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On the slow-time geomagnetic field modulation of cosmic rays

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In this work, monthly means of cosmic ray count rates from two mid latitude (Hermanus and Rome), and two higher latitude (Inuvik and Oulu) neutron monitors (NM) were employed and their variability was compared with geomagnetic stations that are in close proximity to the NMs. The data spans 1966 to 2008 and covers four solar cycles. The difference (CRdiff) between the mean count rate of all days and the mean of the five quietest days for each month was compared with the Dst-related disturbance (Hdiff) derived from the nearby geomagnetic stations. Zeroth- and First-correlation between the cosmic ray parameters and geomagnetic parameters was performed to ascertain statistical association and test for spurious association. The present results show that solar activity is generally strongly correlated (>0.75) with mean strength of GCR count rate and geomagnetic field during individual solar cycles. The correlation between mean strength of cosmic ray intensity and geomagnetic field strength is spurious and is basically moderated by the solar activity. The signature of convection driven disturbances at high latitude geomagnetic stations was evident during the declining phase of the solar cycles close to the solar minimums. The absence of this feature in the slow-time varying cosmic ray count rates in all stations and in the mid latitude geomagnetic stations suggests that the local geomagnetic disturbance do not play a significant role in modulating the cosmic ray flux.

Key words: Geomagnetic field variability, solar activity, galactic cosmic rays, cosmic ray modulation.

INTRODUCTION

Galactic cosmic rays are modulated by both the heliosphere and magnetospheres of planets. The modulation of these cosmic rays both in the heliosphere and magnetosphere have been long studied by many authors and some consensus on the mode of transportation have been established. The most basic approximation is that the cosmic ray diffuse through the turbulent magnetic field with a diffusion coefficient κ determined by the magnetic fluctuation. The mean

freepath for scattering along and perpendicular to the IMF spiral B similar to plasma description is characterizing the motion of CR particles. For the simplified picture in which just the one dimensional radial diffusion against the outward convective motion is assumed and the resulting flux through the surface unit are balanced, the diffusion coefficient is the function of energy, distance and time (Longair, 2004). Propagation of GCRs in the heliosphere is well described by the Parker (1965) equation given

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by Equation 1:

$$\frac{\partial U}{\partial t} = \nabla \cdot (\kappa^s \nabla U - V_{sw} U - \langle V_d \rangle U) + \frac{1}{3} (\nabla \cdot V_{sw}) \frac{\partial}{\partial T} (\alpha T U) \quad (1)$$

where $U(T, r, t)$ is the CR number density per unit interval of the kinetic energy T ; V_{sw} is the solar wind speed, $\alpha = (T + 2T_r) / (T + T_r)$, where T_r is the particles rest energy, κ^s is the symmetric part of the diffusion tensor. Jokipii (2010) suggests that the physical process underlying the transportation of cosmic rays in the interstellar medium and the heliosphere are basically the same. These fluids are always turbulent and collisions with particles are very rare, so the motion of cosmic rays must be described statistically. During two consecutive minima, the CR profiles are different. For instance, the minima of 1975-1976 are different from the minima of 1987 (Figure 1). This observation is usually explained in terms of the change in the polarity of the sun. In 1987, the solar magnetic polarity was negative in the North (that is, pointing into the sun's northern hemisphere and emanating from the southern hemisphere), while for the minima of 1975-1976, it was positive in the north hemisphere of the sun (Kudela, 2009). During the period of negative polarity, the access of positively charged particles into the inner heliosphere is through the equatorial heliosphere, while during the positive polarity, it is through the polar regions. Since particles arriving through the heliospheric equator are more susceptible to latitudinal changes associated with variations in the tilt angle of the neutral current sheet, the CR peaks around such minima will be sharper (Kudela, 2009). In addition, the heliosphere is usually magnetically quieter during solar minimum when compared with solar maximum. However, it has been observed that near a solar minimum, the heliosphere is not quite symmetrical being disturbed in the declining phase of the solar cycle by corotating interaction regions (CIR) (Echer and Svalgaard, 2004).

Coronal mass ejections (CMEs) are currently identified as the responsible agent for short term galactic cosmic ray flux drop. A CME is a massive eruption of solar plasma wind and magnetic field from the sun into space. Following a CME event, there is a rapid decrease in low energy (below 15 GeV) galactic cosmic ray flux caused by sweeping some of the GCR particles away from the earth by the solar plasma wind and its magnetic fields. Pauris (2013) showed that non-narrow CME (that is CMEs with width $> 30^\circ$) had a much better correlation when compared with all wide angle CMEs. Firoz et al. (2010) investigated the variability and the relationship of CR intensity with solar interplanetary and geophysical parameters during solar maxima and minima using data for 1982-2008. They observed that the stronger the interplanetary magnetic field, solar wind, plasma velocity, and solar wind plasma temperature the weaker the cosmic ray intensity. During periods of $qA < 0$ 1960-1970

and 1980-1990, when the solar field polarity is reversed, cosmic rays (positively charges) approach the sun along the heliospheric current sheet (HCS) while during $qA > 0$, 1971-1980 and 1990-2000, it might be expected that incoming cosmic rays will be less affected by drift effects associated with an increase in the tilt angle at the beginning of a solar cycle or by diffusion associated with enhanced coronal mass ejection (CME) activity (Gupta et al., 2006). Mishra and Mishra (2007) showed that sunspot numbers and coronal index showed better correlation with cosmic ray intensity during negative polarity than positive polarity of the solar magnetic cycle. Okpala et al. (2015), analyzed the effect of some solar wind components on the count rates under different interplanetary magnetic field (IMF) disturbance levels and observed different roles for dynamic pressure and B_z component of IMF.

The variability of conditions in space including the geosphere makes it difficult to accurately predict their influence on galactic cosmic rays. The geomagnetic field modulation of GCR is usually described by the rigidity cutoff. The cutoff rigidity at any geographic location is a function of the zenith and azimuth angles of arrival, the altitude of the detection location, and the geomagnetic conditions at the time of measurement. Usually, it was found to be sufficient to use the cutoff rigidity that were determined for vertically incident particles using the trajectory-tracing method using the international geomagnetic reference frame (IGRF) and by taking secular variations into account. By approximating the geomagnetic field to be a dipole, the cutoff rigidity can be expressed by the Störmer's cutoff formula:

$$R_c = \frac{M \cos^4 \lambda}{r^2 (1 + (1 - \cos^3 \lambda \cos \epsilon \sin \eta)^2)^{\frac{1}{2}}} \quad (2)$$

where M is the dipole moment, r is the distance from the dipole centre, λ is the geomagnetic latitude, ϵ is the azimuthal angle measured clockwise from the geomagnetic east direction (for positive particles), and η is the angle from the local magnetic zenith direction (Cooke et al., 1991). Clem et al. (1997) proposed a parameter they termed "apparent" cut off rigidity which is intended to improve upon the vertical cutoff rigidity by including the effects of obliquely incident particles. The ability to predict times of greater galactic cosmic rays (GCR) fluxes is important for reducing hazards caused by these particles to satellites communications, aviation or astronauts (Thomas et al., 2013). The earth's magnetosphere is bombarded by nearly isotropic flux of cosmic rays. The penetration of these very energetic charged particles into the solar system to the vicinity of the earth is influenced and modulated by the condition of the sun, during the active and quiet phases of the solar system. In addition, during the years of solar minimum, the sun is a recurrent source of lower energy particles.

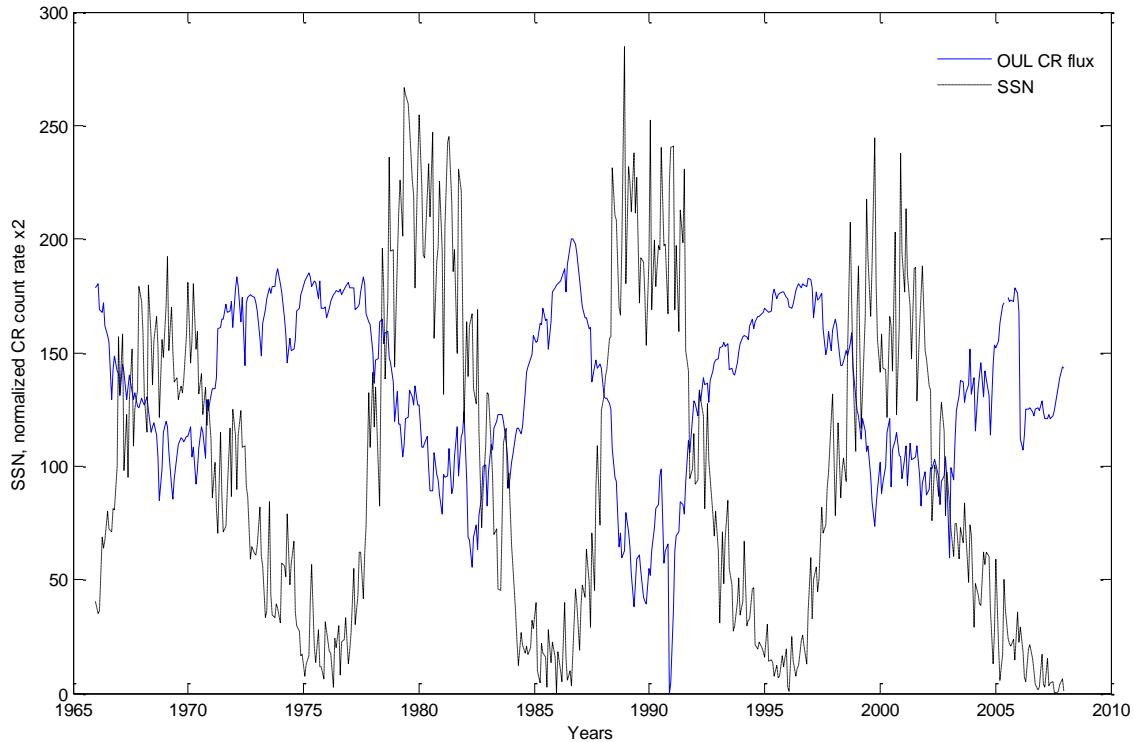


Figure 1. Solar activity modulation of OULU NM count rate.

