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Solar dynamics and cosmic ray intensity: statistical analysis from 1986 to 2019

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Abstract
Interpretations of cosmic ray intensity reflect various solar activities, particularly influenced by changes in solar wind plasma within the heliosphere. To investigate the periodic behavior and relationship of cosmic ray intensity with sunspot number, solar wind plasma velocity, solar wind temperature, and interplanetary magnetic field (IMF), we employed daily and annual data analysis of solar activity from September 1986 to December 2019. In analyzing the relationship between cosmic ray intensity (CRI) and solar activity, the statistical method of "cross-correlation", although widely employed in various disciplines and applications, has been a staple for investigating such relationships. The primary goal of the cross-correlation method is to study the relationship between CRI and solar activity parameters and apply this information in statistical analyses across various solar cycles or periods. In this study, calculations for the most recent solar activity cycles are provided. The analysis confirms a negative correlation between the intensity of cosmic rays and the number of sunspots, with solar wind parameters exhibiting an anachronistic phase relationship also showing a negative correlation. Furthermore, the anti-correlation of cosmic ray intensity with solar wind parameters is expected to yield insights into space weather near Earth.

Keywords: Cosmic ray intensity, sunspot number, cross-correlation, space weather, solar wind

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1 Introduction

Cosmic rays are extremely energetic space-borne particles that primarily originate from the Milky Way, outside the solar system (Aslam and Badruddin, 2012). Although it is anticipated that they may also originate from other galaxies (Oloketuyi et al., 2020), their primary source is indeed the Milky Way. Cosmic ray intensity (CRI) is influenced by various factors, including the speed and temperature of the solar wind (Kane, 2005; Zhang et al., 2006), the instability of the interplanetary magnetic field (IMF) (Potgieter, 2013; Ferreira and Potgieter, 2004), and the sunspot number (SSN) (Sato et al., 2008; Selesnick et al., 2007).

CRI remains nearly constant outside the heliosphere but undergoes modulation as it traverses through the heliosphere because of interactions with the interplanetary magnetic field (Bhattachaya and Roy, 2014; Mavromichalaki et al., 2007). Cosmic ray intensity is known to have a long-term modulation (11 years) and short-term modulation (Forbush decrease) (Kane, 1972). Since the long-term variation of cosmic radiation is still an issue, one of the key research areas is the long-term variation of cosmic ray intensity modulation. Cosmic ray deflection caused by the time-varying solar magnetic field being pulled away from the Sun by the solar wind causes a shift in cosmic ray intensity (Pokharia et al., 2017). The word "solar activity" refers to the fluctuation of turbulence on the surface of the sun. The cycle of solar activity is significantly influenced by the interaction between the solar wind and magnetic activity (Utomo, 2017). An ionized gas called solar wind plasma frequently leaves the sun. The solar wind blocks cosmic rays as they approach our solar system, lowering the amount of energy that reaches the earth (Shrivastava et al., 2005). The interplanetary magnetic field varies significantly over time and longitude, influenced by the speed of solar wind, density, pressure, and temperature, which also affect cosmic ray intensity.

Due to immense energy of cosmic ray, its particles can defy the gravitational pull of the Sun. This solar wind disrupts the magnetic field of Earth as it enters the interplanetary medium; the intensity of the distraction depends on the type of ejecta (Kharayat and Prasad, 2016; Tiwari and Ghormare, 2014; Dumbović et al., 2011). The structure of heliosphere is governed by the solar outputs and their variability, which alter cosmic ray intensity. Sunspots are the result of intense, localized magnetic fields attenuating the light that the Sun emits, and they provide a unique record of the magnetic activity of the Sun (Caballero-Lopez et al., 2019). The strongest magnetic fields gradually move over a period of 11 years from areas roughly halfway between the pole of the Sun to its equator. The 11-year span fluctuates between 9.5 and 12.5 years and is not consistent (Singh and Mishra, 2019). A reliable measure of solar activity is a sunspot. Eleven-year cosmic ray alteration has been extensively researched since the work of Forbush (1954). He discovered an anticorrelation between the number of cosmic rays and the number of sunspots. Sunspots appear on the Sun's photosphere because of the intense magnetic fields.

