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Long-term cosmic ray intensity vs. solar proxies: A simple linear relation does not work

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Abstract. It was recently suggested by Lockwood et al. (2000, 2001) that the cosmic ray intensity in the neutron monitor energy range is linearly related to the coronal source flux, and can be reconstructed for much earlier times using the estimated long term coronal flux. Here we show that a linear regression is oversimplified and leads to unphysical results on long time scales. In particular, the reconstructed cosmic ray intensity has a steep trend which is four times larger than the allowed upper bound. The reconstructed cosmic ray intensity exceeds the local interstellar cosmic ray flux around 1900. Also, the 11-year cycle minimum of the reconstructed cosmic ray intensity in early 1900s is higher than the highest measured maximum in 1965. We argue that the unphysical results using a linear assumption are due to the oversimplified approach which does not account for complexity and significant nonlinearity of CR modulation in the heliosphere.

1 Introduction

Recently, Lockwood et al. (1999, 2000); Lockwood (2001) (hereafter, L99, L00, L01, respectively) estimated the coronal source flux F_s for the time after 1868 using the geomagnetic aa index. L00 and L01 also suggested that F_s is linearly related to the intensity of cosmic rays (CR) and calculated the correlation between F_s and the CR as measured by the Climax neutron monitor (NM) and by the concentration of ^{10}Be isotope in Greenland ice. (The geomagnetic cutoff rigidity of Climax NM is about 3 GV). The logical chain of the linear relations used in L00 and L01 is as follows:

$$\begin{array}{rclll} F_s & \Longleftrightarrow & CR(NM) & (1953-1999) & (A) \\ F_s & \Longrightarrow & CR(NM) & (1868-1999) & (B) \\ {}^{10}Be & \Longleftrightarrow & F_s & (1868-1985) & (C) \\ {}^{10}Be & \Longrightarrow & F_s & (1423-1985) & (D) \end{array}$$

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First, the linear relation between F_s and the cosmic ray (CR) intensity for the neutron monitor era was calculated (statement A) and then this relation was used to reconstruct the NM cosmic ray intensity for the much longer period of 1868-1996 (statement B). Next, they calculated the linear relation between F_s and the cosmic ray intensity as presented by the ^{10}Be isotope (Beer et al., 1998; Beer, 2000) for the period 1868-1985 (statement C), and used this relation and the long record of ^{10}Be data in order to reconstruct the very long-term profile of F_s since 1423 (statement D). It is important to note that only linear relations were used in all steps.

In this paper we show that such a linear approach as adopted in L00 and L01 is oversimplified and leads to unphysical results. We restrict our study to the last 140 years (statements A-C) since several data series exist for this time period. We calculated the coronal source flux F_s since 1868 from the aa index using the recipe published in L99. (The geomagnetic recurrency index (Sargent, 1985) employed in F_s was calculated directly from the aa series.) The source flux F_s depicted in Fig. 1) is in an excellent agreement with the corresponding F_s series in L00 and L01. In the subsequent sections we will reproduce and discuss the relations A to C and show how they result to unphysical results.

2 Cosmic rays during the neutron monitor era

Using annual values for the Climax NM data and the calculated source flux F_s, Lockwood et al. (2000) found the following linear regression

$$CR(NM) = b - m \cdot F_s \qquad (1)$$

with $m = 0.278$ and $b = 5.22$. Here Climax NM count rates are given in counts/h/10^5 and F_s in 10^{14} Wb. Similarly, we found the following regression parameters: $m = 0.28 \pm 0.025$ and $b = 5.25 \pm 0.11$ (using 1σ errors).

Fig. 2 presents our reconstruction (Eq. 1) for the CR(NM), together with the observed Climax NM count rates. Although the detailed structure is reproduced reasonably well, there are

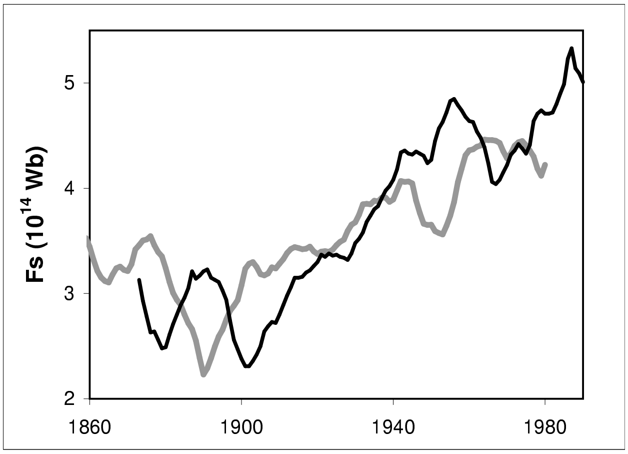

Fig. 1. The coronal source flux F_s constructed by the method of Lockwood et al. (2000) from the geomagnetic aa series (black curve) and from the cosmogenic ^{10}Be isotope (grey curve). The curves are 11-year running mean values.