These particles have varying degree of influence on spacecrafts and aircrafts (Mavromichalaki et al., 2007). Rapid and slow time changes of GCRs have been studied by many authors (Forbush, 1937, 1957; Cane, 2000; Richards, 2004; Firoz, 2008; Okpala and Okeke, 2011; Desorgher et al., 2013; Okpala, 2014). Forbush (1937) observed a world-wide decrease in GCR during a strong geomagnetic storm (Forbush decrease) giving the first evidence for a relationship between solar activity and GCRs. It is well known that there is an inverse relationship between Cosmic rays intensity (CRI) and sunspot number (SSN) is global; it is noted that CRI is much better negatively correlated with SSN during disturbed days than quietest days. Short term depression in galactic cosmic rays flux are either by corotating interaction regions (Richards, 2004) or coronal mass ejection or its shocks that they drive (Cane, 2000). Forbush (1957) was among the first to study the effect of the geomagnetic activity in slow time variability of cosmic rays. He observed that the variability of mean monthly CR intensity is less when the five most disturbed days are excluded. It was also observed that the exclusion of the mean of the quietest day from the mean of the disturbed day was predominantly negative and correlated between stations. It was then concluded that conducting solar streams (which give rise to magnetic storm) which carry “frozen-in” magnetic fields away from the sun during sunspot maximum may pervade the solar system to an

extent which would reduce the flux of cosmic rays arriving at the earth from outside the solar system. It is important to note that during geomagnetic storms, enhanced coupling between the heliospheric magnetic field and the earth’s magnetic field leads to a wide of magnetospheric disturbances which can be associated with the intensification of ring current (manifested by the reduction in the Dst index), enhance magnetic convection leading to the energization and precipitation of the high latitude plasma convection which drives the auroral currents.

Firoz (2008) found significant differences in the distribution of the interplanetary magnetic field and diurnal phase of cosmic ray and concluded that during disturbed days, immense geomagnetic disturbances occurred by the blow of the powerful interplanetary shock wave across the magnetosphere, and comparatively narrower distribution of the interplanetary total magnetic field and its polarity during quiet days indicates the quiet magnetosphere when shock wave is not powerful enough to distort the magnetic field lines across the magnetosphere. Okpala and Okeke (2011), found similar difference in the phase of the diurnal GCR flux for all days and quietest days for consecutive solar cycles. Papailiou et al. (2009), observed a significant correlation between CR activity level with heart rate variation such that heart rate variation seems to decrease during the declining phase of strong cosmic ray events such as FDs and increase during ascending phase of such events.

Table 1. Details of four neutron monitor stations used in this study.

S/N	Station name	Station code	Geographic latitude (°)	Geographic longitude (°)	Altitude (m)
1	Rome	ROM	41.9°N	12.5°E	60
2	Oulu	OUL	65.1°N	25.5°E	15
3	Inuvik	INV	68.4°N	133.7°W	21
4	Hermanus	HER	34.4°S	19.2°E	26

Table 2. Details of geomagnetic observatories used in this study.

S/N	Station name	Station code	Geographic latitude (°)	Geographic longitude (°)	Altitude (m)
1	L'Aquila	AQU	42.4°N	13.3°E	682
2	Sodankyla	SOD	67.4°N	26.6°E	178
3	College	CMO	64.9°N	147.9°W	197
4	Hermanus	HER	34.4°S	19.2°E	26

Studies have linked solar and geomagnetic conditions with a number of human health conditions and may be connected with diseases (Papailiou et al., 2009). The negative health implication of some cosmic ray phenomena (e.g ground level enhancement) for airplane crew members is well expected and has been reported by some authors (Matthia et al., 2009; Mishev et al., 2015), and most recently a simulation by Kataoka et al. (2015) has suggested that solar energetic particle events without ground level enhancements could even pose significant treats to humans travelling by air. Most recently, Frigo et al. (2018) investigated the effect of cosmic rays on climate.

They observed that temperature maxima were almost coincident with the maxima of the solar cycle years. Similarly, Campuzano et al. (2018) provided new clues on the existence of a link between the geomagnetic field and the earth's climate in the past and on the physical mechanism involved.

In order to compare different observational results of neutron monitors (NM) to GCR, the preference is to normalize the NM data to be compared in the same way because it is hard to compare absolute values of NM's count rate. Usoskin et al. (1999) suggested that for the study of long term variation of GCR, it is usual to use the monthly averaged observed count rate of a certain NM during May 1965 as the 100% reference level because May 1965 was considered to be the month of minimum solar modulation of CR.

MATERIALS AND METHODS

The geomagnetic field data was provided by the world data centre (WDC) for geomagnetism Kyoto, Japan, while the daily mean values of disturbance storm time index (Dst), was provided by OMNIWeb (<http://omniweb.gsfc.nasa.gov>). The geomagnetic data

constitutes H and Z components of geomagnetic field measurements from magnetograms at the specific stations. Some station data are given in X, Y, Z components and had to be converted to H component, since H (and Z-) component is of interest in this work. The data used in this work span about 4 solar cycles (1966-2008). The choice of the years is based on the common available data for the stations. Four (4) geomagnetic observatories (Hermanus, L'Aquila, Sodankyla, and College) were selected which were in close proximity to the neutron monitor stations (Hermanus, Rome, Oulu, and Inuvik, respectively) used in the study. The number of stations was constrained by availability of pairs of NM and geomagnetic stations in close proximity. Table 1 shows the details of the neutron monitor stations while Table 2 provides the details of the geomagnetic observatories used in this study.

For the long term cosmic ray variability from 1966-2010, mean monthly values of cosmic rays from 4 neutron monitor (NM) stations were used. For the purpose of this study, we have normalized the cosmic ray variability (using Equation 3) taking the cosmic ray intensity maximum (December 2008) to be 100 and the cosmic ray minimum (June, 1991) equal 0 using Equation 1. In addition to the CR intensity data, we also obtained the mean monthly geomagnetic field data (H and Z) for 4 stations in close proximity to the cosmic rays NM stations. Data for the worldwide disturbance storm time index (Dst) was also used as a proxy for global geomagnetic activity.

$$CR_{norm} = a + \frac{[(CR-C1) \times (b-a)]}{C2-C1} \quad (3a)$$

where $a=0$ and $b=100$ are the minimum and maximum limits of the normalization while $C1$ and $C2$ are the minimum and maximum values of the data. The Dst-related disturbance is the disturbance magnetic field which is obtained from individual stations after eliminating the non-storm component of the field at a specific station. The difference between the average cosmic rays $CR_{norm(all)}$ for all days during each month and the average of the quietest days ($CR_{norm(Sq)}$) is given by $CR_{norm(Sq)}$.

$$CR_{diff} = CR_{norm(all)} - CR_{norm(Sq)} \quad (3b)$$

The stations used in this study generally had few periods of data

Table 3. Zeroth and first order correlation coefficient for HERMANUS stations.

HER/HER H-Comp	CR _{sq} vs. GM _{sq}	Zeroth-order corr. Coef.			SSN vs CR _{diff}	SSN vs CR _{sq}	SSN vs GM _{sq}	First order coefficient (SSN)		
		CR _{all} vs GM _{all}	CR _{diff} vs H _{diff}	SSN vs ΔGM				CR _{sq} vs GM _{sq}	CR _{all} vs GM _{all}	CR _{diff} vs H _{diff}
All	0.180	0.181	0.300	-0.308	-0.137	-0.755	0.115	-0.410	0.171	0.274
Cycle 20	-0.810	-0.826	0.165	-0.137	-0.134	-0.823	0.922	-0.230	-0.260	0.149
Cycle 21	-0.660	-0.641	0.472	-0.196	-0.208	-0.685	0.825	-0.231	-0.182	0.450
Cycle 22	-0.894	-0.870	0.473	-0.449	-0.246	-0.926	0.925	-0.261	-0.172	0.419
Cycle 23	-0.849	-0.772	0.360	-0.421	0.024	-0.779	0.837	-0.236	-0.274	0.408

Table 4. Zeroth and first order correlation coefficient for OULU/SODANKYLA stations.

OUL/SOD H-Comp	CR _{sq} vs GM _{sq}	Zeroth-order corr. coeff.			SSN vs CR _{diff}	First-order coefficient (SSN)		
		CR _{all} vs GM _{all}	CR _{diff} vs H _{diff}	SSN vs H _{diff}		CR _{sq} vs GM _{sq}	CR _{all} vs GM _{all}	CR _{diff} vs H _{diff}
All	-0.228	-0.218	0.250	0.024	-0.064	-0.191	-0.238	0.252
Cycle 20	0.853	0.830	0.205	0.248	-0.049	-0.408	0.355	0.224
Cycle 21	-0.722	-0.679	0.347	0.117	-0.196	-0.438	-0.331	0.380
Cycle 22	-0.892	-0.822	0.386	-0.081	-0.137	-0.402	-0.183	0.379
Cycle 23	-0.661	-0.231	0.289	-0.094	0.153	-0.301	0.157	0.308

gaps. Missing hourly data (that is, isolated) was filled by linear interpolation. Days with continuous missing data were discarded. When calculating the monthly mean values for all days of a given month, we discarded months with greater than five days of continuously missing data, while for monthly quiet day mean, we discarded months with greater than 2 days of missing quietest days to reduce sampling errors.

