Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 72 (2023) 638–648

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Quantitatively relating cosmic rays intensities from solar activity parameters based on structural equation modeling

D. Sierra-Porta [a,*], M. Tarazona-Alvarado [b], Jorge Villalba-Acevedo [a]

[a] Universidad Tecnológica de Bolívar, Facultad de Ciencias Básicas, Parque Industrial y Tecnológico Carlos Vélez Pombo Km 1 Vía Turbaco., Cartagena de Indias, 130010 Bolivar, Colombia

[b] Universidad Industrial de Santander, Escuela de Física., Car 27 #9, Bucaramanga, 680001 Santander, Colombia

Received 26 October 2022; received in revised form 20 February 2023; accepted 28 February 2023
Available online 6 March 2023

Abstract

Cosmic rays measured through neutron monitors on Earth's surface have a strong correlation with the number of sunspots on the solar photosphere. Other indices that affect the dynamics of the heliosphere and distortions in the Earth's geomagnetic field also exhibit significant correlations. Typically, studies focus on these indices individually or combine some into a smaller set of estimators. This study uses Structural Equation Modeling to examine relationships between a broad range of parameters of solar dynamics and cosmic ray intensity (measured by the Moscow neutron monitor) across several solar cycles from 1976 to present day. The study also classifies these indices into three distinct contributions: Photosphere, Solar Wind and Terrestrial Geomagnetic Field Distortions. Regression models were built for all solar cycles and the complete cosmic ray series from 1976 to the present, resulting in good estimators with calculated p-values below 0.05 (95% confidence). Relationships among all contributions were determined using their estimators.

Keywords: Cosmic rays; Sun dynamics; Modelling; Heliospheric Abundances; Photosphere; Solar wind

1. Introduction: aims and scope

The magnetic activity of the Sun and its evolution in the parameters related to the processes of the solar corona greatly impact the flow of Galactic Cosmic Rays that reach the Earth (Nagashima and Morishita (1980); Davis (1955); Cliver et al. (2011)). This has been widely studied and well documented in the field of space weather research. Research on solar phases and cycles in relation to the periodicity of cosmic ray count rates, as measured by both ground-based and satellite detectors, confirms this relationship, with the exception of a time lag that has been determined through cross-correlation (Chowdhury et al. (2011); Bazilevskaya et al. (2014); Potgieter (1995); Sierra-Porta (2018); Iskra et al. (2019); Fiandrini et al. (2021)). The data shows that during solar activity maxima, there is a corresponding minimum in cosmic ray measurements, and vice versa. The reason behind this phenomenon is that during periods of high solar activity, such as explosions and mass ejections, intense magnetic fields are produced. However, solar flares and coronal mass ejections can temporarily increase the counts of cosmic rays in neutron monitor stations in the Earth.

The modulation of galactic cosmic rays is influenced by various factors. The solar wind, for example, carries with it a magnetic field that can interact with cosmic rays. The intensity of cosmic rays can also be modulated as the magnetic field of the solar wind reducing the overall intensity (particle counts) that reaches the Earth. When the solar wind magnetic field is weak, more cosmic rays can reach the Earth, whereas when it is strong, fewer cosmic rays

* Corresponding author.
E-mail address: dporta@utb.edu.co (D. Sierra-Porta).

https://doi.org/10.1016/j.asr.2023.02.044
0273-1177/

can penetrate it. Moreover, the orientation of the heliospheric neutral current sheet changes as it rotates from being almost flat in the equatorial plane during solar minimum to having a 90-degree inclination at solar maximum, and then back to its near equatorial position as solar activity decreases. This rotation is a result of the gradual changes in the solar and heliospheric magnetic fields over the 22-year heliomagnetic cycle McCracken et al. (2004). At solar minimum, the magnetic polarity in the Northern and Southern Hemispheres is opposite, and the polarity reverses again at the next solar maximum, leading to a change in the effect of cosmic ray drift over the following 11 years. The level of current sheet modulation is determined by the magnetic polarity and the angle between the current sheet and the ecliptic, reaching a maximum when the angle is 90 degrees Potgieter and Le Roux (1992); Cliver et al. (1996).

When primary cosmic ray particles travel to the Earth and enter the atmosphere, they interact with atmospheric atoms and generate cascades of secondary particles (mainly neutrons and muons at ground level) that can be measured with neutron or muon detectors. Cosmic rays are divided into three categories: Solar Energetic Protons (SEP), Galactic Cosmic Rays (GCR) and Anomalous Cosmic Rays (ACR).

SEP are particles originating from the Sun with energies ranging from a few tens of keV to several GeV (Reames (2013); Desai and Giacalone (2016)). They are associated with Coronal Mass Ejections (CME) and solar flares, among other phenomena. A CME-driven shock is now believed to be an essential site of SEP acceleration. It is noteworthy that the number of CME is related to the solar magnetic activity: it follows exactly the solar cycle during the maximum (which corresponds to the maximum number of visible sunspots) (Richardson et al. (2000); Richardson et al. (2001); Richardson et al. (2002)). Therefore, the SEP flux is more important during solar maxima. GCR originate from galactic supernova remnants and are accelerated by supernova explosion shocks caused by the expanding remnants. They consist of atomic nuclei of all types. The range of energies encompassed by cosmic rays is truly enormous, starting at about 10^7 eV and reaching 10^{20} eV for the most energetic cosmic ray ever detected Gaisser and Stanev (2006). The third category of cosmic rays, ACR (Klecker et al. (1998); Giacalone et al. (2012)), are light atoms (up to argon) that are initially neutral but are ionized upon reaching the inner heliosphere: both by the solar wind and by UV radiation from the Sun.

Fig. 1 shows the relationship between the flux of galactic cosmic rays measured by the Moscow neutron monitor in relation to the number of sunspots (in daily resolution) for a discretization of cycles 21, 22, 23, 24 and the most recent cycle 25, still in progress.

In the literature, several studies on the measurement and quantification of the cosmic ray intensity in relation to the parameters that determine the dynamics of the heliosphere and the evolution of solar activity are exhaustively obtained. Some works focus on the measurement of the cross-correlation (Koldobskiy et al. (2022); Sierra-Porta (2018) and references therein) for both signals (GCR and sunspot) determining for example a quite high ratio ranging between 0.79 and 0.89 according to the correlation coefficient, varying for a long period of time of several solar cycles or for independent solar cycles. Other works study the hysteresis curves (Ross and Chaplin (2019); Singh et al. (2021)) as a mechanism to evaluate the evolution conditions of both phenomena in complete solar cycles. Some works also aim at quantifying this relationship using semi-empirical models and regressions that take into account some of the most important solar activity parameters (Mavromichalaki et al. (2007); Paouris et al. (2012)). The last authors suggest for example that there is even a different relationship for each detector at different latitudes incorporating the geomagnetic rigidity as an important parameter (although a global one that only determines the mean amplitude of cosmic ray intensity) of such relationships. In general the relationships found attempt to emulate multiple linear regression processes using least squares for the quantification of each of the relationships. The parameters obtained in each relationship account for the magnitude of the importance of each of the solar dynamics parameters in terms of the prediction of cosmic rays at the Earth's surface.

