ~90 [*Simpson*, 1983]. The spectral distributions of all particles look quite similar if they are compared in units of energy per nucleon. The analytical formula for the differential spectra of GCR primary protons consists of a term representing the local interstellar spectrum (LIS) J_{LIS} and a solar modulation term $M(\Phi)$:

$$J(E_p, \phi) = J_{\text{LIS}}(E_p + \phi) M(\Phi) = J_{\text{LIS}} \frac{E_p(E_p + 2m_pc^2)}{(E_p + \phi)(E_p + \phi + 2m_pc^2)}.$$

In our calculations we used the J_{LIS} of *Castagnoli and Lal* [1980]. In this approach the local interstellar spectrum J_{LIS}

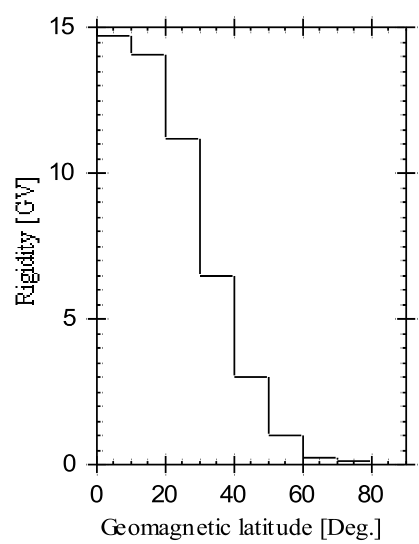

Figure 1. Vertical cutoff rigidity as a function of geomagnetic latitude.

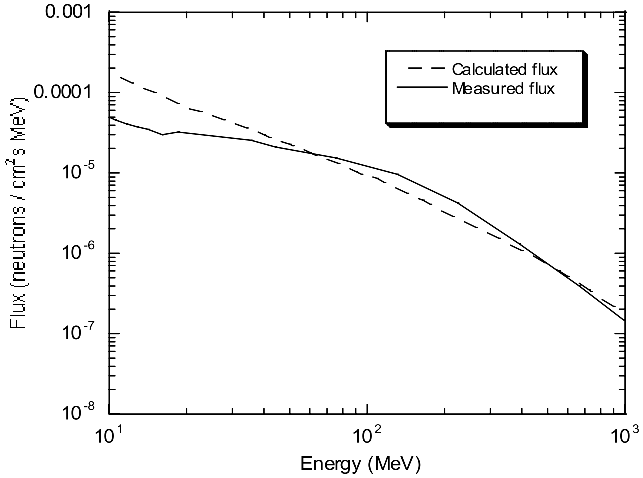

Figure 2. Comparison of our calculated neutron energy spectrum of cosmic ray–induced neutrons on ground with the experimental spectrum [*Gordon et al.*, 2004].

of protons cm^{-2} s^{-1} MeV^{-1} is given by [*Garcia-Munoz et al.*, 1975]

$$J_{\rm LIS}(E_P) = 1.244 \times 10^6 \left[E_p + 780 \exp\left(-E_p/4000\right)\right]^{-2.65}.$$

And after its multiplication by the M term, the final formula for the spectrum at the orbit of Earth is

$$J\left(E_p, \phi\right) = C_p \frac{E_p\left(E_p + 2m_pc^2\right)\left(E_p + x + \phi\right)^{-\gamma}}{\left(E_p + \phi\right)\left(E_p + 2m_pc^2 + \phi\right)}, \qquad (2)$$

where x = 780 exp [-2.5×10^{-4} (E_p + Φ)], E_p is the proton's kinetic energy, Φ is the parameter that takes into account the modulation effect due to solar activity, m_p is the mass of the proton, c is the velocity of light, m_pc^2 is 938 MeV, γ = 2.65, and $C_p = 1.244 \times 10^6$ cm^{-2} s^{-1} MeV^{-1} is the normalization factor. *Masarik and Beer* [1999] used the same formula; however, it was published incorrectly. For GCR alpha particles and heavier nuclei, analogous formulae hold with slightly different parameters (x = 660 exp [-1.4×10^{-4} ($E_\alpha + \Phi$)], $C_p = 2.23 \times 10^6$ cm^{-2} s^{-1} MeV^{-1}, and γ = 2.77) [*Lal*, 1988]. Recently, spectra of cosmic ray protons and alpha particles were reexamined, and a new formula to fit the experimental data was provided [*Webber and Higbie*, 2003]. This formula differs from that of *Castagnoli and Lal* [1980] in the approximation of $J_{\rm LIS}$ and is now given by

$$J_{\rm LIS}\left(E_p\right) = 21.1\left[E_p^{-2.8}\left(1 + 5.85E_p^{-1.22} + 1.18E_p^{-2.54}\right)^{-1}\right]$$

$$J_{\rm LIS}(E_\alpha) = 1.075\left[E_p^{-2.8}\left(1 + 3.91E_p^{-1.09} + 0.90E_p^{-2.54}\right)^{-1}\right]$$