Forbush and Beach (1967) first introduced the concept that departures of the quiet day (H-component of) geomagnetic field ($H_{RC}(Q)$) from the disturbed day field ($H_{RC}(D)$) maintain a fixed ratio to each other throughout the solar cycle such that:

$$k * H_{RC}(D - Q) = \frac{k}{1-k} (H_{RC}(D) - H_{RC}(Q)) \quad (4)$$

Thus by equating $H_{RC}(D)$ - $H_{RC}(Q)$ with $H(D-Q)$, the absolute ring current field can be estimated from observatory data, once an appropriate value for k is found. Furthermore, it was suggested that k is a universal constant. This implies that the geometry of the ring current field is the same throughout the solar cycle and the same on quiet days and disturbed days. The difference measures the absolute strength of the ring current and defines the mean monthly Dst related disturbance. In the present study, we apply Equation 4 and computed monthly mean for all days to reflect mean strength of the ring current for the particular month. The slow time local geomagnetic field disturbance index or slow mode disturbance for H and Z components denoted by H_{diff} and Z_{diff} , respectively and was obtained as the difference between the monthly mean from all days (H_{all} and Z_{all}) and from the monthly mean of the international quietest days of each month (H_{sq} and Z_{sq}) and given by Equation 5a and 5b, respectively:

$$H_{diff} = H_{all} - H_{sq} \quad (5a)$$

$$Z_{diff} = Z_{all} - Z_{sq} \quad (5b)$$

H_{diff} and Z_{diff} represent the mean strength of the net external contribution to the magnetic field strength for a particular station

after removing the non-storm component of the field at the specific station. To understand the statistical association between the parameters, we performed Pearson correlation on pairs of cosmic ray slow-time varying parameters and geomagnetic parameters as detailed in Tables 3 to 10. Probable error for each value of correlation has been calculated by the formula:

$$e = 0.6745(1 - r^2)/\sqrt{N}$$

after Gupta et al. (2006) where r is the correlation coefficient and N is the size of sample. To mitigate the effect of spurious correlation coefficients, we applied a first order correlation with the assumption that the association between geomagnetic and cosmic ray intensity variation is moderated by solar activity represented by the sunspot number index. For the solar cycle analysis, the years flanking the solar minimums were excluded to avoid contamination associated with change in polarity.

RESULTS AND DISCUSSION

Figure 1 shows the monthly variation of neutron monitor (NM) count rates for Oulu with the international sunspot number (SSN). The time series shows how neutron monitors count rates vary with solar activity from 1966-2008. The profile in Figure 1 is very similar to the time series for other stations (not shown). Sunspot cycle is a well-known proxy for solar activity. All the solar features associated with solar activity are directly or indirectly connected with sunspots.

It can be seen clearly (from Figure 1) that the Oulu NM count rate exhibited the 11-year variation which can be easily associated with the 11 year solar cycle. This feature is well known and establishes that SSN are likely

Table 5. Zeroth and first order correlation coefficient for INUVIK/COLLEGE stations (H-component).

INV/CMO H-Comp	CR _{sq} vs GM _{sq}	Zeroth –order corr. coeff.			SSN vs CR _{diff}	First-order coefficient (SSN)		
		CR _{all} vs GM _{all}	CR _{diff} vs H _{diff}	SSN vs H _{diff}		CR _{sq} vs GM _{sq}	CR _{all} vs GM _{all}	CR _{diff} vs H _{diff}
All	0.231	0.233	0.188	0.034	-0.104	-0.307	0.231	0.193
Cycle 20	0.868	0.861	0.067	0.317	-0.051	-0.475	0.479	0.087
Cycle 21	-0.710	-0.624	0.204	0.026	-0.185	-0.369	-0.176	0.213
Cycle 22	-0.876	-0.730	0.377	-0.069	-0.174	-0.286	-0.079	0.372
Cycle 23	-0.877	0.245	0.319	0.359	0.022	-0.573	1.388	0.333

Table 6. Zeroth and first order correlation coefficient for ROME/L'AQUILA stations (H-component).

ROM/LQL H-Comp	CR _{sq} vs GM _{sq}	Zeroth –order corr. coeff.			SSN vs CR _{diff}	First-order coeff. (SSN)		
		CR _{all} vs GM _{all}	CR _{diff} vs H _{diff}	SSN vs H _{diff}		CR _{sq} vs GM _{sq}	CR _{all} vs GM _{all}	CR _{diff} vs H _{diff}
All	0.003	-0.055	-0.258	0.286	-0.155	-0.201	-0.006	0.267
Cycle 20	0.755	0.777	-0.172	0.116	-0.119	0.062	0.123	0.174
Cycle 21	0.679	0.669	-0.401	0.224	-0.217	-0.090	0.086	0.408
Cycle 22	-0.174	-0.172	-0.328	0.401	-0.257	0.029	0.128	0.331
Cycle 23	0.845	0.833	-0.342	0.364	0.033	0.109	0.630	0.381

Table 7. Zeroth and first order correlation coefficient for HERMANUS stations (Z-component).

HER/HER Z-Comp	CR _{sq} vs GM _{sq}	Zeroth-order corr. Coef.			SSN vs CR _{diff}	SSN vs CR _{sq}	SSN vs GM _{sq}	First order coefficient (SSN)		
		CR _{all} vs GM _{all}	CR _{diff} vs Z _{diff}	SSN vs Z _{diff}				CR _{sq} vs GM _{sq}	CR _{all} vs GM _{all}	CR _{diff} vs Z _{diff}
All	0.136	0.134	-0.258	0.264	-0.137	-0.755	0.115	0.387	0.113	-0.232
Cycle 20	-0.803	-0.822	-0.138	0.029	-0.134	-0.823	0.922	-0.210	-0.244	-0.135
Cycle 21	-0.732	-0.731	-0.370	0.135	-0.208	-0.685	0.825	-0.421	-0.413	-0.353
Cycle 22	-0.889	-0.890	-0.463	0.467	-0.246	-0.926	0.925	-0.345	-0.361	-0.406
Cycle 23	-0.897	-0.890	-0.320	0.420	0.024	-0.879	0.837	-0.456	-0.446	-0.364

Table 8. Zeroth and first order correlation coefficient for OULU (CRI) /SODANKYLA (Z-comp).

OUL/SOD Z-Comp	CR _{sq} vs GM _{sq}	Zeroth-order corr. coeff.			SSN vs CR _{diff}	First-order coefficient (SSN)		
		CR _{all} vs GM _{all}	CR _{diff} vs Z _{diff}	SSN vs Z _{diff}		CR _{sq} vs GM _{sq}	CR _{all} vs GM _{all}	CR _{diff} vs Z _{diff}
All	0.364	0.361	-0.111	0.427	-0.064	0.326	0.342	-0.092
Cycle 20	0.783	0.797	0.026	0.488	-0.049	0.110	0.146	0.057
Cycle 21	0.415	0.381	-0.201	0.409	-0.196	-0.056	-0.035	-0.135
Cycle 22	0.806	0.771	-0.171	0.508	-0.137	0.318	0.286	-0.119
Cycle 23	0.724	0.728	-0.115	0.494	0.153	0.443	0.454	-0.223

more associated with complex magnetic fields in addition to be being typical sites of coronal mass ejections (CMEs) and consequently leads to an inverse correlation

with the CR count rates. Other stations used in this work showed similar patterns with major difference being in percentage count rates. However, looking closely at the

Table 9. Zeroth and first order correlation coefficient for INUVIK (CRI)/COLLEGE (Z-comp).

INV/CMO Z-Comp	CR _{sq} vs GM _{sq}	Zeroth-order corr. coeff.			SSN vs CR _{diff}	First-order coefficient (SSN)		
		CR _{all} vs GM _{all}	CR _{diff} vs Z _{diff}	SSN vs Z _{diff}		CR _{sq} vs GM _{sq}	CR _{all} vs GM _{all}	CR _{diff} vs Z _{diff}
All	-0.011	-0.058	-0.226	0.358	-0.104	-0.101	-0.061	-0.204
Cycle 20	0.603	0.576	0.086	0.313	-0.051	-0.184	-0.150	0.107
Cycle 21	-0.923	-0.922	-0.130	0.263	-0.185	-0.846	-0.838	-0.085
Cycle 22	-0.468	-0.585	-0.527	0.507	-0.174	0.085	-0.033	-0.518
Cycle 23	0.814	0.770	-0.282	0.061	0.022	0.170	0.065	-0.284

Table 10. Zeroth and first order correlation coefficient for ROME (CRI)/L'AQUILA (Z-comp).

ROM/LQL Z-Comp	CR _{sq} vs GM _{sq}	Zeroth-order corr. coeff.			SSN vs CR _{diff}	First-order coeff. (SSN)		
		CR _{all} vs GM _{all}	CR _{diff} vs Z _{diff}	SSN vs Z _{diff}		CR _{sq} vs GM _{sq}	CR _{all} vs GM _{all}	CR _{diff} vs Z _{diff}
All	-0.053	-0.055	-0.258	0.286	-0.155	0.041	-0.067	-0.225
Cycle 20	0.755	0.777	-0.172	0.116	-0.119	0.084	0.127	-0.160
Cycle 21	0.679	0.669	-0.401	0.224	-0.217	0.328	0.304	-0.370
Cycle 22	-0.174	-0.172	-0.328	0.401	-0.257	0.092	0.094	-0.255
Cycle 23	0.845	0.833	-0.342	0.364	0.033	0.299	0.242	-0.380

Oulu NM data, we observed also a 22-year cycle exhibited as spiked or flat peaks during consecutive cycle a feature that is not well exhibited by the sunspot number. This reversal could give rise to different cosmic ray particle drift pattern through the heliosphere to the earth between consecutive cycles (Jokipii et al., 1977). In addition, the heliospheric magnetic field (HMF) would be more turbulent during period of increased solar activity which will lead to decreases in the diffusion ability of the GCRs especially at the outer heliosphere and consequently an increased count rate. Conversely, during the period of low magnetic activity, an increase in the diffusion ability is expected to lead to a higher count rate. Nevertheless, the search for dominant players is still an active area of research (Asham and Badruddin, 2015). The result is therefore in agreement with Asham and Badruddin (2015) result which found a good correlation between sunspot number and cosmic ray intensity. They also concluded that the modulation of the GCR intensity shows a stronger dependence on solar variability (SSN) during the increasing phase, while the solar wind parameters dominate the modulation during the solar minimum.

