

Ultra-low frequency (ULF) magnetic field emissions associated with some major earthquakes occurred in Indian Subcontinent

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ABSTRACT

We have analyzed ULF magnetic field emissions data obtained from identical 3-component search coil magnetometers installed at Indian stations of Agra (Geograph. lat. 27.2°N, long. 78°E), Shillong (25.92°N, 91.88°E), and Kachchh (23.78°N, 71°E) for the months of April 2012 and September 2013 in which three major earthquakes occurred, one of magnitude $M = 8.5$ in Indonesian region and two of magnitudes $M = 7.4$ and 6.8 in Pakistan. The results of the analysis show the occurrence of ULF bursts 09–16 days prior to the occurrence of these earthquakes at Agra and Shillong stations. Such bursts are not observed at Kachchh station. Analysis of ULF data obtained from a flux gate magnetometer at a remote station Kakioka in Japan (Geograph. lat. 36.2°N, long. 140.2°E) does not show such burst also. The bursts contain electromagnetic pulses of periods 10–15s ($f = 0.06$ – 0.1 Hz). The origins of these bursts in lithospheric sources (earthquakes) are confirmed by polarization parameter analysis of data. These ULF data are not influenced by lightning and magnetic storms. A long period analysis of the ULF data for the same months between the years 2010 and 2017 shows that occurrence of such bursts are characterized by either large magnitude shallow depth earthquakes ($M > 6$) or multiple shallow depth earthquakes of low magnitudes ($M < 6$). The precursory periods of the recorded ULF bursts match very well with those reported by Singh et al. (2018) who analyzed very low frequency (VLF) and ionospheric total electron content (TEC) data recorded at Agra station.

1. Introduction

In the last three decades, considerable amount of work has been done in the field of earthquake prediction studies employing seismo-electromagnetic technique. A detailed description of such studies has been published in a series of monographs (Hayakawa and Fujinawa, 1994; Hayakawa, 1999; Hayakawa and Molchanov, 2002; Molchanov and Hayakawa, 2008; Singh, 2008; Hayakawa, 2012, 2015; Pullinets and Ouzounov, 2018). Among the various types of experiments employed in seismo-electromagnetic technique, the one based on monitoring of Ultra Low Frequency (ULF, $f = 0.01$ – 10 Hz) magnetic field emissions recorded from the lithosphere directly has been given special

attention due to certain inherent characteristics of such waves such as long wavelength, large skin depth and low attenuation etc. (Park et al., 1993; Kopytenko et al., 2001). The ULF precursors, considered to be reliable one, were first recorded from Spitak earthquakes ($M = 6.9$) in the year 1988 (Molchanov et al., 1992; Kopytenko et al., 1993), then from Loma Prieta earthquake ($M = 7.1$) occurred in the year 1989 (Fraser-Smith et al., 1990) and Guam earthquake ($M = 8.0$) in the year 1993 (Hayakawa et al., 1996).

Keeping in view the importance of ULF studies, several workers have attempted routine observations of such signals at a single and also at multi-stations in network modes. In order to verify the report of Hattori et al. (2004) that ULF emissions could be observed within a distance of

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60 km from the location of earthquakes of magnitude $M \geq 6$ and within 100 km for those of magnitude $M \geq 7$, Hattori et al. (2013) have established a network of observing stations equipped with torsion magnetometers in Kanto area of Japan with inter-station distance of about 60 km. Similarly, a European collaboration runs an array of ULF fluxgate magnetometers providing continuously magnetic field data recorded in mid- and south Europe (Prattes et al., 2011). The main scientific objective is the investigation of signal variation due to seismic activity and discrimination between natural and human influences.

The bulk of available data of ULF observations provides a convenient opportunity to study them statistically and deduce a reliable and convincing conclusion about precursors. In this context various statistical techniques have been applied that include superposed epoch analysis, principal component analysis, inter-station transfer function method, polarization analysis, fractal analysis etc. A detailed description of these techniques has been given by Hayakawa et al. (2011). A new technique known as natural time analysis method has been introduced by Varotsos et al. (2011). Hayakawa et al. (2015) have applied this technique on ULF data associated with 2008 Sichuan earthquake.

It is to be emphasized here that there are two methods which have been adopted widely to study the precursory phenomena related to earthquakes. One is direct method which employs direct observations of electromagnetic emissions (natural emissions) emitted from the lithosphere reach as ULF emissions and the other is indirect method which is based on measurement of seismic effect in the atmosphere and ionosphere. On account of its inherent characteristics mentioned in the introduction section, ULF emissions which are emitted from the earthquake hypocenter due to the generation of electric current by some tectonic effect are useful for earthquake precursor studies as compared to other methods (Hayakawa et al., 2011).

However, ULF magnetic field measurements at a single station are not suitable to solve various problems in the field of earthquake precursory studies such as determination of epicenter location and other earthquake parameters i.e. magnitude, time etc. Further, it will be difficult to ascertain whether the data is seismogenic or due to global geomagnetic disturbances as a result of solar-terrestrial intersection. Identification of seismogenic emissions from local noises is also very important. In order to solve these problems, networks of ULF stations have been installed. Such networks are existing in many parts of the world. For example, in Japan three such networks are working, one in Kanto area as described above (Hattori et al., 2004), other in central part of Japan belonging to Chubu University, and third one in Moshiri and Hokaido area established by University of Electro-Communication (Hayakawa, 2015). In China, there is chain of stations at Kashi, Ansci, and Beijing and attempts have been made to locate the epicenters of large earthquakes (Du et al., 2002). Similarly, in the frame of south European Geomagnetic Array (SEGMA), a European collaboration runs ULF flux gate instruments providing continuous magnetic field data recorded in mid and south Europe (Prattes et al., 2011).

