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The attenuation coefficient for Oulu neutron monitor

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Abstract. The attenuation coefficient (α) for the Oulu neutron monitor data was investigated during all the different phases of the solar cycle n. 22 to establish the nong-term time variability of the α-coefficient. The yearly data sets were divided into quarterly subsets, and using some auxiliary cosmic ray stations we derived an estimation of the annual α values. We show that the value $\alpha = 0.74$ %/hPa, used for the ordinary data correction, is reliable only for low solar activity years. Whereas, during the maximum phase of the solar activity cycle the attenuation coefficient should be smaller than the used one (α = 0.72 %/hPa). Moreover, we found the imprint of the Gnevyshev gap effects on the cosmic radiation clearly discernible in the α-error.

1 Introduction

Counting rates of continuously operating neutron monitors (NMs) show different modulation types over short and long time intervals, some of them related to pressure and temperature variations in the terrestrial atmosphere. Temperature effects are generally small and neglected, while pressure-induced effects need to be evaluated. Barometric effects on LARC NM (Antarctic Laboratory for Cosmic Rays; geographic coordinates: 62.20°S - 301.04°E; height: 40 m a.s.l.) were studied in the past (Massetti et al. 1998a, b). Here we investigated the cyclic variability of the attenuation coefficient for Oulu NM (65.06°N - 25.47°E, 15 m a.s.l.) during solar cycle n. 22.

2 Applied methods and data used

An estimation of the attenuation coefficient a can be derived by calculating the linear regression of an adequate amount pairs of values N_i/P_i. In fact, introducing $I_i = \ln(N_i)$, we obtain:

$$I_i - I_0 = -a\left(P_i - P_0\right) \tag{1}$$

being I_0 and P_0 equal to the averages of the corresponding observed values. Applying the least square method: $\frac{\partial X^2}{\partial a} = 0$, where $X^2 = \sum_1^n \left[I_i - \left(\bar{I} - a\left(P_i - \bar{P}\right)\right)\right]^2$, we obtain the following formula for the attenuation coefficient (asymptotically unbiased when n is large):

$$\hat{a} = -\frac{\sum_1^n \left(I_i - \bar{I}\right)\left(P_i - \bar{P}\right)}{\sum_1^n \left(P_i - \bar{P}\right)^2}$$

If the error over I_i is not known *a priori*, the standard error of a can be evaluated from the sum of the residuals, which defined as $v_i = I_i - \bar{I} + \hat{a}\left(P_i - \bar{P}\right)$, under the hypothesis that they are independent:

$$D_{\hat{a}}^2 = \frac{\sum_1^n v_i^2}{(n-2)\sum_1^n \left(P_i - \bar{P}\right)^2} \tag{2}$$

When there exists a serial correlation (also called self-correlation) of the residuals, the error calculated from Eq. (2) is underestimated. The presence of a self-correlation in the residuals is due to variations in the neutron intensity independent from pressure changes; they arise mainly from primary fluctuations and from changes in the detector efficiency. The above problem can be bypassed as follow:

(i) subdividing the data into subsets (equal and with a sufficient number of values, e.g. subdividing an year into four terms) and then calculating the weighted average of the obtained values of a using the inverse of the standard error as weighting function;

(ii) decreasing the primary cosmic ray fluctuations by subtracting the corrected data of an auxiliary station:

$$I_i = \ln(N_i) - \ln\left(N_i^{AUX}\right) \tag{3}$$

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with a similar cut-off energy, but placed sufficiently remote from the principal station, so that there is no correlation between the local pressure changes of the two monitors;

(iii) filtering the data before to carry on the evaluation of a, with the aims to decrease the self-correlation of residuals.

The combined use of these three methods is very effective. In particular, several works (e.g. Bachelet et al. 1967 and references therein) have demonstrated how the data filtering can notably reduce the self-correlation of the residuals, lowering the error (Eq. (2)) and enabling a best estimate of the attenuation coefficient. While the subdivision of data into subsets concerns only the periods in which the regression is calculated, the application of the latter two methods need changes in the algorithm used. The decrease of primary fluctuation via the use of an auxiliary station can be easily achieved substituting the Eq. (1) with Eq. (3) in the regression analysis. Instead, the data filtering is a little more complex and it is described in the following.

