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Abnormal quiet day variations in Indian region along 75° E meridian

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Abstract

The present study mainly focuses on the anomalous characteristics observed in some abnormal quiet day (AQD) variations of the north–south (H) and east–west (D) components of geomagnetic field at 11 Indian stations for the years 2004, 2005, and 2009 during low solar activity period for summer and winter months. In this study, during some quiet days, horizontal component (H) at stations situated near equator to the Sq focus latitudes has shown double peak structure, exhibiting maximum in the forenoon and afternoon hours. Correspondingly, declination component (D) over the low latitudes has shown features outside the normal trend, i.e., westward-directed field in the morning hours and eastward-directed field in the afternoon hours and shows negative bay-type of variations. The technique of principal component analysis (PCA) has been applied to the data sets for presenting a quantitative estimate of the influence of day-to-day variability in the Sq current system on normal (NQD) and abnormal quiet (AQD) days. AQDs observed at the Indian stations are reflected in the second principal component PC-2. Anomalous changes in day-to-day variations (H and D) are interpreted as an influence of high latitude magnetospheric current systems as well as due to single current vortex (SCV) located in the ionosphere whose focus lie between 10° and 15° N geomagnetic latitude for the northern hemisphere winter AQDs.

Background

Most smooth and regular variations recorded on magnetograms during magnetically quiet days are known as solar quiet daily variations or simply Sq (Campbell 1989). These types of variations were first observed by Graham (1724). The major driving force for quiet day variations are due to X-rays (1–170 A°) and extreme ultraviolet rays (170–1750 A°) from the Sun that ionizes the upper atmosphere (known as ionosphere). These ionized gases known as plasma are forced to move across the Earth's main magnetic field producing electromagnetic forces (EMFs). This EMF drives electric currents in the conducting E-region (ionospheric dynamo) giving rise to daily variations in magnetic field observed at magnetic observatories (Chapman and Bartels 1940). The observed quiet day variations at the ground is a result of several parameters like ionospheric conductivity, ionospheric winds, geomagnetic field configuration, etc. and the ionospheric dynamo is not the only source of these Sq variations but some contributions from magnetospheric origin is also present in this Sq field (Olson 1970). At least two other magnetospheric current systems, the neutral sheet and ring currents, may also make contributions to the quiet magnetic variations at the surface of the Earth (Olsen 1996).

Correlation between the Sq amplitude and solar zenith angle was carried out by Zhao et al. (2008) and found that it was higher in high-latitude as compared to the low-latitude regions due to the effect of the prenoon–postnoon asymmetry of Sq. Ionospheric conductivity and winds vary seasonally due to their dependence on the solar zenith angle (Campbell 1989) and is reflected in magnetic records having a latitudinal dependence affected by the season of year and by the level of solar activity (Klausner et al. 2013). Solar quiet daily variations have been studied in Indian sector by many authors (Yacob and Rao 1966, Rastogi and Iyer 1976, Arora et al. 1980, Patil et al. 1983, Bhardwaj and Rangarajan 1998) and brought out Sq focus close to the vicinity of Gulmarg. Hamid et al. (2014) had demonstrated that the longitudinal dependence of EEJ-Sq relationship for Southeast Asian sector is different from the Indian and South American sectors and attributed to unique physical processes that is related to the electro-dynamo.

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Atmospheric lunar tidal action on ionospheric layers also causes variations in the geomagnetic field (Maeda and Fujiwara 1967) but these are of very small magnitude. The geomagnetic lunar (L) variation is approximately one-tenth in magnitude as compared to the geomagnetic solar (S) variation (Yamazaki et al. 2011). Lunar tidal waves are due to the gravitational force (Moon acting on the atmosphere, ocean, solid Earth) and are lunar-semi-diurnal in its effect on the electrical state of the atmosphere, which is a function of solar time. Long-term changes in the geomagnetic lunar (L) and solar (S) daily variations have been examined by Yamazaki and Kosch (2014). They suggest reduction in the amplitude of the L to S variation that is attributed to the reduction in lunar tidal waves from the lower atmosphere to the upper atmosphere in association with climate change.

Similar to solar quiet (Sq) current system, there is an L current system that appears to be excited by the lunar gravitational tide (Matsushita and Maeda 1965). The L current system has two vortices in each hemisphere due to the semidiurnal nature of the lunar tide. The focus of the Lq current system is generally at lower latitude than that of the focus of Sq current system (e.g., Matsushita 1967, Chapman and Fogle 1968, and Shiraki 1977). Arora et al. (1980, 1984) studied the latitudinal variations of solar and lunar tides in the Indian region and found the position of northern L vortex focus to be ~20° N in summer (J-months) and ~ 25° N during equinoxes (E-months) but no clear evidence of focus was seen during winter (D-months) seasons. On the basis of nature of latitudinal changes in the phase angles of *L*, they suggested that during solstices, the lunar current system consists of single set of vortices with foci in the summer hemisphere rather than the conventional paired vortices, one in each hemisphere. As the intensity of the Lq current system is much smaller than Sq (Evans 1978), it has not been considered for the present study.

Sometime, these Sq variations show abnormal features outside the normal trend called abnormal quiet day (AQD) variations. AQD variations occur occasionally on normal Sq pattern showing abnormal features in the day-to-day variability. On some quiet days, horizontal component (H) at stations located near equator to the Sq focus latitudes have shown double peak structure, exhibiting maximum in the forenoon and afternoon hours. Correspondingly, declination component (D) over the low latitudes have also shown features outside the normal trend, i.e., westward-directed field in the morning hours and eastward-directed field in the afternoon hours and shows southern hemispheric type of variations. Based on a 27-year period for mid-latitude stations, Abinger and Hartland (located on pole ward side of Sq focus), Brown and Williams (1969) have defined $H_{\min}$ occurring outside the normal range (08:30–11:30 LT) as AQDs. AQD properties have been discussed by Brown (1974) and Butcher (1989). Generally, most of these AQDs occur in local winter than summer, more in years around minimum solar activity period than those around maximum solar activity period, and more on days when the Y-component of the interplanetary magnetic field (By) is away from the Sun (A-days, By positive) than towards it (T-days, By negative). Arora (1972) studied the occurrence of AQDs at Alibag over three solar cycles and found out that AQDs occur maximum in winter and there was an inverse relationship between the annual percentage occurrence of AQDs and sunspot number. Rastogi (1993) has brought out changes in the summer-winter variation pattern in the eastward field based on magnetic field component data for the period 1975–1976. Campbell et al. (1993) has studied the track of Sq current focus on quiet days of 1976 and 1977 and reported that Sq vortex disappeared during the winter months for both the years. Similar results were obtained by Alex and Jadhav (2007) by analyzing D- and H-variations for low solar activity period 1977.

The amplitude of the normal Sq (H) is increased on AQDs for stations on the equatorward side of the Sq focus (in the Northern Hemisphere, Butcher and Brown (1981)) i.e., the normal positive excursion was greater on AQDs than on NQDs. This is equivalent to an additional west–east current flowing in the Northern Hemisphere on AQDs producing a superposed northward field (SPNF) at all latitudes (Butcher et al. 1993). The magnitude of the SPNF is found to be latitude and longitude dependent. Butcher and Brown (1981) and Butcher (1982) studied northern hemispheric stations along the 0° longitude meridian and found that SPNF have a peak at 35°–40° latitude in winter and ~ 55° in summer and in both seasons tending to zero near 20° and 60° N geomagnetic latitudes.

The exact cause of these AQDs, whether it is ionospheric origin or extra-terrestrial origin, is still debatable. Brown and Williams (1969) suggested that the variations in the dynamo-induced currents that flow in the E-region of the ionosphere may be the possible cause of these AQDs. However, on the basis of minimum in H occurred near midnight at the same UT at all the five stations almost in the same latitude range but spread over a longitude range of ~115°, Mizzi and Schlapp (1971) suggests that the probable cause of these AQDs event might be extra-terrestrial in origin. Butcher and Brown (1980) also found the connection between the occurrences of AQDs and the interplanetary magnetic field and suggested that the most likely source of the AQDs event would be an extra-terrestrial or magnetospheric origin. Analysis of H-data in both hemispheres along the same longitude meridian, Butcher (1987) proposes that the magnetic effects on AQDs were caused by single current vortex (SCV) that flows clockwise and extended over both hemispheres.

