Solar modulation parameter for cosmic rays since 1936 reconstructed from ground-based neutron monitors and ionization chambers

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[1] The differential energy spectrum of galactic cosmic rays near Earth is often parameterized by the force field model with the only time-dependent parameter, the modulation potential ϕ. Here we present a series of reconstructed monthly values of the modulation potential for the period from July 1936 through December 2009. This work extends our earlier study by employing new data and improving the reconstruction method. The presented series is a composite of three parts. The most reliable part is based on data from the world network of sea level neutron monitors and covers the period since April 1964. The part between February 1951 and March 1964 is based on data from one to two mountain neutron monitors of IGY type and is characterized by larger uncertainties and possible systematic error. The part related to the period before 1951 is based on data from Forbush ground-based ionization chambers and is characterized by large uncertainties and should be taken with caveats. The reconstructed series has been tested against long-term data of balloon-borne measurements of flux of cosmic ray ionizing radiation in the stratosphere performed by the Lebedev Institute since 1957. The comparison shows good agreement since 1964 but suggests that the result before 1964 may contain larger errors in that the NM-based reconstruction method may underestimate the low energy part of GCR spectrum.

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1. Introduction

[2] Studies of energetic particles of galactic cosmic rays (GCR) coming from outside the Solar System are important in many respects, they carry information on the energy release processes in the galaxy, they can serve as a probe for the heliosphere, and finally they affect the atmospheric properties on Earth via ionization/radiation [*Bazilevskaya et al.*, 2008; *Matthiä et al.*, 2009] and ensuing physical and chemical changes (see, e.g., reviews by *Scherer et al.* [2006] and *Usoskin and Kovaltsov* [2008]). Accordingly, knowledge of the behavior of solar modulation of cosmic rays on long timescale is important in many respects. The modulation during last decades is dominated by the 11-year cycle in antiphase with solar activity and a weak 22-year effect observed as alternation of sharp- and flat-peaked CR maxima, which is well understood in the framework of modern theory (see reviews by *Scherer et al.* [2006] and *Jokipii* [2008]). However, the temporal variability of modulation, including centennial trends [e.g., *Usoskin et al.*, 2002a; *Herbst et al.*, 2010], is only generally monitored. The ground-based network of neutron monitors (NMs) is the principal instrument to study variations of cosmic rays on the long-term scale, since 1951. With some caveats, data from ground-based ionization chambers can be used as an index of CR variations since mid-1930s [*McCracken and Beer*, 2007]. A NM, as well as an ionization chamber, is an energy-integrating device and cannot measure the energy spectrum of CR. Count rate of such a detector is defined as an integral, above the threshold energy corresponding to the local geomagnetic rigidity cutoff, of a product of the CR energy spectrum and a specific yield function of the detector [see, e.g., *Clem and Dorman*, 2000; *Usoskin et al.*, 2002b]. However, one can, using a theoretically calculated yield function of the standard NM and data from NMs at different latitudes, reconstruct the spectrum of primary CR, under an assumption on the spectral shape. Using data from the world network of neutron monitors, we have recently reconstructed variations of GCR spectrum for the period of 1951–2004 [*Usoskin et al.*, 2005, hereinafter referred to as U05]. The spectrum was reconstructed in the framework of the so-called force field approximation, which is widely used in various

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applications [*Vainio et al.*, 2009; *Herbst et al.*, 2010]. This reconstruction has been compared with several fragmentary direct measurement of the CR energy spectrum performed onboard balloons or satellites to show a good agreement between the measured and reconstructed spectra. Probably in the future direct data from space-borne cosmic rays spectrometers like PAMELA [*Adriani et al.*, 2009] or AMS [*Alcaraz et al.*, 2002] can be routinely available, but presently data from NMs is the only way to reconstruct cosmic ray modulation in the past.

[3] Here we slightly improve the reconstruction method and, using the newly available data of the world NM network, we extend the reconstructed series until December 2009. In addition, using data of ground-based ionization chambers since 1936 [*Forbush*, 1954] recently reanalyzed by *McCracken and Beer* [2007], we compute the modulation potential for the period 1936–1951. The final series now covers the interval from 1936 through 2009, which is 20 years longer than that in U05. We also directly compare our reconstructions with the long-term (1957–2009) series of regular balloon-borne measurements of the flux of ionizing radiation in the stratosphere performed by Lebedev Institute [*Bazilevskaya and Svirzhevskaya*, 1998; *Bazilevskaya et al.*, 2008; *Stozhkov et al.*, 2009].

[4] In section 2 we describe the model used here and its modifications compared to U05 as well as the data used. Section 3 describes the results obtained, which are confronted with the balloon-borne data in section 4. Summary is presented in section 5.

