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Association Between the Solar Wind Speed, Interplanetary Magnetic Field and the Cosmic Ray Intensity for Solar Cycles 23 and 24

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Abstract. The purpose of the present study is to investigate the association of the cosmic ray intensity (CRI) and interplanetary magnetic field (IMF) with high speed solar wind streams (HSSWS) and slow speed solar wind streams (SSSWS) for solar cycle −23 and 24. We have found very interesting and adequate results where CRI provides inverse relationship with the above mentioned streams. Since the correlation coefficient in case of HSSWS is found to be high as compared to SSSWS, it implies that HSSWS are more competent parameters to produce decrease in CRI as compared to SSSWS. Overall analysis of our study shows that CRI, IMF and product of wind speed and IMF (V.B) are poorly correlated with each other for both solar cycles. The year 2016 showed remarkable behavior as there was a drastic increase in the values of interplanetary magnetic field in comparison to the previous years which caused the change in pattern of solar wind streams.

Keywords. Cosmic ray—solar wind velocity—interplanetary magnetic field—solar cycle.

1. Introduction

It is well known that the Sun and its outputs produce change in interplanetary space as well as near the earth's environment, and one of the most important solar output is solar wind flow.

The solar wind is a stream of charged particles and are of great importance as the passage of these streams produce changes in solar terrestrial atmosphere. Slow solar wind and the fast solar wind streams are termed as two components of solar wind respectively. Both types of these streams produce almost similar transient decrease in CRI (Shrivastava & Jaiswal 2003). The slow solar wind shows more variations in intensity as compared to the fast solar wind (Suess 1999; Kallenrode 2004; Kasper *et al.* 2012).

Mathpal *et al.* (2016) observed that at the time of solar maximum, the poles also emit slow solar wind. The HSSWS are classified into two categories, co-rotating streams that produce Fd's (Belcher & Davis 1971) and flare-generated streams that produce normal decrease in cosmic rays. Badruddin (1996) found that among solar flare associated streams and coronal hole associated streams, the former are much more effective in modulation process than the latter. Cane *et al.* (1999), Iucci *et al.* (1979), Lockwood & Webber (1992), Singh *et al.* (2013) and Kharayat *et al.* (2016) noted that the decrease in cosmic ray intensity is highly anti-correlated with the speed of solar wind.

The study of solar wind streams is very important as the radiations of these streams produce hazardous impact on our solar terrestrial atmosphere.

2. Data analysis and method

A Chree analysis by the superposed epoch method has been done for the present study with the occurrence day of HSSWS (criteria 450 $\mathrm{km\,s^{-1}} \leq V_{\mathrm{sw}} <$ 800 $\mathrm{km\,s^{-1}}$) and SSSWS (criteria 300 $\mathrm{km\,s^{-1}} \leq V_{\mathrm{sw}} <$ 450 $\mathrm{km\,s^{-1}}$) as zero day. To study the long term cosmic ray modulation the pressure corrected data (daily mean) has been taken from Moscow Neutron Monitor Station (http://cro.izmiran.rssi.ru/mosc/main.htm) for the period 1996–2016. The daily mean values of solar wind speed and IMF are taken from the Omniweb

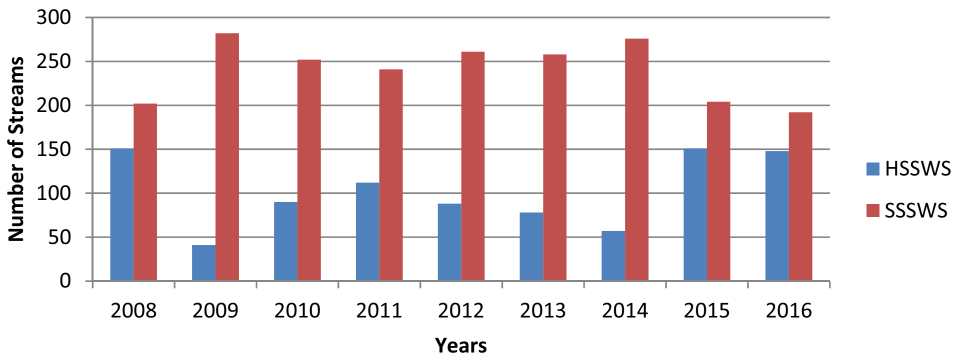

Figure 1. Annual distribution of solar wind streams for solar cycle −24.

