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Study of geomagnetic storms in relation to the solar wind parameters, interplanetary parameters and their product functions during the various phases of solar cycle 22

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Abstract: The purpose of this research is to look at the relationship between geomagnetic activity indices (Dst and Kp inex), solar wind parameters (i.e. solar wind speed V, plasma proton temperature and plasma flow pressure), interplanetary field parameters (B and B_z) and with solar wind speed product functions (i.e. V.B, $V.B^2$, V.Bz and $V.Bz^2$) in different phases of solar cycle 22 (1986-1995). For the investigation, we used Chree analysis by the superposed epoch method. When compared to interplanetary field parameters and solar wind parameters, the results of this study revealed that solar wind speed product functions are more geo-effective. We have found that the Kp index is highly correlated with solar wind parameter (i.e. plasma flow pressure), interplanetary field parameters and their product functions in comparison to the Dst index, which indicates that the Kp index is a good indicator of geomagnetic storm. We also observed that geomagnetic indices i.e. Dst index and Kp index are tightly correlated to each other. We have performed the time delay analysis by the method of correlation coefficient between the extreme value of geomagnetic activity indices, solar wind parameters, interplanetary field parameters and their product functions and observed a time delay of 0 hours for most of the years of solar cycle 22, while for some years, a time delay of 5-20 hours was found between the extreme value of geomagnetic activity indices, solar wind parameters, interplanetary field parameters and their product functions.

Keywords Solar wind parameters, interplanetary field parameters, geomagnetic activity indices.

1. INTRODUCTION

The geomagnetic storm (GS) consists of three phases, namely; initial phase, main phase and recovery phase**.** The initial phase is characterized by Dst (or its one-minute component SYM-H) increasing by 20 to 50 nT in tens of minute. The initial phase is also mentioned as sudden storm commencement (SSC). However, not all geomagnetic storms have an initial phase and not all sudden increase in Dst or SHYM-H are followed by a geomagnetic storm. The main phase of GS is defined by Dst decreasing to less than -50 nT. In the present paper, we studied the solar wind parameters, interplanetary field parameters and their product functions during the main phase of geomagnetic storm (-100nT $<$Dst $\leq$ -50nT) for the solar cycle 22. Interplanetary field parameters and their product functions are well known recognized as significant drivers of increased geomagnetic activity including geomagnetic storms (e.g., , Kumar, et al., 2008, Russell and McPherron, 1973; Crooker, et al., 1977; Tsurutani, et al., 1988; Wang and Sheeley, 2009; Badruddin and Aslam, 2013; Tiwari, et al., 2010; Echer, et al., 2008; Maggiolo, 2017; Opera, et al., 2013; Jurac, et al., 2001; Rathore, et al., 2014; Rathore, et al., 2011; Verbanac, et al., 2011; Saiz, et al., 2008; Kane, 2005; Choi, et al., 2017; Mathpal, et al., 2018). Solar wind speed V, interplanetary magnetic field IMF B and southward directed interplanetary magnetic field B_Z are considered as a geo-effective parameters but the combined solar wind parameters such as V.B, $V.B^2$, $V.B_Z$ and$V.B_Z{}^2$ are turned out to be more important than V, B and B_Z themselves (Verbanac, et al., 2011; Crooker and Gringauz, 1993; Dwivedi, et al., 2010). The interaction of the solar wind with the Earth's magnetosphere, according to Lu, et al., 2002 results in a system of plasma circulation in the magnetosphere and high latitude ionosphere. As a result, the ionospheric convection configuration gives vital information about the solar wind magnetosphere coupling. However, Gonzalez et al., 2001 claims that in order to forecast the existence of a geomagnetic storm, one must be able to predict three interplanetary parameters viz. V, B and B_Z. In the present paper, we study the geo-effectiveness of these interplanetary parameters in different phases of solar cycle 22 and observed that these parameters are significant in determining the strength of geomagnetic storm. Gonzalez et al., 1994 also provided an overview of the most often utilized coupling functions for the solar wind magnetosphere interaction, including $V.B_Z$ (Rostoker, et al., 1972 and Burton, et al., 1975), $V^2.B_Z$ (Holzer, et al., 1982), and $V.B_Z^2$ (Baker, et al., 1983). The present study confirms that interplanetary product functions ($V.B$, $V.B^2$, $V.B_z$ and $V.Bz^2$) play an essential role in the process of transfer of energy from the solar wind to the magnetosphere. The following is the physical process that explains the dominant connection of all analyzed geomagnetic indices (Dst index and Kp index) to $V.B$, $V.B^2$, $V.B_z$ and $V.Bz^2$. A high convective electric field E (V.B) is connected with the passage of the southern oriented interplanetary magnetic field B_Z,which passes over the globe for a sufficiently long time, and is the principal source of geomagnetic disturbances. In the present study, we observed that geomagnetic indices i.e. Dst index and Kp index are tightly correlated to each other.

2. METHODOLOGY

We employed Chree analysis by the superposed epoch approach to investigate the statistical characteristics and geo-effectiveness of solar wind parameters (i.e. solar wind speed V, plasma proton temperature T and plasma flow pressure P), interplanetary field parameters (i.e. B and B_z) and their product functions (i.e. $V.B$, $V.B^2$, $V.B_z$ and $V.Bz^2$). We study the geo-effectiveness of solar wind parameters, interplanetary field parameters and their product function by using their 5 hourly resolutions. Here the sign of geomagnetic storm is considered as Dst index and Kp index. The occurrence day of geomagnetic storm is used as a zero day with the criteria $-100nT < Dst \leq -50nT$. The hourly mean data's of solar wind parameters and interplanetary field parametersare taken from the Omni web data center (omniweb.gsfc.nasa.gov/form/dx1.html) for the studied period 1986-1995 (solar cycle 22). We have also calculated the correlation coefficient between the peak values of geomagnetic activity indices, solar wind parameters, interplanetary field parameters and their product function in different phases of solar cycle 22.

3. RESULTS AND ANALYSIS

We conducted a detailed investigation of moderate geomagnetic storms ($-100nT < Dst \leq -50nT$) in this paper, and studied their dependency on solar wind parameters, interplanetary field parameters and their product function in different phases of the solar cycle 22 viz. rising phase (1986-1989), maximum phase (1990-1992), decay phase (1993-1995) and total period (1986-1995).

3.1. Interplanetary field parameters and geomagnetic activity indices (Dst and Kp index)

For the time span 1986-1995 (solar cycle 22) under consideration, we examined the relation of geomagnetic storms to the interplanetary magnetic field (IMF B) and to the southward directed interplanetary magnetic field B_z. With the exception of 1995, the strongest increase in the interplanetary magnetic field always occurs on the day of geomagnetic storm's occurrence. A time delay of few hours is found between the extreme value of the IMF B and the lowest value of the Dst index for the year 1995 (figure 1). From figure 4, it is clear that a time delay of few hours is found between the southward directed interplanetary magnetic field B_z and the Dst index for most of the year of solar cycle 22. We also calculated an average correlation coefficient between geomagnetic indices (GIs) and interplanetary parameters (IPs) in different phases of solar cycle 22. During the rising phase, the correlation coefficient between Dst index and interplanetary field parameters was found to be -0.47 for the IMF B and 0.78 for the B_z. Similarly, during the maximum phase, the correlation coefficient between the Dst index and interplanetary field parameters was found to be -0.57 for the IMF B and 0.69 for the B_z. And during the decay phase, the correlation coefficient between the Dst index and interplanetary field parameters was found to be -0.57 for the IMF B and 0.36 for the B_z. The correlation coefficient between the Dst index and interplanetary field parameters for complete period was found to be -0.54 for the IMF B and 0.63 for the B_z. Thus, it can be concluded that interplanetary parameters (i.e. B and B_Z) are a relevant parameters for determining the strength of geomagnetic storms. Our outcome support the earlier findings of Arnoldy, 1971; Rathore, et al., 2015; Joshi, et al., 2011; Pande, et al., 2017; Singh, et al., 2017; Kumar, et al., 2008; Mathpal et al., 2018.

Similarly the correlation coefficient between the Kp index and interplanetary field parameters during the rising phase was found to be 0.66 for IMF B and -0.86 for B_z. During the maximum phase, the correlation coefficient between the Kp

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index and interplanetary field parameters was found to be 0.68 for the IMF B and -0.86 for the B_z. And during the decay phase, the correlation coefficient between the Kp index and interplanetary field parameters was found to be 0.83 for the IMF B and -0.80 for the B_z. The correlation coefficient between the Kp index and interplanetary field parameters for the complete period was found to be 0.72 for the IMF B and -0.84 for the B_z. The correlation coefficient, we obtained in the study indicates that the Kp index is highly correlated with interplanetary field parameters than the Dst index for all the phases of solar cycle 22.

3.2. Interplanetary product functions and geomagnetic activity indices (Dst and Kp index)

We looked at how geomagnetic indices (i.e. Dst and Kp index) fluctuates with the interplanetary product functions (i.e. V.B, $V.B^2$, $V.B_z$ and $V.Bz^2$) after looking into the relationship between geomagnetic indices (i.e. Dst and Kp index) and interplanetary field parameters (i.e. B and B_z).

From figure 2, 3, 5 and 6, it is clear that the strongest increase in the interplanetary product functions happen on the day of geomagnetic storm's occurrence for most of the year of solar cycle 22. A time delay of 0 hours is found between the extreme value of these product functions and the least value of the Dst index but for some years a time delay of 5-20 hours is found between the extreme value of interplanetary product functions and the least value of the Dst index. We also calculated the correlation coefficient between the Dst index and the interplanetary product functions. The correlation coefficient between the Dst index and the interplanetary product function V.B was found to be same (r= -0.5) during the rising and maximum phase, -0.73 during decay phase and -0.64 for the complete period. Similarly the correlation coefficient between the Dst index and the interplanetary product function $V.B^2$ was found to be -0.57 during the rising phase, -0.60 during the maximum phase, -0.66 during the decay phase and -0.61 for the complete period. The correlation coefficient between the Dst index and the interplanetary product function $V.B_z$ was found to be 0.79 during rising phase, 0.74 during maximum phase, 0.45 during decay phase and 0.68 for the complete period. Furthermore, the correlation coefficient between the Dst index and $V.B_z^2$ was found to be -0.76 during the rising phase, -0.59 during the maximum phase, -0.49 during the decay phase and -0.61 for the complete period. We have obtained a good correlation between the interplanetary product functions and the Dst index, which supports the findings of Wu and Lepping, 2002; Sabbah, 2000; Kane, 2005; Opera, et al., 2013; Verbanac, et al., 2011. Thus, the interplanetary product functions can be regarded as a geo-effective parameter during the main phase of geomagnetic storm ($-100nT < Dst \leq -50nT$).