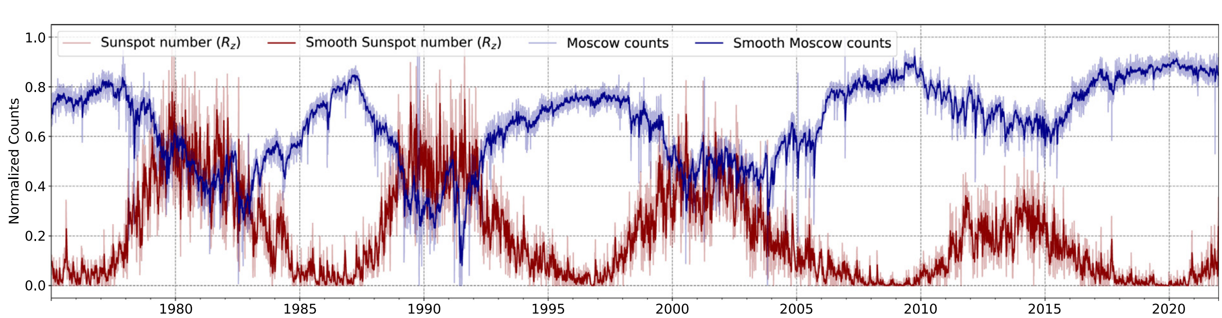

Fig. 1. Cosmic ray intensity for the Moscow neutron monitoring station (Lat = 55.47° N, Lon = 37.32° E) compared to the sunspot number measured by Sunspot Index and Long-term Solar Observations (SILSO, Brussels Observatory).

In general, although multiple data sources are available, a few indices have been selected as important for studying the relationship between the CR intensity and other parameters. The most important include: sunspots, of course, but additionally also coronal mass ejection index, Flare index, Kp index, Ap index, and also measurement of the Interplanetary Magnetic Field (IMF), among a few others.

For example in (Paouris et al. (2012)), the authors make use of empirical relationships from regression analysis to build models with better results than previous works on the hysteresis effect. According to the authors, the best relation model of cosmic ray intensity is one that involves four parameters: sunspot number (R_z); Interplanetary Magnetic Field (IMF, measured in Teslas) which defines the solar magnetic field carried by the solar wind between the planets of the solar system; CME index (CMEs/day) are eruptions of plasma from the solar atmosphere that are ejected into the solar system; Plasma Velocity (km/s); and Heliospheric Current Sheet (HCS tilt angle in degrees) or interplanetary current sheet is a surface separating regions of the heliosphere where the interplanetary magnetic field points toward and away from the Sun, $\mathrm{GCR} = -(a_1 R_z + a_2 P_i + a_3 \mathrm{IMF} + a_4 \mathrm{HCS}) \times 10^{-3}$, finding the coefficients a_i equal to 2.7, 0.41, 71.8 and 0.24, with $i = 1, 2, 3, 4$, respectively, and $P_i = 0.37 \times (\mathrm{CME}) + 0.63 \times (\mathrm{PlasmaVelocity})$.

In this short note, we attempt a methodology different from previous reviews. Our objective consists in the determination of relationships using Structural Equation Modeling (SEM) to differentiate between the relative contributions of each of the prediction components by separating their contributions with respect to the corresponding physics and also to a more or less standard classification of the phenomena involved.

2. Methods and data

2.1. Data used in this study

The data collected in this work come from many different sources. To relate the activity of solar dynamics with the intensity of cosmic rays, we use daily resolution data from two main sources.

2.1.1. Cosmic rays data

In the case of galactic cosmic rays, a large data source is available from detectors located in many parts of the world. We have collected data from neutron detector observatories. The real-time neutron monitor database (or NMDB: Real-Time Database for high-resolution Neutron Monitor measurements: http://www.nmdb.eu/) is a worldwide network of standardized neutron monitors used to record variations of primary cosmic rays (Mavromichalaki et al. (2010)). The measurements complement space-based cosmic ray measurements.

The data used correspond to daily data, corrected by pressure, for the Moscow Neutron Monitor which is located in Troitsk city, Moscow Region. It is operated by Pushkov Institute of Terrestrial Magnetism, Ionosphere and radio wave propagation (IZMIRAN) of Russian Academy of Science uninterruptedly since 1958 consisting of a standard 24NM64 detector at an altitude of 200 m.a.s.l. (latitude: 55.47° N, longitude: 37.32° E) and an effective vertical cutoff rigidity (1965) of 2.43 GV. We selected these data because of their uninterrupted completeness of observations and very low percentage of missing data.

2.1.2. Heliospheric parameters

For the case of the study of solar dynamics, the data used also come from different sources. In particular, the Low Resolution daily-averaged OMNI (https://omniweb.gsfc.nasa.gov/html/ow_data.html) dataset from Space Physics Data Facility (SPDF), OMNI is a standard near-Earth solar wind data set.

For this study we have divided a large set of data describing and participating in the dynamics and evolution of solar conditions. We have divided them into three distinct contributions. We have included the following relevant to our study.

Measurement of the interplanetary magnetic field such as: Field Magnitude Average —B—, Magnitude of Average Field Vector, Bz-component GSE, Bz-component GSM, not all taken into account due to their high correlation among themselves. For parameters related to the solar wind we use; Proton temperature, Proton Density, Plasma (Flow) speed, Alpha-Proton ratio, Flow Pressure, Plasma beta, Alfven mach number and Magnetosonic mach number, as well as parameters related to distortions caused by the solar wind on Earth: Kp index, DST Index, ap-index, Polar Cap (North) index and the AE index and the joint AU and AL indices were introduced as a measure of the global auroral electrojet activity. Finally we also consider measures of sunspot number, and The F10.7 Index has proven very valuable in specifying and forecasting space weather.

2.2. Modeling the relationships between GCR and Sun's parameters

2.2.1. Structural equation modeling

Structural Equation Models (SEM) are a family of multivariate statistical models that allow estimating the effect and relationships between multiple variables (Mueller (1999); Anderson and Gerbing (1988)). Structural equation models were born out of the need to make regression models more flexible. They are less restrictive than regression models in that they allow the inclusion of measurement errors in both the criterion (dependent) and predictor (independent) variables. They can be thought of as various factor analysis models that allow for direct and indirect effects between factors.

Mathematically, these models are more complex to estimate than other multivariate models such as those of Regression or Exploratory Factor Analysis (Jöreskog and Sörbom (1982)). The great advantage of this type of model is that it allows us to propose the type and direction of the relationships expected to be found between the various variables contained in it, and then go on to estimate the parameters specified by the relationships proposed at the theoretical level.

For this reason they are also called confirmatory models, since the fundamental interest is to "confirm" through the analysis of the sample the relationships proposed on the basis of the explanatory theory that it has been decided to use as a reference.

A complete structural equation model consists of two fundamental parts: the measurement model and the structural relationships model. The measurement model contains the way in which each latent construct is measured through its observable indicators, the errors that affect the measurements, and the relationships that are expected to be found between the constructs when they are related to each other. In a complete model there are two measurement models, one for the predictor variables and one for the dependent variables.

A latent variable in structural equation modeling is an underlying, unobservable factor or construct that is believed to influence the relationships between observed variables. Latent variables are represented by latent factors, which are not directly measured, but are inferred based on their relationships with other variables. For example, in this case a latent variable could represent the global activity influence of Sun's photosfere, which can be estimated through the variables for phenomena occur inside it. The use of latent variables in structural equation modeling allows researchers to study complex relationships between variables in a simplified and more parsimonious manner.

The model of structural relationships is the one we actually want to estimate. It contains the effects and relationships between the constructs, which will normally be latent variables. It is similar to a regression model, but may also contain concatenated effects and loops between variables. In addition, it contains prediction errors (which are distinct from measurement errors).