data center (http://omniweb.gsfc.nasa.gov/cgi/nx1.cgi). A comparison of HSSWS and SSSWS with CRI has been done. The correlation of CRI with IMF and V.B is also discussed in this study.

3. Results and discussion

3.1 *High speed solar wind streams* ($450\ \mathrm{km\,s^{-1}} \leq V_{\mathrm{sw}} < 800\ \mathrm{km\,s^{-1}}$)

According to Bame *et al.* (1976) and Gosling & Pizzo (1999), HSSWS is one whose speed increases at least $150\ \mathrm{km\,s^{-1}}$ within a five-day interval. We have defined high speed solar wind streams as the one having velocity range between $450\ \mathrm{km\,s^{-1}}$ to $800\ \mathrm{km\,s^{-1}}$.

3.1.1 *For solar cycle* −24. We have plotted the annual distribution of total number of HSSWS and SSSWS for solar cycle −24 as shown in Fig. 1.

It can be clearly seen from the graph (Fig. 1) that years 2008 and 2015 showed maximum as well as equal number of HSSWS while the year 2009 had the minimum number of HSSWS.

With some discrepancies, we have found that for most of the years of solar cycle −24 (2008–2016), CRI shows inverse relation with HSSWS (Fig. 2). No time lag is found between the maximum peak value of HSSWS and minimum peak value of CRI for the years 2009, 2010, 2012 and 2015 which indicates that HSSWS have high potent to produce decrease in CRI in these years (Fig. 2). The correlation coefficient between these two parameters is found to be −0.56 which is moderate and negative. This confirms our observation of (Fig. 2) that CRI and HSSSWS are inversely related.

The year 2016 showed anomalous behavior, as in this year there was a drastic increase in the values of interplanetary magnetic field as compared to earlier years which caused change in pattern of solar wind streams.

3.1.2 *For solar cycle* −23. Similar inverse relationship is also found between cosmic ray intensity and HSSWS for solar cycle 23 with an average correlation coefficient of −0.54 which is lower as compared to solar cycle 24. Except for the years 1996, 1999, 2003 and 2006, in all other years high correlation coefficient was found between these two parameters (Fig. 3).

3.2 *Slow speed solar wind streams* ($300\ \mathrm{km\,s^{-1}} \leq V_{\mathrm{sw}} < 450\ \mathrm{km\,s^{-1}}$)

The slow solar wind is characterized by having a velocity range ($300 \leq V < 450\ \mathrm{km\,s^{-1}}$). Analysis of Fig. 1 shows that maximum number of SSSWS are found in the year 2009 while minimum number of SSSWS are found in the year 2016.

3.2.1 *For solar cycle* –24. With few exceptions, inverse relation is found between CRI and SSSWS with a correlation coefficient of −0.43 which is low and negative (Fig. 4). Since the correlation coefficient in case of HSSWS is −0.56 while in case of SSSWS it is −0.43 which implies that HSSWS are more competent parameters to produce decrease in CRI as compared to SSSWS.

Contrary to fast solar wind, the slow solar wind shows its minimum peak on day zero. The symmetric sharp V-shaped pattern was observed during our study of slow solar wind profile for the years 2010 to 2015 which implies that during these years there is a sharp decrease in SSSWS followed by a sharp increase (Fig. 4).