One of the most often used geomagnetic activity indices is a Kp index. The study concludes that the peak values of Kp index have a strong relationship with the interplanetary product functions (V.B, $V.B^2$, $V.B_z$ and $V.Bz^2$). We also calculated the correlation coefficient between the Kp index and the interplanetary product functions. The correlation coefficient between the Kp index and interplanetary product function V.B was found to be 0.60 during the rising phase, 0.48 during the maximum phase, 0.82 during the decay phase and 0.63 for the complete period. Similarly, the correlation coefficient between the Kp index and the interplanetary product function $V.B^2$ was found to be 0.63 during the rising phase, 0.53 during the maximum phase, 0.81 during the decay phase and 0.66 for the complete period. The correlation coefficient between the Kp index and the interplanetary product function $V.B_z$ was found to be -0.84 during rising phase, -0.85 during maximum phase, -0.83 during decay phase and -0.84 for the complete period. Furthermore, the correlation coefficient between the Kp index and $V.B_z^2$ was found to be 0.78 during the rising phase, 0.71 during the maximum phase, 0.81 during the decay phase and -0.77 for the complete period. All the interplanetary product functions (V.B, $V.B^2$, $V.B_z$ and $V.B_z^2$) are highly correlated with Kp index. Our findings strongly shows that interplanetary product functions are a valuable parameter for predicting geomagnetic storms, based on the correlation coefficient. It is found to be highly correlated with the interplanetary product functions than the Dst index.

3.3. Solar wind parameters and geomagnetic activity indices (Dst and Kp index)

We study the geo-effectiveness of the various solar wind parameters during the different phases of solar cycle 22 within period of 1986 to 1995. Apart from the year 1995, it is clear that the strongest increase in the solar wind parameters always occurs on the day of geomagnetic storm's occurrence (Figure 7, 8 and 9). A time delay of 10 hour is found between the extreme value of solar wind speed V and least value of Dst index for the year 1995 while a time delay of 15 hour is found between the extreme value of plasma flow pressure P and least value of Dst index. We have also calculated

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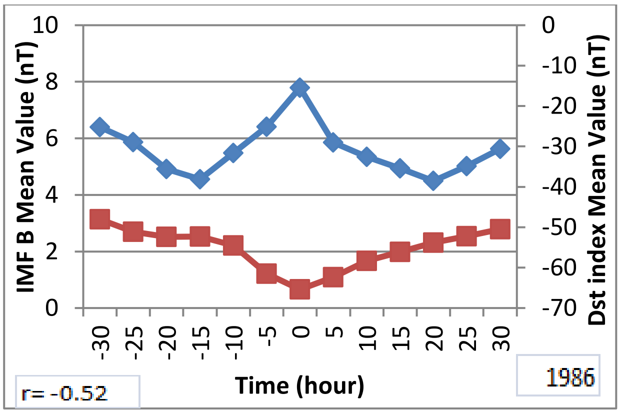
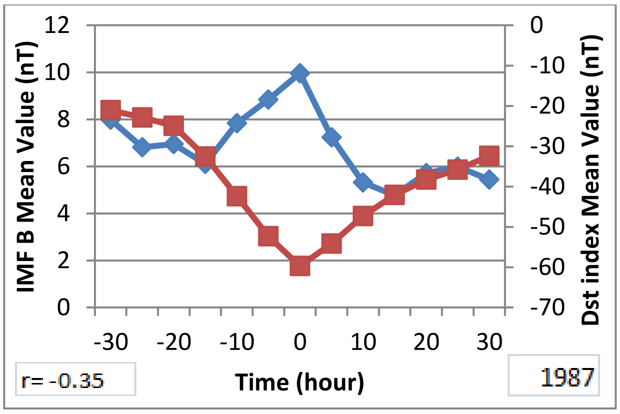
the correlation coefficient between solar wind parameters and the Dst index for the different phases of this cycle. The correlation coefficient between solar wind speed and the Dst index was found to be -0.47 during the rising phase, -0.47 during the maximum phase, -0.74 during the decay phase and -0.56 for the complete period (1986-1995). Similarly, the correlation coefficient between the plasma proton temperature and the Dst index was found to be -0.63 during the rising phase, -0.21 during the maximum phase, -0.80 during the decay phase and -0.56 for the complete period (1986-1995). And the correlation coefficient between the flow pressure and the Dst index was found to be -0.50 during the rising phase, -0.69 during the maximum phase, -0.34 during the decay phase and -0.51 for the complete period (1986-1995).

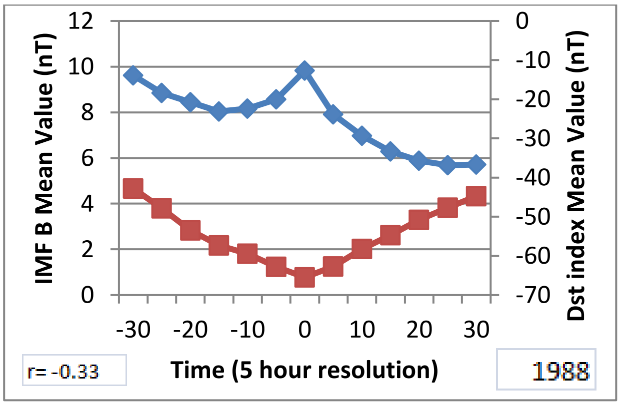
The result indicates that the Dst index is highly correlated with the solar wind speed V and the plasma proton temperature T mainly during the decay phase while the Dst index is highly correlated with the plasma flow pressure P mainly during the maximum phase of the solar cycle 22. The results, we obtained in the study clearly reveals that solar wind parameters are highly geo-effective and is in good agreement with the result of Alves, et al., 2006; Yermolaev, et al., 2005, 2009; Echer, 2007, Richardson, et al., 2002, Crooker and Cliver 1994, Lindsay, et al., 1995; Baker, 1996, and Kamide, et al., 1998.

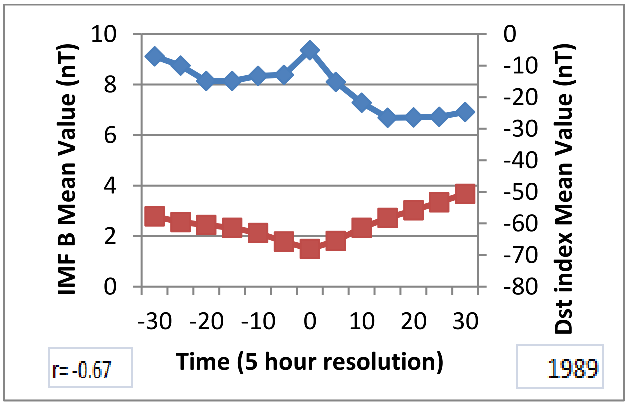
Furthermore, we calculated the correlation coefficient between the geomagnetic index (Kp) and solar wind parameters for the different phases of given solar cycle. The correlation coefficient between the Kp index and the solar wind speed V was found to be 0.27 during the rising phase, 0.13 during the maximum phase, 0.38 during the decay phase and 0.30 for the complete period of solar cycle 22. Similarly, the correlation coefficient between the Kp index and the plasma proton temperature was found to be 0.49 during the rising phase, -0.01 during the maximum phase, 0.64 during the decay phase and 0.38 for the complete period of solar cycle 22. Likewise, the correlation coefficient between the Kp index and the plasma flow pressure P was found to be 0.69 during the rising phase, 0.71 during the maximum phase, 0.79 during the decay phase and 0.72 for the complete period of solar cycle 22.

Our results clearly indicates that Kp index is highly correlated with plasma flow pressure while it is weakly correlated with solar wind speed for all the phases of solar cycle (sc) 22. Kp index is also found to be better correlated with plasma proton temperature mainly during the decay phase of sc 22.