2. Method and Data

2.1. GCR Modulation

[5] Galactic cosmic rays are modulated in the heliosphere because of the variable solar magnetic activity, and this modulation varies in the course of solar cycle. The level of the modulation greatly depends on the energy of cosmic ray particles being orders of magnitude for 100 MeV protons and vanishing for energies exceeding several tens of GeV. The time-dependent differential energy spectrum of galactic cosmic rays as observed near Earth can be reasonably parameterized by the so-called "force-field" approximation [*Gleeson and Axford*, 1968; *Caballero-Lopez and Moraal*, 2004; *Herbst et al.*, 2010], which is briefly described below. The energy spectrum of i-th GCR specie (with charge Z_i and mass A_i numbers) at 1 AU, J_i, is related to the unmodulated local interstellar spectrum (LIS) of the same specie, $J_{\mathrm{LIS},i}$, via the modulation potential ϕ as

$$J_i(T,\phi) = J_{\mathrm{LIS},i}(T+\Phi_i)\frac{(T)(T+2T_{\mathrm{r}})}{(T+\Phi_i)(T+\Phi_i+2T_{\mathrm{r}})}, \quad (1)$$

where T is the particle's kinetic energy per nucleon, $\Phi_i = (eZ_i/A_i)\phi$, and $T_{\mathrm{r}} = 0.938$ GeV/nucleon. The only temporal variable here is the modulation potential ϕ, which is related to solar activity and parameterizes the shape of the modulated spectrum. Equation (1) includes also a fixed function $J_{\mathrm{LIS}}(T)$ which is not exactly known [e.g., *Webber and Higbie*, 2009] and may influence the absolute value of ϕ (see discussion in U05 and *Herbst et al.* [2010]). Thus the exact model of LIS must be specified together with the values of ϕ. Here we use, following the procedure described in U05, the proton LIS in the form [*Burger et al.*, 2000]:

$$J_{\mathrm{LIS}}(T) = \frac{1.9\times 10^4 \cdot P(T)^{-2.78}}{1+0.4866\,P(T)^{-2.51}}, \quad (2)$$

where $P(T) = \sqrt{T(T+2T_r)}$, J and T are expressed in units of particles/(m^2 sr s GeV/nucleon) and in GeV/nucleon, respectively. We want to stress that while the modulation potential formally corresponds to the mean energy loss of a cosmic ray particle inside the heliosphere, it is only a formal spectral parameter whose physical interpretation is not straightforward, especially on short timescales and during periods of active Sun. It is important that the value of ϕ is the same for all the GCR species. Here we consider two most abundant species of GCR, protons and α particles, the latter effectively representing also heavier species.

2.2. Neutron Monitor Data

[6] A neutron monitor is an energy integrating cosmic ray detector whose count rate can be presented as a sum of count rates N_i due to different species of GCR:

$$N = \sum_i N_i = \sum_i \int_{T_{ci}}^{\infty} J_i(T,\phi)\; Y_i(T)\; dT, \quad (3)$$

where Y_i is the specific yield function and T_{ci} corresponds to the local geomagnetic cutoff rigidity. The spectrum J_i is calculated using equations (1) and (2). The yield function, which includes both development of the nucleonic cascade initiated by GCR in the atmosphere and the efficiency of the detector itself, cannot be directly measured and needs to be computed numerically. Uncertainties in the NM yield function computations [U05; *Flückiger et al.*, 2008] may affect the GCR spectrum reconstruction from NM data, especially in the low-energy range. Here we use three different models of the NM yield function computed for a sea level NM of NM64 type, denoted henceforth as DFL82 [*Debrunner et al.*, 1982], CD00 [*Clem and Dorman*, 2000], and M09 [*Matthiä*, 2009; *Matthiä et al.*, 2009]. Then the actually recorded count rate of j-th NM C_j is evaluated as

$$C_j(\phi) = k_j\big(N_j(\phi) + N_o\big), \quad (4)$$

where k_j is the individual NM's efficiency factor, which accounts for the local environment, and N_o is the contribution of high energy GCR, which is not affected by the solar modulation. Finally, for each month we found the value of ϕ which best fits the actually recorded count rates of NMs (see U05 for full details).

[7] The method used here is slightly improved with respect to that of U05, in the following details. First, we now include a new NM yield function M09 in addition to the two used earlier. Next, we account for species of GCR heavier than α particles that were neglected in U05. Since they have roughly the same rigidity as α particles with the same energy per nucleon, we consider them as additional α particles. The nucleonic ratio of α particles (including heavier species) to protons is considered as 0.3 [*Webber and Higbie*, 2003; *Particle Data Group*, 2004] outside the heliosphere, compared to 0.21 (only α particles) used in U05. As

Table 1. List of Neutron Monitors Used in This Study and Their Characteristics[a]

Name	Type	Altitude	P_c	Period
Goose Bay	NM64	46	0.74	01/1965–12/1998
Oulu	NM64	15	0.77	04/1964–12/2009
Kerguelen	NM64	33	1.15	04/1964–12/2009
Kiel	NM64	54	2.4	01/1965–12/2009
Hermanus	NM64	26	4.5	01/1973–10/2009
Rome	NM64	60	6.3	01/1967–12/2009
Climax	IGY	3400	3	02/1951–03/2004
Mt.Washington	IGY	1900	1.3	11/1955–03/1991

[a]Characteristics include altitude (m), geomagnetic rigidity cutoff P_c (GV) for the 1995 epoch [*Shea and Smart*, 2001], and the period of data used here.

discussed in in section 3, the resultant changes in the reconstructed modulation potential are insignificant and remain within the error bars.