It is worthwhile to mention here that closely related to ULF studies described above considerable amount of significant work has been done in the past based on the measurements of DC geomagnetic fields and currents related to earthquakes. For example, Smith and Johnston (1976) have measured the geomagnetic field variations along San Andreas fault in California by installing seven proton precision magnetometers and reported significant increase in the field at a site 11 km away a week before an earthquake of magnitude 5.2 occurred on 28 November 1974. Piezomagnetic effect in the stressed rock was attributed to be responsible for anomalous variations around the site. Thereafter, the VAN group (a group of scientists led by P. Varotsos, K. Alexopoulos, and K. Nomicos) at the University of Athens, Greece, conducted measurements of DC geoelectric signals (called seismic electric signals, SES) in a network of eighteen stations in the country associated with earthquakes and made successful prediction of few of them and created great sensation and hope in the scientific community and public at large (Varotsos and Alexopoulos, 1984a and references

therein). Their main findings include (i) the SES precursors occur 6 h to few days before the main shocks (ii) they have duration between 1 mn to 1.5 h and (iii) they are independent of earthquake magnitudes. From this method, the epicenter distance can be determined with an accuracy of 100 km with uncertainty in magnitude of about 0.5 units (Varotsos and Alexopoulos, 1984b). Some of the questions raised on this method were convincingly answered (Varotsos et al., 1986).

The natural time analysis (Varotsos et al., 2011) reveals novel dynamical features hidden behind the time series in complex systems. This shows that well before the occurrence of earthquakes anomalous changes are found to appear almost simultaneously within independent data sets of different geophysical observational measurements (Varotsos et al., 2013). A similar result was reported by Skordas (2014) also.

Recently, Singh et al. (2018) have studied the ionospheric perturbations due to some very large earthquakes ($6.8 < M < 8.5$) occurred during the years 2011–2013 in Indian Subcontinent. The perturbation in the ionospheric D- and E-layers has been studied by employing night-time fluctuation (NF) technique in the amplitude of fixed frequency VLF transmitter signals, whereas the same in the upper ionosphere has been studied using ionospheric total electron content (TEC) measurements with a dual frequency GPS receiver available at Agra station. It has been shown that ionospheric perturbation due to the above earthquakes occurred 11–15 days prior to the main shocks. The authors have calculated atmospheric gravity wave modulation index (AGWMI) also and suggested atmospheric gravity waves (AGW) responsible for ionospheric perturbations.

In the present paper, we extend the work of Singh et al. (2018), and examine the response of Ultra Low Frequency (ULF) magnetic field emissions recorded at our station to some of the major earthquakes considered by them. We analyze the data in detail by carrying out polarization and power spectral analysis and confirm the lithospheric origin of such emissions. In order to confirm that anomalies observed at Agra station are not caused by malfunctioning of sensors and global geomagnetic field perturbations (magnetic storms) we compare the data with those obtained at two other ULF stations in India namely Shillong (SLG, Geograph. 25.92°N, 91.88°E), and Kachchh (KCH, 23.78°N, 71°E) and a remote station Kakioka (KAK, Geograph. lat. 36.2°N, long. 140.2°E) in Japan.

2. Experimental setup and method of data processing

The routine monitoring of ULF magnetic field emissions at Agra Station in India (Geograph. lat. 27.2°N, long. 78°E) has been in progress ever since the year 2002 except for a large period gap between 2013 and 2015 due to replacement of sensors and other hardware by new units. The new system has been working regularly since November 2016. The ULF data obtained at this station has been utilized to study precursors of earthquakes (Kushwah et al., 2005; Chauhan et al., 2009; and references therein) and study of Schumann resonance phenomena (Singh et al., 2014; Singh and Pundhir, 2014; and references therein).

The experimental setup is similar to that used by our group earlier (Kushwah et al., 2005, 2009; Chauhan et al., 2009; Singh et al., 2014; Singh and Pundhir, 2014). In brief, we mention here that the system employs a 3-component search coil magnetometer (Lemi 30), communication and data acquisition system (CAM unit), and software (Lemi30i) which were procured from LVIV Center of Space Physics Institute, Ukraine where LVIV is the name of the city of Ukraine. The three sensors of the magnetometer are induction coils of length 870 mm and diameter 85 mm whose detailed specifications are given by Singh et al. (2014) and Singh and Pundhir (2014).

The first installation of sensors and other hardware was demonstrated to our group by an engineer who visited our place along with the system. The three sensors oriented along North-South (X-Component), East-West (Y-Component) and vertical (Z-component) directions separated by about 2.5 m are buried 1.5 m underground in agriculture fields of the college which are connected to data acquisition and storage units

(CAM and PC with software) placed in an observation room with specially recommended cables (each cable has to have five twisted pairs of multiple-strand wires, each in one common shield). The distance between the sensors and the observation room is about 150 m (less than 200 m as recommended by the manufacturers), hence the length of the cables. The three cables from X, Y, Z sensors are placed in a PVC pipe and taken to observation room 1 foot underground. Common grounding is done for all the sensors and cables near the observation site 10 feet underground through an expert electrical engineer.

The sensors are to be protected from pilferage of water and the location is so chosen that there should be no magnetic material (source of ferromagnetism) around, no big trees, railway lines, and electric wires etc. which may produce artificial emissions to be picked up by the sensors. The amplifier outputs of the sensors are coupled to low pass filter which provides deep rejection of frequencies higher than 30 Hz (maximum measuring frequency range). Additional noise separation at frequencies near to the mains frequency is provided by the compensation of the magnetic field with the frequency along the sensor core which