AQD studies by earlier workers were based on observations. In the present study, an attempt has been made to determine AQDs by using PCA for 11 low-latitude Indian stations to determine the possible sources for these AQDs by comparing with interplanetary magnetic field (IMF) parameters. This is a well-known technique applied for separating the normal and the abnormal geomagnetic field variations (Vertlib and Wagner 1970, Faynberg 1975). Applying this technique to Indian magnetic observatories, Rajaram (1983) has determined Sq focal latitude and variation in the strength of the electrojet. Using this technique, Alex et al. (1998) have examined the day-to-day variability in the equatorial electrojet strength on days of low equatorial ΔH in the Indian region. Gurubaran (2002) applied this method of natural orthogonal components to the ground geomagnetic data in the Central Asian sector (72°–83° E) to study the equatorial counter electrojet (CEJ), additional current systems that are superposed on the normal Sq current vortex. Yamada (2002) have applied PCA to hourly data of geomagnetic field to extract different oscillations from day-to-day variation of the daily profile of Chichijima observatory. Xu and Kamide (2004) have used the method of natural orthogonal components (NOC) for decomposing the daily magnetic variations. These results show that the first and second NOC eigenmodes represent solar quiet daily variation (Sq) and the disturbance-daily variation (S_D), respectively. The third and fourth eigenmodes may be related to currents in the magnetosphere.

As this technique of PCA separates out the normal and abnormal variations present in the data, we applied this technique to abnormal quiet day variations for separating the normal and abnormal variations as discussed in "Application of PCA in AQDs" section.

Methods

Data sets

Anomalous behavior in the D- and H-components for individual quiet days is examined by classifying the days for summer and winter months for 2004, 2005, and 2009. Normal days are designated as the quiet days of a particular month with a well-defined eastward field (positive D) in the morning hours, changing over to westward-directed field during the noon hours at most of the low-latitude locations along the Indian sector. Abnormal days chosen for the study are days representing a dominant westward-directed field (negative D) in the morning hours, when a dominant eastward field is expected. On such abnormal days, the predominance of the westward field has also suppressed the morning peak (~0900 h LT), unlike the normal day. For H-component, the maximum peak falling between 11 and 12 LT is considered as NQDs and if it falls outside this range or it shows two peaks instead of one peak are termed as AQDs. For comparison of H- and D-components with IMF parameters, we have used Advanced Composition Explorer (ACE) satellite data sets.

The database used in this analysis are the average hourly values of the D- and H-components for the years 2004, 2005, and 2009 at 11 Indian magnetic observatories as shown in Fig. 1/Table 1. The period of study falls under low solar activity. We have selected 9 July 2004 (summer month), 6 and 9 January 2005, and 11 December 2009 (winter months) days that are abnormal quiet days with Ap = 0 and 4. For comparison, we have chosen quiet days data for 7 July 2004 (summer month) with Ap = 3, 27 January 2005 with Ap = 2, and 1 December 2009 with Ap = 0 (winter months). The data were converted from UT to LT by considering 19–24 UT values of the previous day and 1–18 UT hourly values of the same quiet day for both the D and H components. The diurnal changes in D and eastward component show no appreciable difference at low latitudes. The data D (min) were converted into D (nT) for this analysis. Later, these data were corrected for noncyclic correction (Matsushita and Campbell 1967) in order to eliminate the difference of the field between a day's midnight level to the next day's level. To see the day-to-day variability in Sq current system data of 11 northern hemispheric stations in the Indian region that are located from the dip equator (TIR) up to the Sq focus near GUL along 75° E meridian has been analyzed. Table 1 shows the IAGA code, geographic, and geomagnetic coordinates of these stations. Locations of these observatories are shown in Fig. 1.

Results

Latitudinal characteristics of the diurnal variation of D and H for selected pairs of normal and abnormal days of 9 July 2004, 6 January 2005, 9 January 2005, and 11 December 2009 are shown in Figs. 2, 3, 4, and 5. The equatorial electrojet (EEJ) strength, which is calculated by taking the difference of H-component at Tirunelveli and Alibag on these days are also shown at the bottom panel of these figures which is more on AQD in comparison with NQD. The curves for AQD and NQD for H- and D-components in these figures are arranged according to the increasing order of latitude. During normal days, D-component shows the positive variations in the forenoon and negative variations in the afternoon hours with a maximum occurring around 0900 h LT suggesting distinctly defined eastward and westward fields as observed in Indian region. During abnormal days, westward field is observed to persist during the

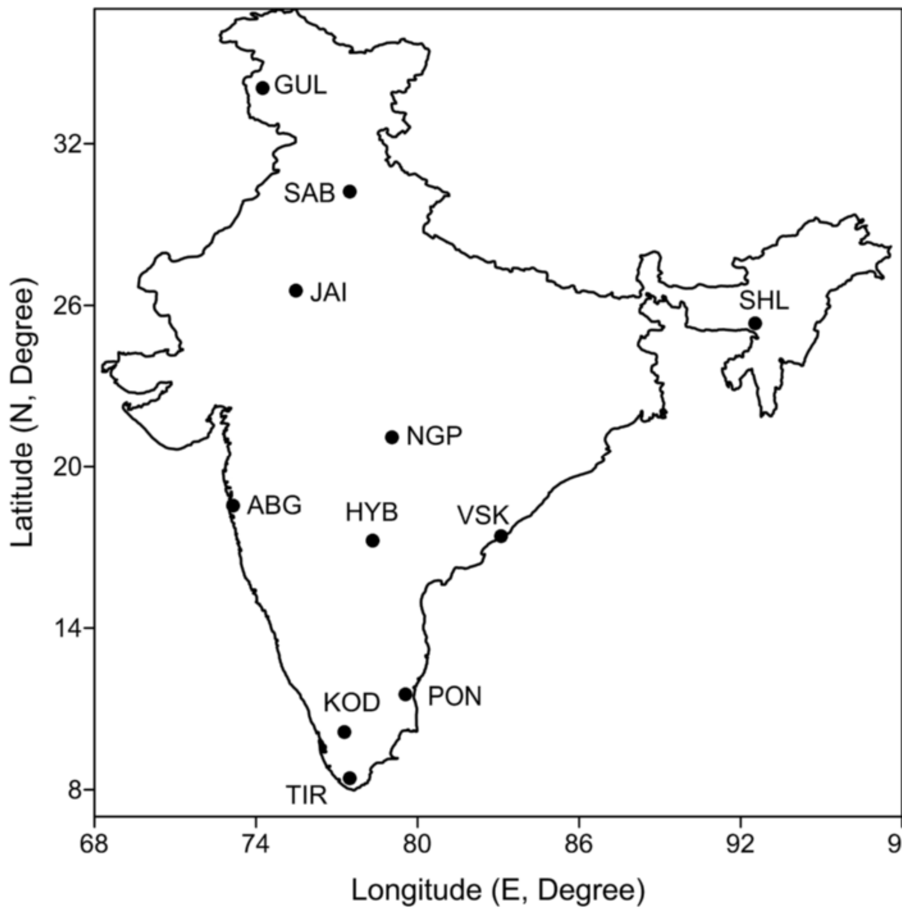

Fig. 1 The location of the 11 Indian magnetic observatories Tirunelveli (TIR), Kodaikanal (KOD), Pondicherry (PON), Visakhapatnam (VSK), Hyderabad (HYB), Alibag (ABG), Nagpur (NGP), Shillong (SHL), Jaipur (JAI), Sabhawala (SAB), and Gulmarg (GUL)

Table 1 List of stations along Indian sector and their geographic/geomagnetic coordinates

Observatory name	IAGA code	Geographic		Geomagnetic	
		Latitude (° N)	Longitude (° E)	Latitude (° N)	Longitude (° E)
Gulmarg	GUL	34.05	74.24	24.90	148.84
Sabhawala	SAB	30.22	77.48	21.40	152.00
Jaipur	JAI	26.55	75.48	18.15	149.80
Shillong	SHL	25.34	92.53	15.10	163.70
Nagpur	NGP	21.09	79.05	12.10	152.30
Alibag	ABG	18.37	72.53	10.02	146.10
Hyderabad	HYB	17.25	78.33	8.45	151.50
Visakhapatnam	VSK	17.41	83.19	8.34	156.10
Pondicherry	PON*	11.55	79.55	2.86	152.30
Kodaikanal	KOD	10.14	77.28	1.39	149.80
Tirunelveli	TIR	8.42	77.48	−0.17	150.00

