Semi-empirical long-term reconstruction of the heliospheric parameters

Eleanna Asvestari[1] and Ilya G. Usoskin[1,2]
[1] *ReSoLVE Centre of Excellence, Space Physics and Astronomy Unit, University of Oulu, Finland*
[2] *Sodankyä Geophysical Observatory, University of Oulu, Finland*
email: Eleanna.Asvestari@oulu.fi

1. Introduction

- The variable solar activity is the principle source of Galactic Cosmic Rays (GCR) modulation in the heliosphere.
- Considering the force field approximation to full modulation model, we develop a semi-empirical model to describe GCR modulation, revisiting the earlier modulation model by [1], with new data including the minimum of 2009.
- Terrestrial archives of radionuclides ^{10}Be and ^{14}C are used to test the validity of the model.
- We also develop an empirical model to reconstruct the cyclic behavior of the tilt angle of the Heliospheric Current Sheet (HCS).

2. Tilt angle model

- The best fit empirical model for annual values of the tilt angle is:

$$\alpha_i = \begin{cases} \min(70^\circ; 1.5^\circ + 909.5^\circ \cdot X_i^2) \ for\ X_i \le 0.4 \\ \min(70^\circ; 11.1^\circ + 118.8^\circ \cdot (1 - X_i)^2) \ for\ X_i \ge 0.4 \end{cases}$$

where $X_i = i/N, i$ is the year in the solar cycle (SC) and N is the cycle length in years: $i = [1, N]$

- The fitting is done using the observations by the Wilcox Solar Observatory (WSO), since 1976.
- Maximum tilt angle is set at 70º due to observational limitations;
- Modeled tilt angle is consistent with the WSO estimated values (Figure 1);
- Reflects the asymmetry of the tilt's cyclic shape;
- Best correlation is during the ascending phase;

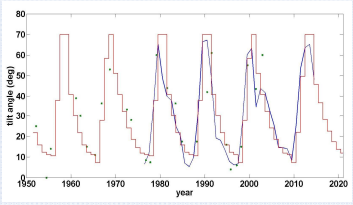

Figure 1. Annual variations of the HCS tilt angle as provided by WSO (blue solid line), and calculated by the model (red curve). Green stars represent reconstructed HCS tilt angles for 1870 until 2002 by image analysis of total solar eclipses courtesy of M. I. Pishkalo).

3. Modulation potential model

- The semi-empirical modulation model has the form:

$$\phi = \phi_0 \times F^{n - \frac{\alpha}{\alpha_0}}(1 + \beta p)$$

where F is the Open Solar Magnetic Flux (OSMF) expressed in 10^{15}Wb, α is the tilt angle of the Heliospheric Current Sheet (HCS) (in degrees) and p the polarity of the large scale HMF.

- To fit parameters we used the reconstructed OSMF by [6,7], the tilt angle computed by the model in Sec. 2 and the polarity defined as p=1 or -1 for positive and negative polarity periods respectively and p=0 for the years when polarity reverses.
- The best fitted parameters are: ϕ_0 = 1479.4MV, α_0 = 145.5°, n = 1.04 and $\beta = -0.091$.
- The discrepancy during the maximum of SC 22 is possibly related to high solar wind plasma flow pressure during years 1991-1992 (Figure 2).
- The discrepancy during the latest SC is related to the polarity reversal leading to positive polarity of both north and south polar fields during the maximum phase of the cycle (Figure 2).

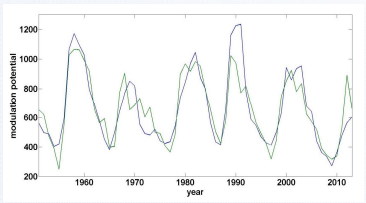

Figure 2. Annual variations of the reconstructed by ground based cosmic rays observations (blue curve) and the modelled (green curve) modulation potential for the period 1951-2013. The correlation coefficient between the two is R = 0.88 ± 0.03

4. Centennial reconstructions

- Using the modulation model we computed the modulation potential for three different OSMF series (figure 3)
- These reconstructions were applied to the cosmogenic production models by [4] and [3], for ^{14}C and ^{10}Be, respectively.
- The 3 reconstructions agree well for the period after 1850s.
- The SS-case ranks significantly higher comparing to the other two for the period prior to 1790, which includes the Maunder Minimum, as well as for the period 1820-1830.