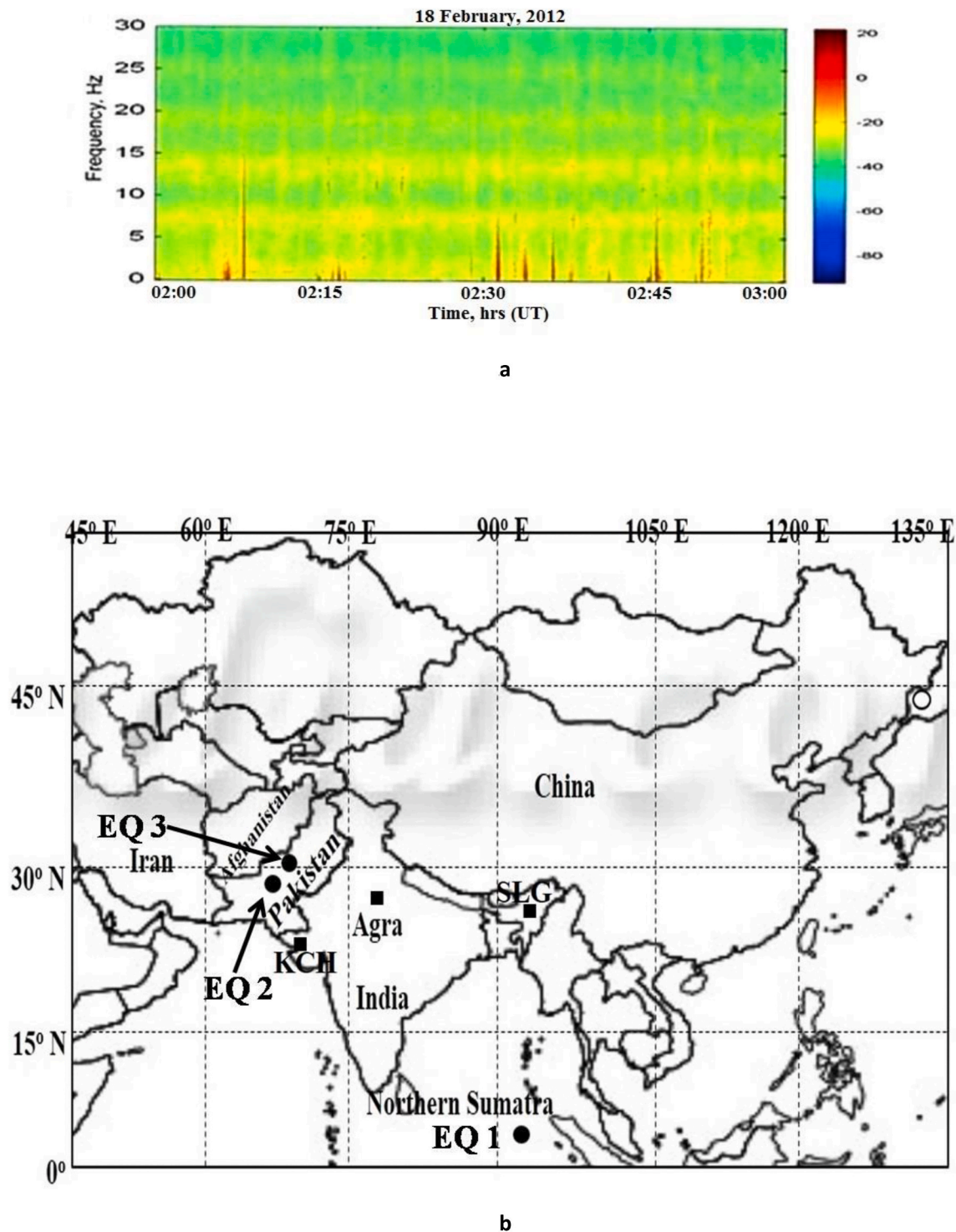


Fig. 1. (a) An example of Schumann resonance phenomenon recorded on 18 February, 2012 at Agra showing four SR lines. (b) Map of India and surrounding countries showing the location of earthquakes (solid circles) and observing station (Solid Square).

is realized by a negative feedback channel.

The location of the sensors is chosen for good quality data. This is done by placing the sensor at different places in the agriculture field and simultaneously looking at the computer monitor for clear Schumann resonance lines. It is well known that Schumann resonance lines appear only in noise free environment. An example of Schumann resonance (SR) phenomenon is shown in Fig. 1a which was recorded on 18 February 2012 at Agra showing four SR lines. The SR phenomenon is characterized by resonant lines caused by standing waves at the frequencies of 8 Hz, 14 Hz, 21 Hz, etc. which are clearly seen in the figure.

3. Results

Any study that attempts to test the hypothesis that ULF pulses occur precursory to earthquakes needs to include (i) multiple ULF sensors to remove local sources and identify sensor system malfunctioning issues (ii) a long time series of data to study showing that precursory signals are unique, reproducible and statistically significant and (iii) quantization of the noise from natural (e.g. lightning and solar terrestrial) and artificial (e.g. power grid and electric trains) sources. In the present paper, attempts have been made to take all of these points into consideration and analyze the data accordingly. Singh et al. (2018), have considered five major earthquakes occurred in Indian subcontinent during the years 2011–2013 from United States Geological Survey (USGS) website <http://earthquake.USGS.gov/earthquakes/>. Here, we consider three of these earthquakes for the months in which the ULF data are available with us and also VLF and TEC results of Singh et al. (2018) are published. The details of these earthquakes are given in Table 1.

The table shows the days, time, location (latitude and longitude), depth and magnitude of the three earthquakes along with distances of their epicenters from the Agra station. The location of these earthquakes and observing station (Agra) are also shown in the map of Fig. 1b in solid circles and solid square respectively. In our earlier studies (Kushwah and Singh, 2004; Kushwah et al., 2005, 2007, 2009; Chauhan et al., 2009, 2012) we have found that ULF amplitudes are either enhanced or occurred in the form of bursts prior to the occurrence of earthquakes. They are not of magnetospheric origin (micropulsation) as they occurred during magnetically quiet periods. Further, they are not generated by lightning activities also. Keeping these results in view, we analyze the ULF amplitude data for the two months (April 2012 and September 2013) in which the three earthquakes mentioned in Table 1 occurred. In Fig. 2a,b, c we show the daily amplitude-time records of X-component of the emissions for the whole month of April 2012 (except 3 April for which data are not available) whereas in Fig. 3 a,b,c we show the same for the month of September 2013. The downward arrows indicate the days of earthquakes. The daily data are shown in three blocks of ten days each for clarity in the figures. However, Fig. 3c is divided further in two blocks because of a number of panels on some days. In these two figures following points are noteworthy;

- i. The data contain a number of ULF noise bursts (clusters of localized fluctuations in the amplitude) of varying amplitude and duration. These bursts occurred on 2, 4, 10, 11, 17, 19, 23, 26 and 30 April in Fig. 2a, b, c whereas on 8, 12, 13, 17 and 25 September in Fig. 3a, b, c and all are encircled.