[8] For our analysis we have used the same set of NMs as in U05. A list of the selected stations, which fulfil the requirement of long-term stable operation is presented in Table 1. One can see that since 1964–1965, a number of sea level stations of NM64 is in operation with good statistics and low possible systematics. A set of optimal parameters (equation (4)) for these stations, estimated similar to U05 using reference periods in June 1998 (AMS-01 flight [*Alcaraz et al.* 2000]) and September 1989 (NMSU balloon-borne experiment [*Webber et al.*, 1991]), is listed in Table 2 for the three NM yield functions.

[9] Before April 1964 only one (since 1951) or two (since 1956) mountain stations of IGY type can be used. This is characterized by higher uncertainties because of the two reasons. First, statistics is lower leading to higher statistical errors, which cannot be evaluated using only Climax NM data before 1956. Both Climax and Mt. Washington stations are of IGY type and located at high altitude while the yield functions are computed for the NM64 type NM and sea level. This may lead to a systematic error (possible bias) which cannot be directly evaluated. Accordingly, we used the following scheme to evaluate ϕ before 1964 (see U05 for full details). Using the overlapping period of 1964–1996, we estimated an empirical regression [*Alanko-Huotari et al.*, 2006] between NM-IGY count rate and the modulation parameter ϕ computed using NM64 monitors listed in Table 1:

$$N = N_0 \left(1 + \frac{1}{A\phi + B}\right) \quad (5)$$

Then this regression was used to evaluate ϕ values for the period 1951–1964.

2.3. Ionization Chamber Data Since 1936

[10] Regular observations of cosmic ray ionizing radiation started already in 1936, 15 years before first neutron monitor observations in 1951. Those were records of ground-based ionization chambers at several locations [*Forbush*, 1954, 1958]. However, these data were affected by a possible uncontrolled instrumental drift due to the "decay of radioactive contamination in the main chamber or in the balance chamber" [*Forbush*, 1954; *Shea and Smart*, 2000], which is difficult to account for. In a recent study, *McCracken and Beer* [2007] performed recalibration of the Forbush data set using the fragmentary balloon-borne ionization data available since 1933 and found an essential long-term trend in the data between 1930s and 1950s. Accounting for that, they published a monthly time series of pseudo-Climax NM count rates from July 1936 through December 1956 (i.e., the expected count rate of Climax NM as if it was in operation at the same location during that period). The suggested uncertainty in monthly values is up to 4.5% [*McCracken and Beer*, 2007]. We used this series to compute the modulation potential before 1951, i.e., before the first NM observation. However, a question on the long-term trend in ionization data may still contain systematic uncertainties, and therefore this reconstruction should be taken with caveats.

2.4. Weighting Procedure and Uncertainties

[11] Let us assume that during ith month we have data from n NMs. For each of the jth NM monthly count rates we compute the corresponding value of $\phi_{i,j,Y}$ using the yield function model Y. Then the mean value of $\phi_{i,Y}$ and its statistical error $\sigma_{i,Y} = \sigma/\sqrt{n-1}$, where σ is the standard deviation of count rates of the individual NMs, is calculated over all NMs for the given month and fixed yield function. Next, the final monthly value of ϕ_i is calculated as the weighted average of the above values:

$$\begin{aligned} \phi_i &= \frac{\sum_Y \phi_{i,Y} \cdot w_{i,Y}}{\sum_Y w_{i,Y}} \\ \sigma_i{}^2 &= \frac{1}{\sum_Y w_{i,Y}}, \end{aligned} \quad (6)$$

where $w_{i,Y} = 1/\sigma^2_{i,Y}$ and summation is over the three yield functions (DFL82, CL00, and M09). The values of σ_i appear to be from a few MV up to 65 MV with the average value of 12 MV. In addition to the statistical error σ_i there is also model uncertainty $\delta\phi$ related to the difference between the used NM yield functions. Similar to U05, we estimate it as the halved range of the ϕ values computed using each of the yield functions separately. It appears $\delta\phi \approx 5$ MV. The final uncertainty of the ϕ_i is the sum of σ_i and $\delta\phi$ and ranges from 10 to 70 MV, with the average value of 26 MV. This has been applied to all the data points since April 1964.