Cosmic ray intensity varies over a range of time scales, from minutes to years. The data from ground-based neutron monitors can be used to study these fluctuations. Using five minutes of data from Tixie Bay Neutron Monitor (Berezhko et al., 1993; Parsai and Singh, 2016), a large solar cycle variation in the cosmic ray fluctuation during the years 1980 to 1990 was discovered. Moreover, the relationship between cosmic ray intensity with solar activity has been studied for the last three decades by a number of cosmic ray studies such as Gupta et al. (2006 a, b), Kane (2006), Mishra and Agarwal (2007), Dwivedi et al. (2010), and Singh et al. (2011). They came to diverse conclusions regarding cosmic ray intensity.

Agarwal and Mishra (2008) carried out a systematic correlative study to determine a significant relationship between cosmic ray intensity and various solar/heliospheric activity parameters. They discovered that the cosmic ray intensity is negatively correlated with the interplanetary magnetic field (B) and sunspot numbers (Rz), but positively correlated with Rz for four different solar cycles. In order to distinguish between modulation effects caused by the 22-year solar magnetic cycle and effects caused by the 11-year solar activity cycle, long-term cosmic ray observations using neutron monitors are now necessary. Popielawska (1992, 1995) reported a positive correlation when examining the variations of solar cycles of around 11 years and cycles of magnetic activity of around 22 years. Numerous studies have been conducted in the past to establish a long-term correlation between solar parameters and cosmic ray intensity. In this article, from 1986 through 2019, covering solar cycles 22 through 24, we looked at the long-term cosmic ray intensity in the heliosphere during the cycle epochs of cycle 22 (September 1986 to August 1996), cycle 23 (August 1996 to December 2008), and cycle 24 (December 2008 to December 2019). We analyze the relationships between cosmic ray intensity variations and three parameters of solar wind supplied by the OMNI database (solar wind velocity, solar wind temperature, and IMF) during the period of solar cycles 22, 23, and 24. Additionally, the availability of CRI, SSN, IMF, and solar wind parameters data for solar cycles 22, 23, and 24 were determined using the "cross-correlation approach" and regression analysis. The intricacies of the temporal behavior of this association are of particular interest, even though the overall negative correlation between cosmic ray intensity and solar activity is widely known. During the course of the investigation, the aptness of the relationship of long-term basis cosmic ray intensity with solar activity variance is studied.

2 Data analysis and methodology

Solar activities such as sunspots, solar flares, coronal mass ejections (CMEs), and proton storms contribute to the modulation of cosmic rays as they propagate through space, which originate primarily from outside the heliosphere. Large amounts of these rays are blocked by the atmosphere of the Earth, which acts as a shield. In particular, cosmic rays pose a risk to astronauts and their equipment in orbit. Consequently, it is crucial to evaluate space weather. This study took CRI data from the Oulu Neutron Monitor (0.81 GV). These neutron monitors are well-maintained stations that provide reliable cosmic ray data for various studies. Data on solar wind plasma parameters such as temperature, velocity, and IMF were obtained from the National Space Science Data Center OMNI database (https://omniweb.gsfc.nasa.gov/coho/form/omni_m.html) from VOYAGER-II spacecraft. These solar cycle sunspot counts were determined using daily data from the Sunspot Index and Long-Term Solar Observations (http://www.sidc.be/silso/datafiles). In the current work, solar cycles 22, 23, and 24 were obtained. In addition, correlation statistical methods were used.

3 Regression analysis (Pearson's correlation coefficient)

One of the most well-liked and beneficial statistics is correlation. A correlation is a single number that expresses how closely two variables are related to one another. The letter “r” stands for the correlation coefficient. Pearson's correlation coefficient

(PCC), often known as a numerical summary of the link between two variables, varies from -1.00 to +1.00. It is a well-known technique for determining where two data series correspond. This approach has been employed by numerous authors (e.g. Bhattachaya and Roy, 2014; Utomo, 2017). The correlation formula looks like this:

$$\mathbf{r} = \frac{\sum(\boldsymbol{x_i} - \overline{\boldsymbol{x}})(\boldsymbol{y_i} - \overline{\boldsymbol{y}})}{\sqrt{(\boldsymbol{x_i} - \overline{\boldsymbol{x}})^2 \sum(\boldsymbol{y_i} - \overline{\boldsymbol{y}})^2}}$$

r = correlation coefficient;
$\boldsymbol{x_i}$= values of the $\boldsymbol{x}$ variable;
$\overline{\boldsymbol{x}}$ = mean of the values of the $\boldsymbol{x}$ variable;
$\boldsymbol{y_i}$= values of the $\boldsymbol{y}$ variable;
$\overline{\boldsymbol{y}}$ = the mean of the values of the $\boldsymbol{y}$ variable.