- ii. The background level contains a number of spikes (thin vertical lines) of varying lengths which are noise interferences. Such noises were also reported by Li et al. (2015) in their ULF observations.
- iii. Fig. 2(b) shows two panels recorded on 11 April between 00:00–12:00 h and 12:00–00:00 h and Fig. 3c shows two panels on 23 September, three each on 24 and 28 September and two on 30 September.
- iv. In Fig. 3c the data show enhanced amplitude for 1 m 30s between 08:00:10 and 08:01:40 on September 24 and 20mn between 08:00:00 and 08:20:00 on September 28. The Y and Z components of the data are similar to that of X component except that there occurred noise bursts of varying amplitude and also the data are more noisy occasionally.

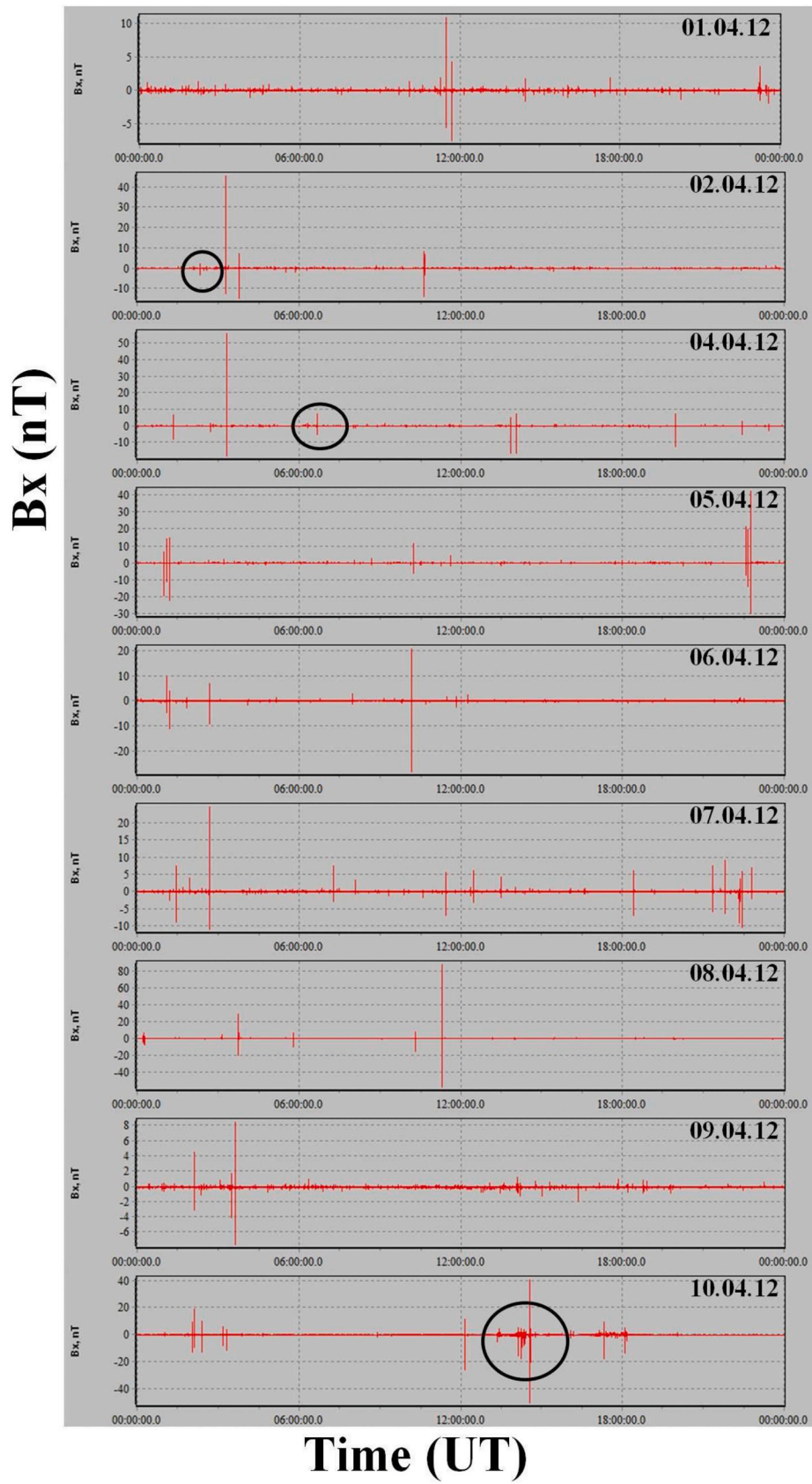
A pertinent question may arise as to what is the criterion of selecting the noise bursts associated with earthquakes and rejecting the others. In order to answer this we may mention here that we have expanded all the bursts in time and looked for any electromagnetic content in them. We found electromagnetic pulses of periods varying between 10 and 15s ($f = 0.06\text{--}0.1\text{ Hz}$) in many of them which are selected and encircled considering them associated with earthquakes. Others are rejected. The selected pulses are shown in Fig. 4(a and b).