for protons and alpha particles, respectively. Both spectra are in units of particles m^{-2} sr^{-1} s^{-1} MeV^{-1}. In order to investigate how a different LIS may affect the calculation of cosmogenic nuclide production rates, these spectra were also used in simulations. As the *Webber and Lockwood* [2001] and *Castagnoli and Lal* [1980] spectra differ in their shape and modulation term (the same measured spectra are fitted with different values of the modulation parameter), we first determined the long-term average modulation parameter for these spectra. The value of the primary GCR particle flux corresponding to Φ = 550 ÌeV used in these comparisons was found to be one that best fits production rates of cosmogenic nuclides measured by Apollo 15 [*Rancitelli et al.*, 1975; *Nishiizumi et al.*, 1984]. The same relative particle abundances as for the Castagnoli-Lal spectra were assumed. The effect on the galactic cosmic ray spectrum's passage through the interplanetary medium is also described by a heliocentric electrical potential with a magnitude at the Earth's orbit equal to the energy lost by interacting with the solar wind. The transition from this formulation to the one employed in our approach is based on the simple relativistic energy-momentum relation.

[16] At high energies, the reaction mechanisms for protons and alpha particles are very similar. Therefore, in extraterrestrial simulations, only interactions of protons are carried out, and the contribution from alpha particles is included by multiplication of the production rate by a constant. In the case of simulations within the Earth's magnetic field, alpha particles have to be treated separately because of the different geomagnetic effects on primary protons and alpha particles. This was not done correctly by *Masarik and Beer* [1999]. As we will show in section 3, their error is the main reason for some changes in previously published production rates. From the fit of lunar experimental data [*Reedy and Masarik*, 1994], the effective flux of protons, including the contribution of alpha particles with energies above 10 MeV at 1 AU, was determined to be 4.56 nucleons cm^{-2} s^{-1}. This value corresponds to the modulation parameter Φ = 550 MeV, which is identical to the long-term average value [*Reedy*, 1987]. To study the influence of solar modulation, we carried out detailed simulations for the modulation parameter Φ, varying it from 0 to 2000 MeV to cover the whole modulation range observed in the past.

[17] The solar cosmic rays consist of ~98% protons and ~2% heavier nuclei [*Simpson*, 1983]. The energies are typically in the range 1–100 MeV. Because of their relatively low energies, nuclear reactions in the Earth's atmosphere are limited to high geomagnetic latitudes (above 60°), and even there, the nuclide production from SCR is restricted to the very top of the atmosphere. The long-term average production of cosmogenic nuclides by SCR is not expected to be significant. Some huge solar particle events produce proton fluxes much higher than the average [*Shea*

Table 2. Correction Factors for Accounting for Alpha Particles

Vertical Cutoff Rigidity (GV)	Correction Factor[a]
14.72	1.76
14.04	1.73
13.94	1.7
11.72	1.7
6.47	1.57
3.02	1.47
0.1	1.44

[a]Correction factor average is 1.64.

Table 3. Dependence of the Production Rates on the Geomagnetic Latitude and the Global Average Production Rates in the Earth's Atmosphere for the Long-Term Mean Solar Activity and the Present Magnetic Field[a]

	Vertical Cutoff Rigidity							
Nuclide	14.72 GV	14.04 GV	13.94 GV	11.72 GV	6.47 GV	3.02 GV	0.1 GV	Global Average
^{3}H	0.139	0.155	0.194	0.264	0.414	0.576	0.602	0.320
^{7}Be	0.0175	0.0193	0.0240	0.0336	0.0521	0.072	0.0740	0.0402
^{10}Be	0.00915	0.0101	0.0127	0.0173	0.027	0.0375	0.0386	0.0209
^{14}C	0.979	1.08	1.342	1.841	2.87	4.00	4.55	2.05
^{36}Cl	$9.33e^{-4}$	$1.10e^{-3}$	$1.281e^{-3}$	$1.702e^{-3}$	$2.75e^{-3}$	$3.83e^{-3}$	$3.96e^{-3}$	0.00214

[a]Production rates are measured in atoms cm^{-2} s^{-1}. Solar activity is $\Phi = 550$ MeV.

and Smart, 1992], which could make a contribution to the production of some cosmogenic nuclides (e.g., ^{7}Be and ^{36}Cl) large enough to be observable in polar ice from Greenland and Antarctica. Calculations confirming these expectations together with the analysis of obtained results were published previously [*Masarik and Reedy*, 1995]. We repeated these simulations using the same codes as for the simulations of galactic cosmic rays.