4 Results and discussion

In this section, data was recorded from 1986 to 2019 to investigate the variability of cosmic ray intensity and solar wind plasma parameters. Fig. 1 shows the diurnal and annual changes in cosmic ray intensity, solar wind plasma parameters, IMF, and sunspot number. From this figure, the first panel exposes elucidates the variation of CRI of solar cycles 22, 23, and 24. The peaks of the CRI decrease during the solar maximum and increase rapidly during the solar minimum because of the magnetic activity of the solar cycle, which means the Sun causes a periodic change in the Earth's climate. In 1989 and 1991, there are two peaks in the solar cycle 22. Thus, measurements of the solar cycle 22 maximum phase were made between 1989 and 1991. Descending solar minimum periods are defined as 1986–1988, 1992, and 1996. As is well known, a very long period of low solar activity, beginning in 2007 and lasting until the end of 2009, with 2008 and 2009 being exceptionally quiet years, was caused by the slow decline of solar cycle 23 and the sluggish ascent of cycle 24. As a result, the low solar activity between solar cycles 23 and 24 was longer and deeper than prior minima, lasting tens of months as opposed to the few months seen in the past cycles.

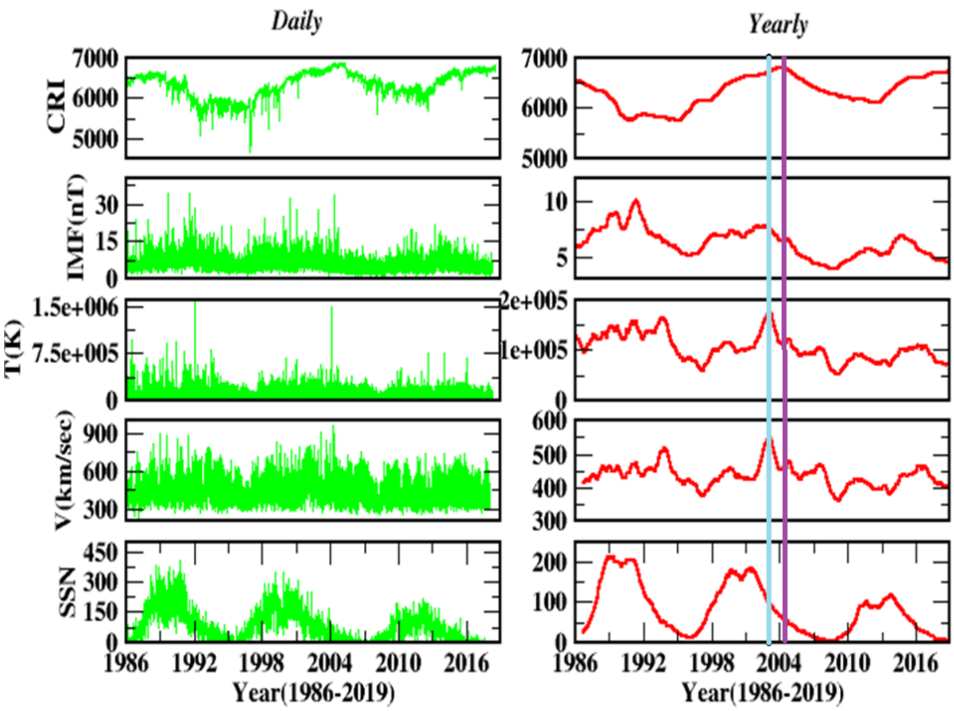

Figure 1. Variation of SSN, solar wind plasma velocity, temperature, IMF, and cosmic ray intensity during the period 1986-2019.