Further, the reasons for the data occurring in two panels in Fig. 2b on 11 April and in two and three panels in similar way on the days of the earthquakes in Fig. 3c and also one day before and one day after the earthquakes need to be studied thoroughly. The enhancements in the data on the days of earthquakes (September 2013) are not seen strongly because data is not in a single panel. They are not caused by instrumental error because, if it was so, such problems would have come frequently on other days also. A possible reason may be due to overloading at the input of the amplifier as a result of strong earthquake signals on these days. In order to verify it we first examine the power spectrum magnitude on all the days of large bursts and enhanced amplitude data such as those on 10, 11 April and 24, 25 and 28 September. For a comparison, we consider two days data of unperturbed events such as those of April 1, 2012 and September 1, 2013 also. An example of the power spectrum magnitude obtained on April 11, 2012 is shown in Fig. 5. The measuring frequency range of the magnetometer is 0.01–30 Hz and power spectrum magnitude is also calculated by the software accordingly, but, since the amplitude peaks at frequencies $f < 2\text{ Hz}$ we have shown the variation of signal power at frequency scale of less than 5 Hz in Fig. 5. We determine the peak frequencies and corresponding power magnitudes from these graphs. Since both the horizontal and vertical scales are linear, the frequency and power corresponding to peak amplitude can be determined easily. The computed data are then verified from MATLAB software. The results are shown in Table 2(a). Then we calculate output power magnitude using the gain to decibel conversion relation $\text{dB} = 10\log(P_2/P_1)$ (Pozar, 2004) where P_1 is the noise level determined from the manufacture's manual of the sensors (which are $10^{-4}\text{ nT}/\sqrt{\text{Hz}}$ at 1 Hz and $7 \times 10^{-5}\text{ nT}/\sqrt{\text{Hz}}$ at 2 Hz) and P_2 is the output power magnitude. The values of output power magnitude (P_2) and how many times it is greater than the noise level (gain) are also given in Table 2(a). Table 2(b) shows the same results but for quiet days. These results will be discussed further in the next section (see Table 3).

We show in Fig. 6a ULF bursts observed at the three stations in India

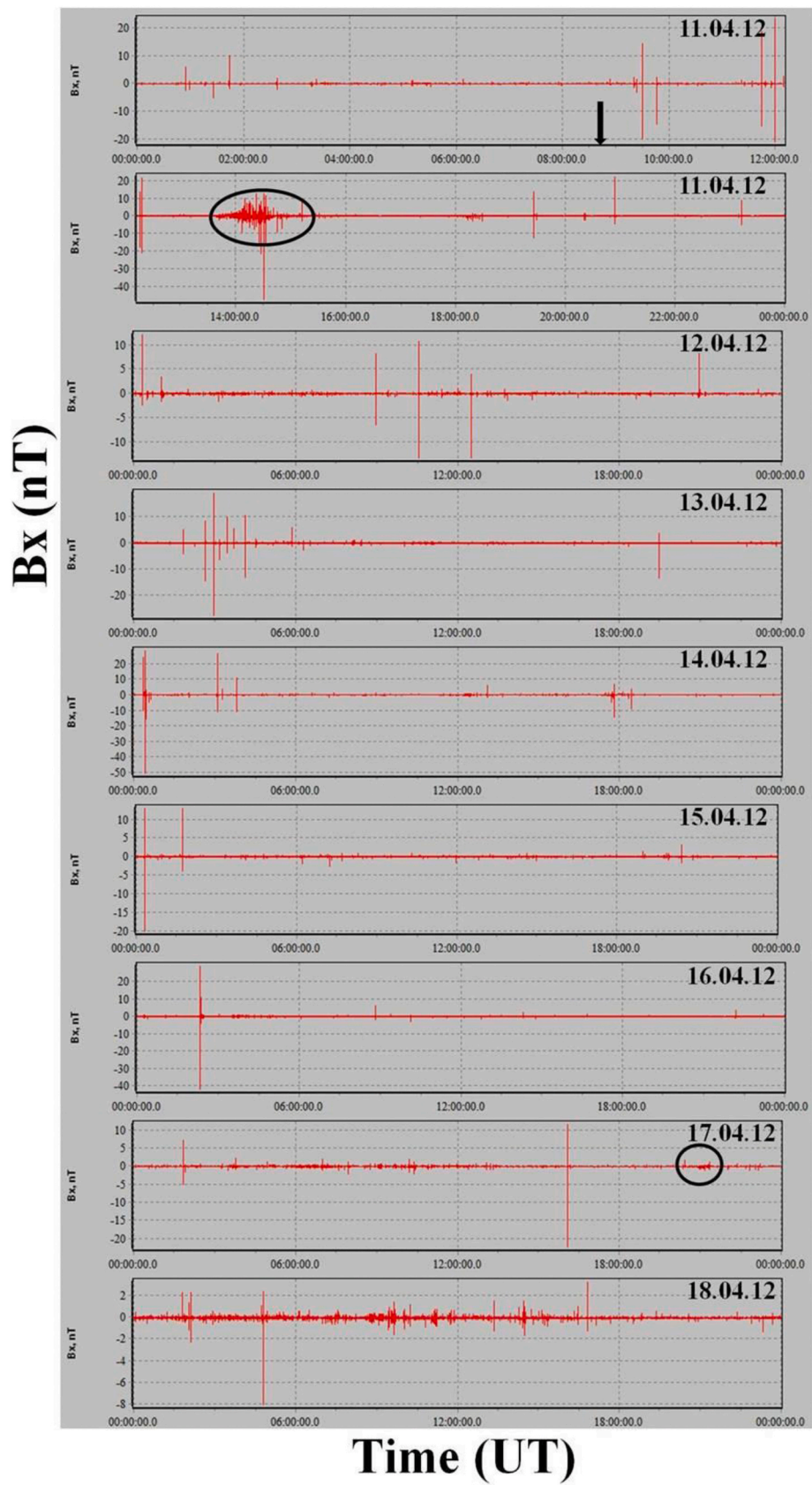
Table 1
Details of the earthquakes considered in the present study.