3.2.2 *For solar cycle* –23. The rising phase of solar cycle-23 does not show any regular variation between CRI and SSSW but after year 1997 the symmetric V shape pattern of SSSW is observed. Except in 2006, in all other year the minimum peak of SSSW coincides with maximum peak of CRI on 0 day. Years 2006 shows anomalous behavior as in this year CRI remains constant from +3 to –3 days with respect to SSSW. The

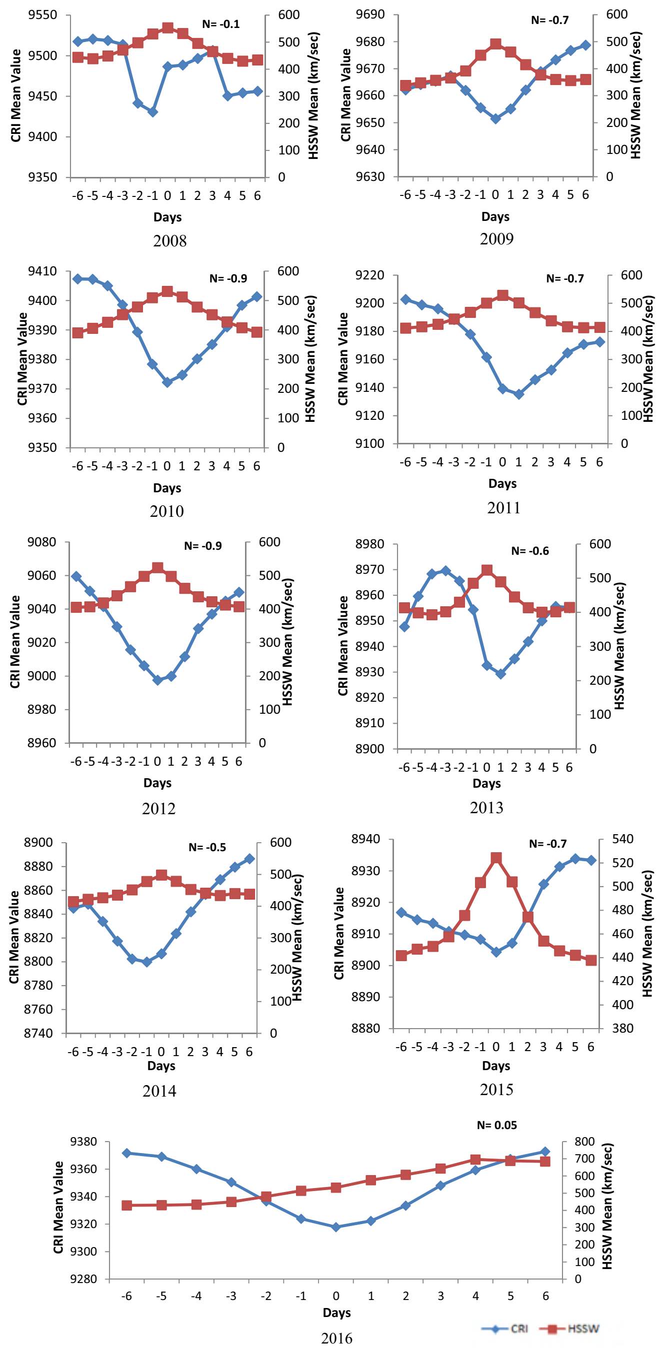

Figure 2. The result of Chree analysis from −6 to +6 days with respect to zero epoch day. The variation of mean values of HSSWS and CRI are plotted. Zero day corresponds to the starting day of occurrence of HSSWS.

average correlation coefficient is found to be moderate (−0.51) which is good when compared to the solar cycle 24 (Fig. 5).

3.3 *Cosmic ray intensity and interplanetary magnetic field*

3.3.1 *For solar cycle* 24. We have studied the relationship between the CRI, IMF and V.B for solar cycle −24 (2008–2016) corresponding to HSSWS and SSSWS and found that the CRI and IMF are inversely related along with some discrepancies. These discrepancies indicate that decrease in cosmic ray intensity does not depend only on IMF, but many other phenomena occur on the Sun's surface that are also responsible for the modulation in cosmic ray intensity.