In this study we use SEM to create generalized regression models that allow to relate the effect of the parameters and variables that determine the conditions of solar dynamics with the intensity of cosmic rays measured on the Earth's surface. For this we then use the independent variables as precisely the conditions of the evolution of the solar cycles, while the dependent variable is the intensity of cosmic rays. In fact, a model is created for each solar cycle from 21 to 24 and also a model for all cycles combined using the same composition and structure of explanatory variables.

As in a usual linear regression, mathematically this implies that GCR are a functional of Sun's parameters:

$$\mathrm{GCR} = \mathrm{GCR}(X_i), \qquad i = 1, \ldots, N, \tag{1}$$

where X_i represent the N explanatory variables that depend on the dynamics of the sun. To additionally create the constructs, we define some explanatory latent variables that capture the effects in different contributions. Each of the latent variables contain predictor variables that have the same characteristics or dominate the same type of contribution.

To establish the structural equation model it is important to take into account the correlations between the independent and dependent variables (cosmic ray intensity). The Fig. 2 graphically shows this information for the data set with all solar cycles 21 to 25.

2.2.2. Sun dynamics variables

Our main objective is to establish modeling relationships for the cosmic ray intensity measured on Earth and some various parameters related to solar activity and to discuss differences and similarities between solar cycles from 1976

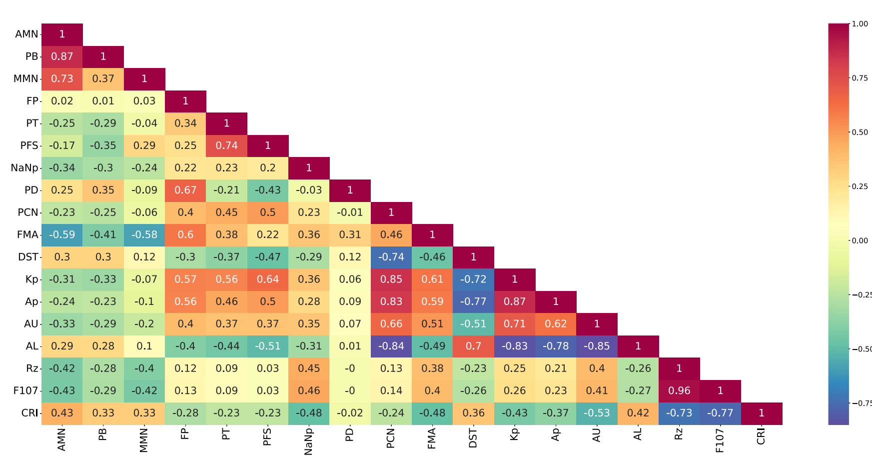

Fig. 2. Correlations coefficients between variables (dependent and independents) for all solar cycles 21 to 25.

(start of cycle 21) to the present (midterm of cycle 25). For this purpose we divide relative contributions on the solar parameters into three groups (each relation have the variables X_i's and their corresponding estimators β_i's):

1. **Photosphere and Coronal activity indices (PCi):** Sunsport number (R_z), the solar radio flux at 10.7 cm (2800 MHz, F107).

$$\text{Photosphere} = Y_1 = \beta_{1,1} \times R_z + \beta_{1,2} \times \text{F107} + \varepsilon_1. \quad (2)$$

GCR has been related in many investigations to sunspot number in the past, for some references see (Popielawska (1992); Dorman (1991); Shrivastava (1997); Inceoglu et al. (2014); Singh et al. (2021); Iskra et al. (2019); Sierra-Porta (2018)) for studies using hysteresis effect, o using correlation and regression methods (Ross and Chaplin (2019); Eroshenko et al. (2004); Mavromichalaki et al. (2011); Mavromichalaki et al. (2010)). Additionally the F10.7 index is known to have a very strong correlation with sunspot, however both are used simultaneously here to confirm this observation (Komitov et al. (2010); Komitov and Duchlev (2014)).

2. **Solar Wind indices (SWi):** Alfven Mach number (AMN), Flow Pressure (FP), Magnetosonic Mach Number (MMN), Na/Np ratio (NaNp), Plasma Beta β (PB), Polar Cap (North) index (PCN), Proton Density (PD), Plasma (Flow) Speed (PFS), Proton Temperature (PT).

$$\begin{aligned}\text{SolarWind} = Y_2 = \;& \beta_{2,1} \times \text{AMN} + \beta_{2,2} \times \text{FP} + \beta_{2,3} \\ & \times \text{MMN} + \beta_{2,4} \times \text{NaNp} + \beta_{2,5} \times \text{FMA} \\ & + \beta_{2,6} \times \text{PB} + \beta_{2,7} \times \text{PCN} + \beta_{2,8} \times \text{PD} \\ & + \beta_{2,9} \times \text{PFS} + \beta_{2,10} \times \text{PT} + \varepsilon_2.\end{aligned} \quad (3)$$

AMN related to the speed of Alfven waves in the plasma of the solar wind, have been extensively considered in the literature as related to the mechanism of acceleration of cosmic rays in the interstellar medium through the solar wind (Shaul et al. (2006); Axford (1965); Engelbrecht et al. (2022)). The magnetosonic Mach number is calculated from solar wind data obtained upstream of Earth, it is calculated from ratio of wind velocity and Magnetosonic speed (Jian et al. (2011); Aslam and Badruddin (2017)) it has also been associated with the mechanism of diffusion of cosmic rays through the solar wind. PCN index as a ground-based indicator of the solar wind energy incoming into the magnetosphere and have been considerend as a proxy for energy that enters into the magnetosphere during solar wind-magnetosphere coupling (Troshichev (2022); Stauning (2015)). The remaining variables measure distinctive characteristics of the solar wind, which is why they are used in this study to consolidate general regression models with cosmic rays as precursors or predictors of the intensity of particles measured on the earth's surface. Additionally, IMF has been included here given recent observations of important relationships between GCR and solar modulation Wibberenz et al. (2002).

3. **Distortions - Geomagnetic Activity indices (GAi):** Field Magnitude Average $|B|$ (FMA), Kp, DST Index, AE-index, Ap-index, AL-index and AU-index.

$$\begin{aligned}\text{Distortions} = Y_3 = \beta_{3,1} \times \text{DST} + \beta_{3,2} \times \text{Kp} + \beta_{3,3} \\ \times \text{AU} + \beta_{3,4} \times \text{Ap} + \beta_{3,5} \times \text{AL} + \varepsilon_3.\end{aligned} \quad (4)$$

The latent variables (Photosphere, SolarWind and Distortions) contain all the information of the predictors due to solar activity divided into the three contributions expressed. Our initial hypothesis is that the cosmic ray intensity is predictable in terms of the latent variables (Eq. 5), which have their relative contribution with respect to the original variables measured and observed by the experimental data (Eqs. (2)–(4)), that is,

$$\begin{aligned}\text{GCR} = \;& \alpha_1 Y_1 + \alpha_2 Y_2 + \alpha_3 Y_3 \\ = \;& \alpha_1 \times (\text{Photosphere}) + \alpha_2 \times (\text{SolarWind}) + \alpha_3 \\ & \times (\text{Distortions}) + \varepsilon_\alpha,\end{aligned} \quad (5)$$

Additionally an hypothesis is incorporated for two objectives: the first is to obtain more robustness in the overall model result; and the second is to establish precursors in the latent variables. These relationships are expressed in the equation:

$$\begin{aligned}\text{SolarWind} = A_1 \times (\text{Photosphere}) + A_2 + \varepsilon_A, \\ \text{Distorsions} = B_1 \times (\text{SolarWind}) + B_2 + \varepsilon_B.\end{aligned} \quad (6)$$

Seventeen variables were obtained with potential significant relation for GCR, removing several other variables that do not provide important information or correlation. The findings showed that two variables, R_z and $F_{10.7}$, contribute onto the first factor (construct 1, Photosphere) are attributed to processes in the sun's photosphere. The second factor (construct 2, Solar Wind) depending in 10 variables, which are indices and measurements that characterize the solar wind. The third factor (construct 3, Distortions) is related with 5 variables, concerning to changes in the magnetosphere and Earth's magnetic field caused by the solar wind. Based on the theoretical approach of the identified factors, it can be concluded that the three factors represent three latent variables or constructs, as defined by the shared meaning of the variables that make them up.