The data filtering method consists in substituting the original values with others obtained from the former by means of a determined algorithm. The "autoregressive filter" consists in evaluating

$$\begin{cases} \tilde{P}_i = P_i - r_u P_{i-1} \\ \tilde{I}_i = I_i - r_u I_{i-1} \end{cases} \tag{4}$$

where P_i , P_{i-1}, I_i and I_{i-1} are respectively the original values (i[th] and i–1[th]) of the pressure and of the intensity logarithm, $\tilde{P}_i$ and $\tilde{I}_i$ the corresponding filtered values, while r_u is the self-correlation first coefficient of the residuals (v_i) obtained from the regression of the original data:

$$r_u = \frac{\sum_2^n v_i \cdot v_{i-1}}{\sum_2^n v_i^2} \tag{5}$$

To calculate the a-coefficient with the "autoregressive filter" it is necessary to make a preliminary regression of the original (i.e., not filtered) data to evaluate r_u and then to perform a second regression with the filtered data. Setting $r_u = 1$, we have the "difference filter" that is a particular case of Eq. (11):

$$\begin{cases} \tilde{P}_i = P_i - P_{i-1} \\ \tilde{I}_i = I_i - I_{i-1} \end{cases} \tag{6}$$

The filtering procedure operated in this case is independent from the distribution of original data residuals; hence it is simple to calculate but also rougher than the autoregressive filter.

To test the above methods we analysed the daily mean values of the Oulu NM counting rates and atmospheric pressure readings. Only those days with a data coverage greater than 75% (i.e. more than 18 hours) were considered. Days affected by ground level enhancements (GLEs) induced by solar particle events were not included in the analysis. We used the following four auxiliary cosmic ray stations:

- Thule (geographic coordinates: 76.58°N, 291.58°E; altitude: 260 m a.s.l.; effective cut-off ~0.0 GV),
- Roma (41.90°N, 12.52°E; 60 m a.s.l.; ~6.3 GV),
- McMurdo (77.90°S, 166.60°E; 48 m a.s.l.; ~0.0 GV),
- Sanae (70.30°S, 357.65°E; 53 m a.s.l.; ~0.9 GV; for this station only the 1986-1994 data were available).

3 Main results

The attenuation coefficient calculated for the Oulu NM, between 1986 and 1996, is reported in Fig. 1. The a-value relative to each year was determined, as stated above, by means of the four auxiliary stations indicated in the legend.

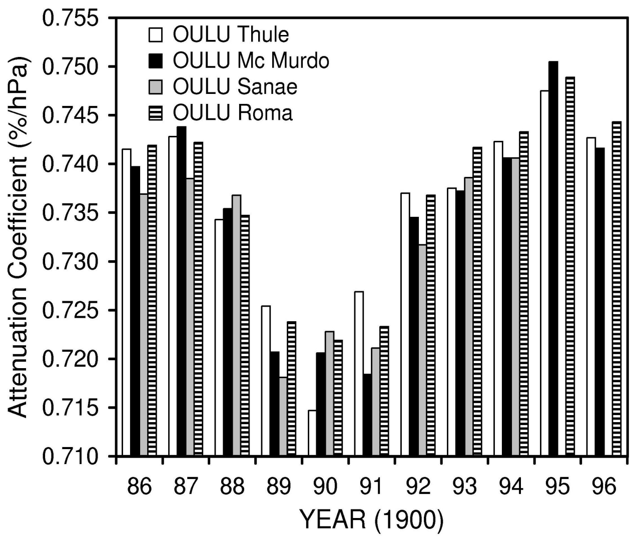

Fig. 1 – Yearly attenuation coefficient relative to the Oulu neutron monitor, derived using the auxiliary stations reported in the legend, and the computational procedure described in the text.

To illustrates differences of the results obtained with the applied methods (S = standard, D = difference and A = autoregressive), Table 1 reports examples for 1986 and 1990, from left to right: method of computation (S-, D-, A- followed by 1, 2, 3 or 4, stands for the first, second, third and fourth part of the year, while followed by 'Y', for the whole year and by 'av' for the weighted average over the four terms), number of values used (n), attenuation coefficient and standard error (a and Δa, expressed in %/hPa), linear correlation coefficient between P and I (R), sum of squared residuals (Res^2) and mean values of pressure and the corresponding standard error in each term ($\overline{P_i}$ and STd_P).

The Oulu attenuation coefficient got the smallest errors using Thule (station placed in the same hemisphere of Oulu) as auxiliary station, while with McMurdo and Sanae (opposite hemisphere) the errors are comparable with those

Table 1. Results from the α study for the 1986 and 1990 Oulu NM data using Thule NM data as auxiliary data set (see the text for details).