One such phenomenon is CMEs, which causes the deflection of charged particles constituting cosmic rays

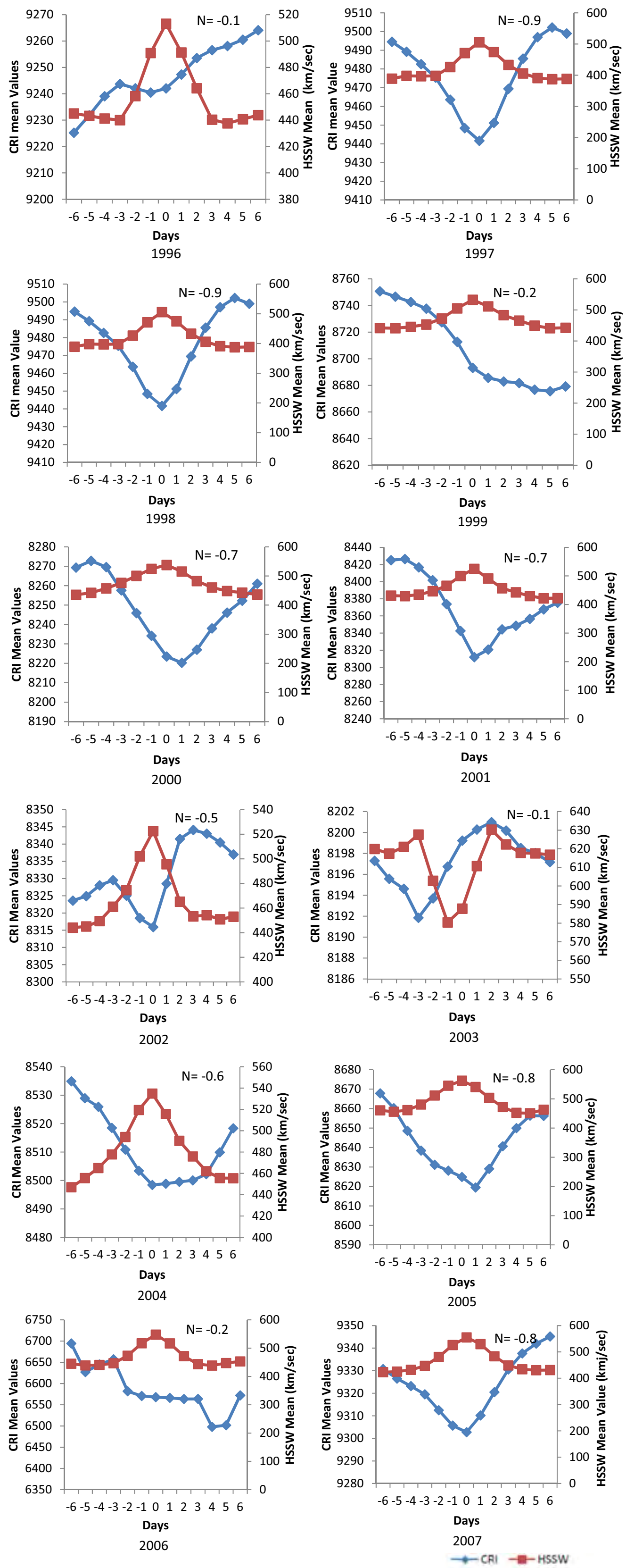

Figure 3. The result of Chree analysis from −6 to +6 days with respect to zero epoch day. The variation of mean values of HSSWS and CRI are plotted. Zero day corresponds to the starting day of occurrence of HSSWS.