[18] The geomagnetic field deflects incoming cosmic ray particles depending on their magnetic rigidity and angle of incidence. The rigidity of a particle is defined as the momentum per unit charge $R = pc/Ze$, where p is the momentum, Ze is the charge of the particle, and c is the velocity of light. The vertical cutoff rigidities used in the calculations are shown in Figure 1 [*Shea and Smart*, 1983]. In the present paper we switched from geographic to geomagnetic latitudes using a typical dipolar cutoff rigidity model of 14.9 $M/M_0 \cos^4(\lambda_{geo})$. This allows a more convenient use of our results for time periods characterized by different shapes and intensities of the geomagnetic field and also for in situ–produced cosmogenic nuclides. It has to be kept in mind that the expression for the magnetic field is just an approximation and that this can lead to biases in calculated values of fluxes and production rates. From the expression for the rigidity it is clear that rigidities for protons are 2 times larger than for alpha particles of a given momentum. The nonvertical cutoff rigidities were calculated with the aid of the computer code ANGRI [*Bland and Cioni*, 1968] version IGRIF 1980 with the geomagnetic model of *Shea and Smart* [1983]. Using just vertical cutoff rigidities leads to an overestimation (~12%) of the total production rate and its latitudinal distribution. This is one of the main sources of differences between our model and that of *Webber and Higbie* [2003]. Using the relativistic equation for energy-momentum, the cutoff energy can be calculated, and all particles with lower energies are excluded from the simulations. This leads to a latitudinal dependence of the primary and secondary particle fluxes. Consequently, it also leads to a latitudinal dependence of the production rate of cosmogenic nuclides, with higher values around the magnetic poles and lower values in the equatorial region. From paleomagnetic records, it is known that the geomagnetic field varied in the past in its intensity, direction, and polarity [*Tauxe*, 1993; *Gosse et al.*, 1996; *Brendel et al.*, 2007]. In order to investigate the influence of geomagnetic field variations on particle fluxes and cosmogenic nuclide production rates, the relative intensity of the geomagnetic field was varied from 0 to 2 relative to the reference field in steps of 0.25. The shape of the field was left unchanged.

[19] The main target elements in the atmosphere are nitrogen, oxygen, and argon. For reactions with oxygen, the same cross sections, supplemented by a few new data points, as in the case of extraterrestrial material were used [*Masarik and Reedy*, 1994; *Reedy and Masarik*, 1994; *Reedy et al.*, 1993]. For nuclear reactions with nitrogen and argon, experimental cross sections were used whenever possible. Otherwise, they were estimated from similar reactions with other elements. Our calculated particle fluxes are accessible on the Web (see http://masarik.dnp.fmph.uniba.sk/toky.html) and can be used to calculate the production of any radionuclide, provided that the corresponding cross sections are available. The uncertainties of proton cross sections are probably within their measurement errors, which are usually <10% for the newest data and >20% for older data. The uncertainties in evaluated cross sections for neutron-induced reactions are difficult to quantify but are probably less than 50%. The reported uncertainties for the measured neutron cross sections are of the order of 25%. The lack of precise cross sections for the production of different nuclei from the target elements of interest represents the largest contribution to the uncertainty of these calculations.

[20] Statistical errors of our simulations were of the order of 5%. The errors resulting from the assumed average composition of the atmosphere and surface are also not significant because earlier simulations [*Masarik and Reedy*, 1994] showed that except for hydrogen, small changes in the abundance of the elements affect the calculated particle

Table 4. Calculated or Measured Mean Cosmogenic Nuclide Production Rates in the Earth's Atmosphere[a]

	Production Rate (atoms m^{-2} s^{-1})				
Nuclide Source	^{3}H	^{7}Be	^{10}Be	^{14}C	^{36}Cl
Masarik and Reedy [1995]	0.26	0.0129	0.0201	2.01	0.00108
Blinov [1988]			0.0260		0.0019
O'Brien [1979]	0.255	0.00578	0.0260	2.01	0.000901
			0.0096.3		0.00173
Oeschger et al. [1970]		0.0185	0.0140		0.00220
Lal and Peters [1967]		0.081	0.0450	1.80	0.0011
Masarik and Beer [1999]	0.28	0.035	0.0184	2.02	0.00188
Damon et al. [1978]				1.99	
Beer et al. [1994]			0.0160		
Reyss et al. [1981]			0.0260		
			0.0200		
Monaghan et al. [1986]			0.0380		
Nir et al. [1966]	0.19				

[a]All nuclide sources are calculated except that of *Nir et al.* [1966], which is measured.