Geomagnetic modulation of galactic cosmic rays

Following the works of Forbush (1957), the difference (CR_{diff}) between the cosmic count rate for all days and quietest days was computed for all the neutron monitor

stations. Figure 3 shows the time series of the CR_{diff} with the H_{diff} calculated similarly using Equations 3b and 5b respectively. The variation of CR_{diff} and H_{diff} showed strong solar activity dependence with major dissimilarity occurring during period of low solar activity. Similar profiles during high solar activity were observed in HER-HER, ROM-LQL, and INV-CMO pairs of station for the solar activity maximum of 1970, 1980, and 1990. The Z-component variation is presented in Figures 4a to d and 2a to d.

H component variation and CR modulation

The INV/CMO and OUL/SOD pairs of stations did not show similar trends. There was more variability in the H_{diff} when compared with the CR_{diff} series. The variability in these stations seem to be highly complex and is likely more controlled by solar magnetic interaction in the high latitude. There is evidence suggesting that the variability of CR_{diff} is less during solar maximum as compared to solar minimum with usually a corresponding overlap with the H_{diff} profile. This shows that there is significant variability with CR_{diff} during the ascending and descending phase of solar cycle. This was observed mostly in the high latitude stations. The cosmic ray variability is much less than the H_{diff} variability in a month to month basis. The geomagnetic field variability is not globally uniform, as currents from different sources contribute to the monthly mean variability at different locations especially during disturbed periods. This could explain the large

variations of H_{diff} in high latitude stations which are modified by aurora currents and asymmetric components of ring currents.

The mid latitude stations HER and ROM exhibited higher variability in CR_{diff} (Figure 4a and d respectively) during ascending and descending phase of solar activity closer to the solar maximum period and less variability during the solar maximum. The variability of both CR_{diff} and H_{diff} was both less than what was generally observed in the high latitude stations. Variation in H_{diff} is indicative of intensified Westward current which is more dominant in the mid and low latitude and thus results in more negative H_{diff} values during the period of high solar activity. During solar minimum, the ring current persists but is less variable as is evident from Figures 3 and 4. The variability of H_{diff} in the high latitudes (Figures 3a and b) during the declining phase of each solar cycle shows a very interesting feature which tends to confirm earlier work by Echer and Scalgaard (2004) suggesting that corotating interaction regions (CIRs) are responsible for the disturbance of the heliosphere during the declining phase of the solar activity. It is well known that the geomagnetic variations are mostly in response to influence from solar and heliospheric variability and thus the magnitude of the variation depends on the nature of ejections from the sun and on the condition of the interplanetary space. It therefore becomes necessary to remove the effects of the solar variation when attempting to study the association between geomagnetic variation and cosmic ray modulation.

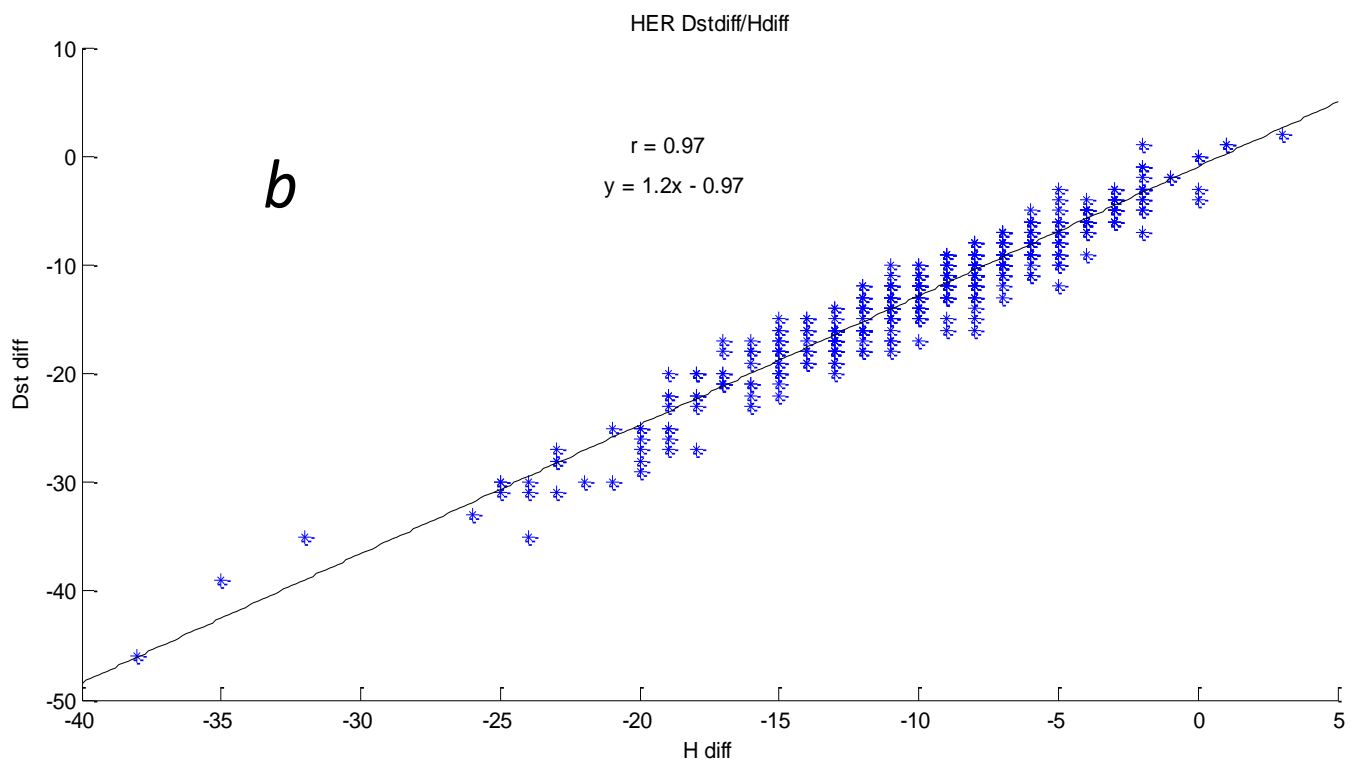
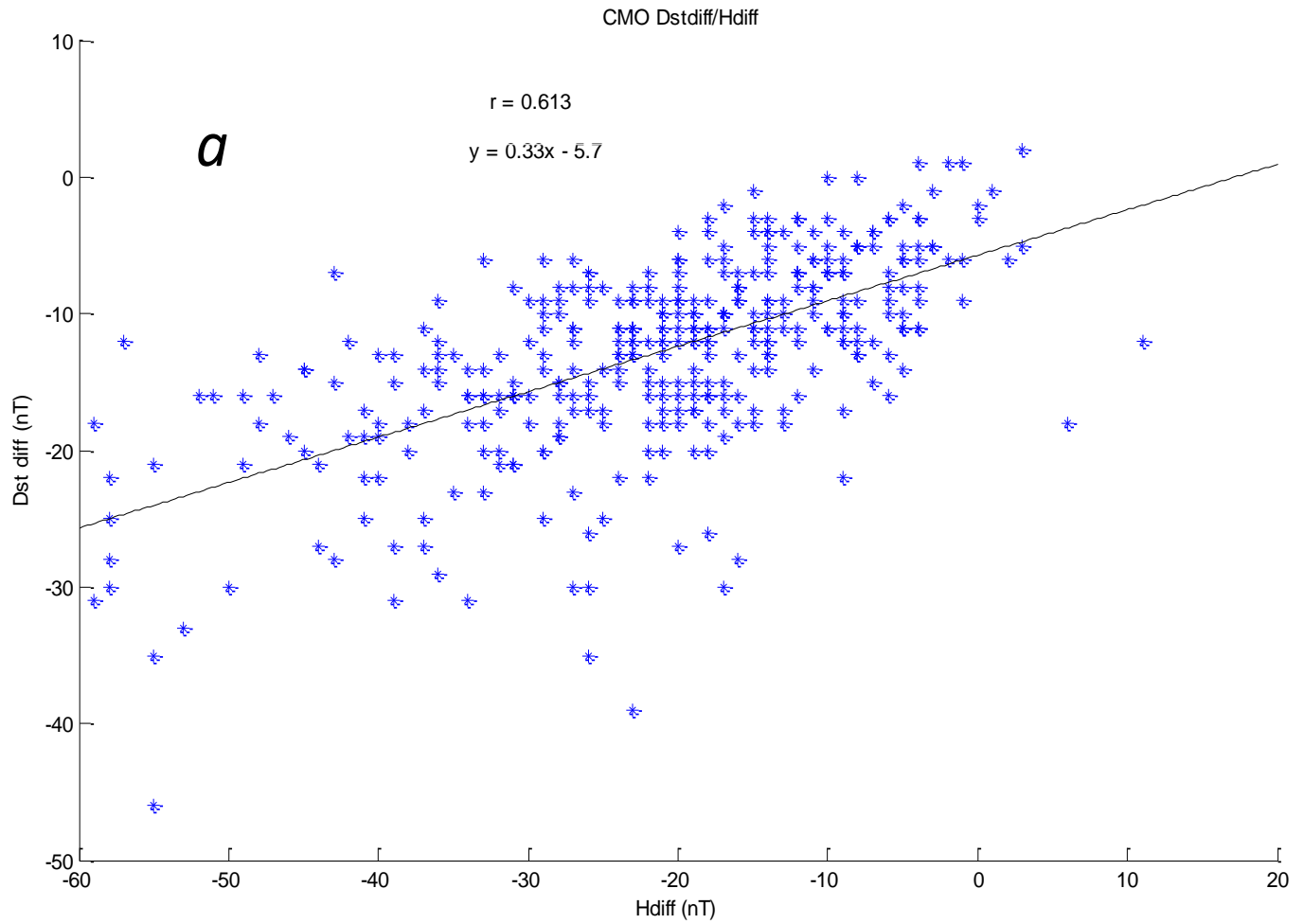
The correlation between the local geomagnetic activity index H_{diff} and the cosmic ray local activity is shown in Tables 3 to 6. The scatter plots presented in figure 2 show that there is greater scatter in the high latitude stations CMO and SOD which could be understood in terms of dominant high latitude currents which modify the field in those regions. The probable error ϵ in the correlations was generally less than 0.068. It is evident that on a cycle by cycle basis, there was good correlation between SSN and cosmic ray intensity which is negative in nature for all stations. This negative correlation was slightly stronger during cycle 20 and 22 when compared with the coefficient calculated for cycles 21 and 23. This could be connected to the similarities in the pairs of solar cycle. Similar correlation coefficient values were observed for monthly mean strength of the H component of the geomagnetic field except for the INV/CMO. The correlation of the H_{diff} did not show any change in sign after the first order correlation suggesting a real effect, in addition, it showed spatial differences as we go from station to station.