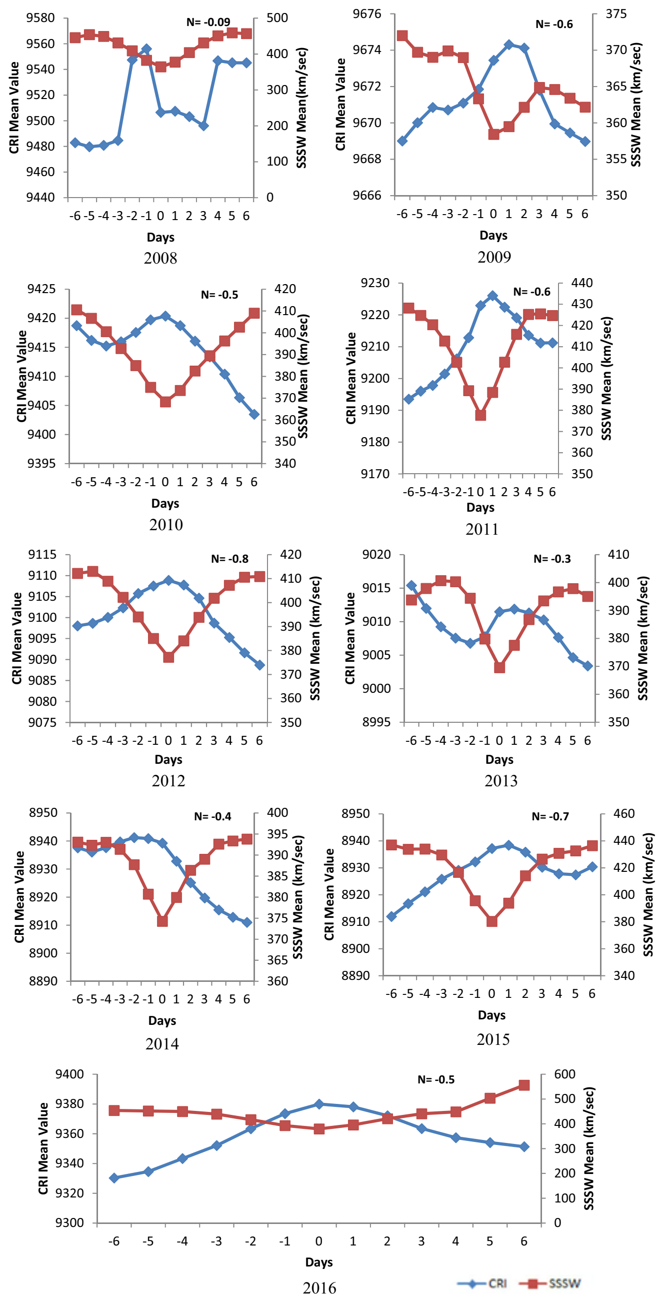

Figure 4. The result of Chree analysis from −6 to +6 days with respect to zero epoch days. The variation of mean values of SSSWS and CRI is plotted. Zero days corresponds to the starting day for the occurrence of SSSWS.

and this results in decrease in intensity of cosmic rays (Kharayat *et al.* 2016). From Fig. 6, it can be clearly seen that for years 2009, 2010, 2011, 2012, 2015, CRI shows its minimum peak on zero (0) day while IMF shows its maximum peak just before zero day, i.e. there exists a time lag of one day between these two parameters. During our study, it was observed that in most of the years on an average the CRI and IMF decreased simultaneously for very short interval from –1 to 0 day which showed that CRI and IMF are directly proportional but for an extremely short period. Further, the correlation coefficient between CRI, IMF and V.B is poor in each case. This implies that IMF and V.B are not effective parameters to produce decrease in CRI (Table 1).