The second panel of Fig. 1 shows the IMF disorder during the solar cycle period 1986 to 2019. For this solar cycle period, the IMF increases beyond the rising phase and decreases beyond the decline phase. It suggests that there is some relation between the magnetic field variation and different phases of the solar cycle. The solar wind flow persisted much longer in 2003 (indicated by a line on the graph). It causes a rapid increase in temperature and velocity, leading to a maximum decrease in CRI and an increase in CRI in 2005. The third panel of Fig. 1 illustrates the variation of solar wind plasma temperature of the solar cycles 22, 23, and 24, respectively. In this figure, solar wind temperature increases when the rise and maximum period of each solar cycle occur. The eminent peaks of temperature manifest the consequence of increasing sunspot numbers (SSN) while solar activity is higher and the solar wind temperature decreases during the decline and minimum phase of the solar cycle.

The fourth panel of Fig. 1 represents the variations of solar wind plasma velocity (km/sec). It shows a significant peak in velocity during the decline phase of each solar cycle. The variations of velocity peaks of solar wind plasma represent the causing the Earth's CRI to perceptible changes. Fluctuations in cosmic ray intensity would be most affected by changes in solar wind velocity. The Earth's magnetic field may be impacted by these variations in solar wind velocity, which could also result in storms. The fifth panel of Fig. 1 shows that significant peaks of SSN are observed during solar cycles 22, 23, and 24. In addition to sudden changes in activity, the Sun also has regular patterns of change. The number of sunspots during a cycle is a good indicator of solar activity. Over an 11-year cycle, solar activity increases and decreases. The number of sunspots reveals the intensity of solar activity. High levels of solar activity result in an increase in the release of matter and electromagnetic fields of the Sun, which makes it more difficult for cosmic rays to reach Earth. When solar activity is high, cosmic ray intensity is higher; conversely, when it is low. A relatively low sunspot number indicates a solar minimum and a relatively high number indicates a solar maximum. The peaks of the SSN of the solar cycle trends clearly manifest the variability in the long-term response to solar activity.
The figure shows that CRI declines when solar activity, such as sunspots, solar wind velocity, temperature, and interplanetary magnetic field increases, so there is an anti-phase relationship between solar activity and cosmic ray intensity.

5 Cross-correlation and Pearson's regression analysis:

The parameters of the solar wind plasma, the IMF, and the SSN on cosmic ray intensity during the period 1986–2019, which includes solar cycles 22, 23, and 24, have been examined in this section. In the investigation, we discovered a number of findings that are discussed below.

5-1 Plot for cosmic ray intensity and sunspot

In order to demonstrate the relationship between cosmic ray intensity and the sunspot cycle, Popielawska (1992) presented a thorough analysis that took data on cosmic ray intensity and sunspot counts into account. The Earth-observed cosmic ray strength is negatively correlated with the sunspot density. The 11-year modulation of CRI exhibits a favorable connection with solar activity indices, as previously described (Chowdhury and Kudela, 2018). The interrelation of cosmic ray intensity (Oulu) and sunspot number of solar activity cycles 22, 23, and 24 denoted that CRI and SSN are inversely correlated, which is opposite to the pattern of sunspot numbers, i.e., the solar activity is at its maximum and cosmic rays are at a minimum (Fig. 2a).