*Kindly note that IAGA code for PON is PND

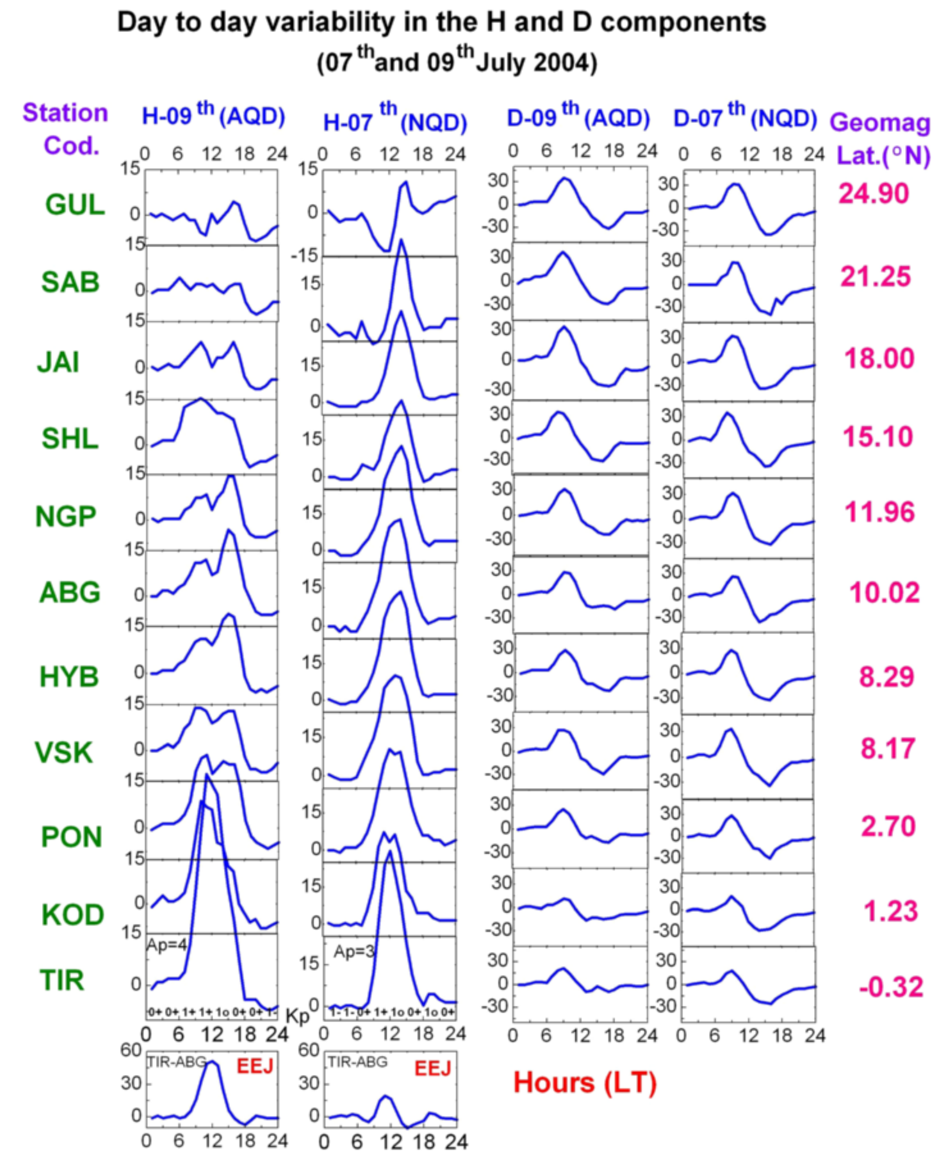

Fig. 2 Day-to-day variations of the H- and D-components for selected abnormal quite day (AQD) and normal quiet day (NQD) pair for 9 and 7 July 2004 in the Indian longitudinal sector

forenoon hours and eastward field during afternoon hours from equator to the latitude of Gulmarg (GUL).

Figure 2 shows the day-to-day variability in the H- and D-components during summer month on 7 (NQD) and 9 (AQD) July 2004 at Indian stations with Ap = 3 and 4 respectively and all eight values of the 3-hourly Kp index are ≤ 1+. The H-component on 9 July 2004 which is an AQD shows two peak structures from Pondicherry (PON) to Gulmarg (GUL), in which the amplitude of afternoon peak is larger than the forenoon peak, which is decreasing with increasing latitude. On 7 July 2004 which is a NQD, the H-component shows expected Sq behavior with local time and latitude. At equatorial stations (TIR and KOD), a very large and "*inverted V*" type of variation is observed with noon maximum in H field and is the characteristic of an equatorial electrojet type of variations. Amplitude of H-variations decreases gradually with increasing latitude and at Gulmarg, the H waveform is about to reverse its sign from "*inverted V*" type to "*V-shaped*". The D-component in Fig. 2 on AQD do not show much difference with normal quiet day (NQD) and show expected northern hemispheric type of variations i.e., easterly maximum in the forenoon and westerly minimum in early afternoon hours. In their latitudinal progression, D-variations are strongest at mid-latitude station (GUL). The D maximum at GUL coupled with reversal of H-variation near these latitudes are clearly indicates that the focus of the northern Sq

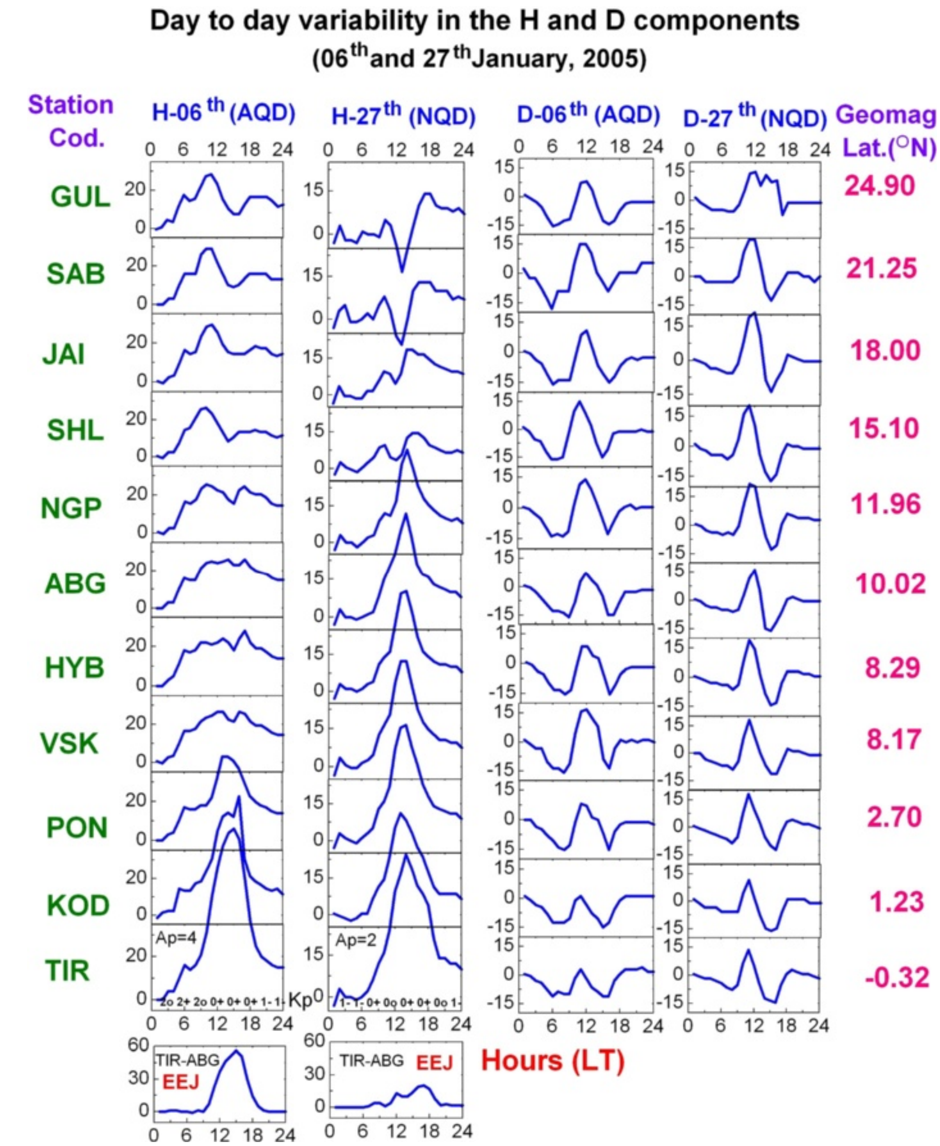

Fig. 3 Day-to-day variations of the H- and D-components for selected abnormal quite day (AQD) and normal quiet day (NQD) pair for 6 and 27 January 2005 in the Indian longitudinal sector

vortex during both the normal and abnormal quiet days is located near GUL (24.9°N geomagnetic latitude) for the stations situated along 75° E longitude.