3.3.2 *For solar cycle* −23. We have also analyzed the relationship between CRI, IMF, V.B for solar cycle

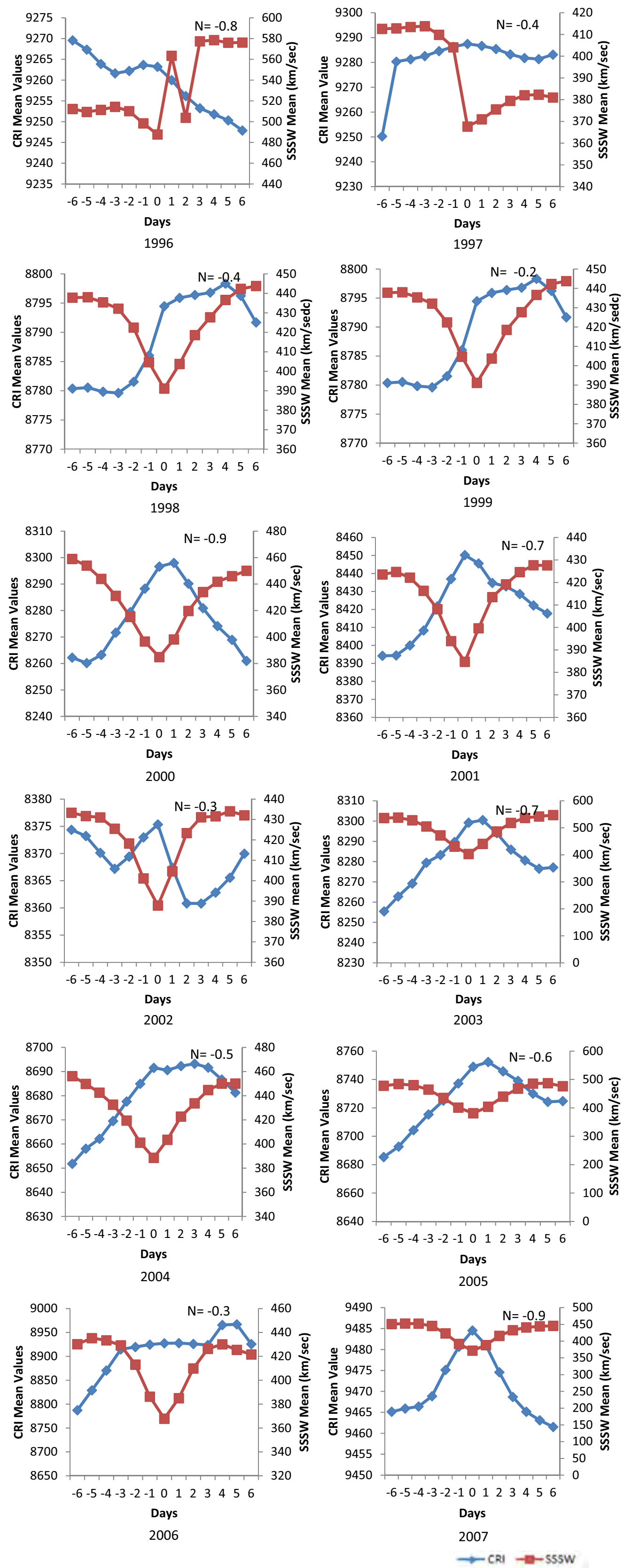

Figure 5. The result of Chree analysis from −6 to +6 days with respect to zero epoch days. The variation of mean values of SSSWS and CRI is plotted. Zero days corresponds to the starting day for the occurrence of SSSWS.