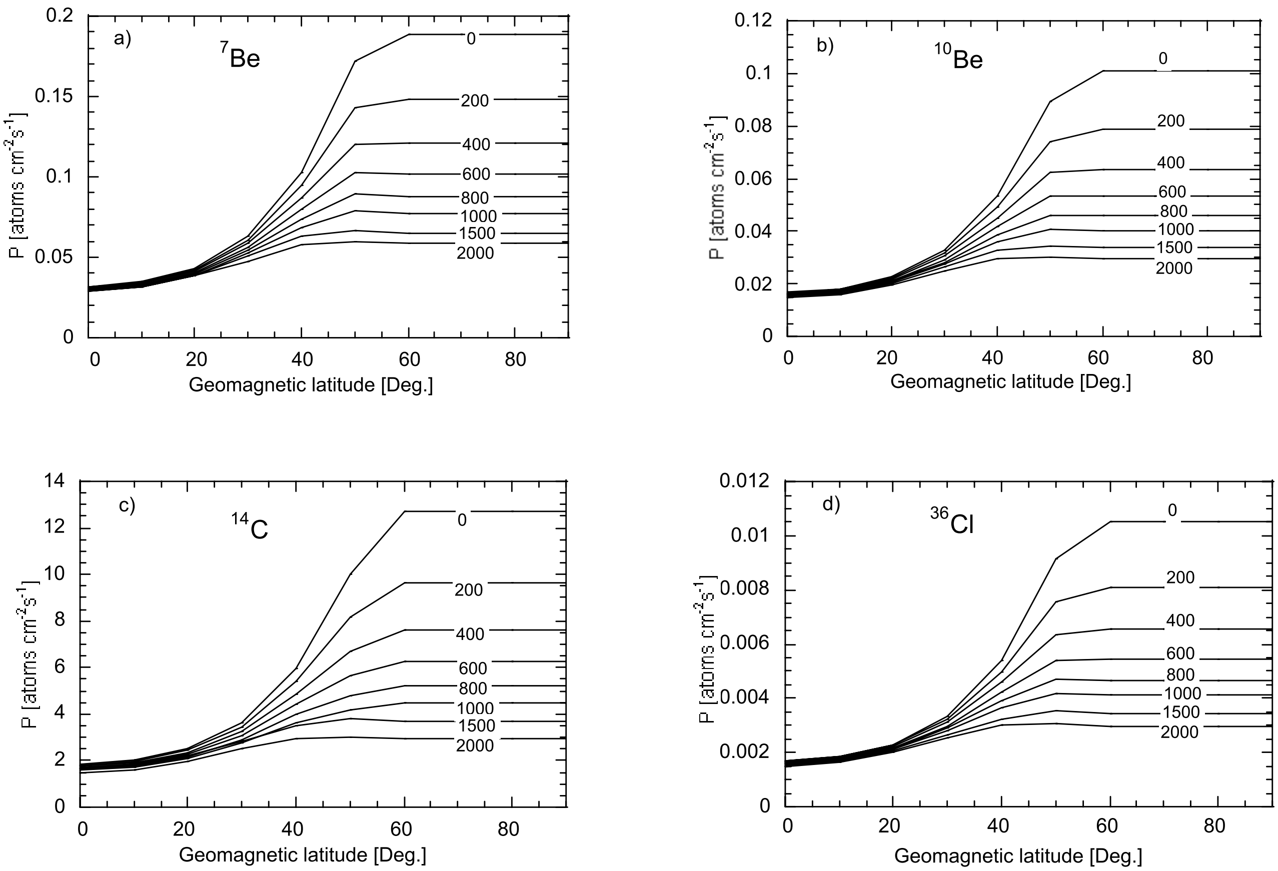

Figure 3. Depth-integrated geomagnetic latitudinal production rates of (a) ^{7}Be, (b) ^{10}Be, (c) ^{14}C, and (d) ^{36}Cl in the Earth's atmosphere for the solar modulation parameter Φ = 0, 200, 400, 600, 800, 1000, 1500, and 2000 MeV.

fluxes only slightly. The systematic uncertainties in our calculated fluxes are difficult to determine but are probably of the order of 10%. A comparison of our calculated neutron energy spectrum of cosmic ray–induced neutrons on ground to the measured spectrum [*Gordon et al.*, 2004] is presented in Figure 2. Differences in the calculated and measured neutron fluxes lead to the difference in production rates of investigated nuclides of the order of 5–13%.

3. Results and Discussion

[21] In our previous papers [*Masarik and Reedy*, 1995; *Masarik and Beer*, 1999], only the interactions of protons with the Earth's atmosphere were simulated, and the contribution from the alpha particles was included by multiplying the production rate by a factor of 1.44 [*Masarik and Reedy*, 1994]. This multiplication factor was obtained from simulations of production rates in meteorites and lunar samples, i.e., in specimens without a magnetic field. In the case of simulations within the Earth's magnetic field, alpha particles have to be treated differently. This is because the cutoff rigidities for protons are 2 times larger than for alpha particles. For low cutoff rigidities this difference does not play any role, as particles of all energies enter the Earth's atmosphere. Since the reaction mechanisms for protons and alpha particles are very similar, there is no need to simulate the interaction of alpha particles separately for any combination of the modulation parameter and field intensity. We did simulations just for extreme cases, and we found that the different cutoff rigidities of alpha particles can be taken into account by applying a latitude-dependent multiplication factor (Table 2).

[22] The calculated fluxes together with appropriate software are accessible on the Internet (see http://masarik.dnp.fmph.uniba.sk/toky.html). They enable the reader to calculate the production rate of any cosmogenic nuclide, provided that the corresponding cross sections are available.

[23] Using the calculated particle fluxes in the atmosphere, the production rates of ^{3}H, ^{7}Be, ^{10}Be, ^{14}C, and ^{36}Cl were estimated. The latitudinally and globally averaged production rates for the long-term mean modulation parameter Φ = 550 MeV are in Table 3. Obtained values are within the range determined from measurements in various archives or estimated by other theoretical approaches (Table 4).