2.3. Metrics for model evaluation

Once a model has been estimated, it is necessary to evaluate its quality. For this we use the goodness-of-fit statistics. In our case we use the absolute fit (considering the value of the residuals), the relative fit (comparing the fit with that of another model with the worst fit) and the parsimonious fit (considering the fit with respect to the number of parameters used) (Byrne et al. (1989); Sheskin (2003)).

To assess the effectiveness of the model, we have considered several indices, including the chi-square and p-value for chi-square, root mean square error (RMSE), Akaike information criterion (AIC), and Bayesian information criterion (BIC). These measures evaluate the relative quality of a statistical model and determine which model is the best fit for the data. The Goodness of Fit Index (GFI) (Joöreskog and Soörbom (1984)) and the Comparative Fit Index (CFI) (Joöreskog and Soörbom (1984)) are two widely used measures with a range of 0 to 1, with a minimum value of 0.5 required to support the model (Bentler and Bonett (1980)). The AIC and BIC indices do not have specific values that define a model as "good" or "bad," but lower values are generally associated with better fits. It is also worth noting that BIC is always greater than AIC and that the absolute value of AIC is not significant.

Regression analysis generates an equation that describes the statistical relationship between one or more predictor variables and the response variable. After fitting a regression model, and verifying the fit by reviewing the residual plots, you will want to interpret the results. A low p-value (< 0.05) indicates that the null hypothesis can be rejected. In other words, a predictor that has a low p-value is likely to be a significant addition to the model because changes in the predictor value are related to changes in the response variable. Conversely, a larger p-value (negligible) suggests that changes in the predictor are not associated with changes in the response. Most of the studies that use regressions to establish relationships between dependent and independent variables must use this information, otherwise, even if the regression yields a high coefficient of determination, if the estimates are not significant then we could have a model which does not necessarily fit the data.

3. Results and discussions

Once the existence of latent relationships immersed in the set of variables observed and which can be grouped by theoretically supported constructs had been established, we proceeded to study the causal relationships present among the latent variables found, to determine the cause-effect relationships (Mueller and Hancock (2018); Mueller (1999)).

Causal relationships were obtained between the factors previously defined as constructs and the intensity of cosmic rays measured by neutron monitors on the Earth's surface, particularly with the measurements of the detector located in Moscow, based on the reference theory and the results obtained by the model. The associated factors have a high impact on the cosmic ray intensity.

Due to the availability of complete data for solar cycles 21, 22, 23 and 24, (also 25 to date), we have developed the model measurement for each of these cycles by splitting the data conveniently from start and end dates of each solar cycle, also a significant data cleaning process has been done although the number of missing data or outliers for each of the time series is actually minimal. Additionally, the model has been measured for the complete data set from 1976 to date for comparison purposes. As a preliminary step we have normalized the data set with a transformation in which each time series of each index and also the variable to be predicted are standardized on a [0,1] scale.

The hypothesized model (shown in Fig. 3 for years between 1976 to today) has been obtained basically using the two-step modeling approach recommended by (Anderson and Gerbing (1988)), for all other cycles an analogous model is built with the same characteristics. The first step consists of an analysis of the measurement model. In a second step we check the structural relationships between the latent constructs. A two-step process is preferred because it ensures that the latent constructs are adequately measured before examining the structural relationships in the model.

The latent variables (or constructs) each contribute to the explanation of the dependent variable GCR. This relationship is determined by the arrows directed toward the cosmic ray count variable. Two values appear expressed. The first (top) represents the estimation coefficient of the regression and the second (p-value) indicates whether the variable is significant or not (p-value < 0.05 indicates that there is a high degree of association and the variable is sig-

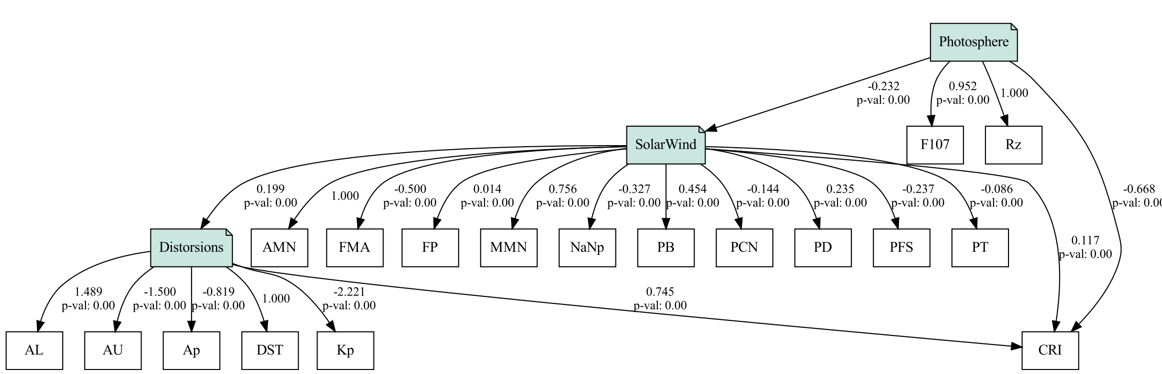

Fig. 3. SEM Model Validation Plot for cosmic rays intensities and solar dynamics indices for complete dataset from 1976 to date. The relationships between variables are represented by the arrows directed between them and the values for the regression estimators are expressed close to them.

nificant). Additionally, the Fig. 3 also expresses the relationships between the latent variables (not observed) and the independent variables (observed) related to the indices that determine the dynamics of the sun in the three constructs (photosphere, solar wind and distortions).

The model builded implies that the p-values for the regression estimators are all less than 0.05 for a confidence interval of 95%, it follows that all estimators are statistically significant for the development of the construct between cosmic ray intensity and latent variables of solar dynamics.

For each solar cycle we compute a regression model taking into account all latent variables and their corresponding observed variables defined in Section 2, plus a model considering all solar cycles, i.e., for the complete cosmic ray time series data set. Fig. 4 presents the results of this application for each of the latent variables. The left panel of Fig. 4 shows the time evolution of the corresponding estimators of the latent variable Photosphere with its independent variables (sunspots and the ratio flux of 10.7 cm) for each solar cycle and also for all complete cycles.

The sunspot activity is decreasing from cycle 21 to the current cycle however the magnitude of the relations are weak in the first three cycles (with inverse relation due $\beta_{1,i}$'s are negative), being very large in cycle 24. This last cycle has an unusually low number of sunspots compared to recent cycles (about half that of cycle 23, see Fig. 1) (Bhargawa and Singh (2021); Takalo (2021)). In other words, correlation coefficient for cosmic rays intensity respect of sunspot are −0.57, −0.83, −0.69, −0.72, for solar cycles 21 to 24, respectively, an increase of 30% between cycles 21 and 22, and additional increase of 5% between cycles 23 and 24, this show that even cycles are better correlated that odd cycles for cosmic rays and better represent in this period that another one.