Earthquake	Date of earthquake	Time (UT)	Latitude (Deg.)	Longitude (Deg.)	Depth (km.)	Magnitude	Region	Distance from Agra(km)
EQ-1	April 11, 2012	08:38:35	2.3°N	93.0°E	10	8.5	Northern Sumatra	3196
EQ-2	September 24, 2013	11:29:48	27.0°N	67.7°E	10	7.4	Pakistan	1217
EQ-3	September 28, 2013	07:34:10	27.2°N	65.9°E	20	6.8	Pakistan	1196



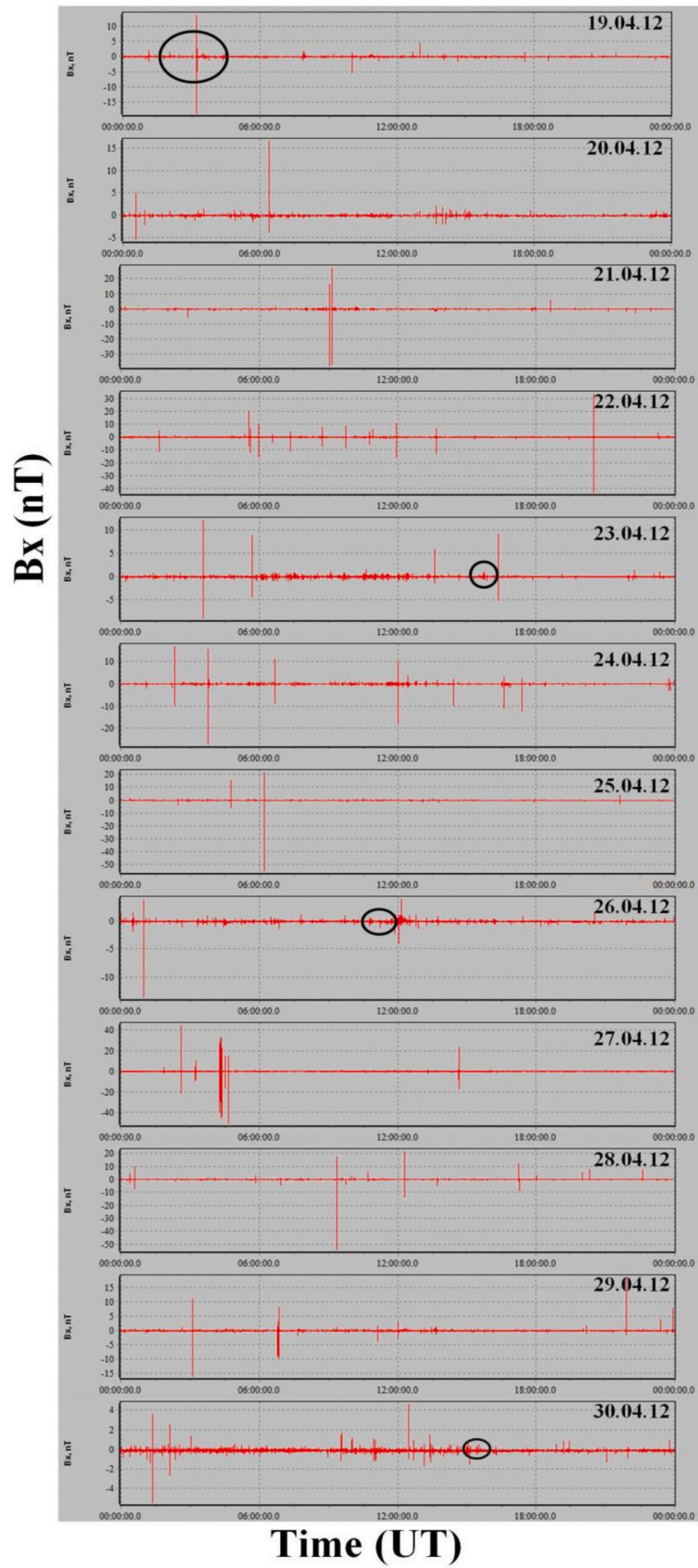
a

Fig. 2. (a,b,c) Daily amplitude time records of X component of the emissions for the whole month of April 2012. The anomalous bursts are encircled. Arrow indicate the date of earthquake.



b

Fig. 2. (continued).



c

Fig. 2. (continued).