[24] The most investigated cosmogenic nuclide in the Earth's atmosphere is ^{14}C. Many theoretical models and experimental procedures have been developed for the determination of its production rate. On the basis of previous work [*Masarik and Reedy*, 1995], we considered only the nuclear reaction ^{14}N(n,p) ^{14}C in our simulations. This reaction, which contributes more than 99% to the total production rate of ^{14}C, is, by far, the most important source of ^{14}C in the atmosphere.

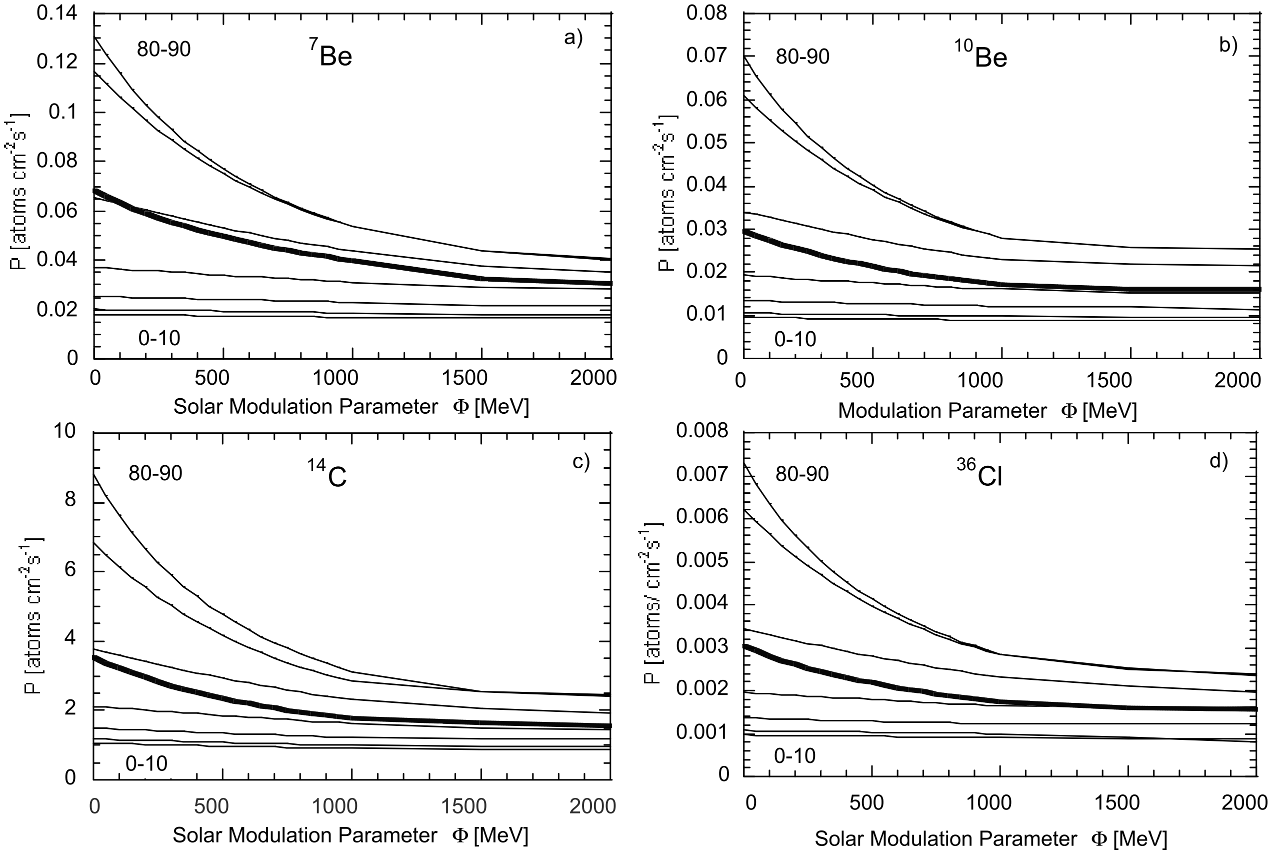

Figure 4. Dependencies of global average (thick line) and geomagnetic latitudinal production rates of (a) ^{7}Be, (b) ^{10}Be, (c) ^{14}C, and (d) ^{36}Cl in the Earth's atmosphere on the solar modulation parameter. Each line represents a latitude interval of 10°. The latitudinal production rates decrease with decreasing latitude for all modulation parameter and become constant for latitudes below 30°.

We calculated a mean production rate of 1.98×10^{-3} ^{14}C atoms g^{-1} s^{-1} in the Earth's atmosphere. Integrating over the depth of the Earth's atmosphere, a global average production rate of 2.05 ^{14}C atoms cm^{-2} s^{-1} is obtained. This value deviates from the value of *Masarik and Beer* [1999] by only 0.03 ^{14}C atoms cm^{-2} s^{-1}. Changes in the low-energy part of the particle production and transport simulations account for this small difference. These changes are discussed by *Kollar et al.* [2006]. The uncertainty of ~10% is mainly due to uncertainties and statistical errors in the neutron fluxes (the cross sections are well measured). For the rest of the nuclides listed in Table 3, the increase in the global average production rate due to the correct treatment of alpha particles is approximately 14%.