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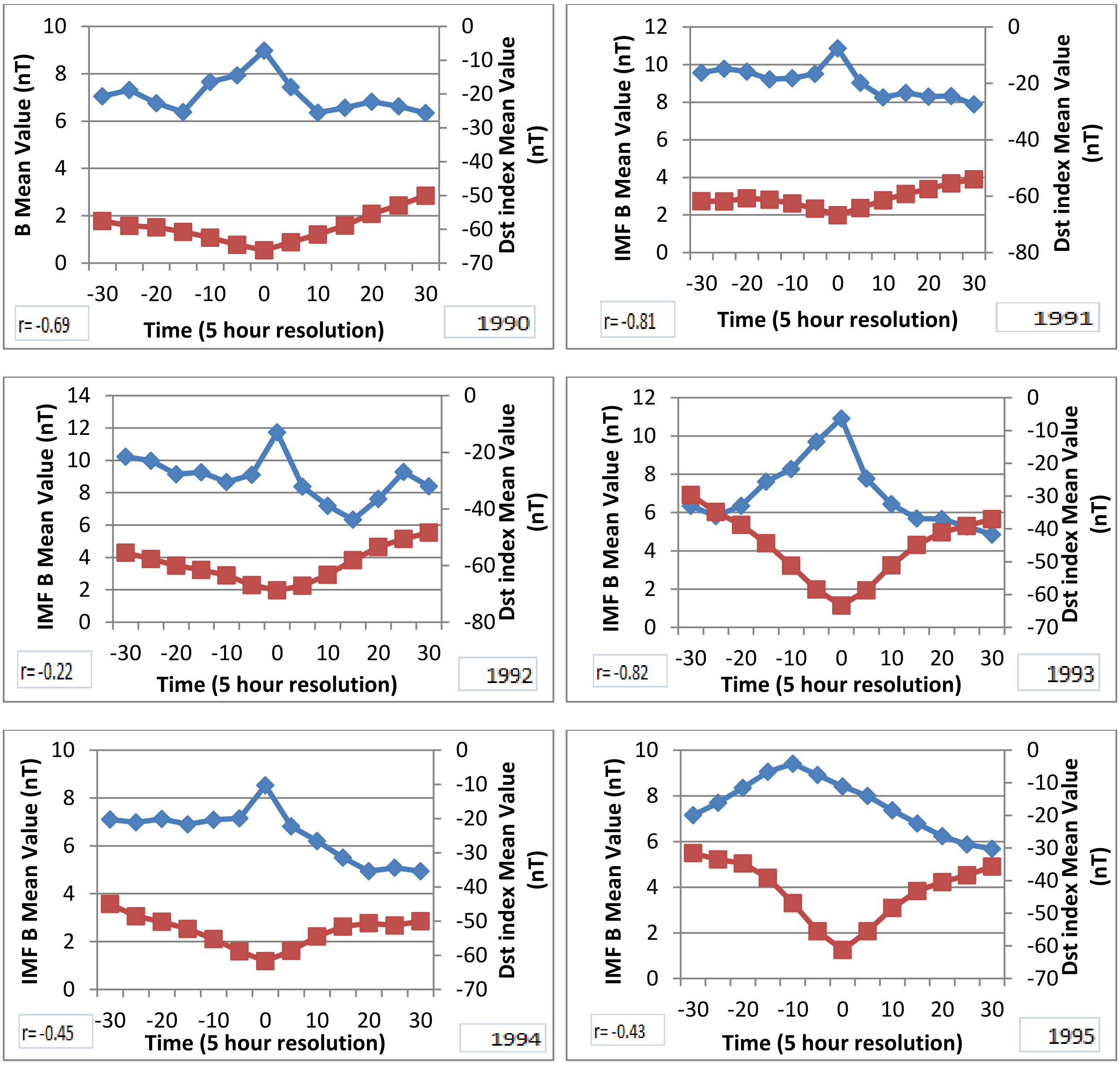
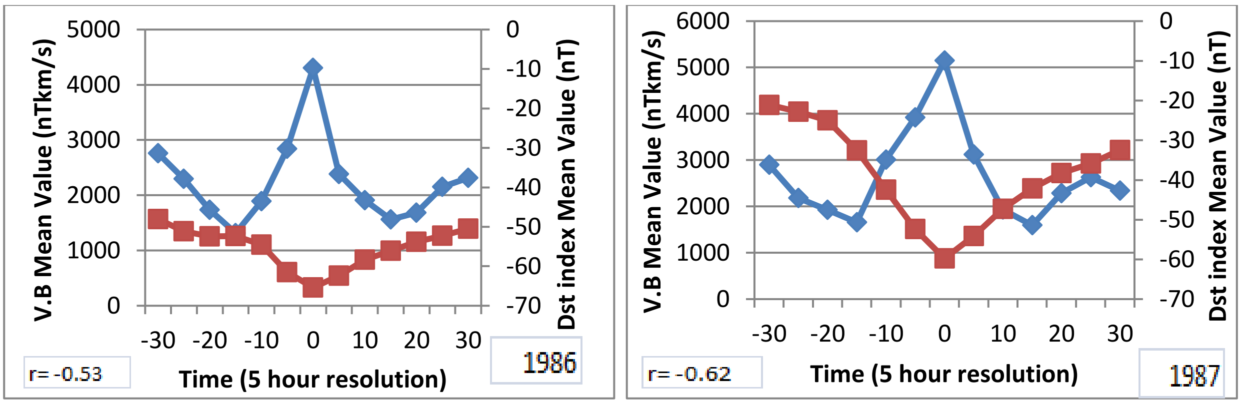


Fig 1: Chree analysis plot depicting the interplanetary magnetic field B and dst index mean value from -30 to +30 hours with respect to zero epoch days.



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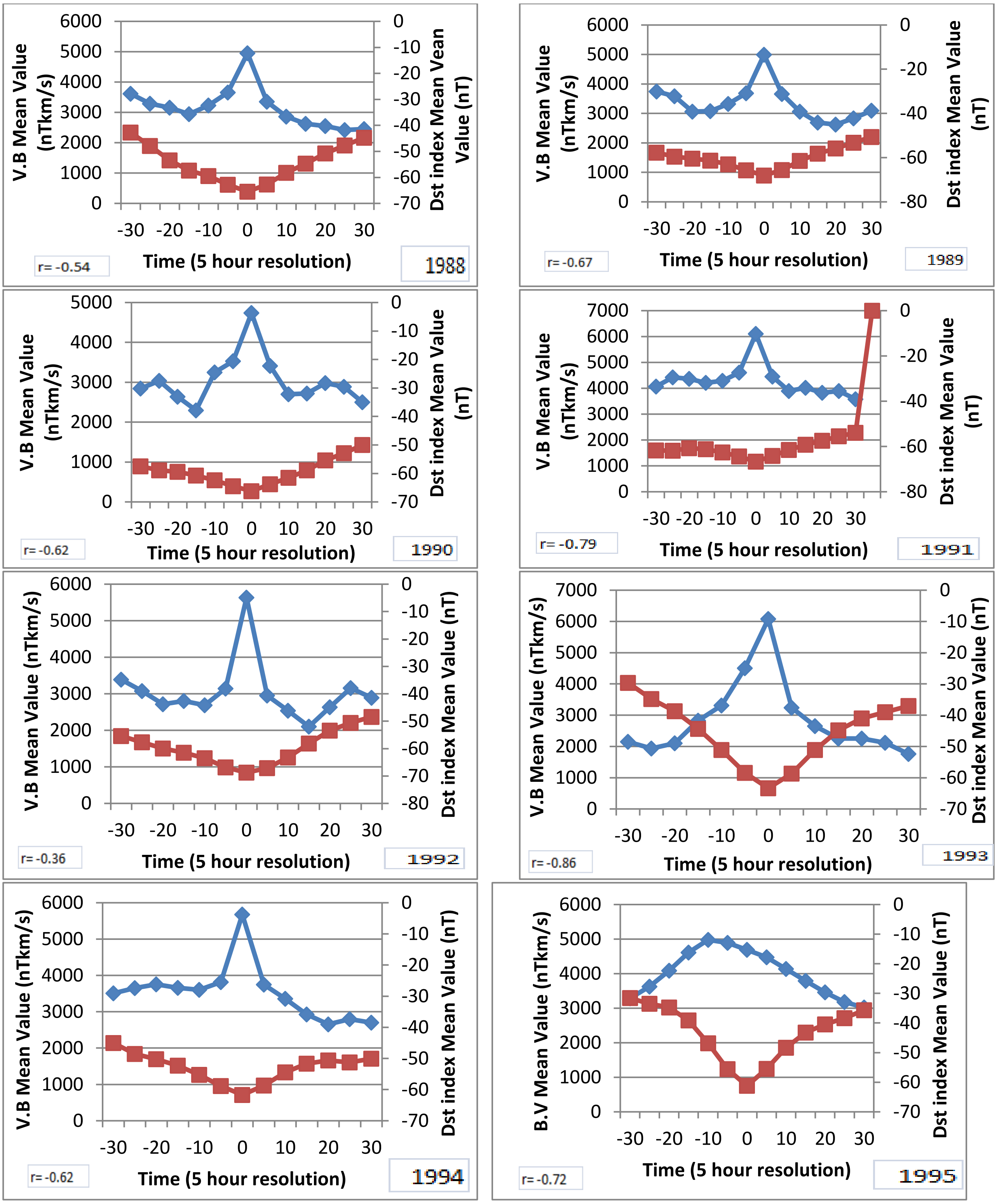

Fig 2: Chree analysis plot depicting the interplanetary product function V.B and dst index mean value from -30 to +30 hours with respect to zero epoch days.

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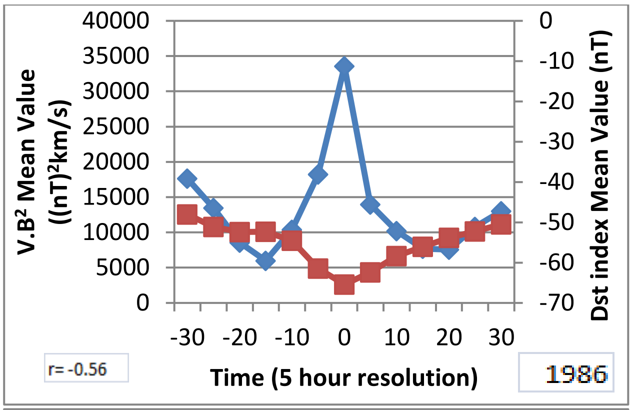