[12] Before 1964, neither statistical (too few stations) nor systematic (no yield function computations for IGY NMs) can be calculated in the above way. Therefore we estimated the overall uncertainty of the ϕ values for the period 1951–1963 as the standard deviation of the difference between the ϕ values computed from all NM and data from only Climax and Mt. Washington stations for the period of data over-

Table 2. Best Fit Model Parameters for the NM Yield Functions by *Debrunner et al.* [1982] (DFL82), *Clem and Dorman* [2000] (CD00), and *Matthiä* [2009] (M09)

Name	k_j (DFL82)	k_j (CD00)	k_j (M09)
Goose Bay	0.823	0.967	0.647
Oulu	0.807	0.948	0.634
Kerguelen	0.842	0.99	0.662
Kiel	0.698	0.823	0.548
Hermanus	0.812	0.975	0.638
Rome	0.760	0.921	0.597
N_o (counts/s)	6.04	5.88	7.79

lapping (1964–1991). The value of 44 MV is taken as the uncertainty of the reconstruction for the period February 1951 through March 1964.

[13] Before 1951, uncertainties related to the pseudo-Climax NM count rate computed from ionization chamber data (see section 2.3) dominate the overall error bars. The 4.5% error translated into the uncertainty of ϕ gives $\sigma_i \approx$ 140 MV, which is taken as the uncertainty of the reconstruction for the period before February 1951.

[14] We note that this method computes the value of ϕ for the NM energy range, i.e., above $\approx$1 GeV/nuc. This may result in larger uncertainties in the lower-energy range [*Herbst et al.*, 2010] as discussed below.

3. Reconstructed Modulation

[15] The reconstructed monthly series of the modulation potential ϕ is tabulated in Table 3. The last column presents the annual value of ϕ computed using the same method but applied to the annual (not monthly) NM data. It is not necessarily equal to the annual mean of monthly ϕ values because of the nonlinearity of the method used. The time profile of the reconstructed ϕ is depicted in Figure 1 together with uncertainties as estimated in the previous section.

[16] One can see quite distinct 11-year cyclic variability of the modulation potential during the last 60 years, varying between 250 MV and 1500 MV. The peak in 1990 was caused by strong Forbush decreases. The reconstructed modulation before 1948 is essentially lower, peaking at about 700 MV during the maximum of solar cycle 17. We also note that the modulation potential during the minimum of cycle 17 (ca. 1945) is about 200 MV, i.e., comparable to that during the current solar minimum. This is consistent with the lower solar open magnetic flux in earlier 20th century suggested by many studies [cf. *Lockwood et al.*, 1999, 2009; *Solanki et al.*, 2002; *Usoskin et al.*, 2002a; *McCracken*, 2007; *Vieira and Solanki*, 2010]. On the other hand, uncertainties of the reconstruction are quite large (about 140 MV) for that period and a possible systematic error cannot be excluded. The reconstruction method employed here is slightly improved compared to U05.

[17] The normalized difference between the present ϕ and earlier values of ϕ_{U05}, 2 $(\phi_{\mathrm{U05}} - \phi)/(\phi_{\mathrm{U05}} + \phi)$ is shown in Figure 2. The difference is within 1.5% (or 10 MV in absolute values) except for two values corresponding to 1991. The systematic shape of the difference is related to the additional NM yield function used here. Therefore the modulation potential reconstructed in U05 remains consistent with the new reconstruction within the uncertainties.

4. Comparison to Balloon-Borne Data for 1957–2009

[18] In this section we test the robustness of the long-term ϕ reconstruction, using a long-term data series of cosmic ray measurements, balloon-borne data of the ionizing radiation in the stratosphere, obtained by the Lebedev Physical Institute. As pioneered by Academician S.N. Vernov, regular balloon-borne measurements of ionizing radiation in the stratosphere are carried out at the Lebedev Physical Institute since July 1957 [*Charakhchyan*, 1964; *Bazilevskaya et al.*, 1991, 2008; *Bazilevskaya and Svirzhevskaya*, 1998; *Stozhkov et al.*, 2009]. The charged particle detector consists of two Geiger counters with steel walls 0.05 g/cm^2 thick, and a 7-mm thick (2 g/cm^2) aluminum filter placed between the counters. The efficiency of the counters for recording charged particles is nearly 100%, while γ rays contribute less than 1%. Measurements are performed at high and middle latitudes on board balloons launched several times a week, each flight lasting for a few hours. In total, more than 80,000 launches have been made until present. Homogeneity of the data is maintained through the use of standard detectors (which are identical during the whole period of measurement) and careful laboratory calibration between the flights. Measurements are performed at the heights from the ground level up to 30–35 km, and then the count rate in the atmospheric layer 8–100 g/cm^2 is used for estimation of the integral flux of cosmic rays with energy above 180 MeV. This flux is henceforth denoted as F_{180}. For full description of the instrument and data set a reader is referred to *Bazilevskaya et al.* [1991] and *Stozhkov et al.* [2007, 2009]. Here we use monthly averages of the F_{180} values from July 1957 through December 2009. The series of the balloon-borne values F_{180} is shown in Figure 3a (open circles) together with the corresponding measurement errors σ_F.