[25] When comparing our calculated production rates to those derived from measurements in various environmental systems, one has to keep in mind that our calculations represent global mean values, whereas the measured data reflect the local values to some extent and are also subject to transport effects [*Heikkilä et al.*, 2008]. The latitudinal production rates as a function of the solar modulation parameter Φ are presented in Figure 3 for the present geomagnetic field intensity. The dependencies of the latitudinal production rates and the global average production rate for the investigated nuclides on the solar modulation parameter are presented in Figure 4.

[26] For many geophysical applications, it is useful to know the dependence of the cosmogenic nuclide production rates on the geomagnetic field intensity. From sedimentary paleomagnetic records, it is known that the intensity of the geomagnetic field varied in the past from almost zero to twice its present value [*Guyodo and Valet*, 1996]. Therefore, we carried out simulations of the production rates of cosmogenic nuclides in the Earth's atmosphere for this intensity range. The latitudinal dependencies of the production rates for long-lived radionuclides (^{10}Be, ^{36}Cl, and ^{14}C) are presented in Figure 5, assuming a solar modulation parameter Φ = 550 MeV. Equivalent dependencies were also calculated for a solar modulation parameter Φ varying from 0 to 2000 MeV in steps of 50 MeV. They were used to calculate the average global production rates in Table 3. Analysis of the calculated dependencies shows that changes in the geomagnetic field intensity lead to substantial changes in the atmospheric production rate pattern for all investigated nuclides.

[27] For the cosmogenic nuclides included in Table 3, we also calculated the production rates by solar protons. The SCR differential flux J per unit of rigidity is usually expressed as