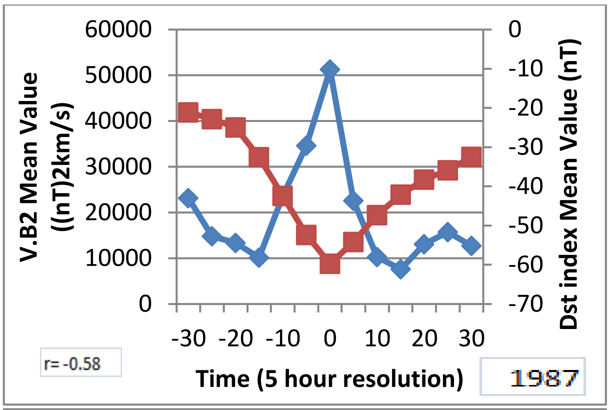

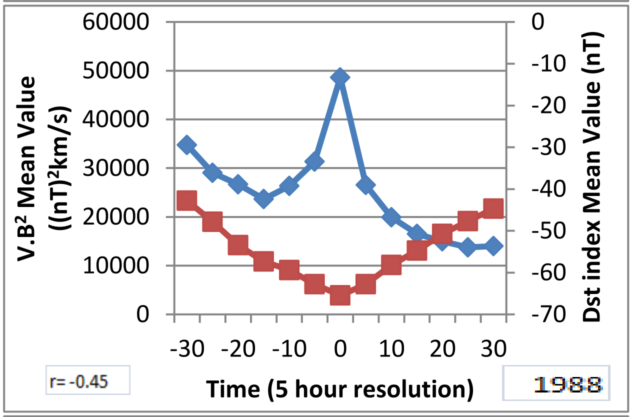

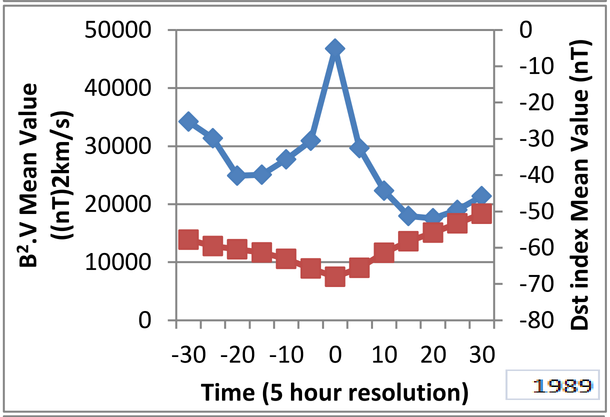

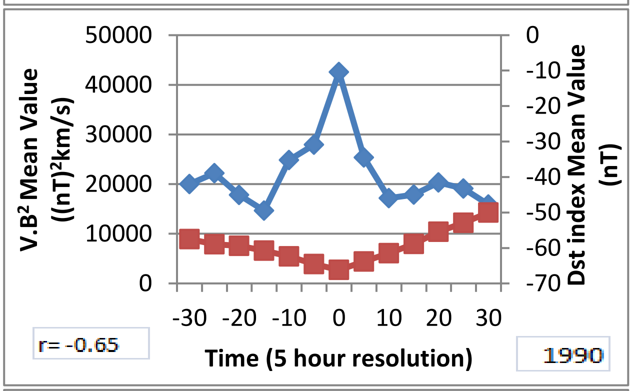

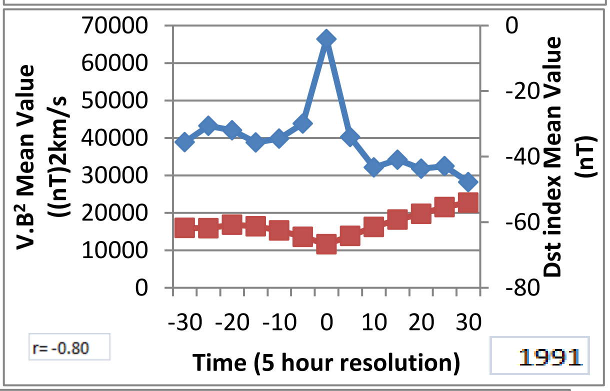

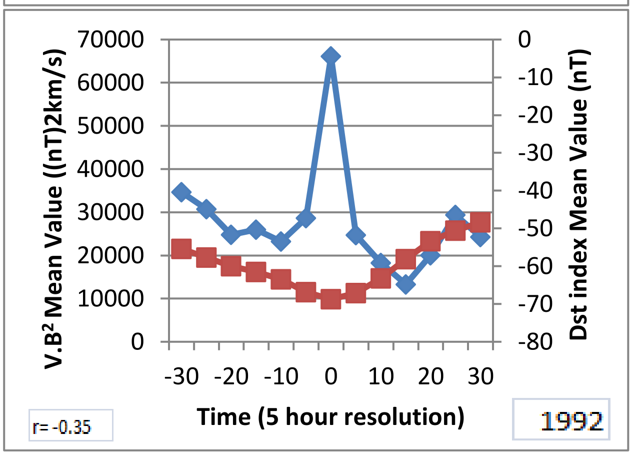

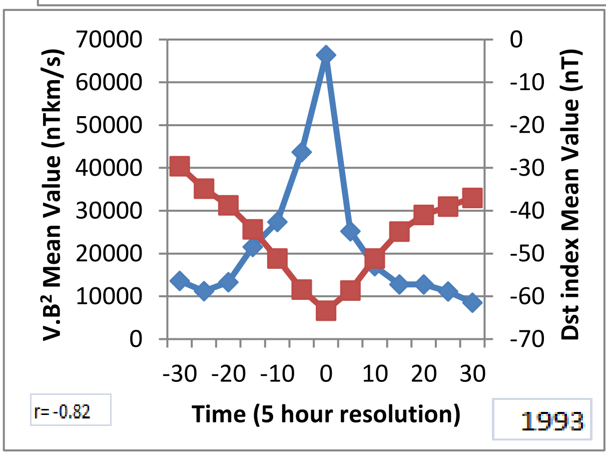

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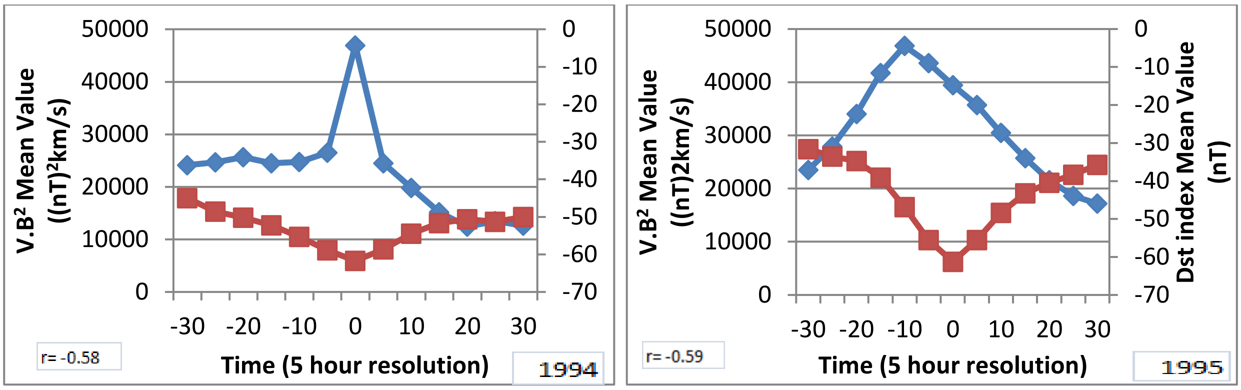
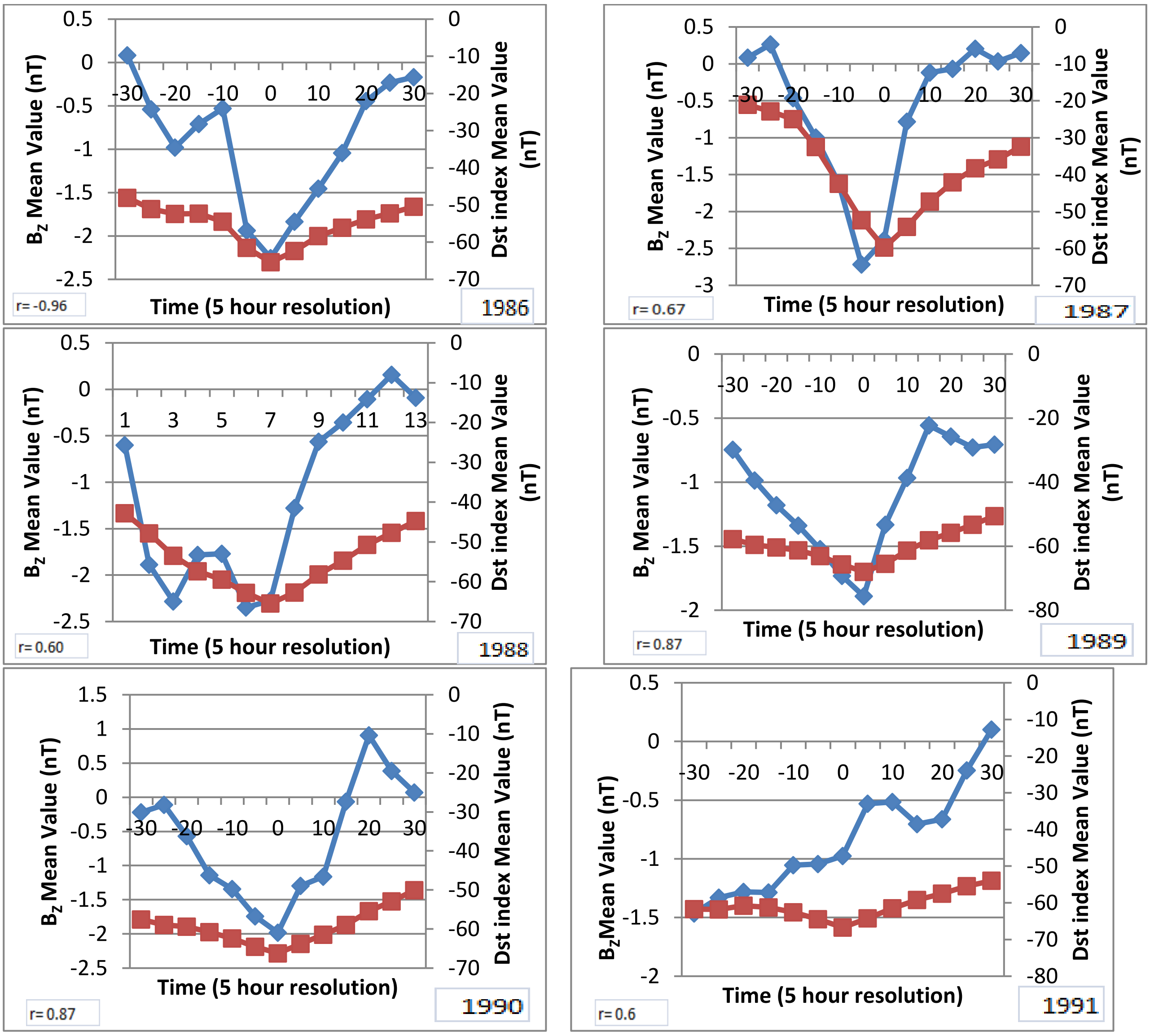


Fig 3: Chree analysis plots depicting the interplanetary product function V.B² and dst index mean value from -30 to +30 hours with respect to zero epoch days.