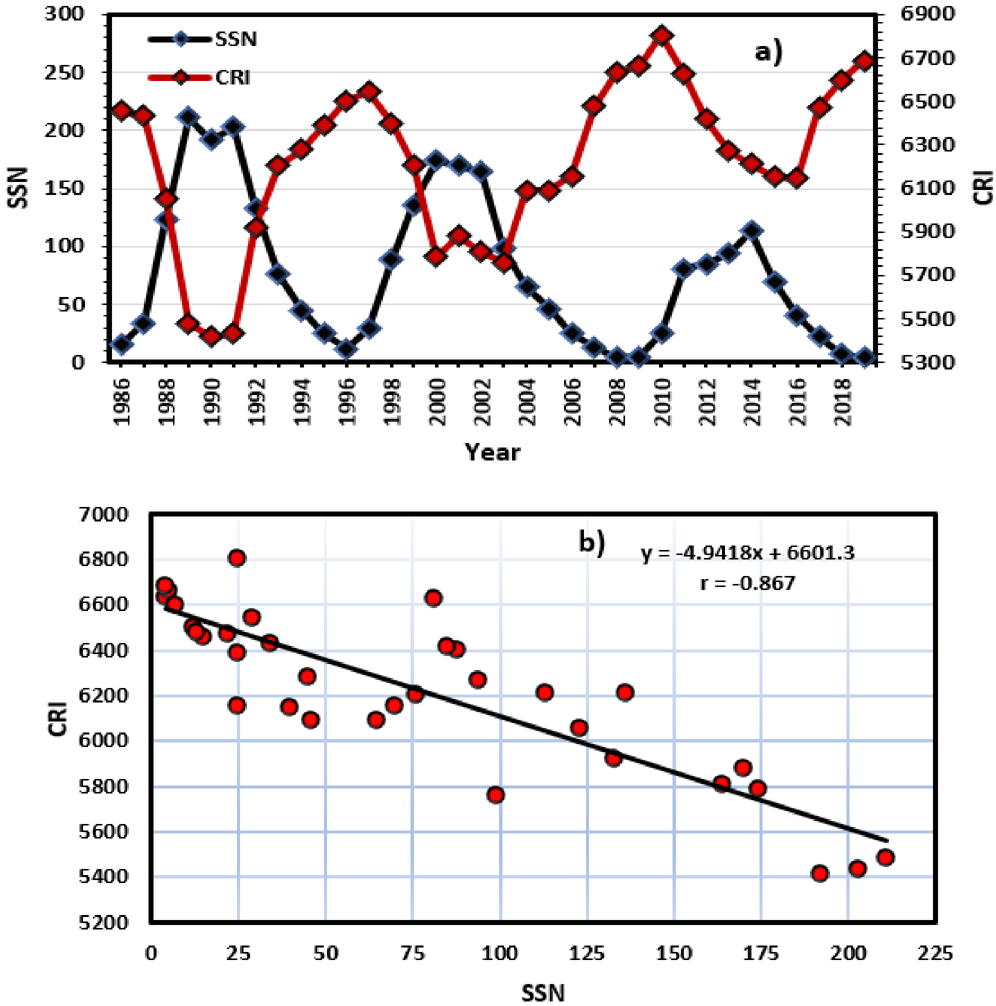

Figure 2. Cross-correlation curve and long-term modulation for the annual mean value of cosmic ray intensity and sunspot number of the solar activity cycles 22, 23 and 24.

The cross-correlation curve between the annual average values of the SSN and CRI (Oulu) for the years 1986 to 2019 is shown in this plot. Solar activity is weaker in solar cycle 24 than in solar cycles 22 and 23, according to variation in annual average cosmic rays and SSN. The scatter plot between CRI distribution and monthly mean SSN is shown in Fig. 2b. Based on the trend line of the scatter plot, it can be deduced that there is an r = -0.867 correlation coefficient between CRI and SSN, which is consistent with the findings of earlier studies of Ahluwalia et al. (1997), Kane (R. P.) (2005) and Dorman (2004).
Finally, we came to the conclusion that the variation in cosmic ray intensity is at odds with the solar activity cycle.

5-2 Plot for cosmic ray intensity and solar wind parameters:

Fig. 3 shows the pattern of the yearly average value of solar wind plasma velocity and cosmic ray intensity which cover the years from 1986 to 2019. The correlation of cosmic ray intensity with solar wind plasma velocity pivots on the physical conditions in the interplanetary space varying with the solar activity. The strongest increment in velocity occurred in the year 2003, while CRI decreased over the years as shown in Fig. 3a. When cosmic rays increased, the solar wind velocity declined; therefore, the long-term relationship between cosmic rays and solar wind velocity is an "opposite" relationship because of the negative correlation type (r = -0.477) which is low as shown in Fig. 3b. Annual variation of CRI to SW velocity shows some discrepancies (Fig. 3a), which exposes the increased levels of solar wind plasma velocity caused by the impact on the ionosphere. It is obvious that as the solar wind velocity increases, the variation in cosmic ray intensity diminishes. Fig. 4 demonstrates the relationship between the intensity of cosmic rays and solar wind plasma temperature of solar cycles 22, 23, and 24. In the year 2003, the strongest increment in temperature occurred while CRI decreased over the year as shown in Fig. 4a. When the solar wind temperature increased, the cosmic ray intensity declined; therefore, the long-term correlation coefficient between these two parameters is negatively correlated with each other and is found to be r = -0.686, implying that the CRI and solar wind temperature were moderately anti-correlated with each other. Cosmic ray intensity on SW temperature exhibits some divergence (Fig. 4a), which exposes the increased levels of solar wind plasma temperature leading to global change impacting the ionosphere. It is clear from the layout that an increase in solar wind temperature is accompanied by a decrease in the variation of cosmic ray intensity.