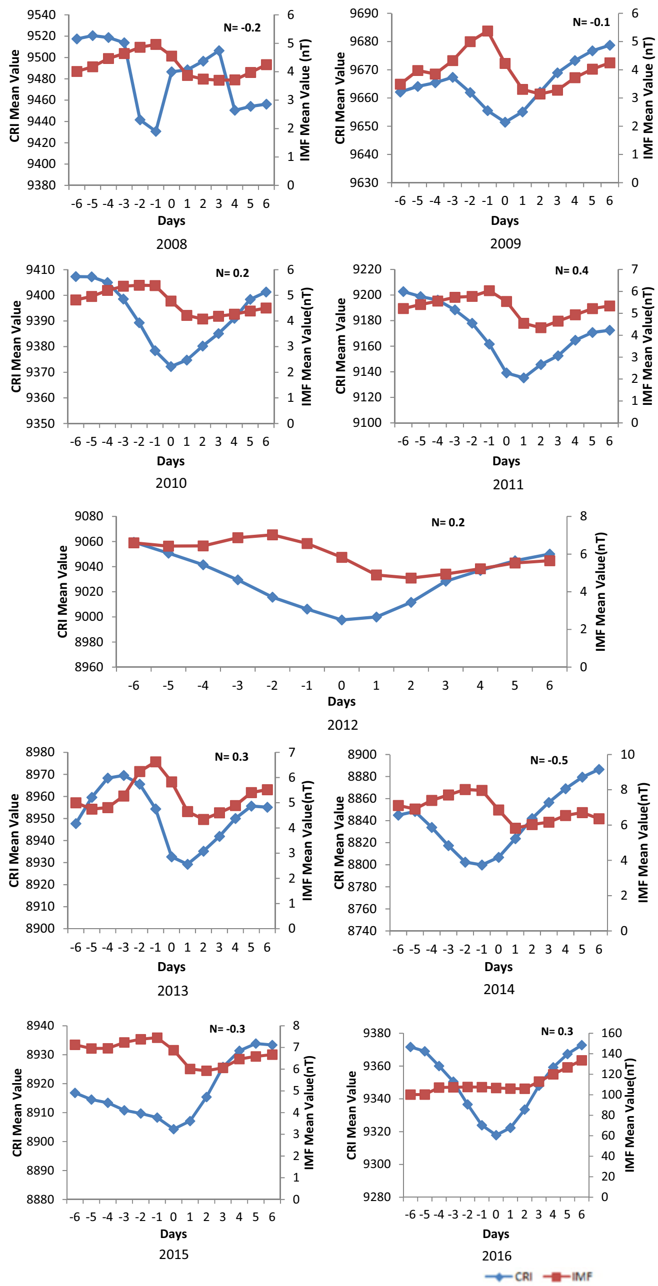

Figure 6. The result of Chree analysis from −6 to +6 days with respect to zero epoch days. The variation of mean values of IMF and CRI is plotted. Zero days corresponds to the starting day for the occurrence of HSSWS.

23 and found that all these parameters are poorly correlated with each other (Table 1). For the years 1997, 1998, 2000, 2001, 2002, 2004 and 2007 there exist a time lag of one day between the peak value of IMF and CRI. The time lag can be considered as delay response of IMF to produce variation in CRI. The year 2007 showed remarkable pattern and in addition to this the high correlation coefficient is also observed for this year in comparison to the rest of the years (Fig. 7).

Table 1. The correlation coefficients of various parameters.

Parameters	Solar cycle −23	Solar cycle −24
CRI and HSSWs	−0.54	−0.56
CRI and SSSWs	−0.51	−0.43
CRI and IMF (HSSWS)	−0.11	0.03
CRI and IMF (SSSWS)	−0.02	0.04
CRI and V.B (HSSWS)	−0.41	−0.31
CRI and V.B (SSSWS)	−0.22	−0.31