1986	**n**	a	Da	**R**	*Res²*	$\overline{P}$	**STd_P**
S-1	84	0.7342	.0034	-.9991	.0017	1012.71	15.61
A-1	84	0.7362	.0040	-.9988	.0006		
D-1	84	0.7359	.0041	-.9987	.0006		
S-2	91	0.7293	.0077	-.9951	.0023	1011.71	6.88
A-2	91	0.7387	.0038	-.9988	.0003		
D-2	91	0.7387	.0038	-.9988	.0003		
S-3	92	0.7422	.0052	-.9978	.0011	1006.33	7.15
A-3	92	0.7433	.0045	-.9983	.0005		
D-3	92	0.7433	.0044	-.9984	.0006		
S-4	92	0.7496	.0025	-.9995	.0006	1004.52	11.28
A-4	92	0.7448	.0027	-.9994	.0004		
D-4	92	0.7430	.0028	-.9994	.0005		
S-Y	359	0.7405	.0028	-.9975	.00123	1008.72	11.26
A-Y	359	0.7405	.0018	-.9989	.0019		
D-Y	359	0.7404	.0018	-.9989	.0020		
S-av		0.7431	.0018				
A-av		0.7415	.0018				
D-av		0.7407	.0018				

1990	**n**	a	Da	**R**	*Res²*	$\overline{P}$	**STd_P**
S-1	87	0.7141	.0029	-.9993	.0012	996.59	14.83
A-1	87	0.7138	.0036	-.9989	.0009		
D-1	87	0.7137	.0040	-.9987	.0012		
S-2	73	0.7176	.0193	-.9753	.0120	1010.11	8.12
A-2	73	0.6991	.0067	-.9968	.0007		
D-2	73	0.6996	.0065	-.9969	.0007		
S-3	90	0.7100	.0040	-.9986	.0006	1009.90	6.84
A-3	90	0.7112	.0051	-.9978	.0005		
D-3	90	0.7127	.0073	-.9954	.0007		
S-4	82	0.7215	.0139	-.9854	.0168	1005.84	11.59
A-4	82	0.7293	.0052	-.9980	.0013		
D-4	82	0.7287	.0049	-.9982	.0013		
S-Y	332	0.7397	.0057	-.9904	.0510	1005.45	12.19
A-Y	332	0.7172	.0026	-.9979	.0041		
D-Y	332	0.7169	.0025	-.9979	.0041		
S-av		0.7130	.0023				
A-av		0.7147	.0024				
D-av		0.7155	.0026				

obtained by using Roma, being characterised the latter by high rigidity particles (see Fig. 2 and Storini et al., 2000 for details).

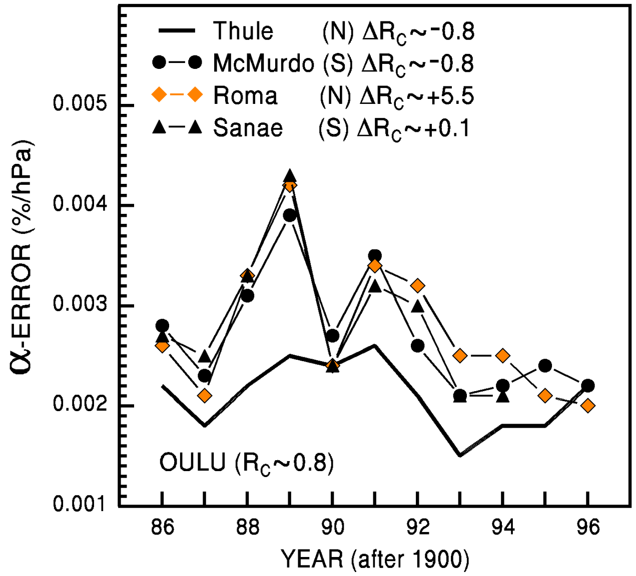

Fig. 2 – The error in the yearly attenuation coefficient of Oulu NM: R_c stands for the vertical rigidity cutoff of the Oulu location and ΔR_c the difference between the auxiliary station cutoff and one of the Oulu. Hemispheric position of used stations is also reported.

The a-dependence on the solar activity cycle is clearly seen in Fig. 1: around the solar maximum the coefficient decreases till the value of 0.715 %/hPa (1990), while during the minimum the coefficient approaches the one of 0.740 %/hPa, which is the standard value used to correct the Oulu NM data. Moreover, there is another interesting result connected with the long term cosmic ray modulation. At least during the analysed cycle (n. 22) the a-error trend (Fig. 2) clearly exhibits a double-peaked structure, because in 1990 the a-errors are smaller compared with those for the neighbours (1989 and 1991). Furthermore, the 1990 errors tend to converge to a similar value, independently of the auxiliary station used. We suggest that Gnevyshev gap effects on cosmic rays are at the origin of the phenomenon (Storini et al., 2001 and references therein). We know that the time history of the power spectrum density using T=26-29 days for Climax (low cutoff) and Huancayo/ Haleakala (high cutoff) data exhibits a significant reduction during 1990 (Bazilevskaya et al., 1998). Hence, during such a period the cosmic ray variability is less dependent on the rigidity cutoff of the used NM station (Storini and Pase, 1995; Storini et al., 1997).