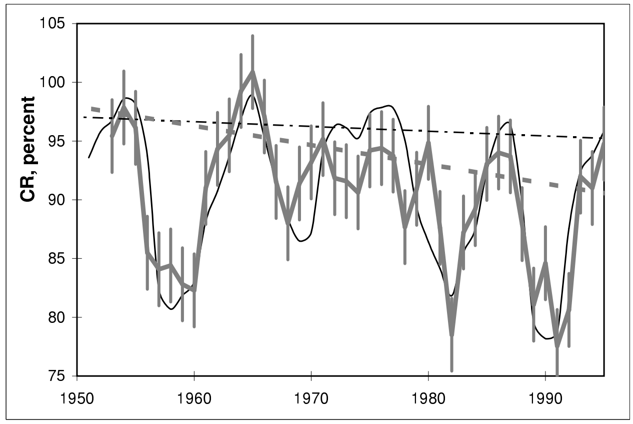

Fig. 2. Climax NM count rates in percent (count rate in May 1965 is 100%). Black thin curve depicts the actual count rates and the thick grey curve (including estimated errors) gives the count rate reconstructed from F_s. The dash-dotted black line and the grey dashed line give the trends for the respective series.

differences between the two time series. Fig. 2 includes the trends for both time series, calculated from the periods of CR maxima (solar activity minima). This trend has been used to estimate the stability of CR intensity outside the heliosphere (Stozhkov et al., 2000). The slope of the trend for the actual Climax data (dash-dotted line in Fig. 2) is -0.04 ± 0.04 % /year (cf. Stozhkov et al. (2000)), while the trend for the reconstructed CR(NM) series (grey dotted line in Fig. 2) is much steeper -0.16 ± 0.07 % /year. As will be discussed later in more detail, this overshooting trend leads to unphysical results for longer time scales.

3 Cosmic ray reconstruction in the past

Using the established linear regression between F_s and CR(NM) for the period of 1953-1999 (Eq. 1), we have reconstructed the CR(NM) for the time since 1868, similarly to L00 and L01. The reconstructed CR(NM) series is shown in Fig. 3a) together with the 1σ error. This series is in a good agreement with the results presented by L00 and L01 (see, e.g., Fig. 7 in L00). In L00 they estimated that "...the cosmic ray fluxes above 3 GeV were 15% higher, on average, around 1900 than they are now". This estimate is also in agreement with our results (see Fig. 3a).

Let us now analyse this reconstructed long-term CR intensity in more detail. The NM count rates were highest in May 1965 during the last five solar cycles. Therefore, it is common that the monthly CR intensity in May 1965 is used as the 100% normalisation level for NM count rates. The corresponding line is shown also in Fig. 3. Note that the reconstructed CR intensity exceeds this level during several CR maxima before 1930s. This implies that either the heliospheric suppression of cosmic rays was significantly weaker or that the local interstellar CR flux was significantly higher at around 1900 than nowadays. Let us discuss these two options.

Heliospheric suppression. Note first that the level of CR minima (corresponding to solar activity maxima) is comparable or even higher before 1930s than the level of CR maxima during recent times. This would mean that CR intensity during early solar maxima was comparable, or even higher than during solar minima nowadays. On the other hand, it is known that the time lag between changes in solar activity and the corresponding responses in CR intensity at 1 AU is less than 2 years (see, e.g., Usoskin et al. (1998); Belov (2000)). Accordingly, the CR modulation reflects a fairly recent solar activity within about 1–2 years, rather than a much longer-term overall solar activity level. While the overall level of sunspot activity was somewhat lower before 1930 than during recent times (see Fig. 3b), the level of sunspot activity during minimum times has been very low for all cycles. In particular, the level of activity during the recent minima is significantly lower than the sunspot activity during sunspot maxima at around 1900.