$$\frac{dJ}{dR} = k \exp(-R/R_0),$$

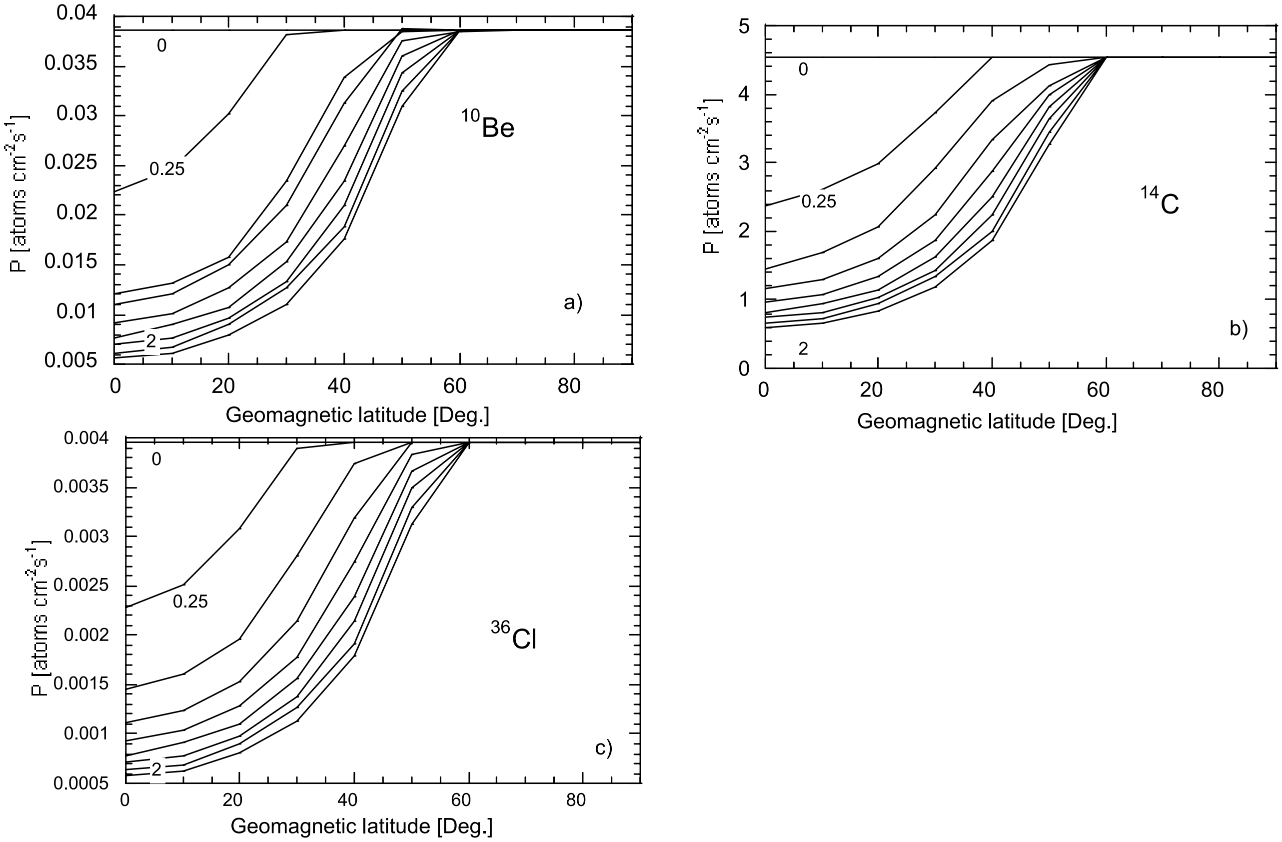

Figure 5. Latitudinal dependence of the depth-integrated production rates of (a) ^{10}Be, (b) ^{14}C, and (c) ^{36}Cl in the Earth's atmosphere on the geomagnetic field intensity. The field intensity was varied between 0 and 2 times its present value in steps of 0.25. Each line represents a single field intensity. The latitudinal production rates decrease with increasing field intensity for all geomagnetic latitudes.

where the rigidity R is the momentum of a particle per unit charge. The spectral parameter R_0 for solar protons from individual solar flares ranges from 10 to 150 MV for event-integrated spectra observed over the last 4 decades [*Reedy*, 1998, 2006]. The steep decrease in particle flux as a function of energy limits the production of SCR-induced nuclides to the upper few g cm^{-2} of the atmosphere. In our simulations we used R_0 = 80 MV and k = 100 particles cm^{-2} s^{-1} MeV^{-1}. For the simulations of strong solar particle events, we kept R_0 unchanged but increased the parameter k, which corresponds to the total number of particles emitted during an event. Because most of the solar cosmic ray particles have energies that are below the cutoff values, their contribution is nonzero only in polar regions. As can be seen from Table 5, SCR production rates for polar regions are below a percent of the galactic cosmic ray production rates. Considering only polar regions, the average calculated SCR/GCR production rate ratio for ^{7}Be and ^{36}Cl is 0.11. These relatively high ratios can be explained by the fact that both nuclides have relatively large cross sections at low energies (above 10 MeV) and relatively small cross sections at much higher energies (hundreds of MeV). A similar explanation also holds for cosmogenic nuclides produced by huge solar particle events. Production rates in polar regions from particles emitted during these events can be a few times higher than the average annual SCR production rate for the same regions during a typical year without any strong particle events.

[28] To investigate how much the production rate of cosmogenic nuclides depends on the chosen LIS, we calculated the production rates of the above nuclides using the LIS of *Castagnoli and Lal* [1980] and *Webber and Lockwood* [2001] shown in Figure 6. The modulation functions that fit the observed data for a particular year are slightly different; however, this does not matter for our simulations because all the production rates are normalized to an integral particle flux of 4.56 nucleons cm^{-2} s^{-1}. The difference in the production rate calculated from these two

Table 5. Calculated Mean Cosmogenic Nuclide Production Rates in the Earth's Atmosphere[a]

Nuclide	Production Rates (atoms cm^{-2} s^{-1}) GCR	Average SCR	October 1989 Event
^{3}H	0.320	4.69×10^{-3}	0.0193
^{7}Be	0.0402	0.00422	0.0075
^{10}Be	0.0209	1.91×10^{-4}	6.9×10^{-4}
^{14}C	2.05	3.38×10^{-4}	1.7×10^{-3}
^{36}Cl	0.00214	2.32×10^{-4}	1.1×10^{-3}

[a]Production rates are globally averaged for GCR particles and represent polar region values (latitude above 60°) for SCR protons. For the October 1989 event the total proton flux registered for the period 19–30 October 1989 was taken, and this flux was divided by 1 year.

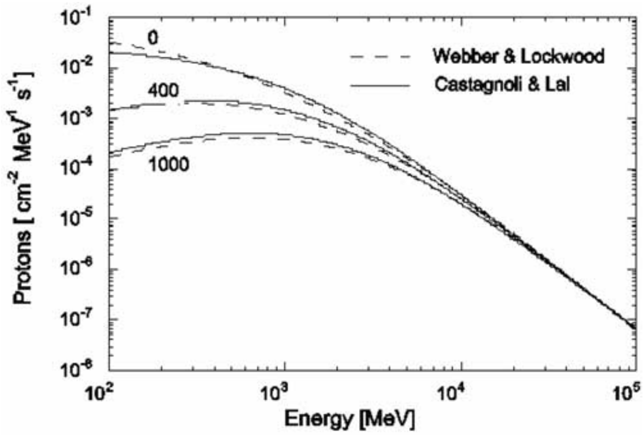

Figure 6. Comparison of Castagnoli-Lal and Webber-Lockwood spectra for three modulation functions: 0, 400, and 1000 MeV.