4 The Oulu GLE event of September 29, 1989

The effect of a deviation from the real attenuation coefficient on the corrected counts can be easily calculated:

$$\frac{\Delta C}{\Delta a} = U e^{a(P-P_0)}(P-P_0)$$

$$\Delta C = C \Delta P \Delta a \qquad (7)$$

$$\frac{\Delta C}{C} = \Delta P \Delta a$$

where U, C, P, P_0 are respectively: the uncorrected and corrected counts, the atmospheric pressure and the pressure reference level. The variation DC is proportional to C and due to both $\Delta\alpha$ and ΔP (Eq. 7). In the present case $\Delta\alpha$ = 0.025 %/hPa causes a $\Delta C/C = 0.25\%$ for every $DP = 10$ hPa of deviation from the pressure reference level P_0=1000.0 hPa; this means a $\Delta C/C = 1\%$ for $DP = 40$ hPa. To visualise this effect we have considered the Oulu data relative to the Ground Level Enhancement (GLE) occurred on September 29, 1989.

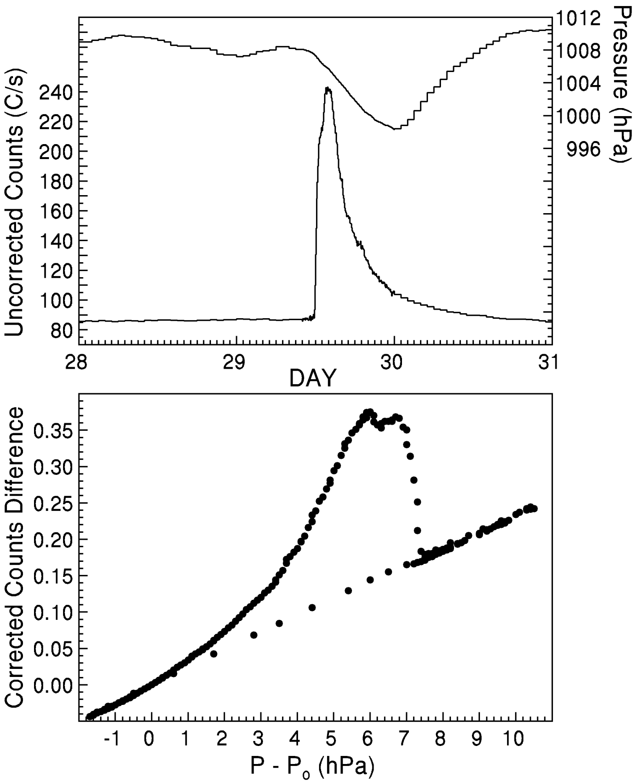

Fig. 3 – Oulu data relative to the GLE occurred September 29, 1989. Upper panel: atmospheric pressure (right scale) and uncorrected counts (left scale) for September 28-30. Lower panel: difference between counts corrected by applying two α-values (0.715 %/hPa and 0.74 %/hPa) relative to the maximum and the minimum of the solar cycle, plotted as function of DP with respect to the reference pressure P_o=1000.0 hPa.

The upper panel of Fig. 3 shows the atmospheric pressure (right scale) and the uncorrected counts (left scale) for September 28-30, 1989 event. We have recalculated the pressure corrected counts assuming $\alpha = 0.715$ %/hPa, and then plotted (lower panel of Fig. 3) the difference between these values and the ones calculated with the standard $a = 0.740$ %/hPa in function of $\Delta P = P - 1000.0$ hPa. The plot puts in evidence the linear relation existing between DC and ΔP ($\Delta\alpha = 0.025$ %/hPa) when the counts C are constant, i.e. during the period before the GLE event, and then the increase of ΔC in function of the increasing C values during the GLE event.

5 Conclusion

The heliospheric modulation induced by the solar activity, causes variations in the energy spectrum of the primary cosmic rays that affect the degree of attenuation produced by the terrestrial atmosphere on the neutron monitor recordings. Therefore, awareness should be taken when using long-term time series of cosmic ray data corrected by means of a constant attenuation coefficient. Also particular attention must be paid during the analysis of GLE events occurring in periods of fast changing barometric conditions.

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