Second, there is an absolute upper bound for CR(NM) which is related to the local interstellar spectrum (LIS) of cosmic rays outside the heliosphere. We have depicted this upper bound in Fig. 3a (Usoskin et al., 1999, 2001), calculated using LIS as given by Webber & Potgieter (1989) and the Climax NM yield function. Accordingly, this is the absolute upper bound to CR(NM) intensity, and corresponds to the case of no heliospheric suppression. However, the reconstructed CR intensity exceeds this upper bound several times before 1930s. Concluding, the above facts exclude the possibility that the steep trend in the reconstructed CR intensity would be due to corresponding changes in the heliospheric suppression.

Changes in LIS. The long-term trend of the reconstructed CR(NM) could only be explained if the LIS was rapidly decreasing, leading to a 15% change in the local interstellar CR flux in the energy range of several GeV (the most effective

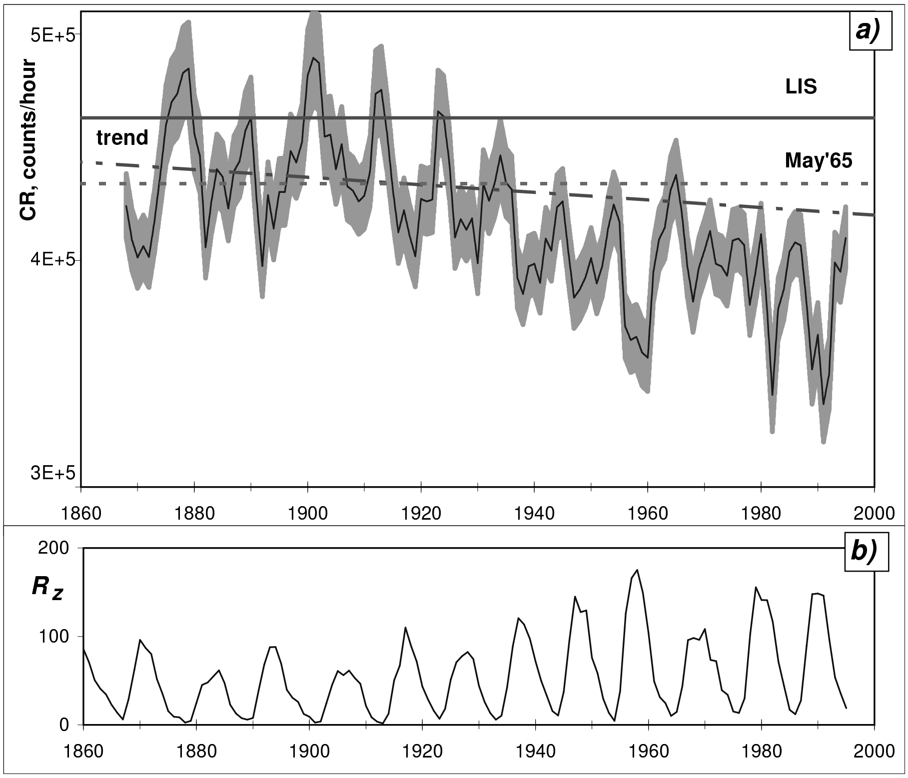

Fig. 3. a) Climax NM count rates reconstructed from the F_s series (black curve) with grey shading denoting the 1σ error. The constant LIS line corresponds to the local interstellar spectrum, the grey dashed May'65 line shows the CR level during May 1965, and the dash-dotted trend line corresponds to the largest possible negative CR trend (Stozhkov et al., 2000).
b) Sunspot numbers R_z.

energy for neutron monitors Clem & Dorman (2000)) during the last 100 years. A possible long-term trend in CR intensity has been recently estimated by Stozhkov et al. (2000) to be about -0.04 % /year (presented as the trend line in Fig. 3a). Such a trend could be due, e.g., to a supernova explosion in vicinity of the solar system (Stozhkov et al., 2000). Note however that the existence of a non-zero trend is still a subject of debate and the above estimate is an upper bound for the trend. Even with this maximum possible trend the CR level at about 1900 would only be 4% higher than the current CR level. Lockwood's method yields a much steeper trend than accepted by this argument.

4 F_s vs. ^{10}Be

Using 11-year running mean values, we have found the following linear relation between ^{10}Be and F_s (statement C) for the time interval 1873-1980:

$$F_s = b - m \cdot C_{Be} \tag{2}$$

where F_s is given in 10^{14} Wb and C_{Be} in 10^4 $atom/g$ and $m = 3.1 \pm 0.4$ and $b = 6.3 \pm 0.3$. Using this relation we have reconstructed F_s for 1873-1980 and depicted it in Fig. 1. This is in a good agreement with the results presented in L00 and L01 (see, e.g., the latter part of Fig. 8 in L00).