The correlation between the main cosmic ray intensity using quiet days is similar to the correlation when all days are used. The correlation tends to be different from cycle and does not have any discernable trend. The removal of the effect of solar activity from the perceived associations between cosmic rays and geomagnetic field revealed that

the correlation is spurious and thus the solar activities drives the changes in both cosmic ray intensity and geomagnetic field strength. In addition, it is observed that CRI versus GM (H) southern hemisphere station (HER) showed a positive and fairly stronger correlation between CRI versus GM (H) after removing the effect of solar activity. The northern station all showed weak negative correlation which appear to depend on rigidity. SSN correlated well with the mean geomagnetic field on a cycle by cycle basis. However, the correlation was weak when all the period was considered. This finding supports the notion that changes in polarity of the solar magnetic field during consecutive solar cycle affect the CR flux and geomagnetic field strength in different ways. These differences tend to affect the correlation of cosmic ray vs. geomagnetic field (H-component) especially for low rigidity stations. This finding tend to support the work of Meng (1979) which showed that conditions of the polarity of the IMF can have profound effect on the size and intensity of auroral current and consequently on the geomagnetic field in that region. Richardson (2013) observed that the rate of storm days during the rise phase of each cycle from cycles 17 to 23 is approximately correlation with the peak SSN in the cycle.

The observation of higher geomagnetic activity during the rising phase of all the solar cycle (Figure 4) has been reported by earlier studies such as Richardson (2013). It suggested that further studies is needed to identify common sources of variability during ascending and descending phases of the solar activity to ascertain the major heliospheric drivers during such periods. Tables 7 to 10 show the zeroth- and first order correlation coefficients for Z component variation with cosmic ray variability including Z_{diff} . Correlation was generally good between mean monthly Z-component field (including Z_{diff}) and mean cosmic ray count rate for quietest days. A similar trend of correlation was observed for all days except for a few exceptions. The removal of the solar activity effect for this association resulted in poor coefficients which suggest that the earlier (good) association was in fact a spurious association highly moderated by the solar activity. Negative correlation coefficient was observed both for the northern hemisphere stations and the southern hemisphere station (HER). As in the H-component coefficient, the even no. cycles (20, 22) exhibited slightly higher correlation than the odd number cycles (21, 23).

SSN did not correlate well with CR_{diff} during different cycles but showed fairly good correlation during isolated cycles. Reason for this arbitrariness is not yet known at this time, but the consistent nature of the coefficient afterremoval of the effect of SSN suggests also that the results were actual association. Each solar cycle showed unique signatures. The SSN exhibited strong correlation between cosmic ray count rates and geomagnetic field even for quietest days during specific cycles. Similar correlation was maintained when all days were



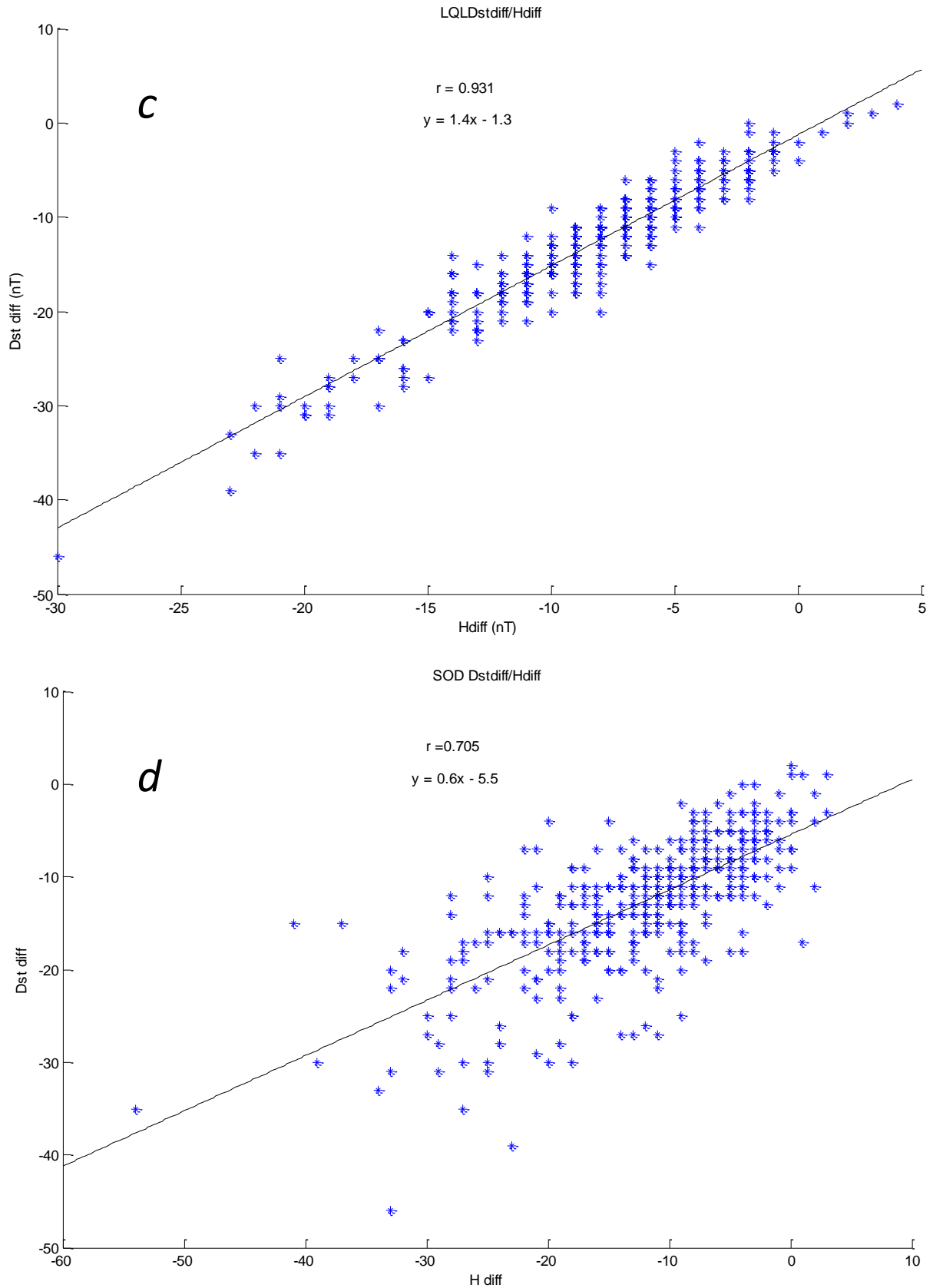
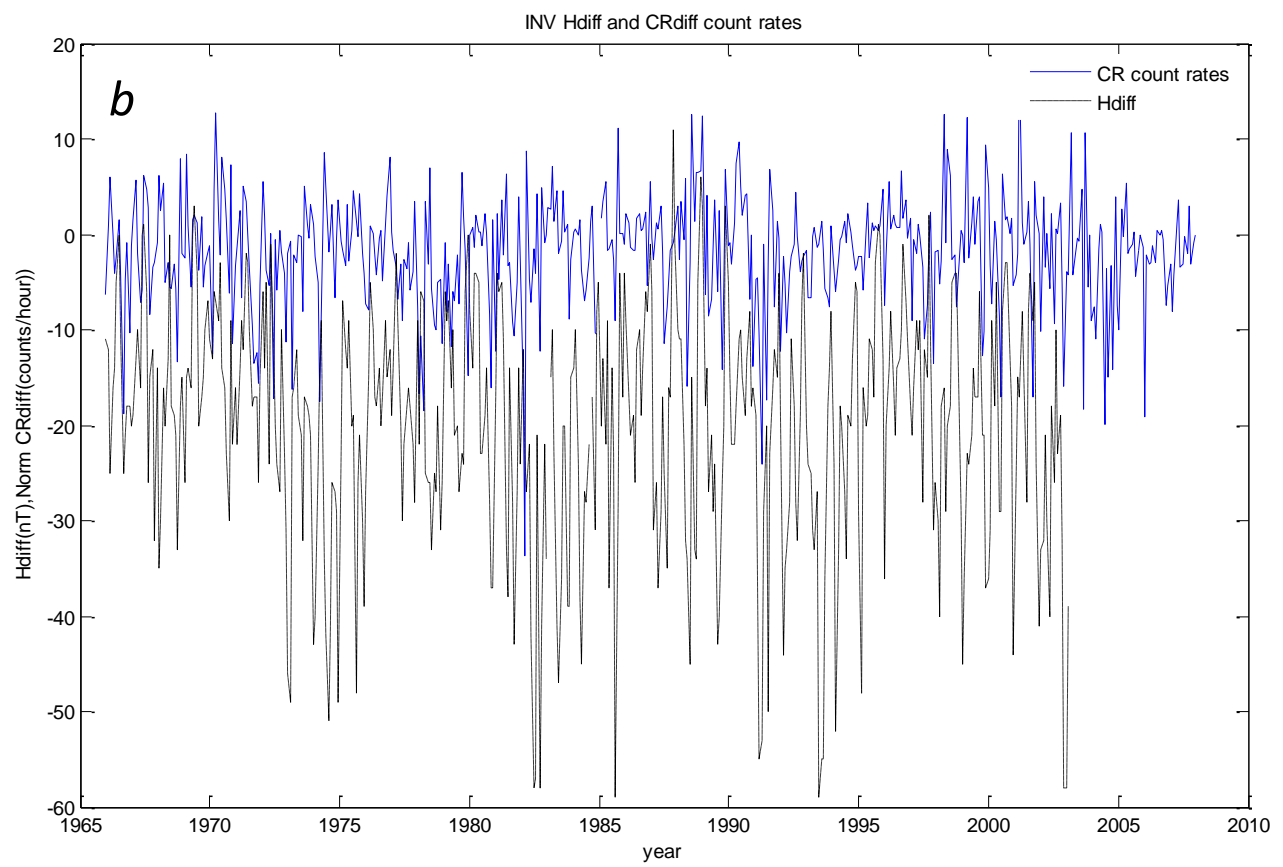
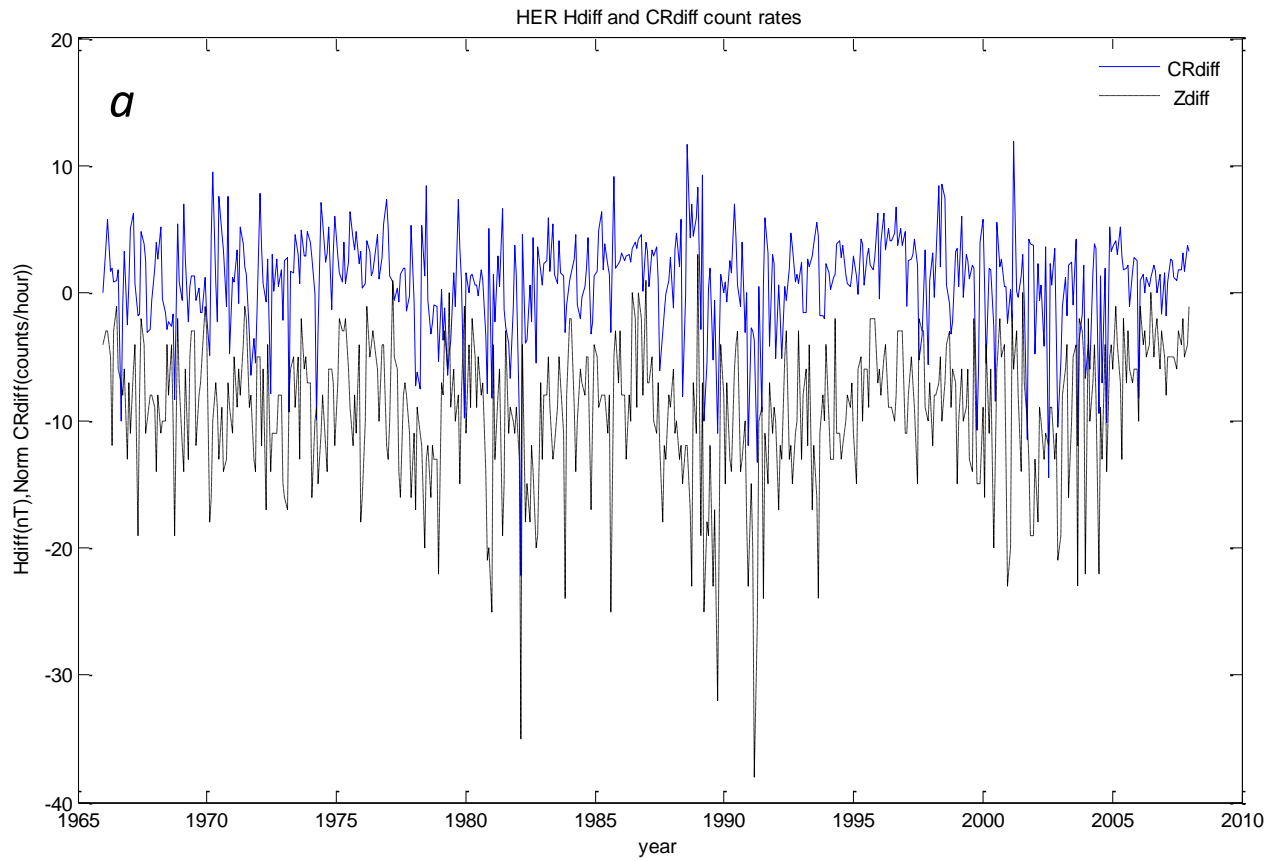