[19] Since this data corresponds to energy integrated flux, we make the comparison in the following way. First, using the modulation potential reconstructed here, we compute the GCR spectrum (both protons and heavier species) for each month using equations (1) and (2). Then we compute an integral of thus calculated spectrum $J(T,t)$:

$$F^*_{180}(t) = \int_{T_o}^{\infty} \left(J_{\mathrm{p}}(T, \phi(t)) + J_{\alpha}(T, \phi(t))\right) \cdot dT, \qquad (7)$$

where time t corresponds to the month under consideration and T_o corresponds to the kinetic energy of 180 MeV. The 68% uncertainties, denoted as σ^*_F, of the computed values of F^*_{180} were calculated using the corresponding uncertainties of the ϕ reconstructed here. Thus computed values F^*_{180} are shown in Figure 3a as the solid curve with the grey shading denoting the uncertainty.

[20] One can see from Figure 3a that the values of F^*_{180} computed from NM-based reconstructions agree well with the directly measured ones; the bivariate cross-correlation is 0.96. On the other hand, there are some small discrepancies worth to be studied. We notice that the absolute difference between the two profiles has little sense since the value of F_{180} varies by a factor of 5 within the solar cycle. Moreover, the uncertainty σ^*_F is not constant and depends on the level of solar activity, varying by an order of magnitude from 20–50 [m^2 sr s]$^{-1}$ for solar maxima up to about 500 [m^2 sr s]$^{-1}$ during solar minima.

[21] Accordingly, we consider the normalized difference

$$\delta F_{180} = \frac{F^*_{180} - F_{180}}{0.5\left(F^*_{180} + F_{180}\right)}, \qquad (8)$$

shown in Figure 3b. The difference generally (90% of time) remains within the ±20% range, which is consistent with the uncertainty of the difference $\sigma' = \sqrt{(\sigma_F)^2 + \left(\sigma^*_F\right)^2}$. There are several short periods (ca. 1970–1972, 1986, late 1989