Figures 3 and 4 shows AQD H- and D-variations on 6 and 9 January 2005 with Ap = 4 and all eight values of the 3-hourly Kp index are ≤ 2+ and compared the same with NQD on 27 January 2005 with Ap = 2. The H component in Fig. 3 on 6 (AQD) January 2005 does not show expected peak in the noon time except equatorial stations TIR, KOD, and PON. However, a minimum is observed in the afternoon hours from VSK to SHL which also disappear at mid-latitude stations SAB and GUL. On 27 (NQD) January 2005, the H component shows a sharp peak around noon time from TIR to NGP and minima from SHL to GUL. The D component on 6 January 2005 does not show expected northern hemispheric type of variations but shows negative bay-type variations at all Indian stations, while on 27 (NQD) January 2005, it shows expected northern hemispheric type of variations with easterly maximum in the forenoon and westerly minimum in the afternoon. In Fig. 4, also the H component on 9 January 2005 (AQD) does not show expected peak in noon time hours. However, a sharp peak in H-field is observed during afternoon hours at all stations except TIR. The D-component also shows abnormal variations on 9 January 2005, minimum in the

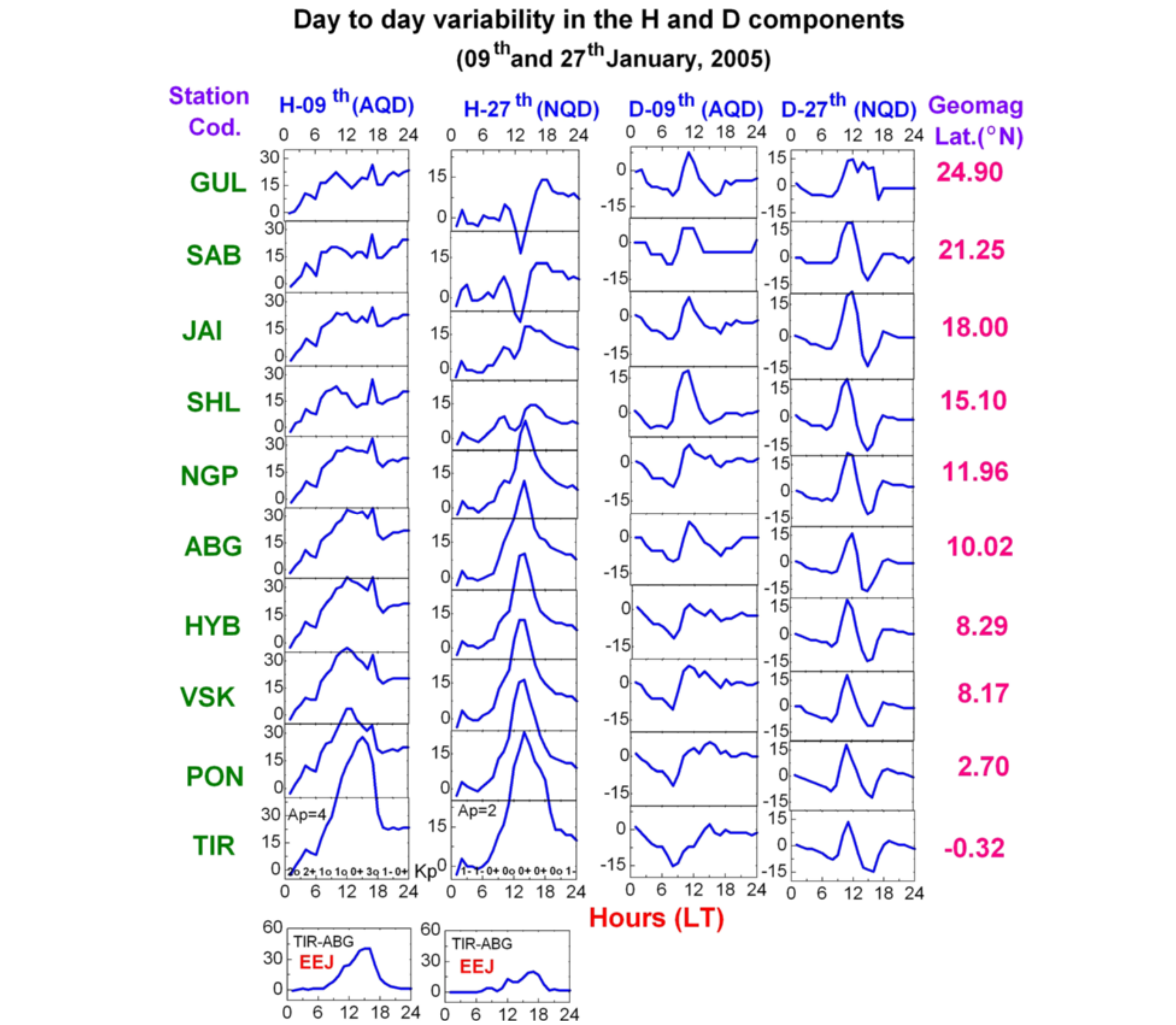

Fig. 4 Day-to-day variations of the H- and D-components for selected abnormal quite day (AQD) and normal quiet day (NQD) pair for 9 and 27 January 2005 in the Indian longitudinal sector

forenoon and maximum in the afternoon hours, and does not show northern hemispheric type D-variations. Also, the D- and H-components in winter months 6, 9, and 27 January 2005 (Figs. 3 and 4) show different features with summer months 7 and 9 July 2004 (Fig. 2) for both the AQDs and NQDs due to seasonal variations. Similarly, AQD 11 December 2009 is compared with NQD 1 December 2009 for 10 Indian stations as shown in Fig. 5 with Ap = 0. The H-component on 11 December 2009 shows a double peak structure with two maxima, one in the forenoon and other in afternoon hours from Visakhapatnam to Gulmarg, and shows abnormal variations. The D-component on 11 December 2009 does not show abnormal variations and shows expected northern hemispheric type of variations.

Determination of AQD current system

Nature of inequalities in AQD current system along Indian sector can be seen by the current vector plots shown in Fig. 6. Here, the hourly values of H and D are combined to produce the magnetic vector. The resulting magnetic vector when rotated clockwise by 90° gives the equivalent current vector. When placed on the latitude-local time cross-section, it helps to trace the nature of equivalent AQD current system. Figure 6a shows the feature of AQD current system along 75° E meridian, determined by equivalent current vector plots on 9 July 2004 (AQD) and indicates an anti-clockwise Sq loop with focus near GUL (24.9° N geomagnetic latitude) and around 12-h local time. Figure 6b shows anti-clockwise loop in the central part but shows irregular pattern