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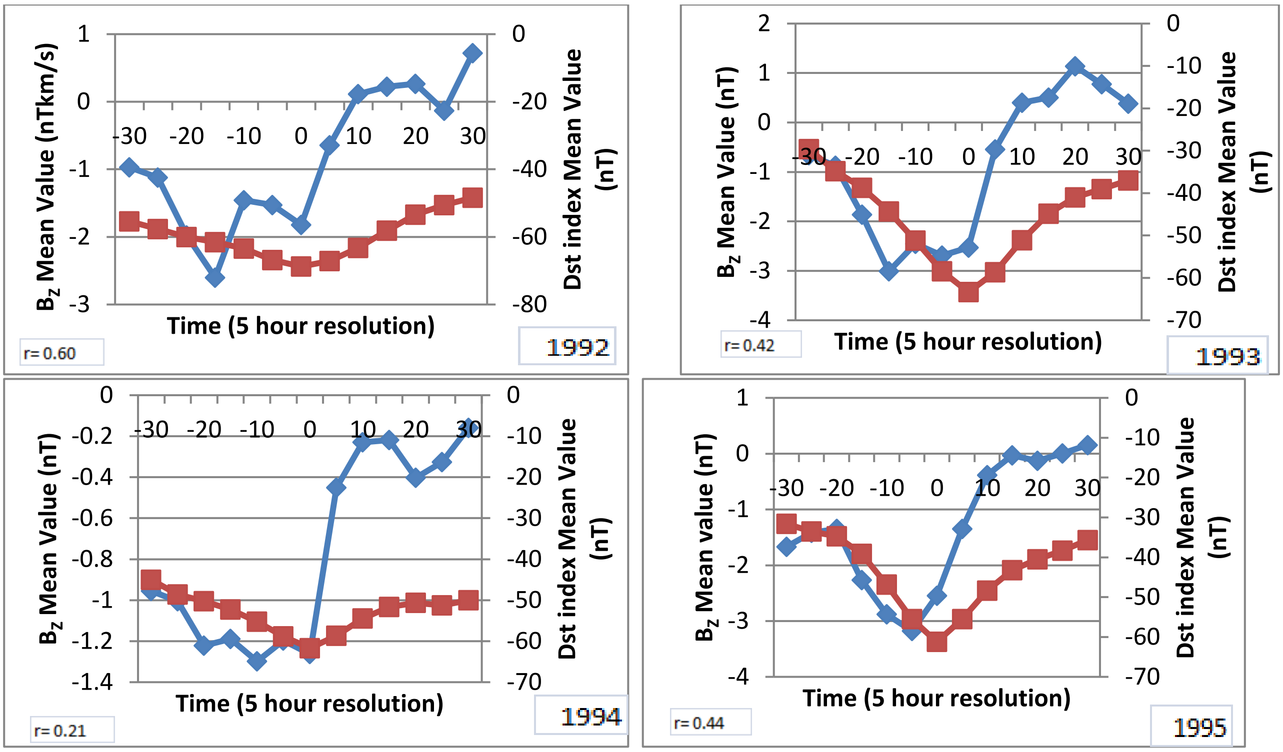
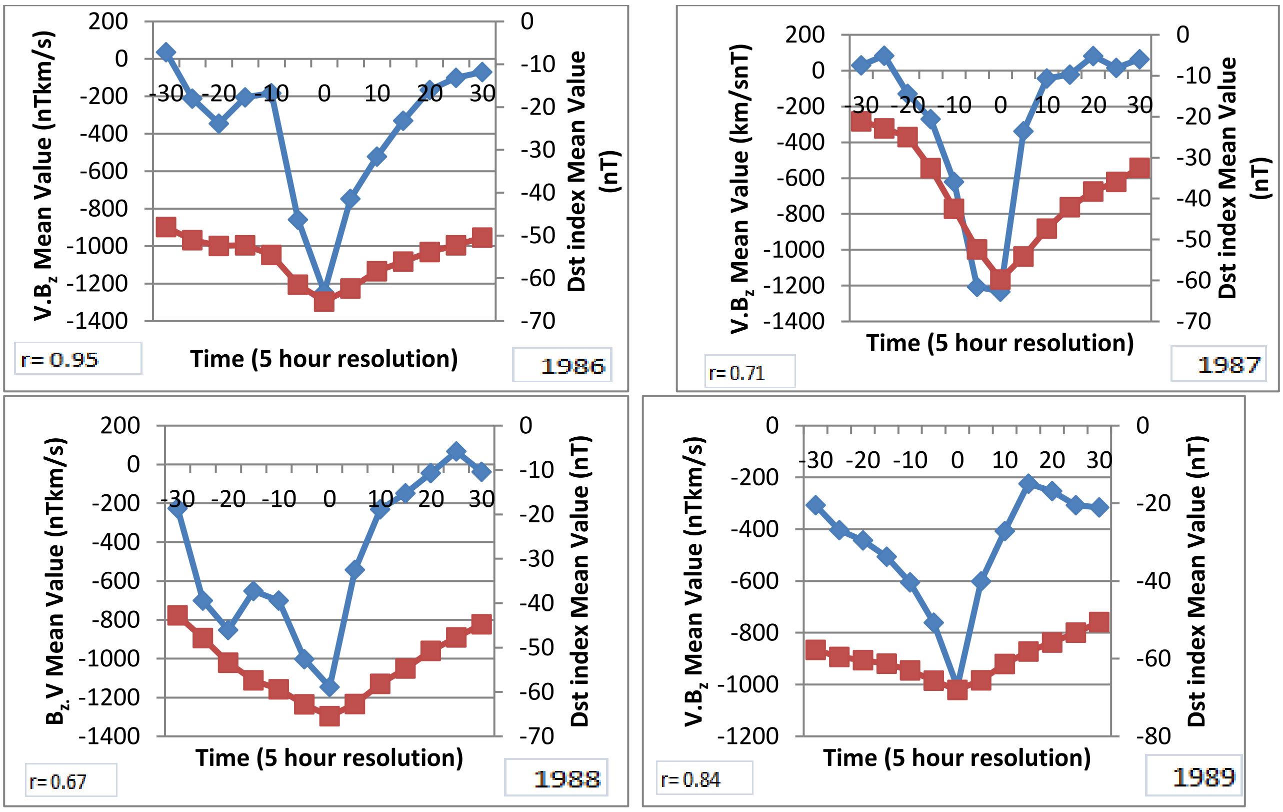


Fig 4: Chree analysis plots depicting the southward directed interplanetary magnetic field B_Z and dst index mean value from -30 to +30 hours with respect to zero epoch days.



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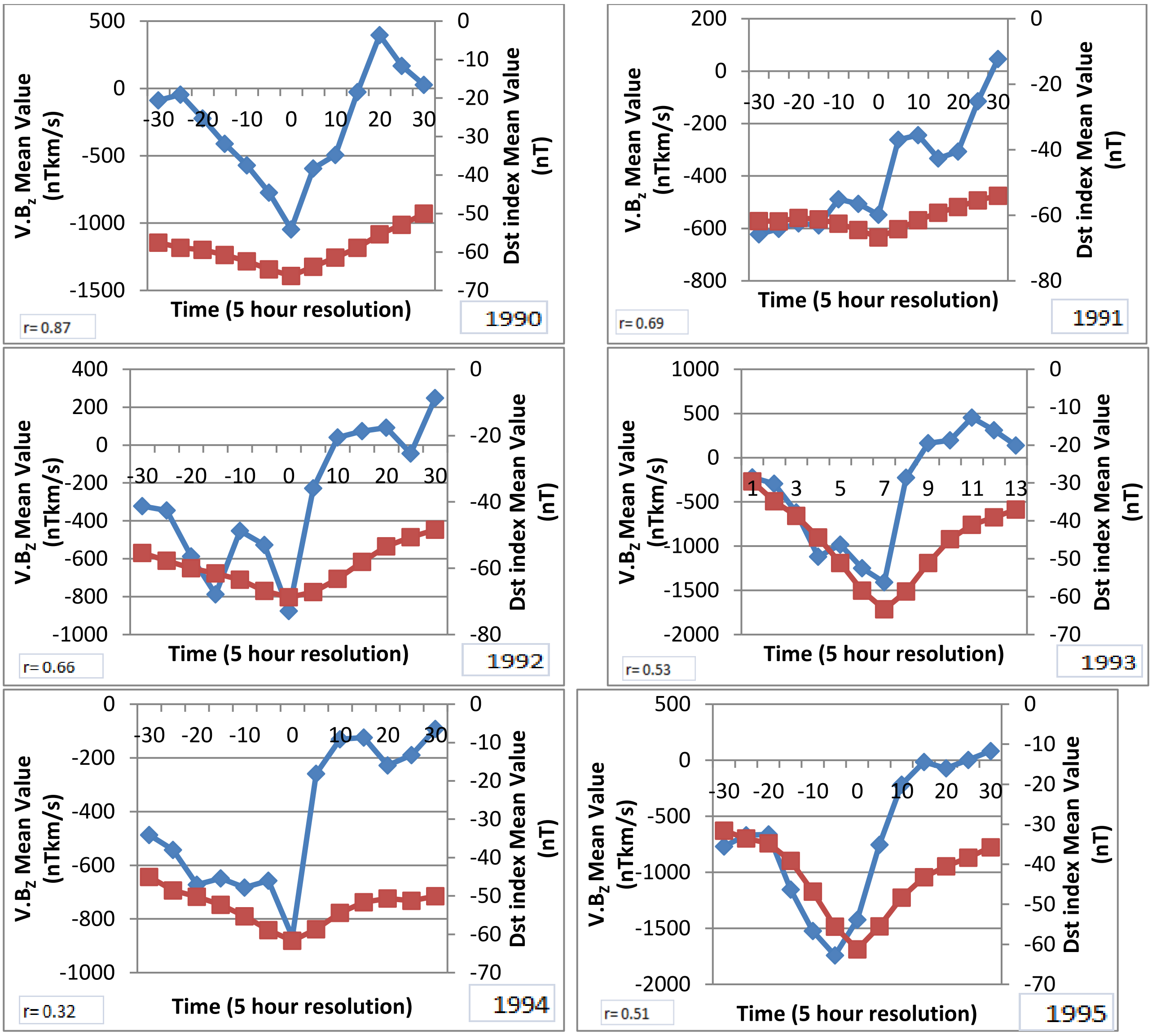
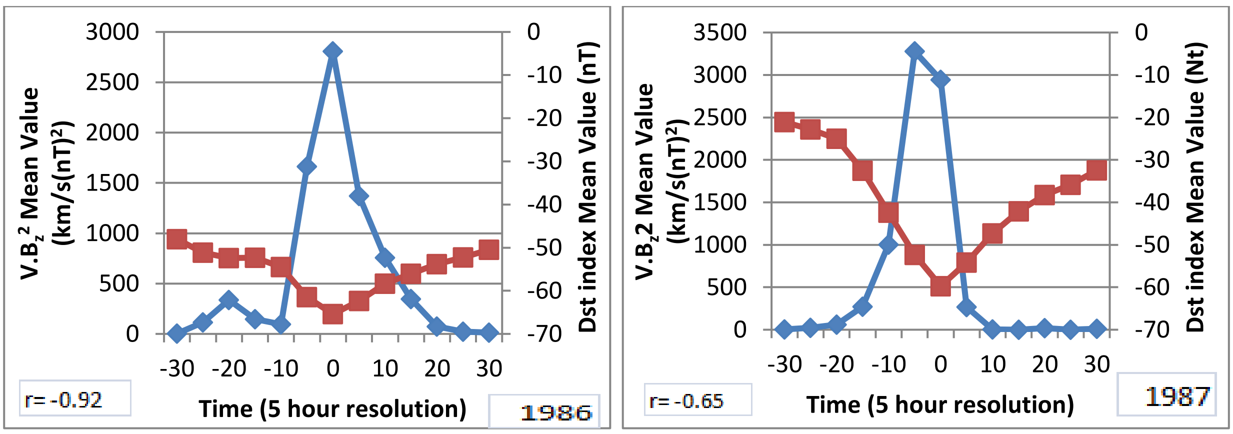


Fig 5: Chree analysis plots depicting the interplanetary product function V.B_Z and dst index mean value from -30 to +30 hours with respect to zero epoch days.