Table 3. Reconstructed Monthly Values of the Modulation Potential ϕ, MV[a]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1936	-	-	-	-	-	-	252	242	260	271	290	363	279
1937	401	451	516	550	546	662	557	588	546	553	492	496	528
1938	716	696	560	650	502	401	348	371	389	401	401	416	481
1939	416	509	506	599	632	509	422	345	389	389	295	303	438
1940	287	300	292	290	255	273	268	281	287	295	320	345	291
1941	389	342	371	354	323	287	303	271	309	268	273	311	316
1942	273	273	447	340	287	268	279	239	237	245	242	237	279
1943	250	255	258	271	268	271	306	309	314	292	279	273	279
1944	279	263	258	239	211	187	184	192	177	184	170	211	212
1945	250	250	334	340	258	258	255	245	234	229	242	245	261
1946	303	768	610	581	647	595	602	550	578	486	457	407	543
1947	432	413	560	685	658	1166	925	1031	1128	1001	911	827	788
1948	716	677	708	602	748	581	581	595	712	669	602	588	647
1949	696	677	613	632	585	539	486	522	479	599	526	486	568
1950	606	628	512	512	526	473	496	463	512	512	435	416	506
1951	492	647	631	618	555	510	553	587	523	514	535	513	562
1952	551	567	587	546	489	464	447	448	436	490	465	483	497
1953	515	497	506	500	500	482	495	488	483	469	472	453	488
1954	445	427	401	411	404	407	399	376	384	386	399	411	404
1955	462	413	409	409	399	406	405	417	400	429	425	476	420
1956	511	551	623	567	604	592	555	562	598	521	647	822	593
1957	955	967	929	1053	984	1033	1087	1021	1226	1149	1180	1284	1068
1958	1266	1226	1330	1308	1167	1090	1216	1120	1093	1089	1063	1125	1172
1959	1080	1139	1029	965	1072	996	1327	1269	1187	1044	1022	1056	1095
1960	1136	1080	1007	1112	1109	1042	1042	953	956	953	1024	945	1028
1961	848	815	813	822	776	783	956	836	787	749	676	698	795
1962	700	723	708	737	689	678	667	667	699	705	668	678	693
1963	612	587	592	567	603	566	562	575	613	578	561	538	579
1964	515	519	495	479	468	469	459	456	430	433	436	406	451
1965	389	394	371	348	338	386	406	413	406	394	371	376	382
1966	412	420	441	452	431	479	507	515	665	575	541	584	499
1967	632	656	597	579	630	655	625	671	658	645	690	689	643
1968	674	707	713	669	694	765	761	742	789	850	985	934	770
1969	811	799	820	823	962	1014	948	861	819	798	796	791	852
1970	810	769	784	834	835	937	934	855	780	758	834	706	818
1971	717	641	646	624	591	515	514	493	497	465	475	488	553
1972	507	520	453	427	457	528	461	636	475	461	505	476	491
1973	463	473	498	565	616	524	491	466	427	428	416	418	481
1974	420	402	438	461	527	567	630	563	605	590	565	499	520
1975	494	459	450	429	420	407	417	442	436	437	471	448	442
1976	446	440	436	461	434	426	412	408	407	408	404	411	424
1977	421	417	419	416	417	442	487	476	475	438	408	418	436
1978	478	496	510	588	669	602	591	495	495	566	528	530	544
1979	584	609	653	738	706	812	799	906	860	778	774	688	739
1980	716	743	686	762	757	886	885	855	866	960	1052	1038	845
1981	878	968	995	1055	1124	967	930	923	871	1046	1010	886	969
1982	813	982	828	798	758	1009	1258	1240	1422	1222	1150	1256	1046
1983	1086	969	877	874	1029	928	826	836	803	787	762	761	874
1984	709	736	800	846	967	880	842	778	753	751	772	746	797
1985	724	656	636	609	596	542	549	543	501	495	464	485	564
1986	486	575	507	434	416	405	403	402	401	378	433	382	434
1987	339	311	312	328	349	406	435	468	501	492	534	534	414
1988	626	593	581	602	590	610	681	697	682	714	728	819	658
1989	893	898	1183	1132	1234	1187	1022	1114	1195	1356	1470	1362	1161
1990	1232	1196	1275	1424	1452	1435	1247	1294	1187	1073	996	985	1226
1991	872	862	1257	1197	1158	2016	1938	1471	1190	1126	1115	1028	1234
1992	1019	1066	948	815	860	748	682	695	724	658	679	616	785
1993	632	634	685	621	599	580	573	571	548	545	534	541	588
1994	536	598	603	605	576	573	544	518	497	507	499	505	546
1995	484	470	494	476	468	472	473	464	459	457	451	437	467
1996	436	414	412	411	419	424	425	429	431	449	451	437	428
1997	418	400	404	413	404	405	409	394	404	424	439	424	412
1998	427	423	413	513	572	555	514	568	515	478	502	540	500
1999	602	602	589	573	589	539	513	609	691	733	751	787	629
2000	752	794	865	848	967	1073	1167	1057	992	882	1023	960	944
2001	881	774	725	995	874	832	808	904	897	959	865	833	860
2002	977	826	888	895	900	863	948	1058	963	926	1023	986	936
2003	895	892	876	909	945	1067	959	908	869	963	1281	930	954
2004	936	784	705	676	630	636	693	662	632	545	645	615	677

Table 3. (continued)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2005	788	642	620	589	681	610	643	676	798	596	542	540	641
2006	516	462	435	430	423	423	443	436	440	407	408	467	440
2007	391	396	376	355	351	354	357	361	352	348	353	340	361
2008	360	367	362	361	370	367	356	342	336	322	302	309	334
2009	302	285	276	267	267	270	269	274	270	260	258	255	271

[a]Mean 68% uncertainties are 140 MV for July 1936 to January 1951; 44 MV for February 1951 to March 1964; 26 MV since April 1964.

through mid-1991, 2000–2001, and 2009) when the difference may exceed 20%. Generally, the comparison confirms the correctness of the overall approach on the long-term scale of several decades. The discrepancy does not depict any apparent relation to solar cycle.

[22] The short-term discrepancies may be related, e.g., to the fact that balloons take fragmentary samples (especially after 1990 when the frequency of balloon launches was greatly reduced because of economical reasons), while NMs continuously monitor GCR variability. We also note that a NM, whose yield function quickly grows with energy, is sensitive to GCR with relatively high energy; its median energy [*Lockwood and Webber*, 1996] depends on the local geomagnetic cutoff rigidity and varies between 10 and 15 GeV/nuc [*Jämsén et al.*, 2007]. On the other hand, the Lebedev Institute instrument is sensitive to lower energy of cosmic rays, with the median energy being about 1.2 GeV/nuc. Thus the larger difference between data sets from the two types of instruments is not a surprise during periods when the cosmic ray spectrum is distorted, namely during Forbush decreases or strong solar energetic particle events which are excluded from the balloon data but not from NM data. This may potentially explain the observed discrepancy in 1970s, 1989–1991, and 2000 with enhanced rate of strong solar transient events. It is interesting that seemingly large discrepancies observed in Figure 3a around solar minima, e.g., ca. 1986 or after 2006, are not very significant (within 20–25%) in the normalized difference δF_{180}, but remain systematic. This indicates that the values of F^*_{180} calculated from the reconstructed ϕ are likely overestimated around solar minima with the negative ($A < 0$) heliospheric polarity. The minimum around 1965 confirms this idea. This implies that the low energy part of GCR spectrum (below a few hundred MeV) can deviate from the force field shape estimated basing on NM data or, in other words, extrapolation of the GCR spectrum reconstructed from NM data into low-energy range may be quite uncertain [cf. *Lockwood et al.*, 2001]. This can be associated to the heliospheric current sheet drift effect which differently affects lower and higher energy particles [e.g., *Heber et al.*, 2009]. This difference is expected to be particularly pronounced during the current solar minimum. Note, however, that this deviation is essential only for the upper atmosphere and during solar minima with negative polarity of the interplanetary magnetic field. Thus we can conclude that the two data sets are totally consistent, within the uncertainties, with each other after 1964, with only a few short periods of discrepancy.