This is consistent with the regression estimators calculated for each solar cycle (see Fig. 4). Even solar cycles have larger estimators (in absolute value) than odd cycles (Ross and Chaplin (2019), Koldobskiy et al. (2022)).

A similar situation and analysis occurs in the case of the relationship established for the parameters that measure solar wind in the heliosphere medium (see Fig. 4 - third from left to right). Again, interestingly, the regression estimators are lower for the even cycles than their corresponding odd cycle predecessors. In general, even solar cycles have a weaker relationship than odd solar cycles for the regression with respect to cosmic ray counts in terms of the independent variables. Less activity in Sun's corona is followed by higher abundance of particles in heliosphere and viceverse.

In this case, the variables that contribute most to the explanation of the behavior of cosmic ray intensities are three, namely: AMN with positive correlations of 0.44, 0.45, 0.49, 0.39 and 0.43, for cycles 21 to 24 and also for all complete cycles, respectively, followed by an inverse correlation relationship for IMF with negative correlations of −0.39, −0.42, −0.45, −0.34, −0.48, for cycles 21 to 24 and also for all complete cycles, respectively.

Magnetic distortions in the vicinity of the Earth are shown to be strong estimators for cosmic ray intensity, increasing from cycle 21 to 23 and dropping very rapidly by cycle 24. The distortions caused by the solar wind from coronal activity have also been significantly smaller in cycle 24, so the Earth's magnetic field is expected to have few alterations.

The indices AU and AL, known as two of three auroral electrojet indices, have been a popular tool in monitoring geomagnetic activity, space weather, and conducting research in geomagnetism, aeronomy, and solar-terrestrial physics since their introduction by Davis and Sugiura (1966). The indices AU and AL measure the strongest eastward and westward current intensities of the auroral electrojets respectively, as recorded by selected magnetometers located in the auroral zone. For the case of the latent variable "Distortions", in which its most important contributor is the AU index, the correlation coefficients are −0.48, −0.51, −0.45, −0.33 and −0.53, respectively for cycles 21, 22, 23, 24 and the complete series. The next most important index is Kp-index, utilized to characterize the severity of geomagnetic storms. It serves as an effective indicator of disruptions in the Earth's magnetic field and is employed by the SWPC (Space Weather Prediction Center) to determine the necessity of issuing geomagnetic alerts and warnings for those affected by the disturbances, the correlation coefficients are −0.28, −0.32, −0.42, −0.24 and −0.43, respectively for cycles 21, 22, 23, 24 and all cycles.

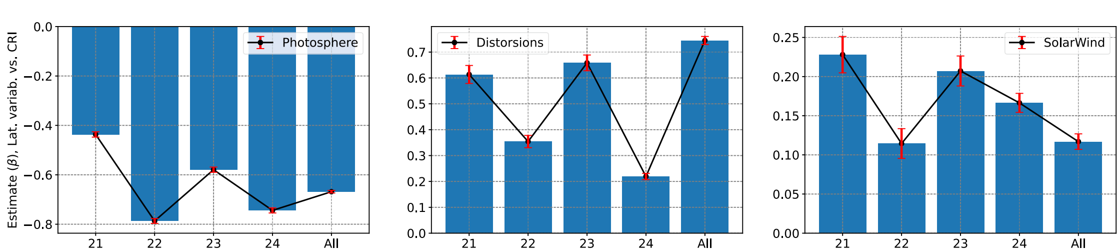

Fig. 4. SEM Model Validation Plot for cosmic rays intensities and solar dynamics indices for complete dataset fron 1976 to today. Figure shown the contributions (estimators) for relation of latent variables in each solar cycle.

The study suggests in agreement with (Somaïla et al. (2022); Takalo (2021)), that the last two cycles are antagonistic. First, the solar cycle 23 was a magnetically disturbed solar cycle with 41.52% disturbed days versus 72.35% very quiet conditions for the solar cycle 24 which in turn has one of the lowest records of storm and substorm conditions in recent years in the history of recent solar cycles, which ultimately evidences that the solar cycle 24 experienced low solar activity compared to solar cycle 23, and this translates into a very low correlation and therefore low influence on the model for cosmic ray prediction (see center panel in Fig. 4).

As is already known by several authors (see for example Sierra-Porta (2018) and others) and also in Fig. 1, lower levels of solar activity are associated with higher levels of cosmic ray occurrence on Earth preceded by very low solar wind activity changing the dynamics of interplanetary and Earth magnetic fields. Then, geomagnetic activity during the minimum following solar cycle 23 was exceptionally low (Richardson and Cane (2012a); Richardson and Cane (2012b); Tsurutani et al. (2011); Russell et al. (2010)), and was associated with unusual solar wind conditions, especially low magnetic field strengths, and slow flow velocities. It is also easy to see that the occurrence of the class of quiet days is much more important during the entire period of solar cycle 24 compared to that of solar cycle 23.

Furthermore, the number of magnetically quiet days shows that solar cycle 24 is the more magnetically quiet of the two solar cycles, with 72.35% of quiet days compared to 58.64% of solar cycle 23. This observation is in line with research by (Zerbo and Richardson (2015) and Nakagawa et al. (2019)) showing a significant decrease in solar wind parameters over the last decade. Weak solar polar fields (Kilpua et al. (2014)) may result in fewer low-latitude excursions of coronal polar holes and thus a wider area of slow solar wind. This slow solar wind condition also induces low solar wind pressure.

Finally, the evaluation of the statistical models is shown in the Table 1. As can be seen, all the constructed models offer good statistical significance for testing the hypothesis of the feasibility of using solar dynamics indices and parameters in structural regression models for cosmic ray prediction.

The best model reproduced in this study is the one that considers all solar cycles, in relation to their high values of chi2, AIC and BIC. This could mean that the model with the best confirmatory effect is the one that takes into account the whole time series of the data. However, we can see that in the last two solar cycles separately better models are obtained than in cycles 21 and 22, this may be due to improvements in the measurement instruments and methodologies for data collection and curation. This may be due to a clearly higher value of the chi2 function as can be seen in the Table 1.

4. Conclusions and final remarks

The main objective of this study is to determine a structural relationship for the occurrence and modeling of cosmic ray counts measured by observatories on Earth in terms of solar dynamic conditions, using for this purpose several parameters that we have divided into three distinct contributions: solar photosphere phenomena, solar wind and distortions in the magnetosphere and geomagnetic conditions of the Earth.

The main findings focus on:

- The structural model for the prediction has been found by identifying each of the estimators describing the model. The p-values found in the models all less than 0.05 (see for example Fig. 3) confirm the hypothesis that all the indices and parameters taken into account are predictors of cosmic rays in the developed relationships.
- In terms of the solar photosphere parameters (sunspots and $F_{10.7\text{cm}}$), cosmic rays exhibit a strong relationship in cycles 21, 22 and 23 respectively, but decreasing by up to 25% for cycle 24 showing a negative correlations.
- In terms of the solar wind parameters (Alfven Mach number, Flow Pressure, Magnetosonic Mach Number, Na/Np ratio, Plasma Beta β, Polar Cap (North) index, Proton Density, Plasma (Flow) Speed and Proton Temperature), cosmic rays exhibit a strong relationship in cycles 21, 22 and 23 respectively, but decreasing by up to 30% for cycle 24 showing a positive correlations.
- In terms of the magnetic distortions parameters (Field Magnitude Average $|B|$, Kp, DST Index, AE-index, Ap-index, AL-index and AU-index), cosmic rays exhibit a strong relationship in cycles 21, 22 and 23 respectively, but decreasing by up to 50% for cycle 24 showing a positive correlations.
- In general for the best model achieved, the odd cycles are found to be different from the even cycles, except for cycle 24 which has been recognized to be unusual (Janardhan et al. (2018); Gopalswamy et al. (2016)) due to a magnetic configuration of the Sun different from the previous two solar minima with direct implications on the heliosphere and magnetosphere.