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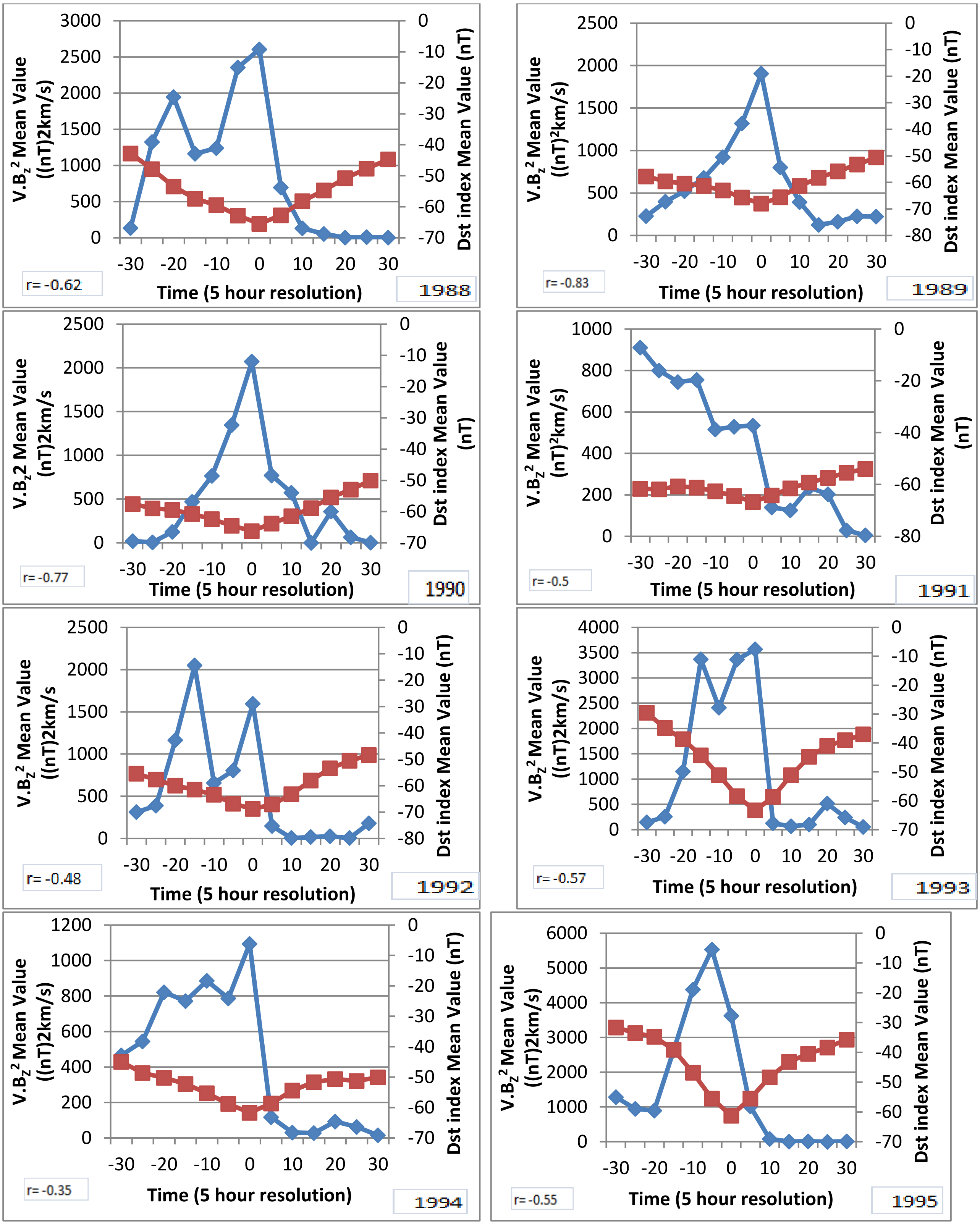

Fig 6: Chree analysis plots depicting the interplanetary product functionV.B_z^2 anddst index mean value from -30 to +30 hours with respect to zero epoch days.

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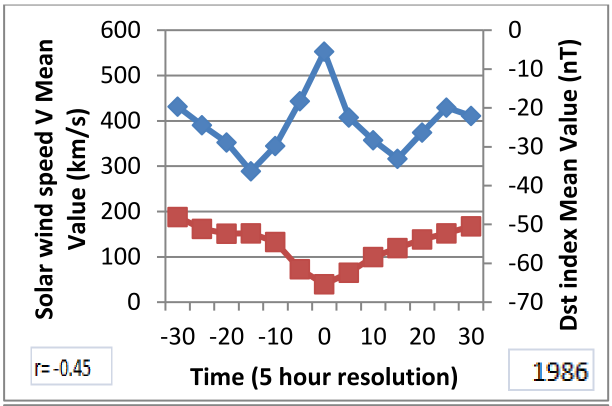