[23] It appears that the NM-based method systematically underestimates the observed flux before 1964, which is seen in Figure 3b as systematically and significantly negative values of δF_{180}. Although from such a simple comparison we cannot distinguish which data set is suspect, we note that

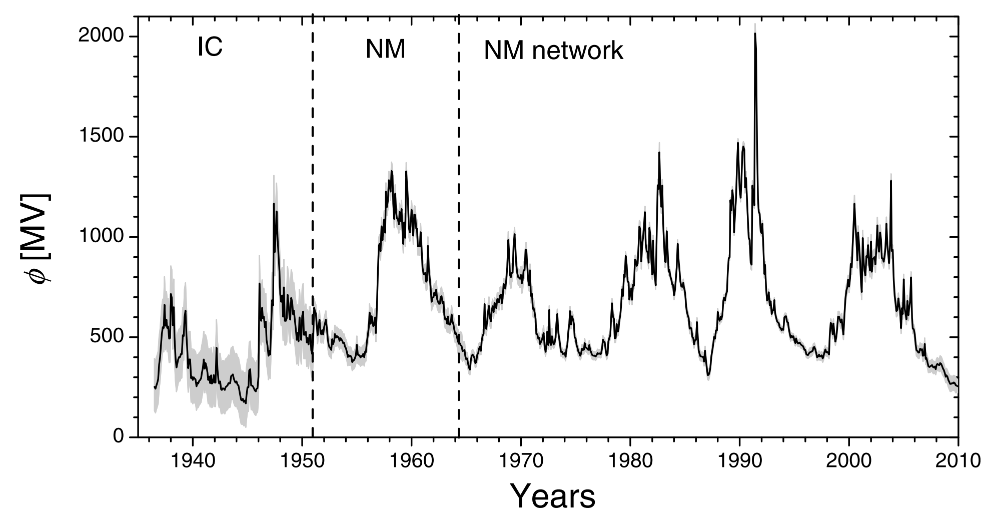

Figure 1. Time profile of the reconstructed modulation potential ϕ together with 68% confidence interval. The vertical dashed lines separate epochs of different instruments used for the reconstruction. The world network of neutron super-monitors of NM64 type was used since April 1964 (the "NM network" epoch). A few high-altitude neutron monitors of IGY type were used for the period February 1951 through March 1964 ("NM"). For the period July 1936 through January 1951 ("IC" epoch) the reconstruction is based on ground-based ionization chambers and may contain larger uncertainties.

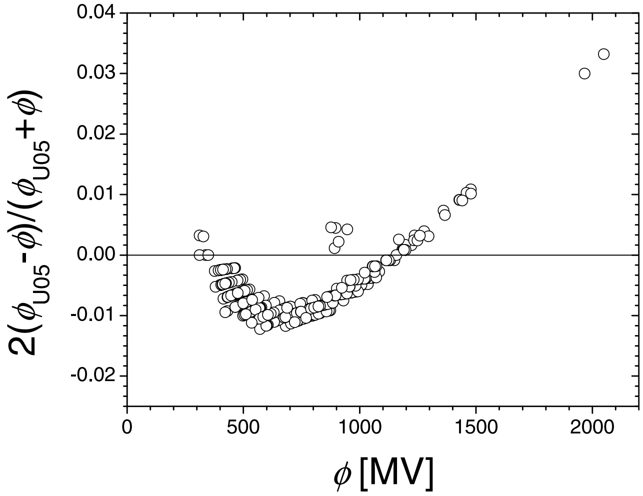

Figure 2. Scatterplot of the relative difference between the monthly values of the previous U05 reconstruction ϕ_{U05} and the present values ϕ for the period 1951–2004 as a function of the values of ϕ.

the year 1964 is very special for the NM-based set F^*_{180} as discussed above. In particular, the NM-based reconstruction might have underestimated the low-energy CR flux for the period 1957–1964 because of the insufficient amount of neutron monitors in the world network. The measurements performed by the Lebedev Institute are based on the same instrumentation and techniques throughout the entire period under investigation. On the other hand, balloon-borne data may be contaminated by-products of atmospheric nuclear tests in the 1960s.