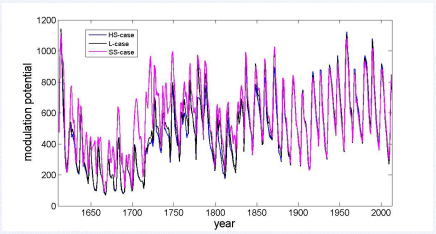

Figure 3. Reconstructed modulation potential over the period 1610 – 2014, based on 3 different OSMF series computed using as input the group sunspot number (GSN) by [5] (HS-case), the SN proposed by [6] (L-case) and the SN proposed by [10] (SS-case).

5. Comparison with radionuclides records

- The radionuclides calculations are compared with the ^{14}C global production, computed from INTCAL09 data [9] (Figure 4).
- The reconstructions based on HS and L-cases appear to agree well with the radiocarbon record, however the computations based on the SS-case show that it underestimates the global radiocarbon production. This is also apparent when one plots the difference between the record and the computations for each case (Figure 5).
- The relation between ^{10}Be production and measurements is not absolute and includes a scaling factor, related to the unknown wet/dry deposition [2] as a free parameter. Thus, the model results cannot be compared with the data for ^{10}Be . There is a good agreement in the overall time variability but the distinction between different SN reconstructions is not possible.

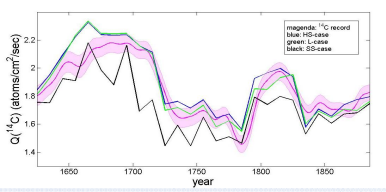

Figure 4. Decadal variations of the global radiocarbon production.

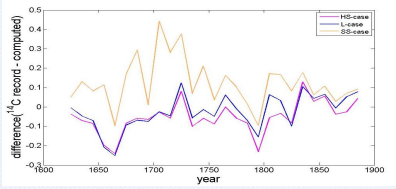

Figure 5. Temporal variation of the difference between the record curve and the reconstruction curves shown in Figure 3 for different cases.

6. Summary

- We propose two semi-empirical models for centennial reconstructions of the HCS tilt angle and the modulation potential respectively.
- The tilt angle model describes the cyclic behavior of the HCS tilt angle and its dependence on the phase of the solar cycle only.
- The modelled ϕ shows good correlation with the reconstructed by ground based neutron monitor measurements for the period 1951-2014 with a small deviation during the solar maximum of cycle 22 (possibly related to high pressure of solar wind plasma flow velocity) and the latest solar maximum (possibly due to the extended polarity reversal period).
- The global radionuclides production records from terrestrial archives such as tree rings and ice cores supports the validity of our model, since there is a good correlation between the records and computations based on the reconstructed modulation potential.
- The global radiocarbon production records from tree rings indicates a discrepancy during the Maunder Minimum for the computations based on the SS-case.
- However, the ice core records of ^{10}Be can not be considered for this study, since there is a free scaling parameter, making it difficult for comparisons.

References

[1] K. Alanko-Huotari, K. Mursula, I. G. Usoskin, and G. A. Kovaltsov. Solar Physics, 238:391–404, November 2006.
[2] Beer, J., K. McCracken, and R. von Steiger. Cosmogenic Radionuclides, 2012
[3] G. A. Kovaltsov and I. G. Usoskin. Earth and Planetary Science Letters, 291:182–188, March 2010.
[4] G. A. Kovaltsov, A. Mishev, and I. G. Usoskin. Earth and Planetary Science Letters, 337: 114–120, July 2012.
[5] D. V. Hoyt and K. H. Schatten. Solar Physics, 181: 491 – 512, August 1998
[6] M. Lockwood and M. J. Owens. Journal of Geophysical Research (Space Physics), 119:5193–5209, July 2014.
[7] M. Lockwood, H. Nevanlinna, L. Barnard, M. J. Owens, R. G. Harrison, A. P. Rouillard, and C. J. Scott. Annales Geophysicae, 32:383–399, April 2014.
[8] M. Lockwood, M. J. Owens, L. Barnard. Journal of Geophysical Research (Space Physics), 119:5172-5182, July 2014.
[9] R. Roth and F. Joos. Climate of the Past, 9:1879–1909, 2013.
[10] L. Svalgaard and K. H. Schatten,ArXiv e-print, 2015.

Acknowledgments: This work was done in the framework of the ReSoLVE Center of Excellence (Academy of Finland, project no. 272157). Part of this work was supported by the COST Action ES1005 "Toward a more complete assessment of the impact of solar variability on the Earth's climate".