Figure 2. Scatter of Hdiff vs Dst for a-CMO station, b-HER station, c-AQU station, and d-SOD station. Each data point corresponds to a month.



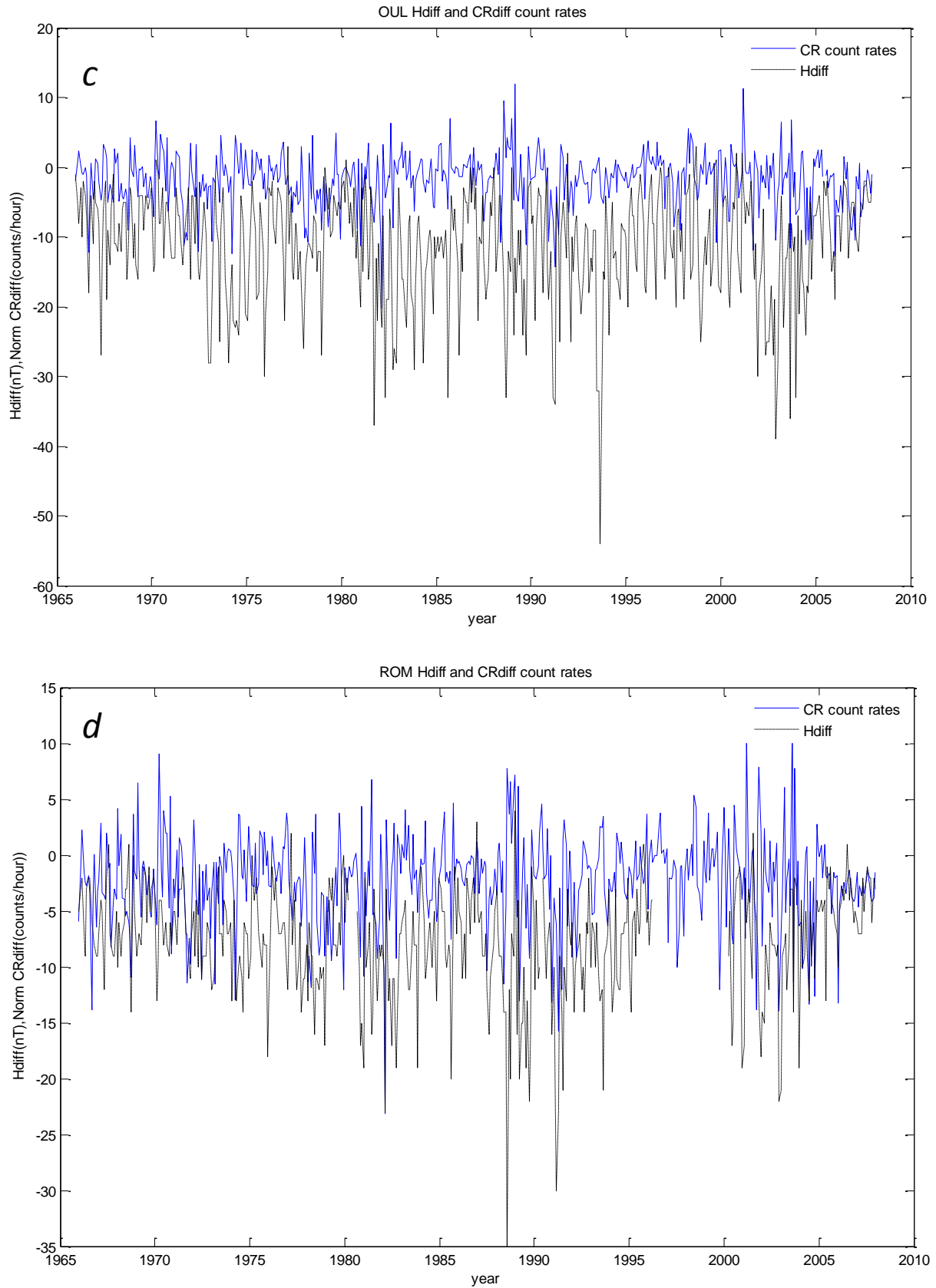
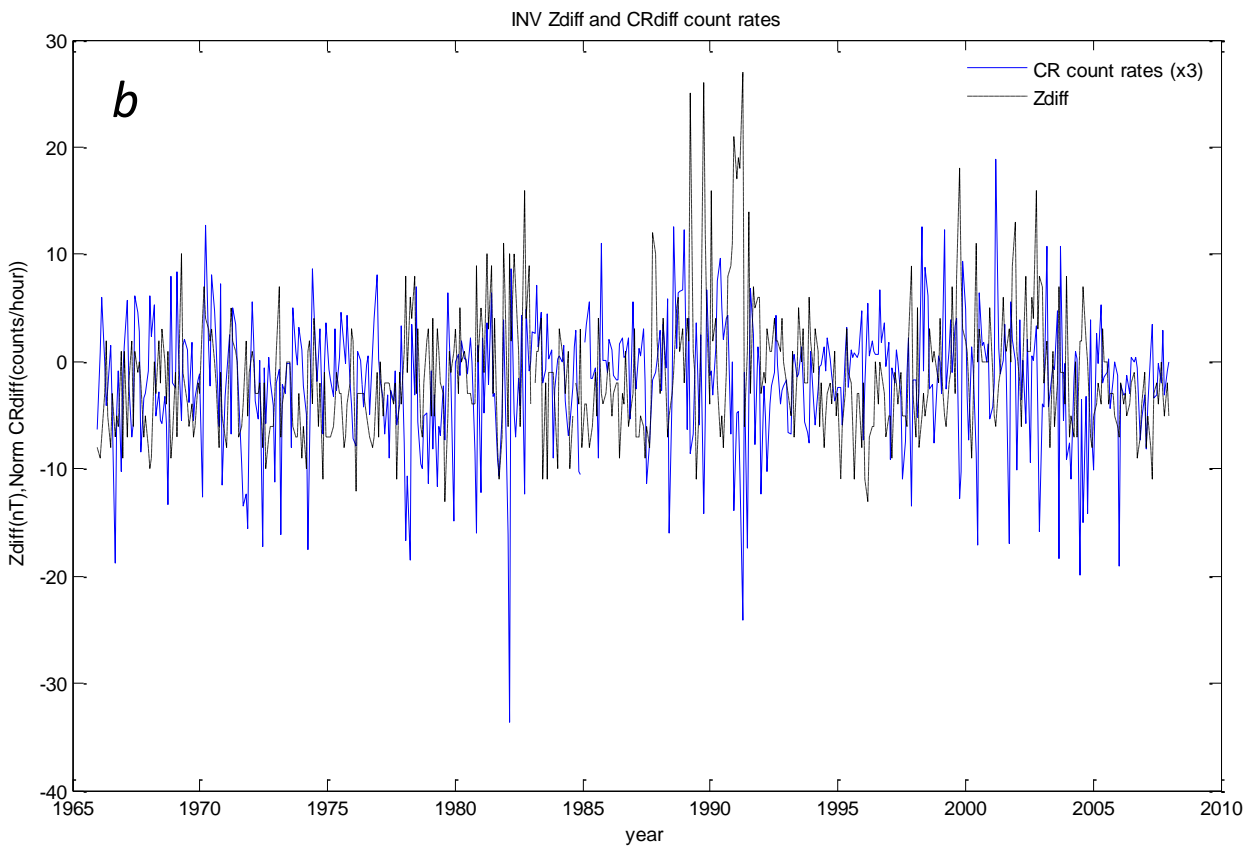
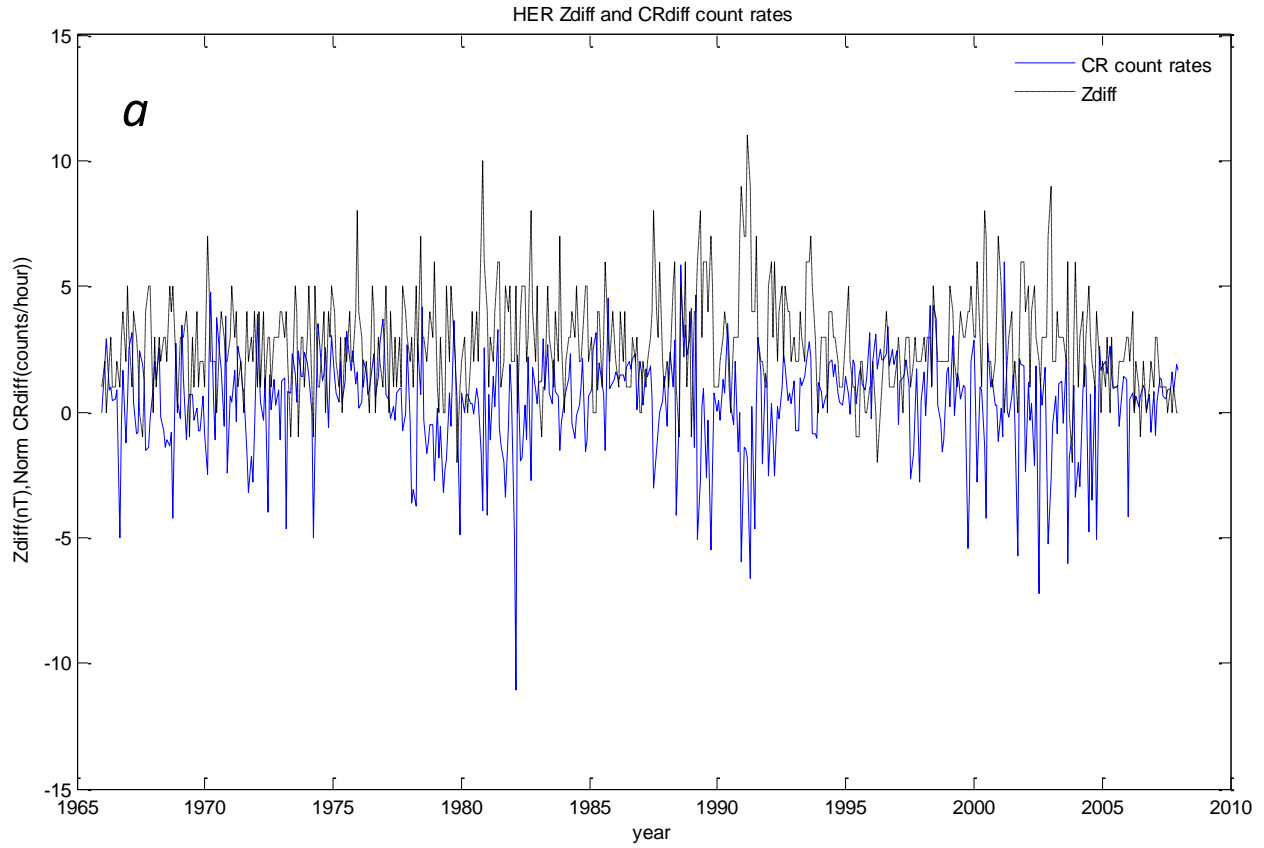