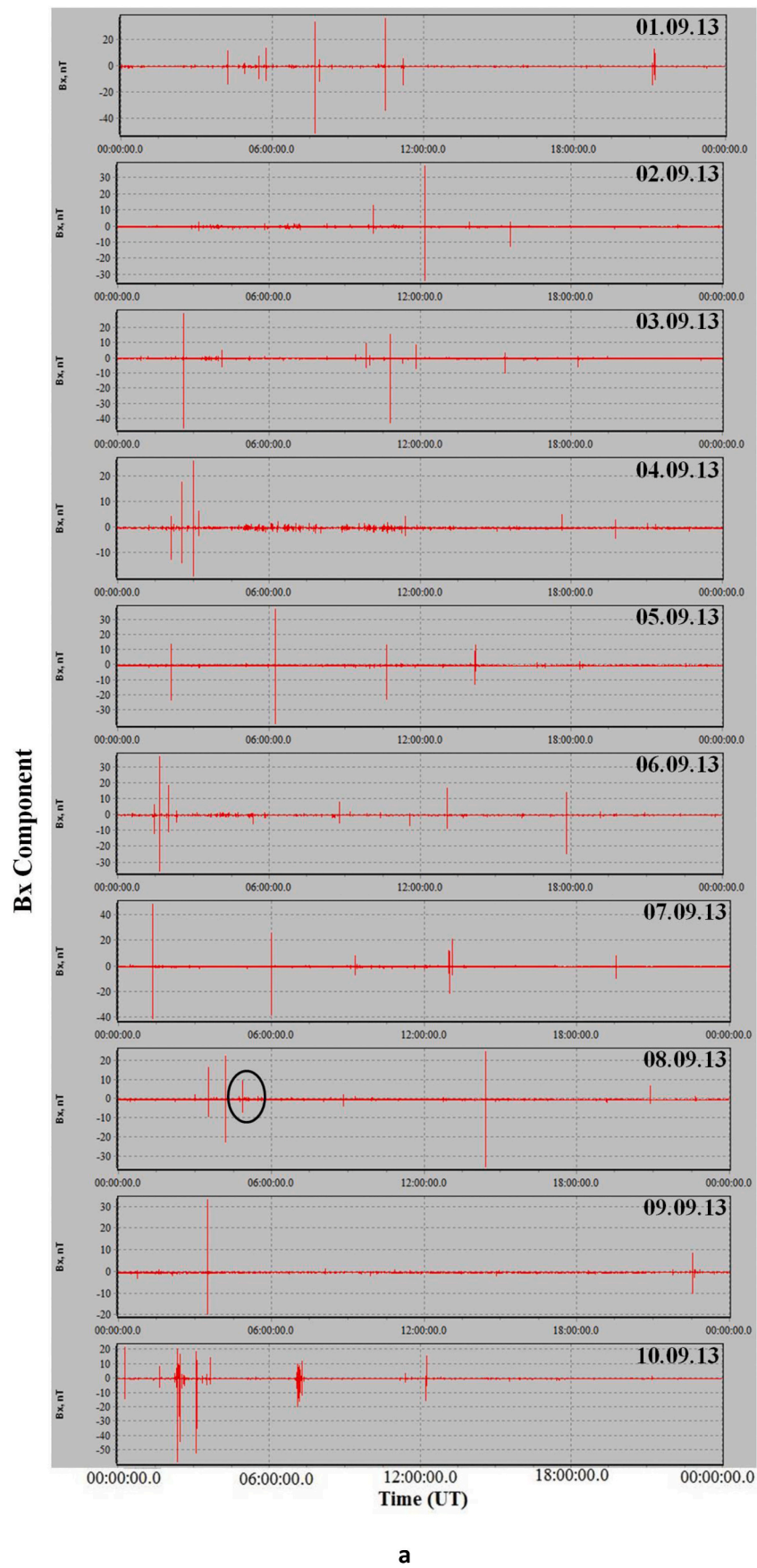


Fig. 3. (a,b,c) same as Fig.2 but for the month of September 2013.

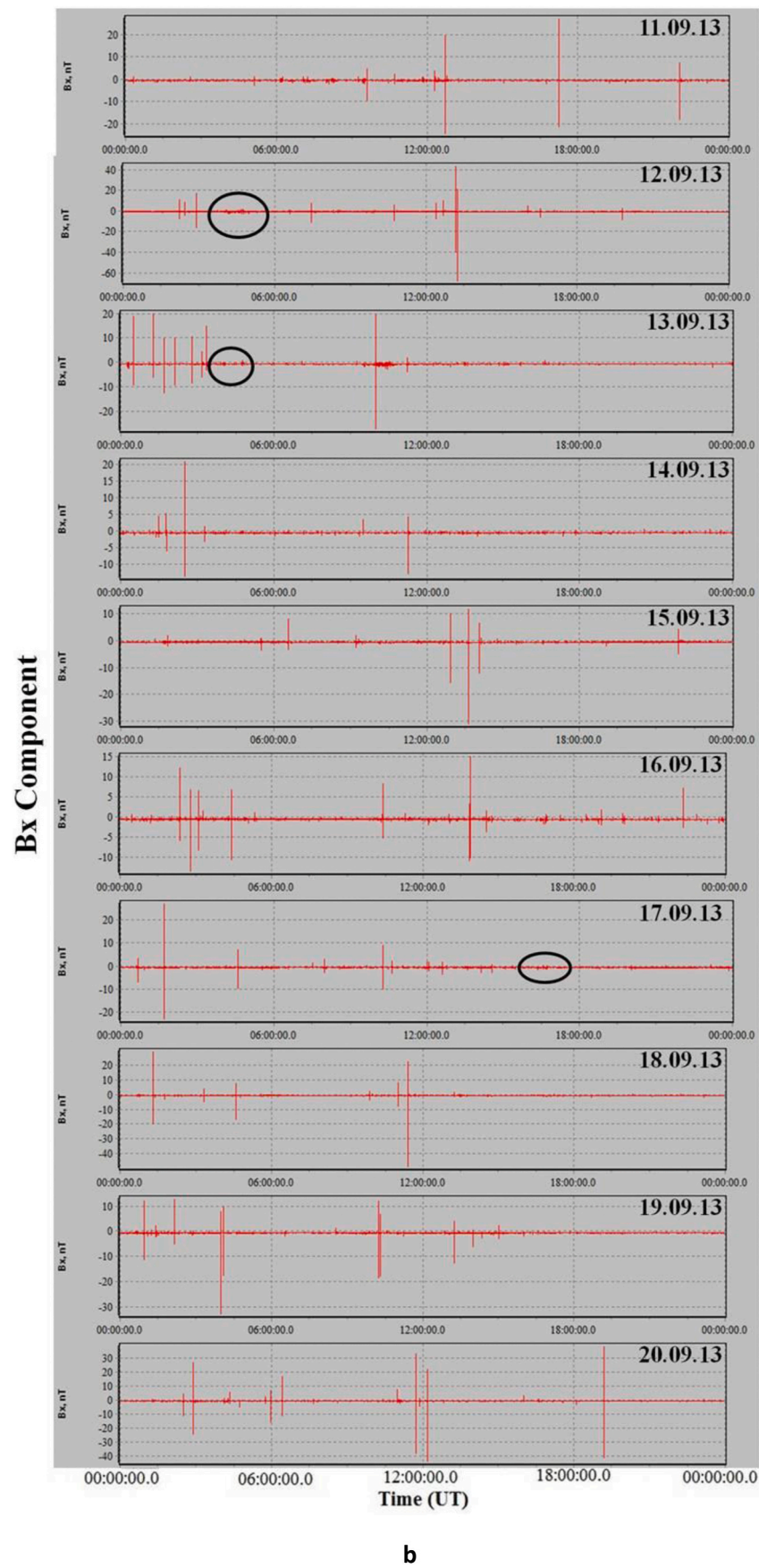


Fig. 3. (continued).