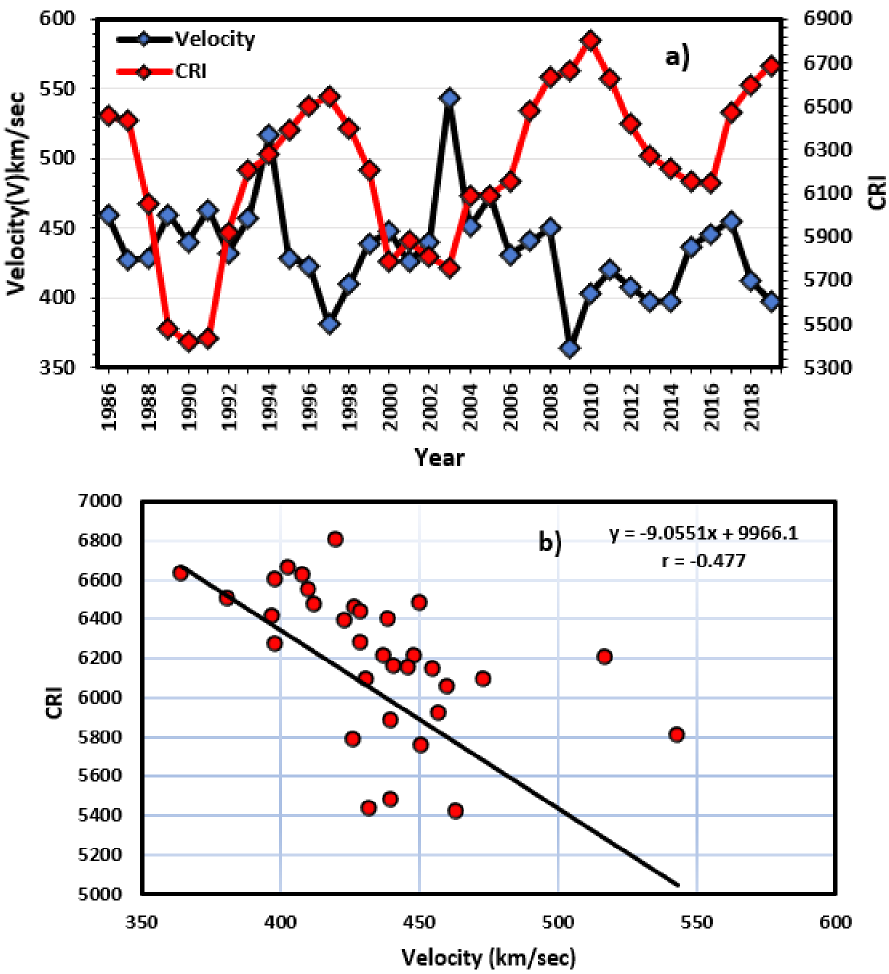

Figure 3. Cross-correlation curve and long-term modulation for the annual mean value of cosmic ray intensity and SW velocity of the solar activity cycles 22, 23 and 24.