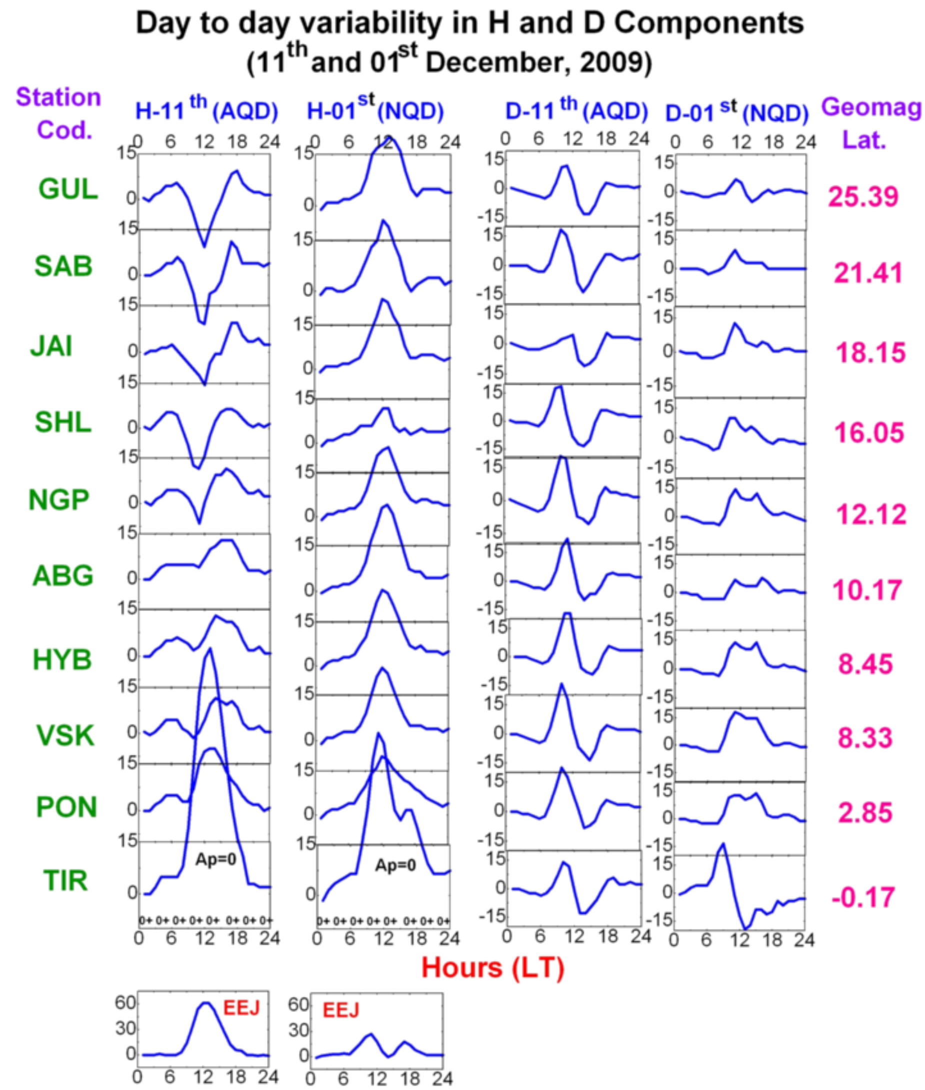

Fig. 5 Day-to-day variations of the H- and D-components for selected abnormal quite day (AQD) and normal quiet day (NQD) pair for 11 and 1 December 2005 in the Indian longitudinal sector

during forenoon and evening hours on 6 January 2005 (AQD). Figure 6c shows the feature of AQD current system along 75° E meridian, determined by equivalent current vector plots on 11 December 2009 and indicates an anti-clockwise Sq loop with focus somewhere around NGP (12.1° N) and SHL (16.1° N geomagnetic latitude) and around 12-h local time.

Application of PCA in AQDs

In this paper, we have applied the PCA method to the AQDs for investigating normal and abnormal variations. This method is variance oriented and the first principal component is the linear combination of the variables that explains the greatest amount of variations. The second principal component defines the next largest amount of variations and is independent to the first principal component. According to Rajaram (1985), the major advantages of PCA as applied to geomagnetic field variations are the following: (a) The eigenvectors are derived directly from the input data, (b) maximum variance of the data is contained in the first few principal components, (c) different components generally correspond to different spatio-temporal characteristics of the source field, and (d) one can simultaneously look at both the space and time characteristics of the input data. Using this technique, Rajaram (1980, 1983) (for more details, see references therein) studied the common and anomalous features of equatorial geomagnetic variations and also determined the latitude of the Sq focus.

The merit and relevance of the PCA to the present study is illustrated by applying to the abnormal quiet day variations in H and D at Indian stations. Figure 7a

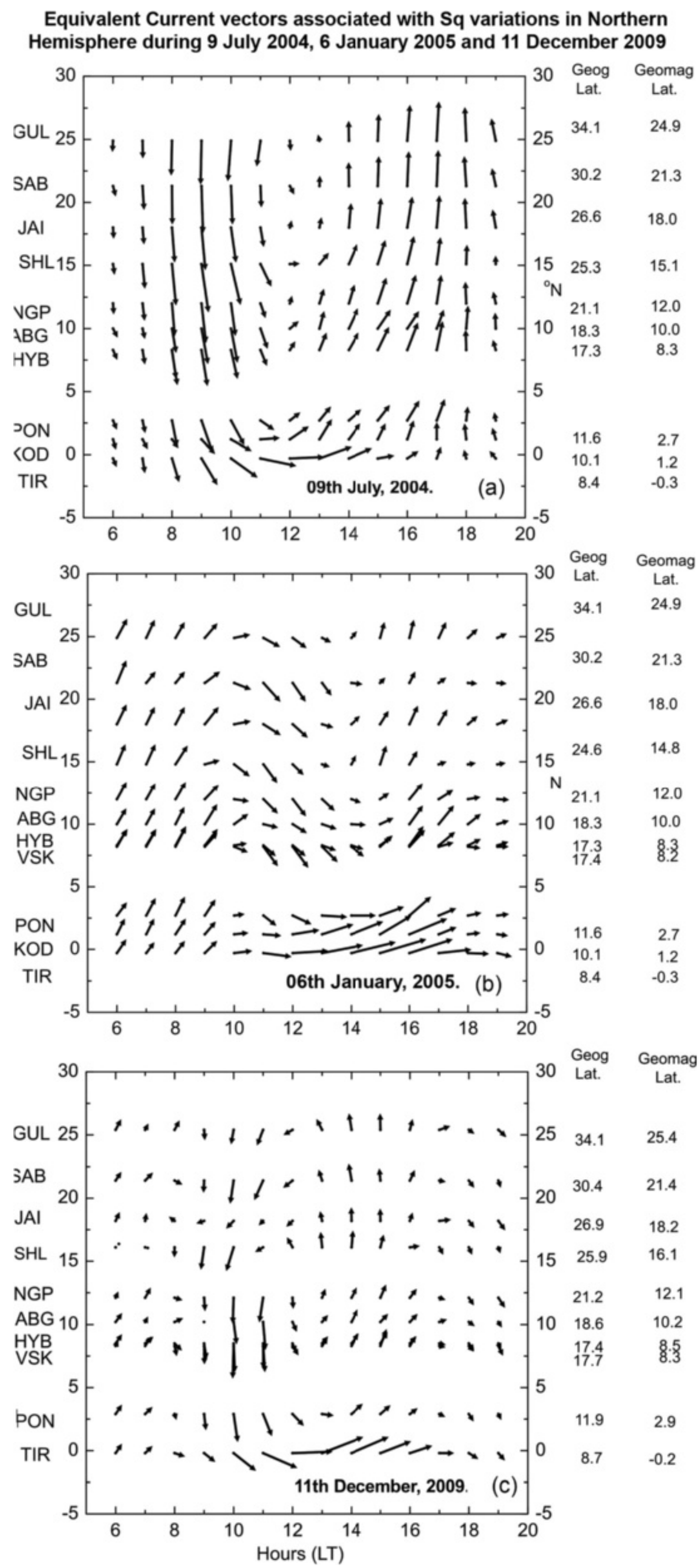

Fig. 6 a Plots of equivalent current vectors on the local time-latitude sector during summer (9 July 2004) and during winter months **b** 6 January 2005 and **c** 11 December 2009 for abnormal quiet days in the Indian region