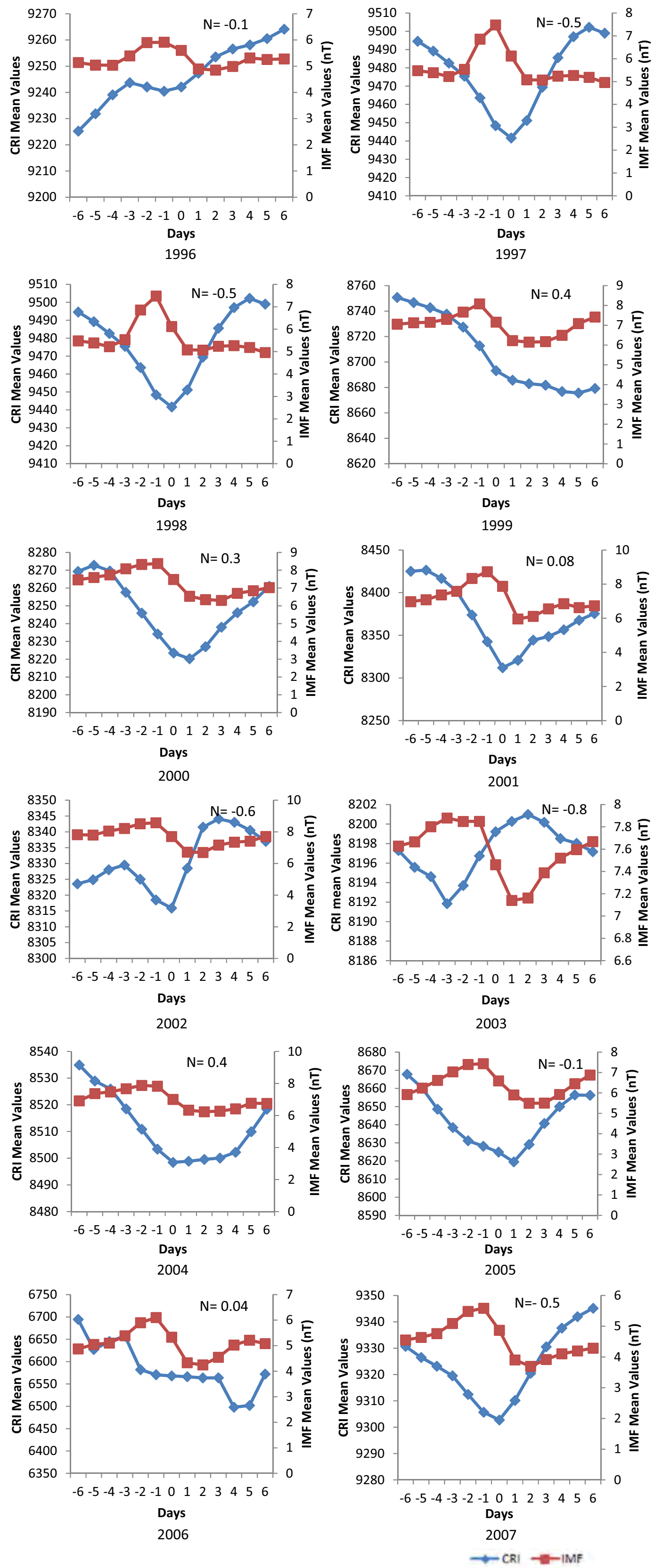

Figure 7. The result of Chree analysis from −6 to +6 days with respect to zero epoch days. The variation of mean values of IMF and CRI is plotted. Zero days corresponds to the starting day for the occurrence of HSSWS.

4. Conclusions

The conclusions of our study is summarized below :

(a) With some dissonance, we found that HSSWS and SSSWS show inverse relationship with CRI for solar cycle 23 and solar cycle 24.
(b) The correlation values between CRI and HSSWS for solar cycle 23 and 24 is found to be −0.54 and −0.56 respectively. Contradictory to this, correlation values between CRI and SSSWS for solar cycle 23 (−0.51) is found to be more as compared to solar cycle 24 (−0.43).
(c) No time lag was found between maximum peak value of HSSWS and maximum decrease of CRI for years 2009, 2010, 2012, 2015 which indicated that HSSWS have high potent to produce decrease in CRI for these years.
(d) Since the correlation coefficient in case of HSSSWS is more as compared to SSSWS for both solar cycles, implies that HSSWS are more competent parameters to produce decrease in CRI as compared to SSSWS.
(e) Poor correlation coefficient between CRI, IMF and V.B shows that they are not effectively related to each other.
(f) Excluding 2015 and 2016, the IMF profiles looked like a lagged copy of the high speed solar wind profile having a time lag of one day between the peak value of HSSWS and IMF.
(g) The year 2016 showed anomalous behavior as in this year there was drastic increase in the values of interplanetary magnetic field which caused the change in pattern of solar wind streams.

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