Figure 3. Plot showing monthly H_{diff} and CR_{diff} : a-for HER/HER station pair, b-INV/CMO station pair, c-OUL/SOD-station pair, and d-ROM/AQU station.



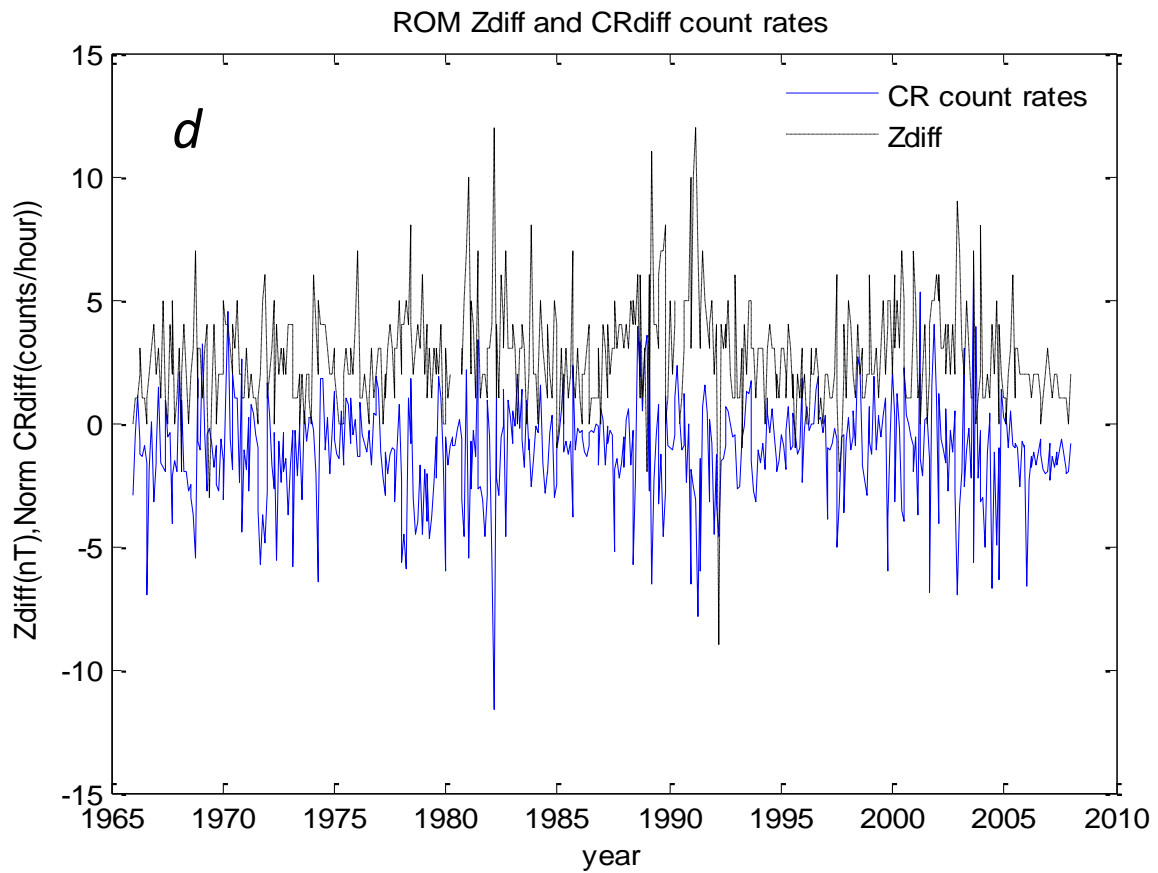
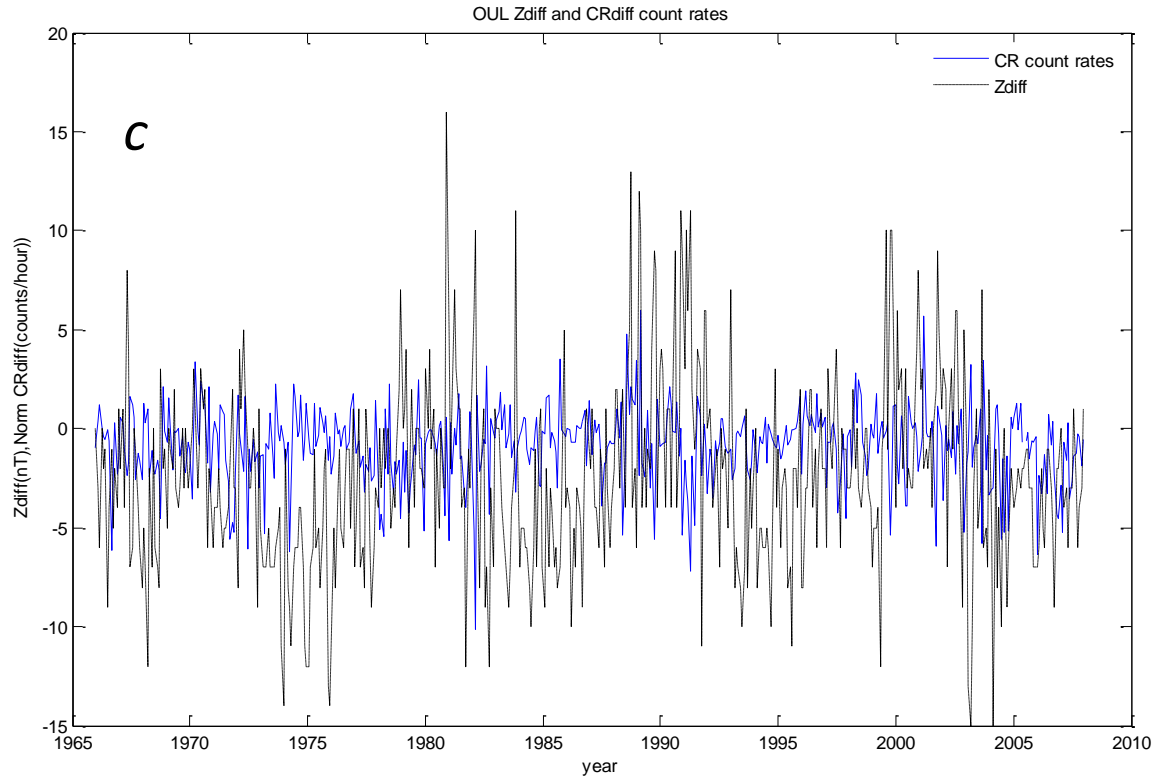