One can see in Fig. 1 that, despite some similarity in the increasing trend, the source flux reconstructed from C_{Be} (grey curve) is in a disagreement with the "original" flux derived from the aa index (black curve). It is interesting to note that, during the depicted interval 1873-1980, the relation between F_s and C_{Be} was inhomogeneous. Fig. 4 shows the scatterplot separately for three periods. During periods (1873–1903 and 1944–1980) when F_s was roughly stable (see Fig. 1), the correlation between F_s and C_{Be} was slightly positive (the slope of regression in Eq. 2 was $m = -1.6 \pm 0.3$ and $m = -0.5 \pm 0.4$, respectively). This is also seen in Fig. 1 as a rough antiphase between the F_s reconstructed from ^{10}Be and the "original" flux. The two stable periods were intervened by a period of a monotonous increase of F_s in 1903–1944. The correlation for that period was strongly negative, with $m = 5.5 \pm 0.3$. Accordingly, the relation between F_s and C_{Be} is completely different for stable periods and for periods of fast monotonous changes. Thus, the procedure of reconstructing F_s from ^{10}Be in L00, L01 is invalid.

5 Discussion

We have shown in this paper that the linear reconstruction of cosmic ray intensity from the solar coronal magnetic flux F_s for the last 150 years leads to unphysical results. This implies that the simple linear method suggested in L00 and L01 is not valid in the long-term time scale.

This result can be understood from two points of view. From a physical point of view, a simple linear influence of the coronal source flux (intensity of the interplanetary magnetic field) on the cosmic ray intensity is oversimplified. While the interplanetary magnetic field (IMF) is an important agent in heliospheric CR modulation (Cane et al., 1999; Belov, 2000),

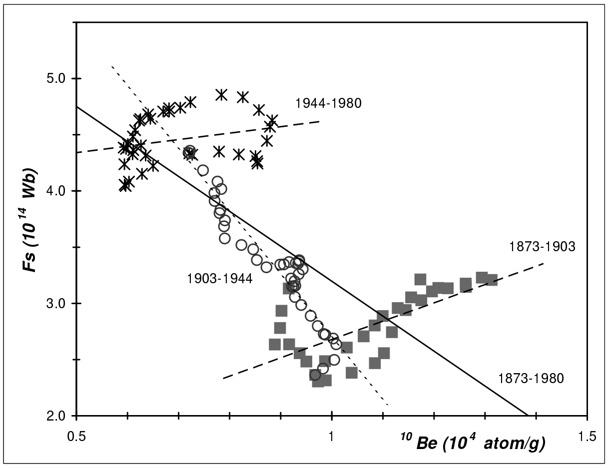

Fig. 4. Scatterplot of 11-year smoothed values of F_s vs. ^{10}Be concentration for 1873-1980. Solid line represents the best linear regression for the entire period while grey squares and dashed line, open circles and dotted line, and asterisks and dashed line depict points and the best linear regression for 1873-1903, 1903-1944 and 1944-1980, respectively.

its influence is fairly direct and local, affecting the CR level for less than two years. Moreover, an accumulation of flux is not possible in an expanding system like the solar wind/IMF. This is opposite to a spatially restricted and stable system like the solar photosphere where magnetic flux can be accumulated for long times and cause considerable long-term changes (Solanki et al., 2000). Moreover, propagation of cosmic rays in the heliosphere is influenced not only by the IMF but also by the heliospheric neutral sheet, solar wind speed, IMF polarity, etc. (see, e.g., Belov (2000) and references therein). Moreover, the global heliospheric magnetic field may sometimes have an unusual structure and the magnetic field measured in the ecliptic plane can not be extrapolated to higher latitudes. Such an unusual period took place, e.g., during solar cycle 20 (Howard, 1974; Ustinova, 1983; Benevolenskaya, 1998) and perhaps during the Maunder minimum (Sokoloff & Nesme-Ribes, 1994).

Methodologically, extrapolating a linear regression far beyond the range where it has been established is not straightforward. In particular, the heliospheric modulation of CR is very complicated and significantly non-linear, and the relation may be approximated by a linear regression only within a very limited time inteval. E.g., the relation between F_s and CR was established only during 45 years when F_s was fairly stable and high (Fig. 4) and then extended for 130 years, including periods of rapid changes of F_s and of stable but low F_s values.

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