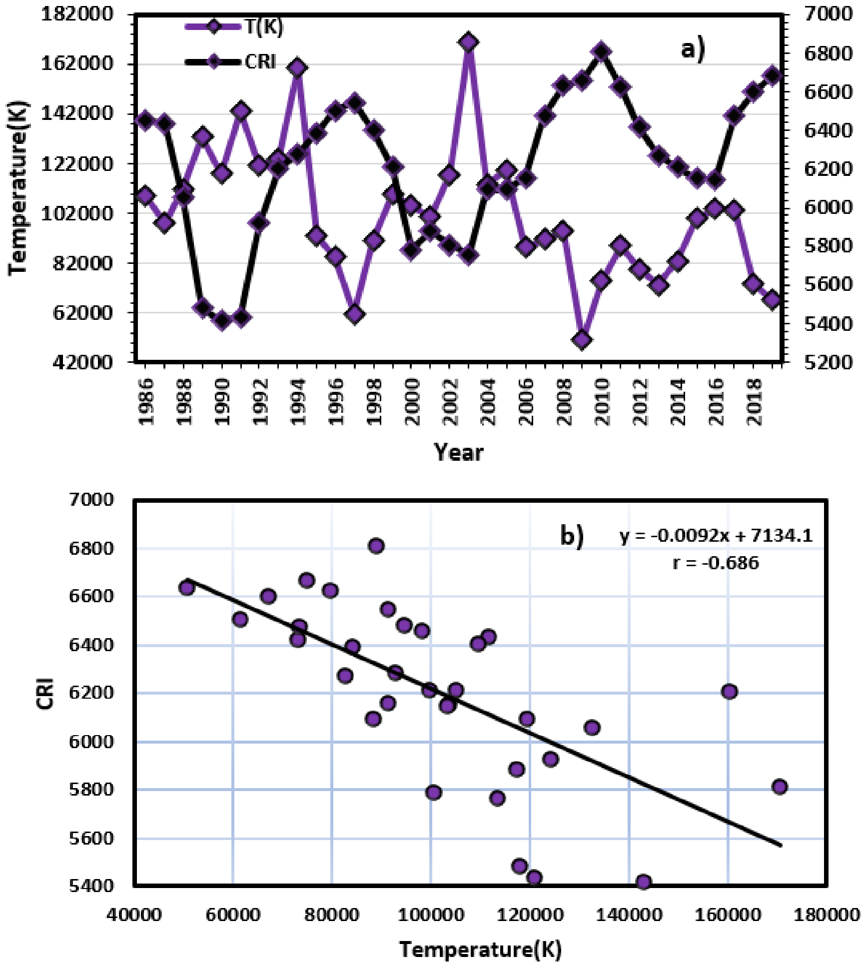

Figure 4. Cross-correlation curve and long-term modulation for the annual mean value of cosmic ray intensity and SW temperature of the solar activity cycles 22, 23 and 24.

5-3 Plot for interplanetary magnetic field and cosmic ray intensity variation

The main factor striking the CRI is the IMF report (Rajesh et al., 2008). IMF plays a significant role in controlling cosmic ray modulation at the site of observation. In this analysis, the relation between an interplanetary magnetic field and cosmic ray intensity is depicted in Fig. 5. Increasing IMF (nT) during periods of high solar activity significantly lowers CRI, whereas decreasing IMF during periods of low solar activity increases CRI. As shown in Fig. 5b, the negative correlation between the long-term modulation of cosmic ray intensity and the IMF with r = -0.879 suggests that IMF is weakly anti-correlated with CRI. Where cosmic rays are scattered, CRI specifies the inhomogen eities of the magnetic field in interplanetary space. IMF and CRI have an antagonistic relationship with some discrepancies.