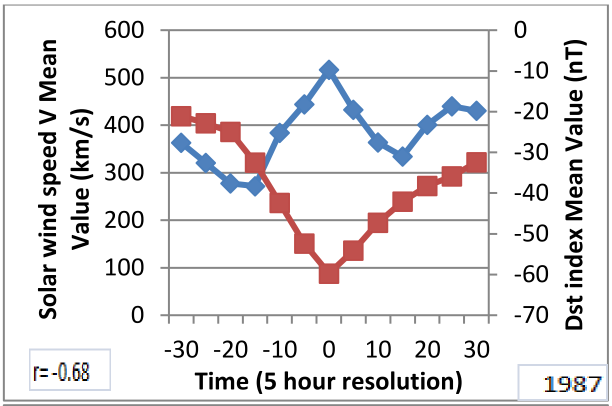

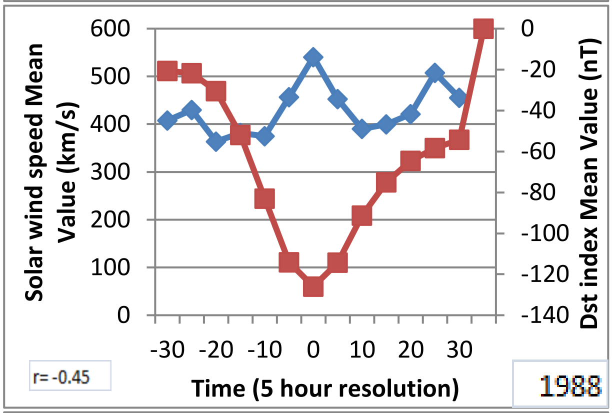

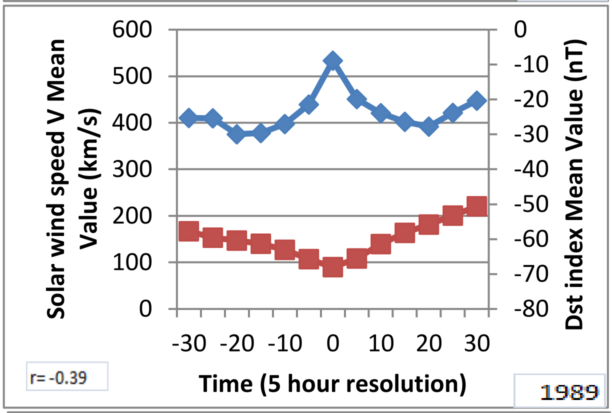

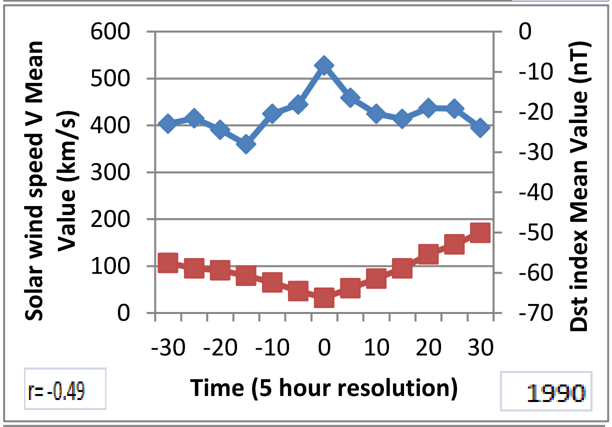

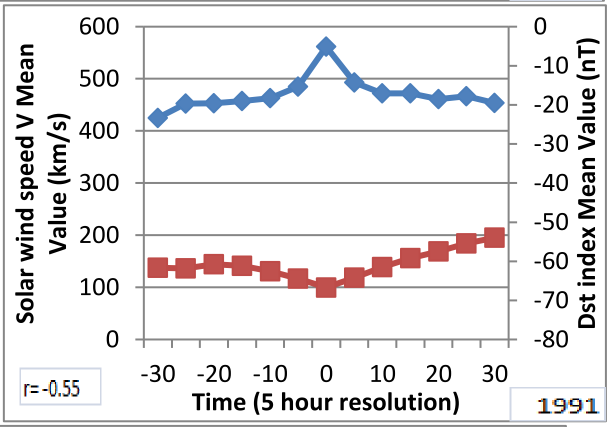

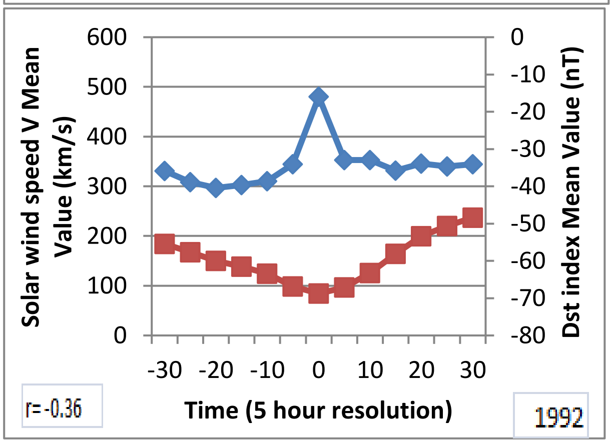

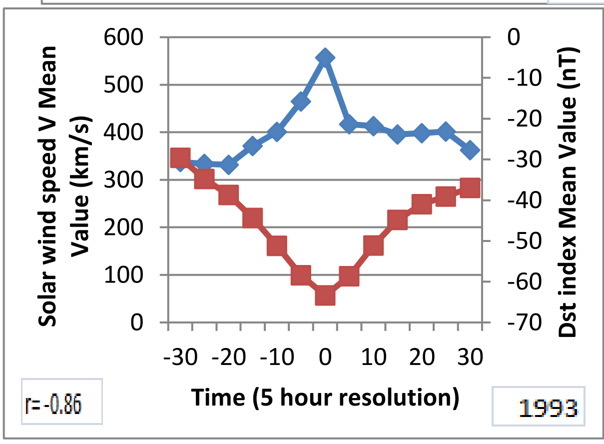

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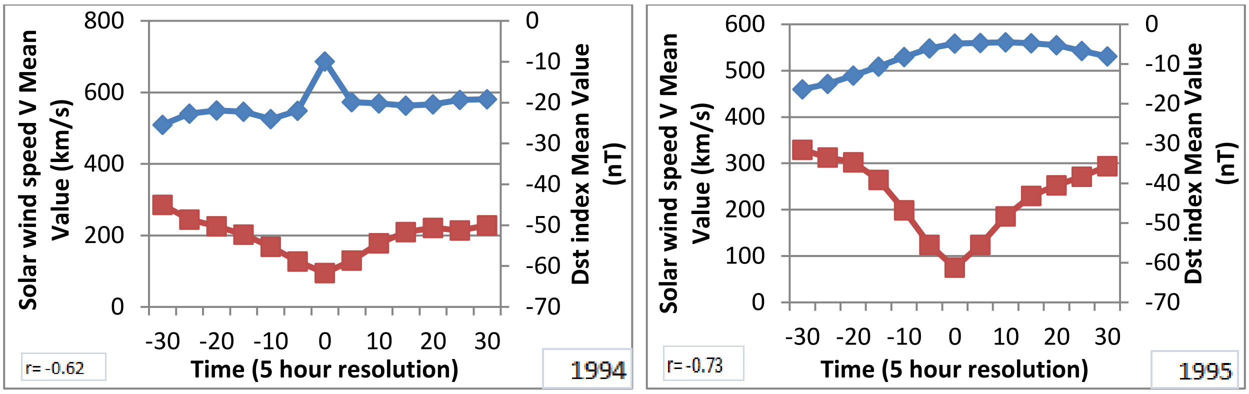
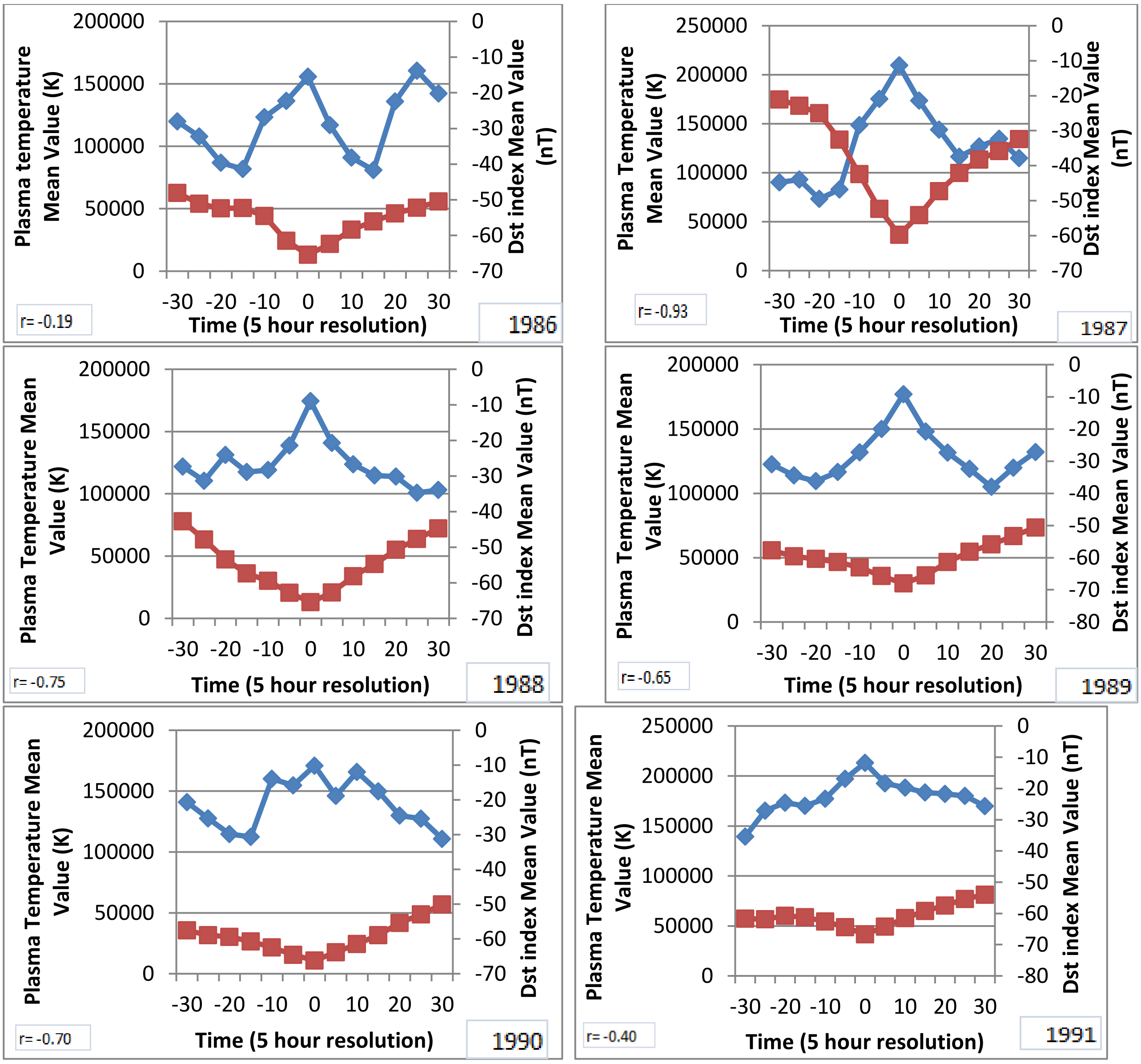


Fig 7: Chree analysis plots depicting the solar wind speed and dst index mean value from -30 to +30 hours with respect to zero epoch days.