spectra is depth sensitive. It is of the order of a few percent for shallow depths in the atmosphere and then reaches the maximum (7.5%) at depths around 200 g cm^{-2}. After that, the difference gradually decreases to 0 (Figure 7). This behavior leads to a difference in the global average production rate of 2.8% for ^{10}Be, which is below the statistical uncertainties of the calculations. The results for other isotopes are very similar, and therefore, only the results for ^{10}Be are presented explicitly. The difference in production rates obtained from these two input spectra can be explained from Figure 6. At shallow depths, the Webber-Higbie particle spectra (primary plus secondary) are harder to detect than the Castagnoli-Lal spectra, and therefore, the Castagnoli-Lal spectrum leads to a larger production rate than the Webber-Higbie spectrum because cross sections for the production of cosmogenic nuclides have their maxima at low and intermediate energies. At larger depths, low-energy particles are more important, and therefore, the ratio of production rates changes. The difference in production rates is smaller for low-energy products because in order to reach low energies, particles have to undergo many scatterings and they "forget" from which spectrum they started. Direct comparison of production rates obtained by *Webber and Higbie* [2003] is not straightforward because the modulation functions corresponding to the same solar activity in both spectra are slightly different [*Usoskin et al.*, 2006]. This and the use of vertical cutoff rigidities by *Webber and Higbie* [2003] can largely explain the differences between our production rates and the ones given in their paper. Other sources of discrepancies in production rates are the different production cross sections used in the two simulations.

4. Conclusions

[29] A purely physical Monte Carlo model based on the codes GEANT and MCNP was used to simulate production and transport of galactic cosmic ray particles in the Earth's atmosphere. The model enables us to calculate differential fluxes of secondary proton and neutron fluxes as a function of geomagnetic latitude, altitude, chemical composition, geomagnetic field intensity, and solar modulation. These particle fluxes have been used to calculate cosmogenic nuclide production rates in the Earth's atmosphere.

[30] Alpha particles were included in our model by taking into account their correct cutoff rigidity. This correction leads to an increase of about 14% in the production rates for ^{3}H, ^{7}Be, ^{10}Be, and ^{36}Cl relative to our previous calculations [*Masarik and Beer*, 1999]. The calculated production rate of ^{14}C in the Earth's atmosphere is 2.05 atoms cm^{-2} s^{-1} and agrees well with experimentally determined and other calculated values. The comparison of our calculated values for ^{3}H, ^{7}Be, ^{10}Be, and ^{36}Cl to measured values is not unique, as experimental and other calculated values often differ substantially. We showed that the contribution from solar cosmic rays to the global average production rates of cosmogenic nuclides is negligible. A measurable contribution from solar cosmic rays was only obtained for polar regions during huge solar particle events, mainly for ^{7}Be and ^{36}Cl. Comparing the production rates obtained in simulations starting from different primary GCR spectra, we conclude that differences in global average production rates are within the statistical uncertainties of our simulations.

[31] The dependence of the production rates on variations in solar activity and the geomagnetic field strength was investigated in detail. The good agreement of our calculations with modern measurements shows that our model can be used to obtain reliable production rates of terrestrial cosmogenic nuclides and also that our model should be good for samples from very large depths in extraterrestrial objects, including those with an atmosphere and magnetic field. These results provide the basis for a quantitative reconstruction of the history of the solar activity and the geomagnetic field intensity using records of cosmogenic isotopes in natural archives such as sediments and ice cores [*Vonmoos et al.*, 2006; *Muscheler et al.*, 2005].

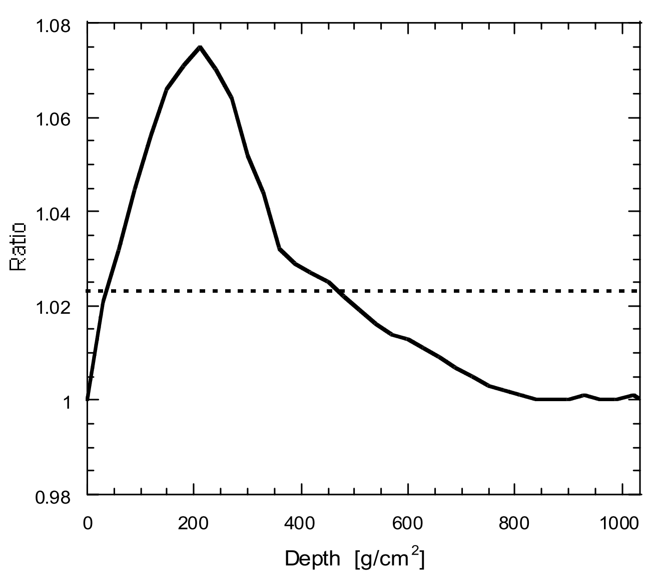

Figure 7. Ratio of the ^{10}Be production rates based on the LIS after *Castagnoli and Lal* [1980] and *Webber and Lockwood* [2001] as a function of atmospheric depth. The dashed line is the mean value.

[32] **Acknowledgments.** We thank many of our colleagues for their comments and encouragement, for some of the data used in this work, and for benchmarking our calculations. We especially appreciate the constructive comments by R. C. Reedy and K. McCracken that significantly improved this manuscript. We also thank R. C. Reedy for providing us cross sections of nuclear reactions. This work was supported by the Slovak Research and Development Agency under contract APVV-0569-07 and by the Swiss National Science Foundation.

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