Table 1
Statistical significance of the built models and model evaluation metrics.

Cycle/Stats.	chi2	chi2 p-value	RMSE	AIC	BIC	CFI	GFI
21	31435.18	0.0	0.25	63.61	313.71	0.55	0.56
22	37205.27	0.0	0.28	59.46	307.26	0.69	0.70
23	53267.40	0.0	0.30	56.35	312.88	0.73	0.73
24	49626.62	0.0	0.30	55.29	307.23	0.64	0.64
All cycles	169749.20	0.0	0.27	60.22	370.24	0.68	0.69

In this study we have used long-range correlations and have not specified into short-range correlations, therefore, further study can be done in the future to understand how these models can change to account for local phenomena such as Forbush decreases or solar rotation. Additionally, although there are no significant differences with respect to the relative counts in the neutron detectors, but amplitude of the GCR modulation decreases with increasing rigidity at different latitudes or longitudes, another study can be carried out to determine if there are significant differences linked to the magnetic cutoff rigidity for each of the detectors.

Finally, the data used in this study as well as the algorithms and codes used for the analysis of the data and generation of the figures shown in the manuscript, as well as some others, can be found at the web address: https://data.mendeley.com/datasets/2zjbkct5xt. All our results can be freely reproduced and used.

CRediT authorship contribution statement

D. Sierra-Porta: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **M. Tarazona-Alvarado:** Data curation, Formal analysis, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Jorge Villalba-Acevedo:** Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to thank the editor as well as the referees for many lengthy discussions that we believe have greatly improved the quality of this manuscript. The authors would like to thank the Dirección de Investigaciones of the Universidad Tecnológica de Bolivar for the support provided during the development of this research and under grant project number INV03CI2209 of the year 2022. In addition, DSP would like to thank Santiago Vargas for his valuable comments and collaboration in reading the manuscript and discussions about its contents. We acknowledge use of NASA/GSFC's Space Physics Data Facility's OMNIWeb (or CDAWeb or ftp) service, and OMNI data.

References

Anderson, J.C., Gerbing, D.W., 1988. Structural equation modeling in practice: A review and recommended two-step approach. Psychol. Bull. 103, 411–423. https://doi.org/10.1037/0033-2909.103.3.411.

Aslam, O.P.M., Badruddin, 2017. Study of the geoeffectiveness and galactic cosmic-ray response of VarSITI-ISEST campaign events in solar cycle 24. Sol. Phys. 292, 135. https://doi.org/10.1007/s11207-017-1160-x.

Axford, W.I., 1965. The modulation of galactic cosmic rays in the interplanetary medium. Planet. Space Sci. 13, 115–130. https://doi.org/10.1016/0032-0633(65)90181-9, URL: https://www.sciencedirect.com/science/article/pii/0032063365901819.

Bazilevskaya, G.A., Cliver, E.W., Kovaltsov, G.A., Ling, A.G., Shea, M. A., Smart, D.F., Usoskin, I.G., 2014. Solar cycle in the heliosphere and cosmic rays. Space Sci. Rev. 186, 409–435. https://doi.org/10.1007/s11214-014-0084-0.

Bentler, P.M., Bonett, D.G., 1980. Significance tests and goodness of fit in the analysis of covariance structures. Psychol. Bull. 88, 588–606. https://doi.org/10.1037/0033-2909.88.3.588.

Bhargawa, A., Singh, A., 2021. Elucidation of some solar parameters observed during solar cycles 21–24. Adv. Space Res. 68, 2643–2660.

Byrne, B.M., Shavelson, R.J., Muthén, B., 1989. Testing for the equivalence of factor covariance and mean structures: The issue of partial measurement invariance. Psychol. Bull. 105, 456–466. https://doi.org/10.1037/0033-2909.105.3.456.

Chowdhury, P., Dwivedi, B.N., Ray, P.C., 2011. Solar modulation of galactic cosmic rays during 19–23 solar cycles. New Astron. 16, 430–438. https://doi.org/10.1016/j.newast.2011.03.003, URL: https://www.sciencedirect.com/science/article/pii/S1384107611000248.

Cliver, E.W., Boriakoff, V., Bounar, K.H., 1996. The 22-year cycle of geomagnetic and solar wind activity. J. Geophys. Res.: Space Phys. 101, 27091–27109. https://doi.org/10.1029/96JA02037, URL: https://onlinelibrary.wiley.com/doi/abs/10.1029/96JA02037.

Cliver, E.W., Richardson, I.G., Ling, A.G., Solar drivers of 11-yr and long-term cosmic ray modulation. Space Sci. Rev. URL: https://ntrs.nasa.gov/citations/20110023416, https://doi.org/10.1007/s11214-011-9746-3. NTRS Author Affiliations: Air Force Research Lab., Maryland Univ., Atmospheric and Environmental Research, Inc. NTRS Report/Patent Number: GSFC.JA.5411.2011 NTRS Document ID: 20110023416 NTRS Research Center: Goddard Space Flight Center (GSFC).

Davis, L., 1955. Interplanetary magnetic fields and cosmic rays. Phys. Rev. 100, 1440–1444. https://doi.org/10.1103/PhysRev.100.1440.

Davis, T.N., Sugiura, M., 1966. Auroral electrojet activity index AE and its universal time variations. J. Geophys. Res. (1896–1977) 71, 785–801. URL: https://onlinelibrary.wiley.com/doi/abs/10.1029/JZ071i003p00785, https://doi.org/10.1029/JZ071i003p00785.

Desai, M., Giacalone, J., 2016. Large gradual solar energetic particle events. Living Rev. Sol. Phys. 13, 3. https://doi.org/10.1007/s41116-016-0002-5.

Dorman, L.I., 1991. Cosmic ray modulation. Nucl. Phys. B Proc. Suppl. 22, 21–45. https://doi.org/10.1016/0920-5632(91)90005-Y, URL: https://www.sciencedirect.com/science/article/pii/092056329190005Y.

Engelbrecht, N.E., Effenberger, F., Florinski, V., Potgieter, M.S., Ruffolo, D., Chhiber, R., Usmanov, A.V., Rankin, J.S., Els, P.L., 2022. Theory of cosmic ray transport in the heliosphere. Space Sci. Rev. 218, 33. https://doi.org/10.1007/s11214-022-00896-1.

Eroshenko, E., Belov, A., Mavromichalaki, H., Mariatos, G., Oleneva, V., Plainaki, C., Yanke, V., 2004. Cosmic-ray variations during the two greatest bursts of solar activity in the 23rd solar cycle. Sol. Phys. 224, 345–358. https://doi.org/10.1007/s11207-005-5719-6.

Fiandrini, E., Tomassetti, N., Bertucci, B., Donnini, F., Graziani, M., Khiali, B., Reina Conde, A., 2021. Numerical modeling of cosmic rays in the heliosphere: Analysis of proton data from AMS-02 and PAMELA. Phys. Rev. D 104, 023012. https://doi.org/10.1103/PhysRevD.104.023012.