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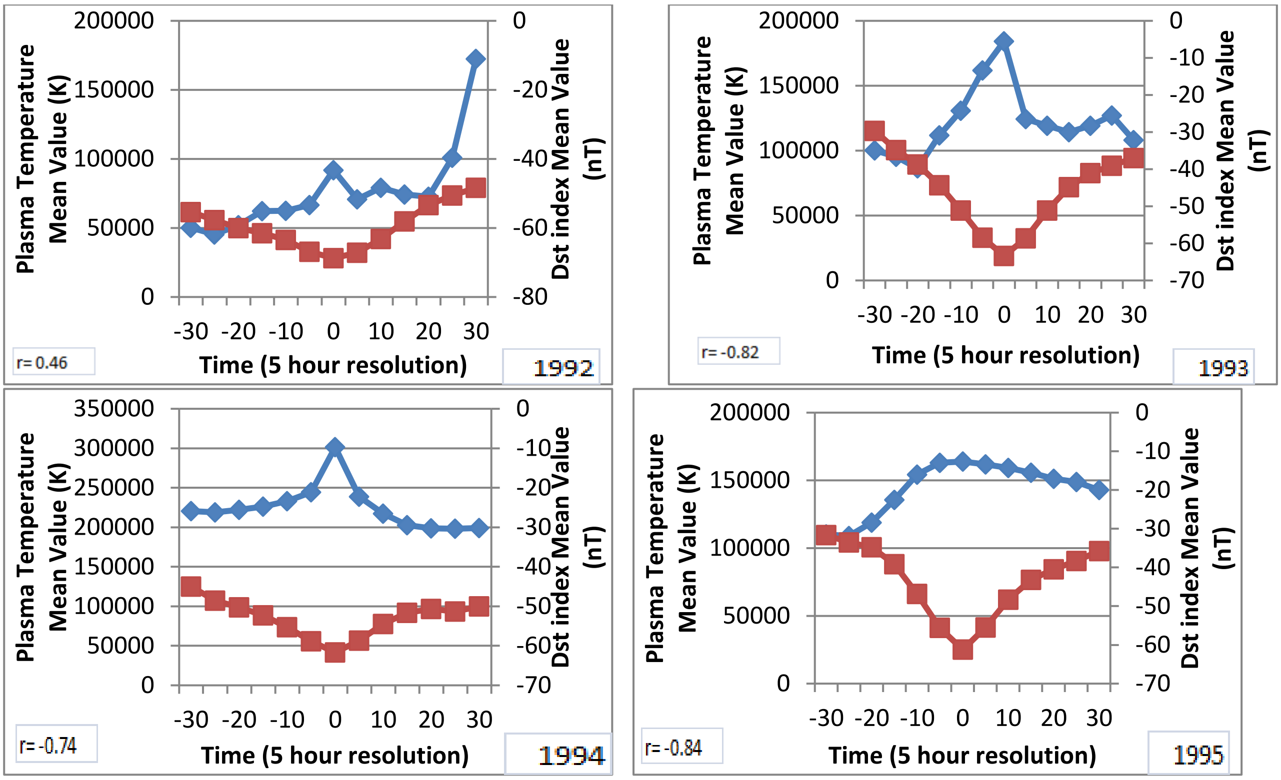
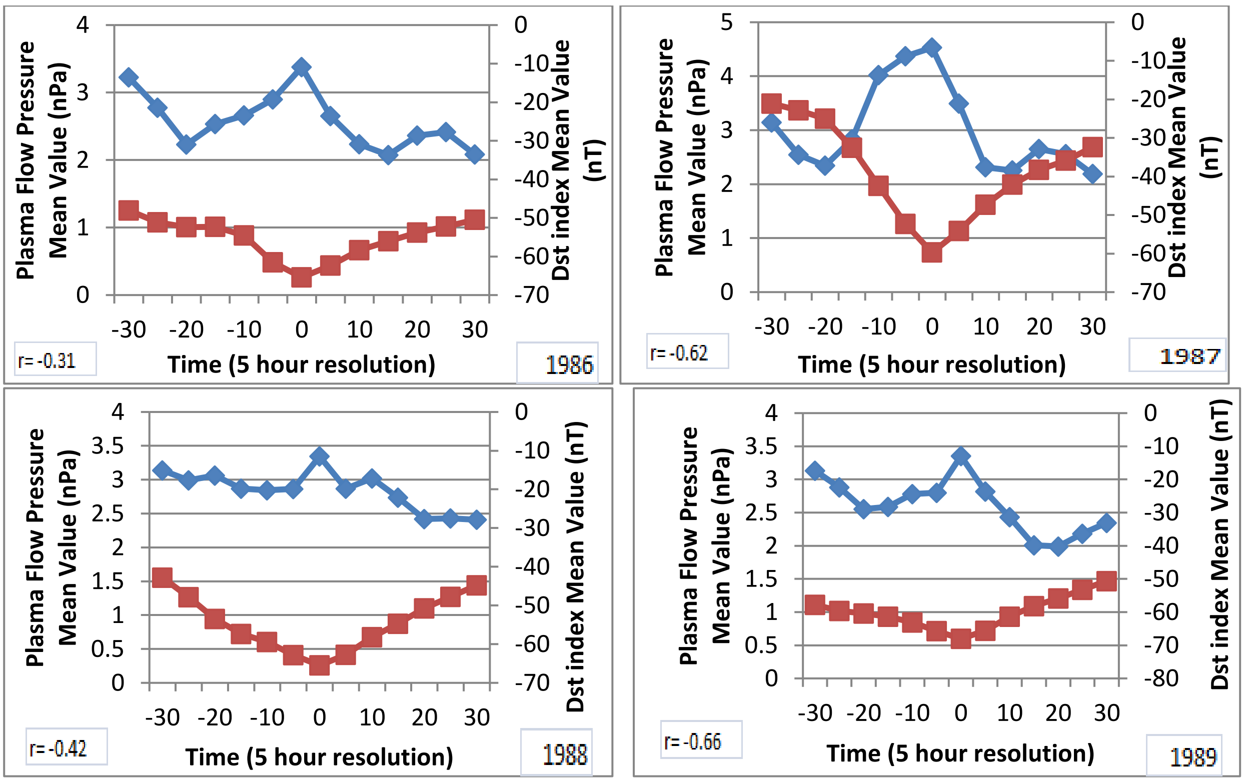


Fig 8: Chree analysis plots depicting plasma proton temperature and dst index mean value from -30 to +30 hours with respect to zero epoch days.



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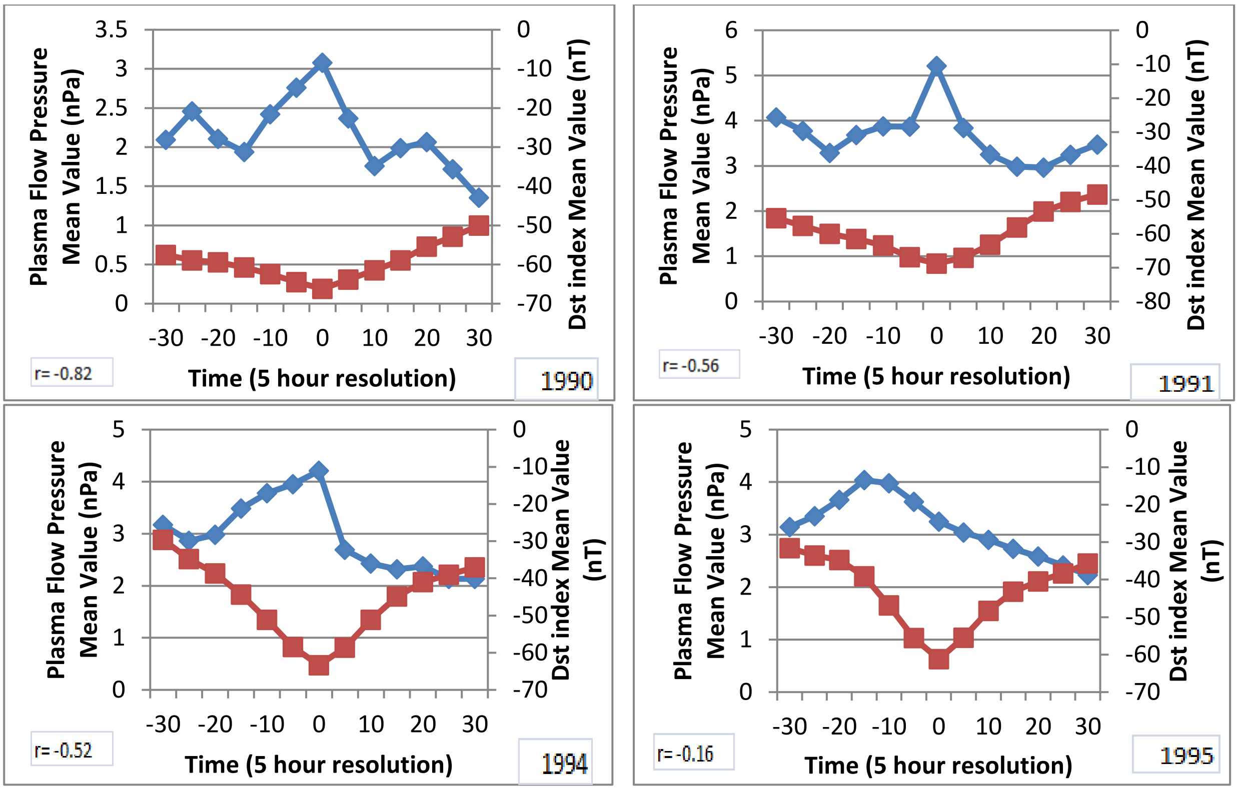

Fig 9: Chree analysis plots depicting plasma flow pressure and dst index mean value from -30 to +30 hours with respect to zero epoch days.

Parameters	Rising phase (1986-1989)		Maximum phase (1990-1992)		Decay phase (1993-1995)		Total period (1986-1995)	
	Dst	Kp	Dst	Kp	Dst	Kp	Dst	Kp
B (nT)	-0.47	0.66	-0.57	0.68	-0.57	0.83	-0.54	0.72
V (km/s)	-0.49	0.27	-0.47	0.13	-0.74	0.38	-0.56	0.30
V.B (nTkm/s)	-0.59	0.60	-0.59	0.48	-0.73	0.82	-0.64	0.63
$V.B^2$ $((nT)^2 km/s)$	-0.57	0.63	-0.6	0.53	-0.66	0.81	-0.61	0.66
B_Z(nT)	0.78	-0.86	0.69	-0.86	0.36	-0.80	0.63	-0.84
$V.B_Z$ (nTkm/s)	0.79	-0.84	0.74	-0.85	0.45	-0.83	0.68	-0.84
$V.B_Z^2$ $((nT)^2 km/s)$	-0.76	0.78	-0.59	0.71	-0.49	0.81	-0.61	0.77
T (K)	-0.63	0.49	-0.21	-0.01	-0.80	0.64	-0.56	0.38
P (nPa)	-0.50	0.69	-0.69	0.71	-0.34	0.79	-0.51	0.72

Table 1: Correlation coefficient between various parameters during the different phases of solar cycle 22.

4. CONCLUSIONS

After the detailed analysis of our study, various conclusions have been observed and are discussed. In the present paper, we used the hourly mean averages of various solar wind parameters (such as solar wind speed, plasma proton temperature, plasma proton density, and plasma flow pressure) and interplanetary parameters (IMF B and IMF Bz) for solar cycle 22 to construct their association with moderate geomagnetic storms by the incorporation of the analysis technique of superposed epoch method. We have observed that the interplanetary product functions are found to be highly correlated with kp index as compared to the Dst index during the various phases of solar cycle 22. The interplanetary product function V.Bz is found to be highly correlated with kp index (r= -0.85) during the maximum phase while the product functions such as V.B, $V.B^2$, $V.Bz^2$ are found to be highly correlated (r= 0.82 for V.B, r= 0.81 for $V.B^2$, and 0.81 for $V.Bz^2$) with kp index during the decay phase. The highest correlation coefficient between solar wind parameters and kp index are found to be -0.74 for solar wind speed and -0.80 for plasma proton temperature during the decay phase of solar cycle 22. Similarly, the highest correlation coefficient between interplanetary parameters and the kp index are found to be 0.83 for IMF B during the decay phase and -0.8 for IMF Bz during the maximum phase. The correlations, we obtained in our study indicates that solar wind parameters (such as solar wind speed V, plasma temperature T, and plasma flow pressure P), interplanetary parameters (IMF B and IMF Bz), and their product functions (such as V.B, $V.B^2$, $V.B_z$ and $V.Bz^2$) are the crucial parameters in determining the strength of geomagnetic storms. We have also performed the time delay analysis by the method of correlation coefficient between the different parameters and observed a time delay of 0 hour between the extreme value of solar wind parameters (such as solar wind speed, plasma proton temperature) and the least value of dst index while a time delay of 15 hour is observed between the extreme value of plasma flow pressure and the least value of the dst index. Similarly, a time delay of 10 hour is observed between the extreme values of IMF B, product functions (such as V.B, $V.B^2$) and the least value of the dst index. A time delay of more than 20 hours is also observed between the two different parameters, showing the irregular variations. The presence of time delay can give us an idea of the mechanism operating in the energy transfer.

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