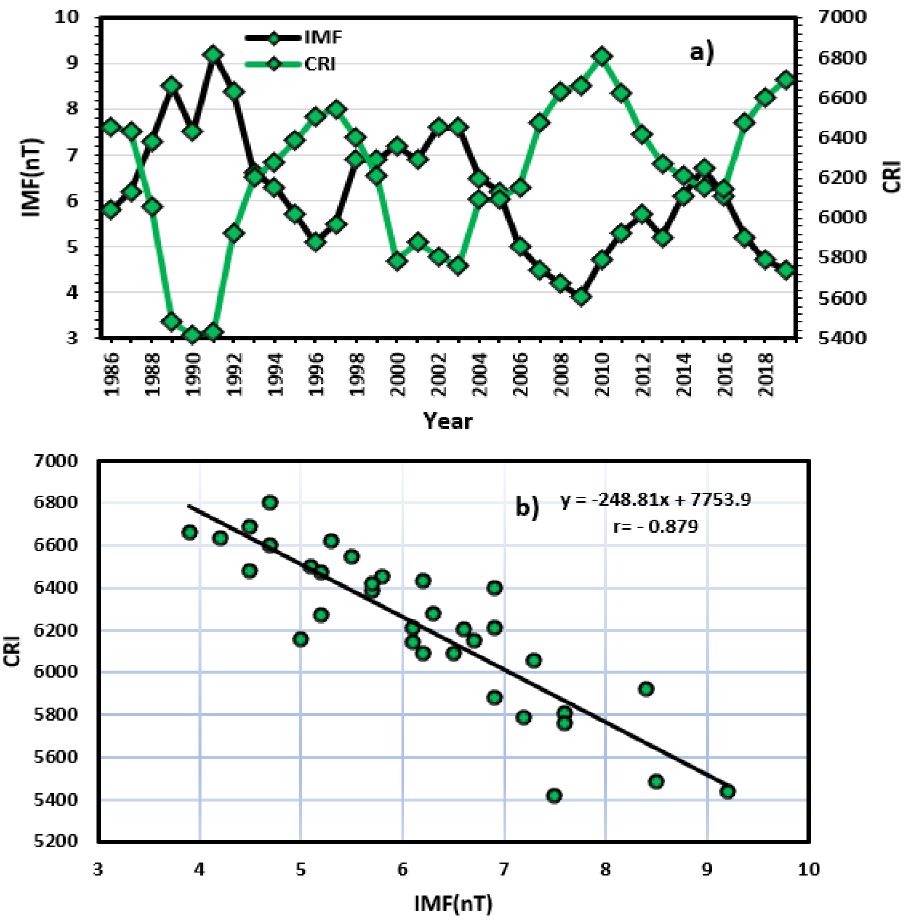

Figure 5. Cross-correlation curve and long-term modulation for the annual mean value of cosmic ray intensity and IMF of the solar activity cycles 22, 23 and 24.

These discrepancies show that the decline in cosmic ray intensity is due to IMF; furthermore, the variation in cosmic ray intensity is also caused by a range of other processes that occur on the Sun's surface. Therefore, based on the aforementioned results, it can be inferred that, with some discrepancies, the cosmic ray intensity is negatively linked with the sunspot number (SSN), solar wind plasma temperature (T), solar wind plasma velocity (V), and interplanetary magnetic field (IMF) for three different solar cycles.

6 Conclusion

In fact, the Sun repeatedly emits magnetic plasma into space. The disturbances in the Earth's magnetic field are tied to the Sun and its outputs, such as a variety of extra-terrestrial properties like solar plasma, the interplanetary magnetic field (IMF), and solar wind stream. In this study, we track cosmic ray variations at neutron monitor stations with solar wind velocity, temperature, and interplanetary magnetic field. The present analysis shows that the velocity of the solar wind plasma is a very effective parameter in creating the attenuation of the cosmic rays. Additionally, the competing impacts of the solar wind temperature are quite effective in causing long-term variations in cosmic ray intensity (CRI). Furthermore, correlation analysis and linear regression between CRI, SSN, solar wind parameters, and IMF have been done for the period 1986-2019. From these scatter diagrams, we have shown that the general trend of the negative correlation of CRI with solar activity is essentially the same during the majority of the three recent solar cycles. Cosmic ray variability on Earth depends on the solar wind, despite the fact that variations in cosmic ray intensity and solar wind are inversely connected. The analysis and statistics lead to the following conclusions:

- The correlation between CRI and SSN is very inverse (r = -0.867);
- The low correlation coefficient between CRI and solar wind velocity (V) indicates that they are not effectively related (r = -0.477);
- The solar wind temperature shows a moderate anti-correlation with CRI (r = -0.686);
- A negative correlation coefficient (r = -0.879) was found between IMF and CRI.

These inverse correlations demonstrate the relationship between solar activity and CRI, which offers forecasts for near-Earth space weather (climate variability). Furthermore, the results of this work provide a study of the relationship between the Sun and Earth on a long-term scale.

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