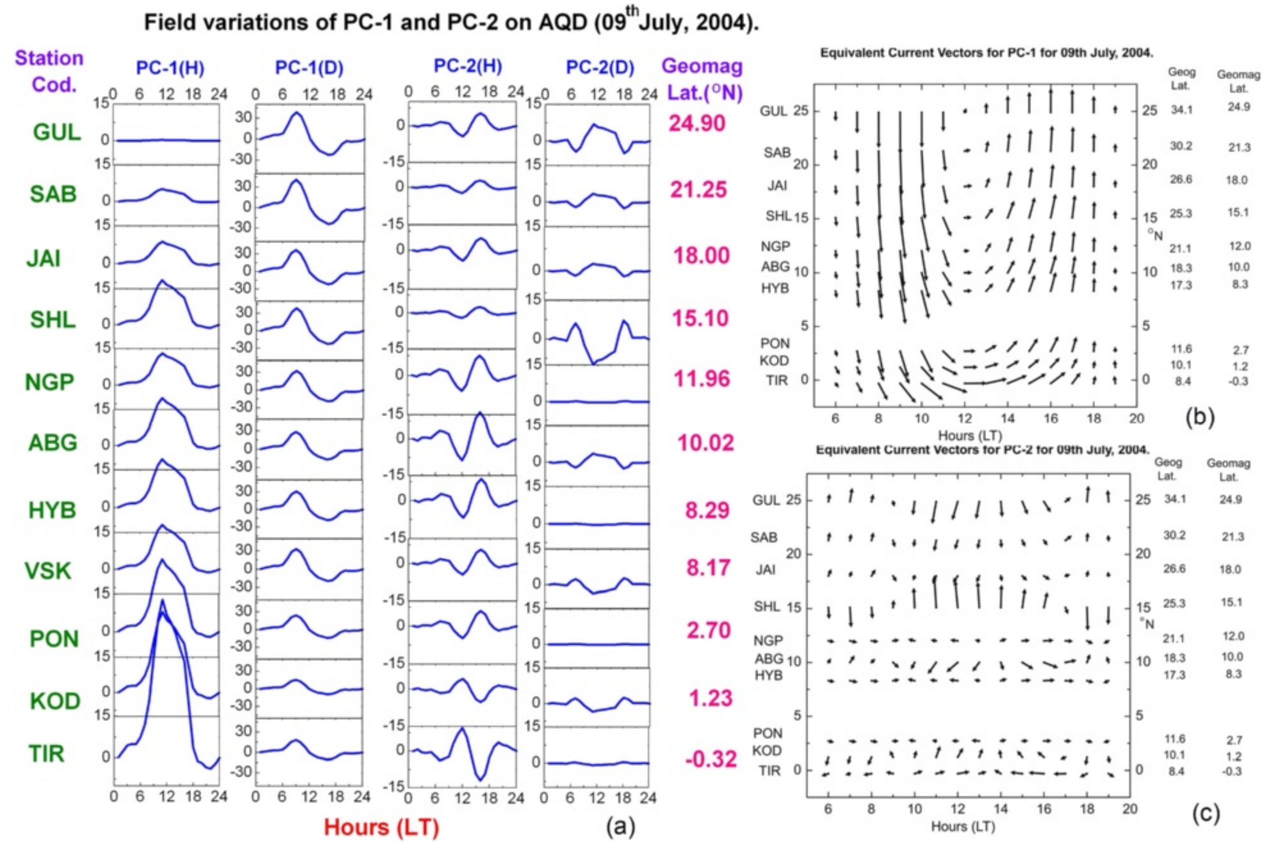

Fig. 7 a Field variations of first and second principal components of H and D during summer (9 July 2004) month on abnormal quiet day. Plots of equivalent current vectors on the local time-latitude sector for **b** PC-1 and **c** PC-2 in the Indian region

shows the time variation plots in H and D corresponding to first and second principal components (PCs) on 9 July 2004 for abnormal quiet day at selected northern hemispheric stations. The curves for PC-1(H) and PC-1(D) portray the expected Sq behavior with local time and latitude. Here, also, at equatorial stations (TIR and KOD), a very large and "*inverted V*" type of variation is observed with broad noon maximum in H-field, and is the characteristic of an equatorial electrojet type of variations. Amplitude of these variations decreases gradually with increasing latitude and at Gulmarg, it hardly shows any variation in PC-1(H). The PC-2(H) curves in Fig. 7a show positive variations in the forenoon and negative in the afternoon hours at equatorial stations TIR and KOD; the waveform reverses its sign to negative in the forenoon and positive in the afternoon hours for other stations above KOD, i.e., from PON to GUL. The PC-1(D) curves in Fig. 7a also show expected northern hemispheric type of variations, i.e., easterly maximum in the forenoon and westerly minimum in afternoon hours. In their latitudinal progression, D-variations are strongest at mid-latitude station (GUL). The PC-2(D) curves do not show any variations at TIR, PON, HYB, and NGP and show two peak structures at other stations. Figure 7b, c shows the current vector plots for PC-1 and PC-2 on 9 July 2004 (AQD). In these figures, also the hourly values of H and D are combined to produce the magnetic vector; the resulting magnetic vector when rotated clockwise by 90° gives the equivalent current vector. When placed on the latitude-local time cross-section, it gives the nature of equivalent Sq current system. From Fig. 7b, it is evident that the flow path is dominated by an anti-clockwise Sq vortex with focus somewhere around GUL, whereas, in Fig. 7c, no signature of current loop can be seen for the second principal component.

Figure 8 shows an example of PCA, the first two principle components for H and D on 6 January 2005 (AQD). In Fig. 8a, the curves for PC-1(H) and PC-1(D) portray the Sq behavior with local time and latitude. The characteristic of an equatorial electrojet type of variations are observed at equatorial stations (TIR and KOD) as "*inverted V*" with broad noon maximum in H-field, and the amplitude of these variations decreases gradually with increasing latitude. In Fig. 8a, no reversal is observed in H-field near SAB and GUL as usually observed

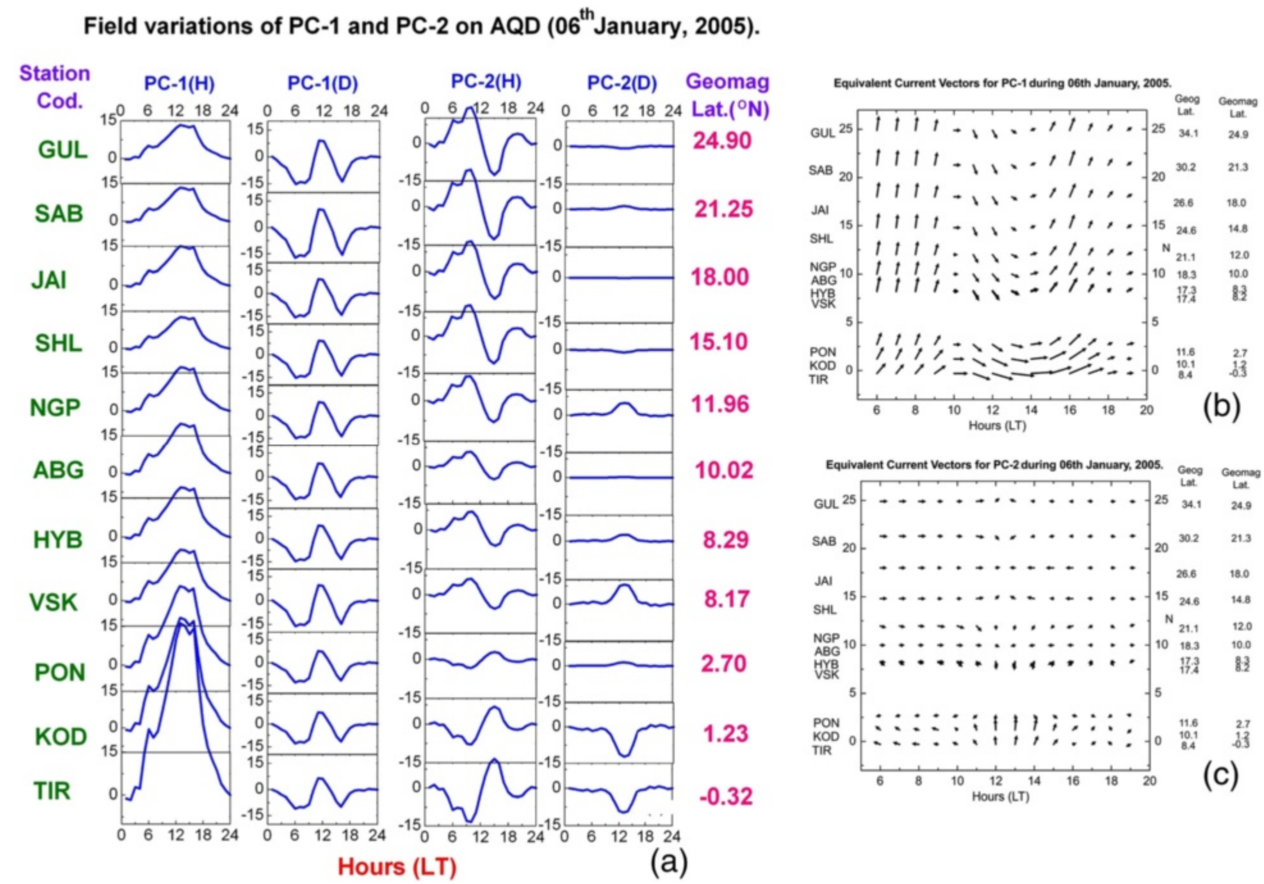

Fig. 8 a Field variations of first and second principal components of H and D during winter (6 January 2005) month for abnormal quiet day. Plots of equivalent current vectors on the local time-latitude sector for **b** PC-1 and **c** PC-2 in the Indian region