Figure 4. Plot showing monthly H_{diff} and CR_{diff} : a-for HER/HER station pair, b-INV/CMO station pair, c-OUL/SOD-station pair, and d-ROM/AQU station.

considered. This trend observed for all the stations suggests that the asymmetric conditions during the period of reversal of the phase preceding each cycle could be responsible for much of the (poor) observed statistical association.

Conclusion

The relationship between slow-time varying cosmic ray count rates and geomagnetic field across different latitudes and hemispheres has been investigated using data for about four solar cycles and spanning the years 1966 to 2008. The results can be summarized as follows:

- (1) There was strong inverse correlation between cosmic ray intensity with sunspot numbers. With cosmic rays being minimum during period of high solar activity and maximum during low solar activity. The correlation varied on a cycle by cycle basis.
- (2) The evolution of the cosmic ray count rate is different for odd cycles and even cycles in confirmation of the drift theory.
- (3) The cosmic ray flux showed a weak but significant correlation with the corresponding H and Z components of the magnetic disturbance. Z component generally exhibited a negative correlation while H-component exhibited a positive correlation for all the stations. No particular hemispheric difference was observed.
- (4) The approximately 11-year variation in cosmic ray intensity is about the same when only solar quiet-days (5 in a month), and all days are considered. Removal of solar activity effect from the statistical association between geomagnetic field and cosmic ray intensity generally indicates that the 11-year cosmic ray variation is not due directly to the variations in the geomagnetic field (e.g during storms) but rather on variations in the heliospheric conditions which modify both the cosmic ray intensity and the geomagnetic field.
- (5) The signature of convection driven disturbances at high latitude geomagnetic stations is evident during the declining phase of the solar cycles close to the solar minimum. The absence of this feature in the slow-time varying cosmic ray count rates in all stations, and in the mid latitude geomagnetic stations suggest that the local geomagnetic disturbance do not play a significant role in modulating the cosmic ray flux. Further work is needed to ascertain the role of corotating interaction regions (CIRs) and/or coronal mass ejections (CMEs) in modulating the cosmic ray flux especially during the declining phase of the solar cycle possibly using the 27-day solar rotation averages.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES

- Aslam OPM, Badruddin (2015). Study of Cosmic Ray Modulation during the Recent Unusual Minimum and Mini Maximum of Solar Cycle 24. Accepted in Solar Physics. DOI: 10.1007/s11207-015-0753-5.
- Belov AV, Drobzhev VI, Eroshenko EA, Kryakunova ON, Nikolavskiy NF, Ynake VG, Zhantaa Sh (2004). Space weather research by means of high mountain alma-ata neutron monitor. Proceedings of the International Astronomical Union 2004(IAUS223):543-544.
- Belov AV, Eroshenko EA, Yanke VG, Antonova VI, Kryakunova ON (1999). Global and Local Indices of Cosmic Ray Activity, Proceeding of 26th International Cosmic Ray Conference 6:472-475.
- Campuzano SA, De Santis A, Pavón-Carrasco FJ, Osete ML, Qamili E (2018). New perspectives in the study of the Earth's magnetic field and climate connection: The use of transfer entropy. PLoS ONE 13(11):e0207270. <https://doi.org/10.1371/journal.pone.0207270>
- Cane HV (2000). Coronal Mass Ejections and Forbush Decreases, Space Science Reviews 93:55.
- Cooke DJ, Humble JE, Shea MA, Smart DF, Lund N, Rasmussen IL, Byrnek B, Goret P, Petrou N (1991). On the Cosmic Ray Cutoff terminology, Il Nuovo Centimento 14C:213-234.
- Desorgher L, Kudela K, Fluckiger EO, Butikofer R, Storini M, Kalegaev V (2009). Comparison of Earth's Magnetospheric Magnetic field Models in the context of Cosmic Ray, Physics, Acta Geophysica 57(1):75-87.
- Echer E, Svalgaard L (2004). Asymmetry in the Rosenberg-Coleman effect around solar minimum revealed by wavelet analysis of the interplanetary magnetic field polarity data (1927-2002) Geophysical Research letters 31(1) 12808.
- Firoz KA (2008). On Cosmic Ray Diurnal Variations: Disturbed and Quiet days, WDS Proceedings of Contributed papers (II), Matfzy Press pp. 183-188.
- Firoz KA, Kumar DVP, Cho K-S (2010). On the relationship of cosmic ray intensity with solar interplanetary, and geophysical parameters, Astrophysics and Space Science 325:185-193.
- Forbush SE (1957). Solar Influences on Cosmic Rays. Geophysics 43:28-41.
- Forbush SE, Beach L (1967). The absolute geomagnetic field equatorial ring current, Carnegie Institution Year book 65:28-36.
- Forbush SE (1937). On the Effects in Cosmic Ray Intensity Observed During the Recent Magnetic Storm, Physical Reviews 51(12):1108.
- Frigo E, Antonelli F, da Silva DS, Lima PCM, Pacca IG, Bageston JV (2018). Effects of solar activity and galactic cosmic ray cycles on the modulation of the annual average temperature at two sites in southern Brazil. Annales Geophysicae 36:555-564.
- Gupta M, Mishra VK, Mishra AP (2006). Correlation of the long-term cosmic ray intensity variations with sunspot numbers and tilt angle. Indian Journal of Radio & Space Physics 35:387-395.
- Jokipii JR, Levy EH, Hubbard WB (1977). Effects of particle drift on cosmic-ray transport. I-General properties, application to solar modulation. The Astrophysical Journal May, 213:861-868.
- Kataoka R, Nakagawa Y, Sato T (2015). Radiation dose of aircrews during a solar proton event without ground-level enhancement, In Annales Geophysicae 33(1):75-78.
- Kudela K (2009). On Energetic Particles in Space, Acta Physica slovacca 59(5):537-652.
- Mavromichalaki H, Papaianou A, Mariatos G, Papailiou M, Belov A, Eroshenko E, Yanke V, Stassinopoulos EG (2007). Cosmic Ray Radiation Effects on Space Environment Associated to Intense Solar and Geomagnetic activity, IEEE Transactions on Nuclear Scin 54(4):1089-1096.
- Meng CI (1979). Polar cap variations and the interplanetary Magnetic field in Akasofu S.I. (Eds), Dynamics of Magnetosphere, D. Reidel Publishing Company. Dordrecht pp. 23-46.
- Mishev AL, Adibpour F, Usoskin IG, Felsberger E (2015). Computation of dose rate at flight altitudes during ground level enhancements no. 69, 70 and 71, Advances in Space Research 55:354-362.
- Mishra RK, Mishra RA (2007). A study of daily variation in cosmic ray intensity during high/low amplitude days. Pramana – Journal of Physics 68(3):407.
- Okpala KC, Okeke FN, Ugwuoke AI (2015). Cosmic ray modulation in high and Mid latitudes during solar cycles 22 and 23, Canadian

- Journal of Physics 93(1):100-104.
- Okpala KC, Okeke FN (2011). Investigation of diurnal and seasonal galactic cosmic ray variations on quiet days in two mid latitude stations. *Astroparticle Physics* 34(12):878-885.
- Okpala KC (2014). Galactic Cosmic Ray Variability at Two Neutron Monitors: Relation to Kp Index, *Journal of Astrophysics* (2015):1-5.
- Papailiou M, Mavramichalaki H, Vassilaki A, Kelesidis KM, Mertzanos GA, Petropoulos B (2009). Cosmic Ray Variation of Solar Origin in relation to human Physiological State during Dec, 2016 Solar Extreme Events, *Advances in Space Research* 43:533-529.
- Parker EN (1965). The Passage of Energetic charged particle through interstellar space. *Planet Space Science* 13(1):9-49.
- Pauris E (2013). Ineffectiveness of narrow CMEs for cosmic ray modulation. *Solar Physics* 284(2):589-597
- Richardson IG (2013). Geomagnetic activity during the rising phase of solar cycle 24. *Journal of Space Weather and Space Climate*, 3, A08.
- Thomas SR, Owen MJ, Lockwood M (2013). The 22-year hale cycle in cosmic ray flux—evidence for direct heliospheric modulation. *Solar Physics* 289(1):407-421.
- Usoskin IG, Gladysheva OG, Bobik P, Kudela K, Kananen H (1998). Connections between Neutron monitor count rate and solar modulation strength. *Czechoslovak Journal of Physics* 49(12):1743-1749.