5. Summary

[24] Here we present a series of reconstructed monthly values of the modulation potential ϕ for the period from July 1936 through December 2009. The modulation potential parameterizes the energy spectrum of GCR (in the framework of the force field approach) near Earth with good accuracy sufficient for practical applications, such as radiation dosimetry, cosmic ray induced atmospheric ionization, production of cosmogenic isotopes, etc. The presented series is a composite of three parts. The most reliable reconstruction, which is based on data from the world network of sea level neutron monitors, covers the period since April 1964 and is characterized my the mean 68% significance level uncertainty of 26 MV. Reconstruction for the period between February 1951 and March 1964 is based on a few mountain neutron monitors of IGY type. It is characterized by larger uncertainties (formal error is 44 MV). The reconstruction before 1951 is based on data from Forbush ground-based ionization chambers, recalibrated by *McCracken and Beer* [2007]. It is characterized by large uncertainties of about 140 MV. The reconstructed series of ϕ has been tested against long-term series of balloon-borne measurements of flux of cosmic ray ionizing radiation in the stratosphere performed by the Lebedev Institute since 1957. The comparison shows excellent agreement since 1964, within 10% in the overall level and with only a few short periods of noticeable discrepancy which fall upon periods of enhanced

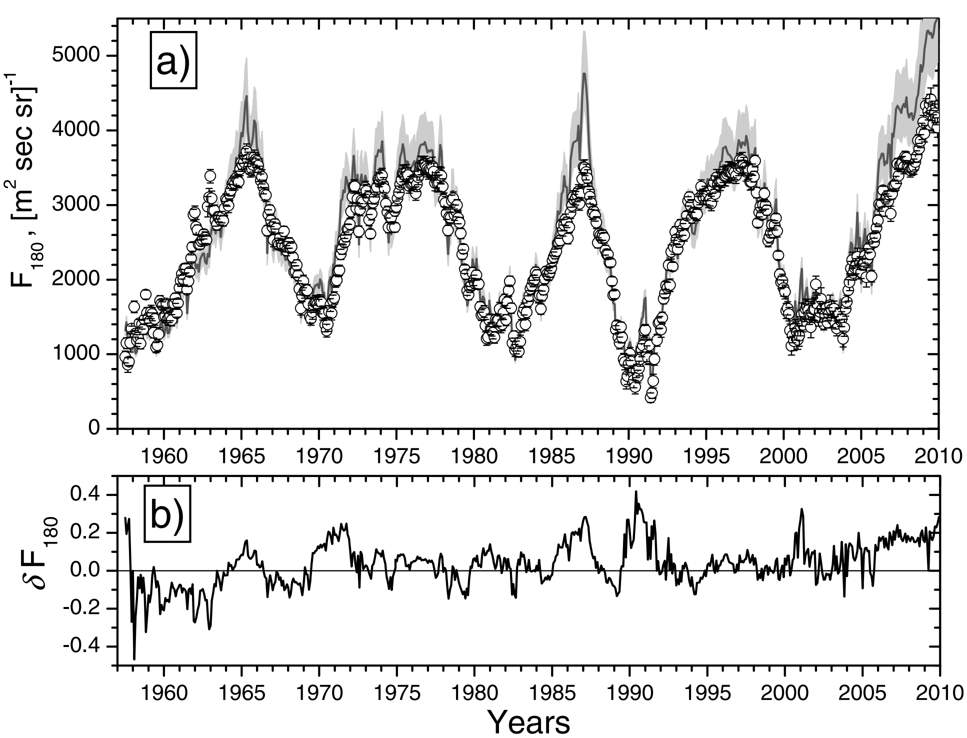

Figure 3. (a) Time profile of the cosmic ray flux (>180 MeV/nuc) F_{180} as measured at balloons (open dots with error bars) and computed from NM-data (solid curve with grey shading denoting 1σ uncertainty). (b) The normalized difference δF_{180} (see equation (8)) between the two profiles shown in Figure 3a.

rate of solar transient events or solar activity minima with the negative polarity of the solar magnetic field. The comparison also indicates that the result before 1964 may contain a systematic error in that the NM-based reconstruction method may underestimate the low energy part of GCR spectrum. This has, however, only little importance for studies on terrestrial effects of cosmic rays because high-energy/rigidity thresholds posed by atmospheric and geomagnetic cutoffs reduce the possible error for lower altitudes and latitudes.

[25] The reconstruction method used here was slightly improved comparing to the previous study of U05; nevertheless, the modulation potential reconstructed earlier remain consistent with the new reconstruction within the uncertainties. Concluding, we have presented an extended series of the reconstructed modulation potential since 1936 and discussed its uncertainties and limitations.

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