in Sq (H). The PC-2(H) curves in Fig. 8a show negative variations in the forenoon and positive in the afternoon hours at TIR and KOD. The waveform reverses its sign to positive in the forenoon and negative in the afternoon hours for stations above PON up to GUL. The PC-1(D) curves in Fig. 8a do not show northern hemispheric types of variations but negative bay-type variations are observed at all Indian stations. The PC-2(D) curves show negative variations with minimum around noon at TIR, and KOD and positive variations at VSK and NGP with maximum near noon and no variations are observed at other stations. Figure 8b, c shows the current vector plots for PC-1 and PC-2 on 6 January 2005 (AQD). The current vectors follow an anti-clockwise pattern in the central part for the PC-1 that is not so clear whose Sq focus should be lying above GUL. For PC-2, no signatures of current loop are observed.

Figure 9a shows another examples of PCA, the first two PCs for H and D on 11 December 2009 (AQD). The first PC shows normal variations whereas the second PC shows the abnormal features in both the H- and D-components at all the Indian stations. Here in Fig. 9a, very large and "*inverted V*" type of variation is observed at equatorial station TIR with noon maxima and amplitude decreases with increasing latitude. The H waveform for the first principal component PC-1(H) reverses its sign from inverted V type to V shaped from SHL, which indicates that the focus of Sq current system is shifted to lower latitudes, i.e., in between the latitude of NGP and SHL. PC-1(D) shows expected northern hemisphere type of variations whereas abnormality is reflected in PC-2(D) as shown in Fig. 9a. Figure 9b, c shows the equivalent current vector plots for PC-1 and PC-2 on 11 December 2009 (AQD). From Fig. 9b, it is evident that the flow path is dominated by an anti-clockwise Sq vortex with focus somewhere in between the latitude of NGP and SHL and around 12-h local time, whereas in Fig. 9c, no signature of current loop can be observed for the second principal component (PC-2).

Discussion

There are different thoughts for explaining the distortions in the Sq current system and its variability (attributed to magnetosphere or ionosphere). Magnetospheric

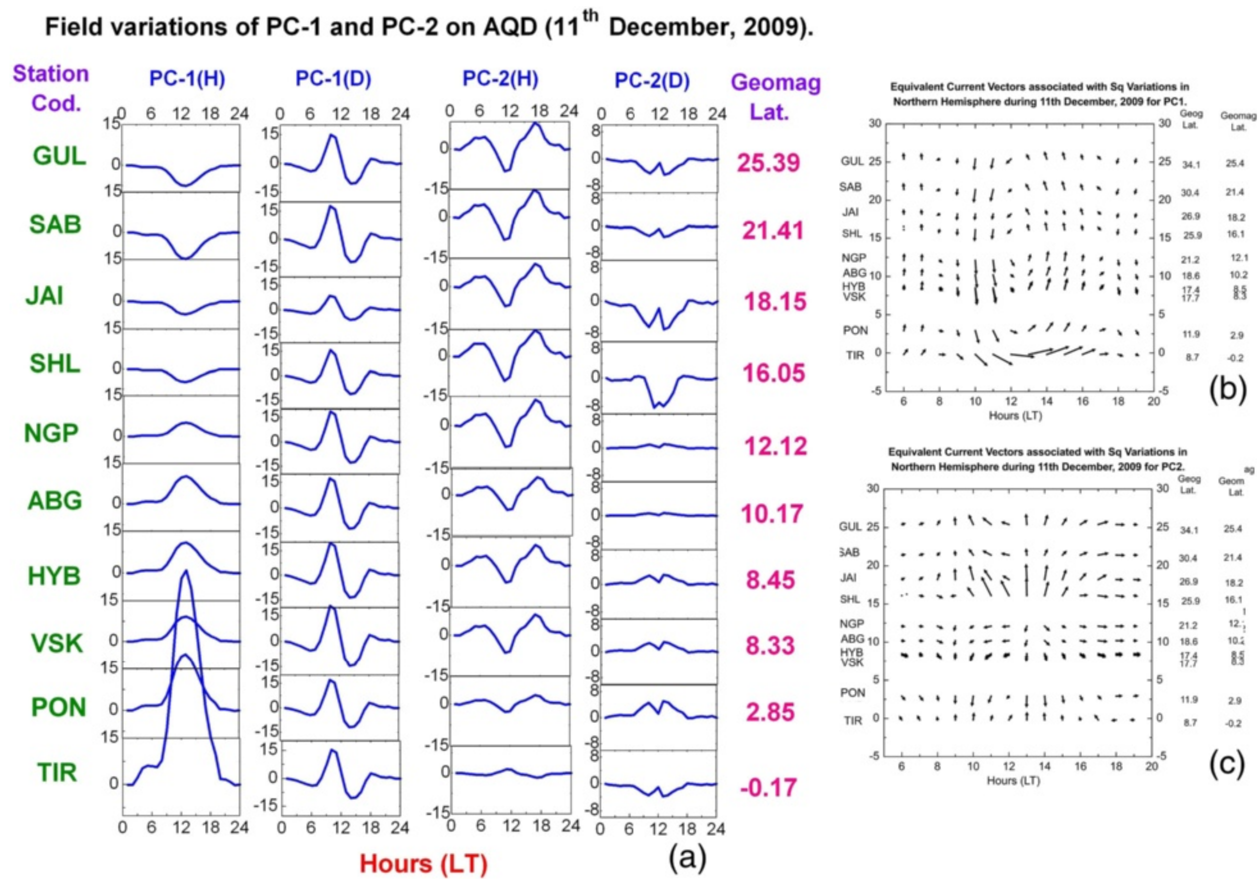

Fig. 9 a Field variations of first and second principal components of H and D during winter (11 December 2009) month for abnormal quiet day. Plots of equivalent current vectors on the local time-latitude sector for **b** PC-1 and **c** PC-2 in the Indian region

currents (magnetopause, tail, and ring currents) contribute to the Sq variations (Olson 1989). All these systems produce magnetic variations which are consistent with a conventionally paired vortex current system, one vortex in each hemisphere, and are symmetric about the equator (Butcher et al. 1993). Butcher (1987) proposes that the magnetic effects on AQDs were caused by a SCV which flows clockwise and extended over both hemispheres. Thus, if a single vortex-type current were to flow in the ring current system, it may be possible for the focus to be pushed northward in northern winter as required on AQDs by the mechanism proposed by Malin and Isikara (1976). If the SCV is of ionospheric origin, one needs to consider the effect in the equatorial electrojet region. The effect of EEJ is shown in Figs. 2, 3, 4, and 5. EEJ affect is more on AQD as compared to NQD suggesting additional current system superimposed on normal Sq variations that also affect Sq focus. From Figs. 6c and 9b, it is clear that the focus of the current vortex on AQDs is shifted to the lower latitudes between SHL and NGP. Butcher et al. (1993) and Butcher (1987) suggest that an additional field occurring on AQDs may be represented by a SCV that has a focus in the latitude range 15°–20° N for the northern hemispheric AQDs based on 80 observatory data. The source for AQDs (during winter months) is SCV located in the ionosphere. Okeke and Hamano (2000) have analyzed magnetic data from Japanese observatories and attributed abnormal quiet days to be due to local irregularities in the Sq current system whereas Sastri (1982) analyzed AQD in the Indian region and changes in fields have been attributed to the ionospheric dynamo region. Klausner et al. (2013) have also shown that the magnetic records have a latitudinal dependence affected by the season of year and by the level of solar activity. It has been shown that Sq variations in the low- and mid-latitudes region are produced by electric currents arising from the wind dynamo process in the E-region of the ionosphere (90–130 km in altitude) and that magnetospheric source is of only secondary importance at middle and low latitudes (Richmond et al. 1976, Richmond 1979). Pedatella et al. (2011) attribute the longitudinal Sq current variations to non-migrating tides which may influence the dynamo-generated electric fields and currents in the