Gaisser, T.K., Stanev, T., 2006. High-energy cosmic rays. Nucl. Phys. A 777, 98–110. https://doi.org/10.1016/j.nuclphysa.2005.01.024, URL: https://www.sciencedirect.com/science/article/pii/S0375947405000540.
Giacalone, J., Drake, J.F., Jokipii, J.R., 2012. The acceleration mechanism of anomalous cosmic rays. Space Sci. Rev. 173, 283–307. https://doi.org/10.1007/s11214-012-9915-z.
Gopalswamy, N., Yashiro, S., Akiyama, S., 2016. Unusual polar conditions in solar cycle 24 and their implications for cycle 25. Astrophys. J. Lett. 823, L15. https://doi.org/10.3847/2041-8205/823/1/L15.
Inceoglu, F., Knudsen, M.F., Karoff, C., Olsen, J., 2014. Modeling the relationship between neutron counting rates and sunspot numbers using the hysteresis effect. Sol. Phys. 289, 1387–1402. https://doi.org/10.1007/s11207-013-0391-8.
Iskra, K., Siluszyk, M., Alania, M., Wozniak, W., 2019. Experimental investigation of the delay time in galactic cosmic ray flux in different epochs of solar magnetic cycles: 1959–2014. Sol. Phys. 294, 115. https://doi.org/10.1007/s11207-019-1509-4.
Janardhan, P., Fujiki, K., Ingale, M., Bisoi, S.K., Rout, D., 2018. Solar cycle 24: An unusual polar field reversal. Astron. Astrophys. 618, A148. https://doi.org/10.1051/0004-6361/201832981, URL: https://www.aanda.org/articles/aa/abs/2018/10/aa32981-18/aa32981-18.html.
Jian, L.K., Russell, C.T., Luhmann, J.G., 2011. Comparing solar minimum 23/24 with historical solar wind records at 1 AU. Sol. Phys. 274, 321–344. https://doi.org/10.1007/s11207-011-9737-2.
Joöreskog, K.G., Soörbom, D., 1984. LISREL VI, analysis of linear structural relationships by maximum likelihood, instrumental variables, and least squares methods, 4th ed ed. Scientific Software Inc, Mooresville, Ind, OCLC: 38667546.
Jöreskog, K.G., Sörbom, D., 1982. Recent Developments in Structural Equation Modeling. J. Mark. Res. 19, 404–416. https://doi.org/10.1177/002224378201900402.
Kilpua, E.K.J., Luhmann, J.G., Jian, L.K., Russell, C.T., Li, Y., 2014. Why have geomagnetic storms been so weak during the recent solar minimum and the rising phase of cycle 24? J. Atmosph. Sol.-Terrestrial Phys. 107, 12–19. https://doi.org/10.1016/j.jastp.2013.11.001, URL: https://www.sciencedirect.com/science/article/pii/S1364682613002903.
Klecker, B., Mewaldt, R.A., Cummings, A.C., 1998. Anomalous Cosmic Rays. In: Fisk, L.A., Jokipii, J.R., Simnett, G.M., von Steiger, R., Wenzel, K.P. (Eds.), Space Science Reviews, vol. 3. Springer, Dordrecht, Netherlands, pp. 259–308, URL: https://resolver.caltech.edu/CaltechAUTHORS:20150107-155451895.
Koldobskiy, S.A., Kähkönen, R., Hofer, B., Krivova, N.A., Kovaltsov, G.A., Usoskin, I.G., 2022. Time lag between cosmic-ray and solar variability: sunspot numbers and open solar magnetic flux. Sol. Phys. 297, 38. https://doi.org/10.1007/s11207-022-01970-1.
Komitov, B., Duchlev, P., 2014. Synthetic solar x-ray flares time series since 1968 ad 40, D2.2-35-14. URL: https://ui.adsabs.harvard.edu/abs/2014cosp...40E1562K. aDS Bibcode: 2014cosp...40E1562K.
Komitov, B., Duchlev, P., Koleva, K., Dechev, M., 2010. Synthetic solar X-ray flares time series since AD 1968/s2. URL: http://arxiv.org/abs/1007.2735, https://doi.org/10.48550/arXiv.1007.2735. arXiv:1007.2735 [astro-ph].
Mavromichalaki, H., Paouris, E., Karalidi, T., 2007. Cosmic-ray modulation: an empirical relation with solar and heliospheric parameters. Sol. Phys. 245, 369–390. https://doi.org/10.1007/s11207-007-9043-1.
Mavromichalaki, H., Papaioannou, A., Plainaki, C., Sarlanis, C., Souvatzoglou, G., Gerontidou, M., Papailiou, M., Eroshenko, E., Belov, A., Yanke, V., Flückiger, E.O., Bütikofer, R., Parisi, M., Storini, M., Klein, K.L., Fuller, N., Steigies, C.T., Rother, O.M., Heber, B., Wimmer-Schweingruber, R.F., Kudela, K., Strharsky, I., Langer, R., Usoskin, I., Ibragimov, A., Chilingaryan, A., Hovsepyan, G., Reymers, A., Yeghikyan, A., Kryakunova, O., Dryn, E., Nikolayevskiy, N., Dorman, L., Pustil'nik, L., 2011. Applications and usage of the real-time Neutron Monitor Database. Adv. Space Res. 47, 2210–2222. https://doi.org/10.1016/j.asr.2010.02.019, URL: https://www.sciencedirect.com/science/article/pii/S0273117710001249.
Mavromichalaki, H., Papaioannou, A., Sarlanis, C., Souvatzoglou, G., Gerontidou, M., Plainaki, C., Papailiou, M., Mariatos, G., Nmdb Team, 2010. Establishing and Using the Real-Time Neutron Monitor Database (NMDB), p. 75. URL: https://ui.adsabs.harvard.edu/abs/2010ASPC.424...75M. aDS Bibcode: 2010ASPC.424...75M.
McCracken, K.G., McDonald, F.B., Beer, J., Raisbeck, G., Yiou, F., 2004. A phenomenological study of the long-term cosmic ray modulation, 850–1958 AD. J. Geophys. Res.: Space Phys. 109. https://doi.org/10.1029/2004JA010685, URL: https://onlinelibrary.wiley.com/doi/abs/10.1029/2004JA010685.
Mueller, R.O., 1999. Basic Principles of Structural Equation Modeling: An Introduction to LISREL and EQS. Springer Science & Business Media, Google-Books-ID: sXy2r5gQlB0C.
Mueller, R.O., Hancock, G.R., 2018. Structural Equation Modeling. In: The Reviewer's Guide to Quantitative Methods in the Social Sciences, 2 ed. Routledge.
Nagashima, K., Morishita, I., Twenty-two year modulation of cosmic rays associated with polarity reversal of polar magnetic field of the sun. Planet. Space Sci. 28, 195–205. https://doi.org/10.1016/0032-0633(80)90095-1. URL: https://www.sciencedirect.com/science/article/pii/0032063380900951.
Nakagawa, Y., Nozawa, S., Shinbori, A., 2019. Relationship between the low-latitude coronal hole area, solar wind velocity, and geomagnetic activity during solar cycles 23 and 24. Earth, Planets Space 71, 24. https://doi.org/10.1186/s40623-019-1005-y.
Paouris, E., Mavromichalaki, H., Belov, A., Gushchina, R., Yanke, V., 2012. Galactic cosmic ray modulation and the last solar minimum. Sol. Phys. 280, 255–271. https://doi.org/10.1007/s11207-012-0051-4.
Popielawska, B., 1992. Components of the 11- and 22-year variation of cosmic rays. Planet. Space Sci. 40, 811–827. https://doi.org/10.1016/0032-0633(92)90109-2, URL: https://www.sciencedirect.com/science/article/pii/0032063392901092.
Potgieter, M.S., 1995. The long-term modulation of galactic cosmic rays in the heliosphere. Adv. Space Res. 16, 191–203. https://doi.org/10.1016/0273-1177(95)00334-B, URL: https://www.sciencedirect.com/science/article/pii/027311779500334B.
Potgieter, M.S., Le Roux, J.A., 1992. The Simulated Features of Heliospheric Cosmic-Ray Modulation with a Time-dependent Drift Model. I. General Effects of the Changing Neutral Sheet over the Period 1985–1990. Astrophys. J. 386, 336. https://doi.org/10.1086/171020, aDS Bibcode: 1992ApJ...386.336P. URL: https://ui.adsabs.harvard.edu/abs/1992ApJ...386.336P.
Reames, D.V., 2013. The Two Sources of Solar Energetic Particles. Space Sci. Rev. 175, 53–92. https://doi.org/10.1007/s11214-013-9958-9.
Richardson, I.G., Cane, H.V., 2012a. Near-earth solar wind flows and related geomagnetic activity during more than four solar cycles (1963–2011). J. Space Weather Space Climate 2, A02. https://doi.org/10.1051/swsc/2012003, URL: https://www.swsc-journal.org/articles/swsc/abs/2012/01/swsc120017/swsc120017.html.
Richardson, I.G., Cane, H.V., 2012b. Solar wind drivers of geomagnetic storms during more than four solar cycles. J. Space Weather Space Climate 2, A01. https://doi.org/10.1051/swsc/2012001, URL: https://www.swsc-journal.org/articles/swsc/abs/2012/01/swsc120012/swsc120012.html.
Richardson, I.G., Cane, H.V., Cliver, E.W., 2002. Sources of geomagnetic activity during nearly three solar cycles (1972–2000). J. Geophys. Res.: Space Phys. 107, SSH 8–1–SSH 8–13. https://doi.org/10.1029/2001JA000504. URL: https://onlinelibrary.wiley.com/doi/abs/10.1029/2001JA000504.
Richardson, I.G., Cliver, E.W., Cane, H.V., 2000. Sources of geomagnetic activity over the solar cycle: Relative importance of coronal mass ejections, high-speed streams, and slow solar wind. J. Geophys. Res.: Space Phys. 105, 18203–18213. https://doi.org/10.1029/1999JA000400. URL: https://onlinelibrary.wiley.com/doi/abs/10.1029/1999JA000400.
Richardson, I.G., Cliver, E.W., Cane, H.V., 2001. Sources of geomagnetic storms for solar minimum and maximum conditions during 1972–2000. Geophys. Res. Lett. 28, 2569–2572. https://doi.org/10.1029/