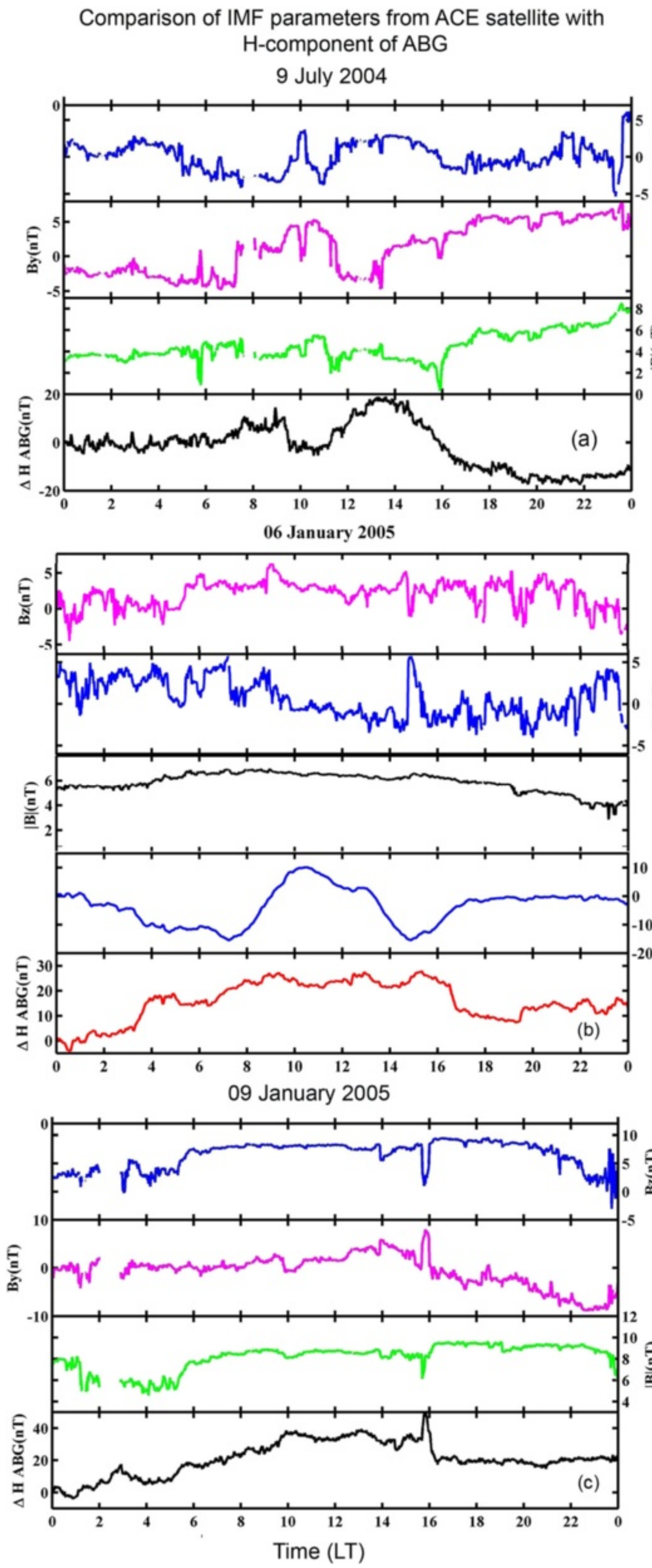

Fig. 10 Comparison of interplanetary magnetic field (IMF) parameters (B, By, and Bz) download from ACE satellite with H-component of geomagnetic field at Alibag during 9 July 2004 (**a**), 6 January 2005 (with D-component) (**b**), and 09 January 2005 (**c**) for AQDs

E-region. From PCA, we suggest that the possible source of the AQD on 11 December 2009 event may be located in the ionosphere with an equivalent current system in the form of a SCV that flows in a clockwise direction as evident from Fig. 9b in which the focus is shifted to lower latitudes between SHL and NGP. Equivalent current vector plot for PC-2 do not show any signature of current loop.

Regarding the shift of the Sq focus, another possibility in the daily variation of H recorded at ground is the contribution of non-ionospheric origins. The contribution of these non-ionospheric origins enhanced a wide range of short period fluctuations in horizontal component. To find the source of these AQD variations, data sets are compared with IMF parameters B, By, and Bz that are downloaded from ACE satellite. AQD events are also linked to the IMF and are well correlated with negative values of the Bz component (Butcher and Brown 1981). Figure 10a shows an example of Alibag (ABG) H-component with B, By, and Bz on 9 July 2004. The two peak structures in Fig. 2 in the H-component at all stations for 9 July 2004 (AQD) can also be seen in the B, By, and Bz components of IMF parameters (Fig. 10a). Two peak structures at Alibag (ABG) are well correlated with B, By, and Bz as observed from this figure. The sharp dip in H-component at Alibag shows an in-phase variation with B and By and out-of-phase variation with Bz. Figure 3 shows an example of AQD for 6 January 2005 with a peak observed around 15:00 LT in H-component and same is reflected in PC-1(H) as shown in Fig. 8a. Observed D curves in Fig. 3 do not show northern hemispheric type of variations but shows two minimum at 06:00 and 15:00 LT with a maxim around 12:00 LT (negative bay-type variations) and the same is observed in PC-1(D) curves as shown in Fig. 8a. On comparison with IMF parameters as shown in Fig. 10b, these peaks are also observed in By and Bz components of IMF.

Figure 4 shows another example of AQD (9 January 2005) during which a bay-type peak is observed around 18:00 LT at all Indian observatories expect Tirunelveli (TIR) which is an EEJ station. Most of the bays occur during the main and recovery phases of magnetic storms but as suggested by Ratcliffe (1972), they may also occur during quiet times. The energy associated with bay activity is transferred from the solar wind into the tail of the magnetosphere, i.e., the IMF is directed southward, although the mechanisms of the energy, momentum, and mass transfer are not yet understood (Butcher and Brown 1981). Rostoker (1969) suggests that long period bay could be produced at mid- and low latitudes by asymmetric ring current system. Comparison of this bay-type event in H-component at Alibag (ABG) with IMF parameters for 9 January 2005 is shown in Fig. 10c. Here, the sharp peak at ABG is in phase with By and out of phase with B and Bz due to change in polarity of IMF.

For stations located on the equatorward side of the Sq (H) focus, the normal Sq (H) amplitude has increased on AQDs, i.e., the normal positive excursion was greater on AQDs than on NQDs. This is equivalent to an additional west–east current flowing in the northern hemisphere on AQDs, producing a superposed northward field (SPNF) at low and mid-latitudes (Butcher and Brown 1981) as shown in Figs. 2, 3, 4, and 5. On the other hand, for the stations situated on the poleward side of the Sq (H) focus, this SPNF reduces the normal Sq (H) amplitude on AQDs. The same is compared with IMF parameters (downloaded from ACE satellite) that show two peak structures in both H-component and IMF parameters on 9 July 2004 (AQD) (Fig. 10a) and a sharp peak at ABG on 6 (also shown for D-component) and 9 January 2005 (AQD) (Fig. 10b, c). These peaks are due to an additional west–east current flowing in the northern hemisphere on AQDs that arises due to extra-terrestrial or magnetospheric origin.

Conclusions

- Principal component analysis results show that the two peak structures in H-component on 9 July 2004 and 11 December 2009 (AQD) observed at all the Indian stations are reflected in the second principal component PC-2(H); also, PC-2(D) shows the abnormal feature on these days.
- Equivalent current vector plots for PC-1 show expected anti-clockwise loop while plot for PC-2 does not show any type of loop on these abnormal quiet days. The focus is also shifted to lower latitudes (between NGP and SHL) for PC-1 on 11 December 2009.
- Comparison of the data with IMF parameters shows that the AQD events on 9 July 2004 and 6 and 9 January 2005 (Fig. 10a–c) are due to extra-terrestrial or magnetospheric origin (Butcher and Brown, 1980), whereas the source of the 11 December 2009 AQD (Fig. 9) event is due to an ionospheric origin.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
Both SKB & PBVS have selected the data sets and performed the statistical analysis, numerical interpretation and drafted the manuscript. BV has provided ACE satellite data and its interpretation. All authors read and approved the final manuscript.

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