2001GL013052. URL: https://onlinelibrary.wiley.com/doi/abs/10.1029/2001GL013052.

Ross, E., Chaplin, W.J., 2019. The behaviour of galactic cosmic-ray intensity during solar activity cycle 24. Sol. Phys. 294, 8. https://doi.org/10.1007/s11207-019-1397-7.

Russell, C.T., Luhmann, J.G., Jian, L.K., 2010. How unprecedented a solar minimum?. Rev. Geophys. 48. https://doi.org/10.1029/2009RG000316 URL: https://onlinelibrary.wiley.com/doi/abs/10.1029/2009RG000316.

Shaul, D.N.A., Aplin, K.L., Araújo, H., Bingham, R., Blake, J.B., Branduardi-Raymont, G., Buchman, S., Fazakerley, A., Finn, L.S., Fletcher, L., Glover, A., Grimani, C., Hapgood, M., Kellet, B., Matthews, S., Mulligan, T., Ni, W., Nieminen, P., Posner, A., Quenby, J.J., Roming, P., Spence, H., Sumner, T., Vocca, H., Wass, P., Young, P., 2006. Solar And Cosmic Ray Physics And The Space Environment: Studies For And With LISA, pp. 172–178. https://doi.org/10.1063/1.2405038. URL: https://aip.scitation.org/doi/abs/10.1063/1.2405038.

Sheskin, D.J., 2003. Handbook of Parametric and Nonparametric Statistical Procedures, third ed. Chapman and Hall/CRC, New York. https://doi.org/10.1201/9781420036268.

Shrivastava, P.K., 1997. Charecteristics of long-term cosmic ray modulation during different phases of sun spot cycles in relation with polarity of solar magnetic field., p. 65. URL: https://ui.adsabs.harvard.edu/abs/1997ICRC....2...65S. aDS Bibcode: 1997ICRC....2...65S.

Sierra-Porta, D., 2018. Cross correlation and time-lag between cosmic ray intensity and solar activity during solar cycles 21, 22 and 23. Astrophys. Space Sci. 363, 137. https://doi.org/10.1007/s10509-018-3360-8.

Singh, M., Badruddin, B., Asiri, H., 2021. Hysteresis, time lag, and relation between solar activity and cosmic rays during solar cycle 24. New Astron. 89, 101652. https://doi.org/10.1016/j.newast.2021.101652, URL: https://www.sciencedirect.com/science/article/pii/S1384107621000841.

Somaïla, K., Yacouba, S., Louis, Z.J., 2022. Solar wind and geomagnetic activity during two antagonist solar cycles: Comparative study between the solar cycles 23 and 24. Int. J. Phys. Sci. 17, 57–66. https://doi.org/10.5897/IJPS2022.4998, URL: https://academicjournals.org/journal/IJPS/article-abstract/4A39F8869748.

Stauning, P., 2015. A critical note on the IAGA-endorsed Polar Cap index procedure: effects of solar wind sector structure and reverse polar convection, pp. 1443–1455. https://doi.org/10.5194/angeo-33-1443-2015. URL: https://angeo.copernicus.org/articles/33/1443/2015/.

Takalo, J., 2021. Comparison of Geomagnetic Indices During Even and Odd Solar Cycles SC17 – SC24: Signatures of Gnevyshev Gap in Geomagnetic Activity. Sol. Phys. 296, 19. https://doi.org/10.1007/s11207-021-01765-w.

Troshichev, O.A., 2022. PC index as a ground-based indicator of the solar wind energy incoming into the magnetosphere: (1) relation of PC index to the solar wind electric field EKL. Front. Astron. Space Sci. 9, 1069470. https://doi.org/10.3389/fspas.2022.1069470, aDS Bibcode: 2022FrASS...969470T. URL: https://ui.adsabs.harvard.edu/abs/2022FrASS...969470T.

Tsurutani, B.T., Echer, E., Guarnieri, F.L., Gonzalez, W.D., 2011. The properties of two solar wind high speed streams and related geomagnetic activity during the declining phase of solar cycle 23. J. Atmos. Solar Terr. Phys. 73, 164–177. https://doi.org/10.1016/j.jastp.2010.04.003, URL: https://www.sciencedirect.com/science/article/pii/S1364682610001197.

Wibberenz, G., Richardson, I.G., Cane, H.V., 2002. A simple concept for modeling cosmic ray modulation in the inner heliosphere during solar cycles 20–23. J. Geophys. Res.: Space Phys. 107, SSH 5-1–SSH 5-15. https://doi.org/10.1029/2002JA009461, URL: https://onlinelibrary.wiley.com/doi/abs/10.1029/2002JA009461.

Zerbo, J.L., Richardson, J.D., 2015. The solar wind during current and past solar minima and maxima. J. Geophys. Res.: Space Phys. 120, 10250–10256. https://doi.org/10.1002/2015JA021407, URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/2015JA021407.