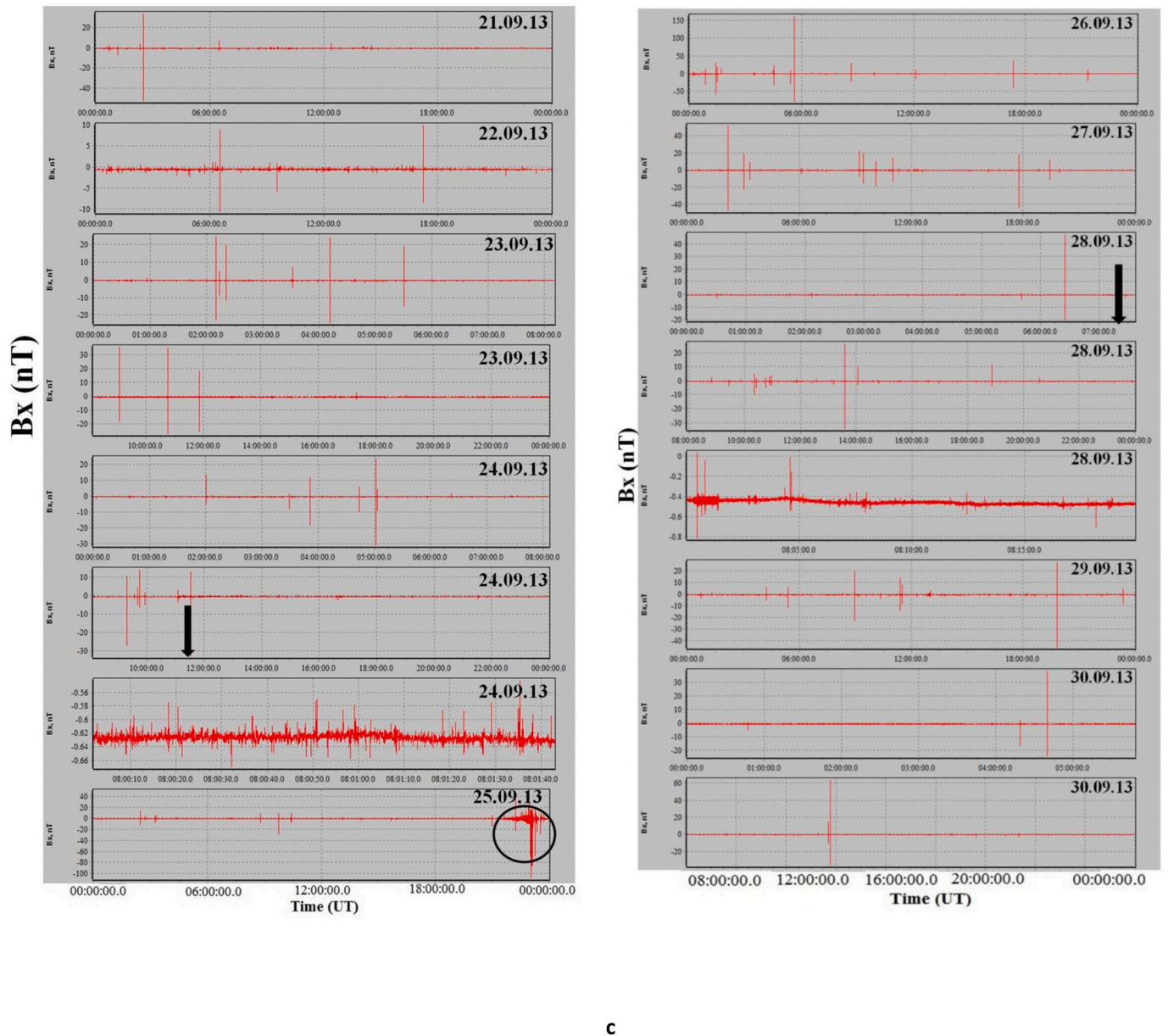


Fig. 3. (continued).

of Agra, Shillong (SLG), and Kachchh (KCH) for the same months of April 2012 (left panel) and September 2013 (right panel) in which the three major earthquakes occurred. All the encircled bursts in Figs. 2 and 3 observed at Agra and those observed at other stations are considered and their average amplitude per day is shown in Fig. 6a. The precursor bursts occurring before the earthquake day (shown by arrow) can be easily identified. Now we consider the ULF data recorded at a remote station Kakioka, Japan (Geograph. lat. 36.2°N , long. 140.2°E) employing a flux gate magnetometer ($f \leq 1$ Hz) for the two months and the results are presented in Fig. 6b. This station is located at distances of 6132 and 6932, 6786 km from the epicenters of Sumatra and Pakistan earthquakes respectively. We show here the averaged daily variation of the raw data (unprocessed, unfiltered, and sampling frequency = 1 Hz) taken from the website: <http://www.kakioka-jma.geo.jp/>. The top panel of this figure shows a minor enhancement (shown by arrow) in the data on 11 April (day of large earthquake, $M = 8.5$) and a deep reduction on 24 April due to magnetic storm occurred on 22 April ($\Sigma Kp = 40$, $Dst = -80$), whereas a decrease in the data on 24 September (day of the earthquake marked by arrow) is found in the lower panel of September

2013. Further, we process the ULF data available at Agra for the same months of April and September in the years, 2010, 2011, 2014, and 2017 and the results are shown in Fig. 6c. Although there is lack of data in many months, two points are noteworthy from this figure (i) a single earthquake of large magnitude $M = 6.3$ but occurred at large depths of 220 km produces a single burst as precursor (see the data of September 2010 in the top panel) (ii) multiple earthquakes of magnitudes $M < 6$ occurred at shallow depths may produce multiple bursts as precursors similar to those in the case of large magnitude shallow depth earthquakes observed at Agra and Shillong stations.

Fig. 7(a and b) show the variation of global magnetic field and solar flux parameters (ΣKp , Dst , $F10.7$) for a period of three months March–May 2012 (top) and August–October 2013 (bottom). Downward arrows in the figures indicate the days of the earthquakes. The data in Fig. 7a shows two magnetic storms one on 9 March and other on 22 April 2012 whereas the earthquake occurred on 11 April and ULF bursts occurred between 2 and 30 April which may not be attributed to these storms. Fig. 7b shows the whole month of September 2013 free from magnetic storms.

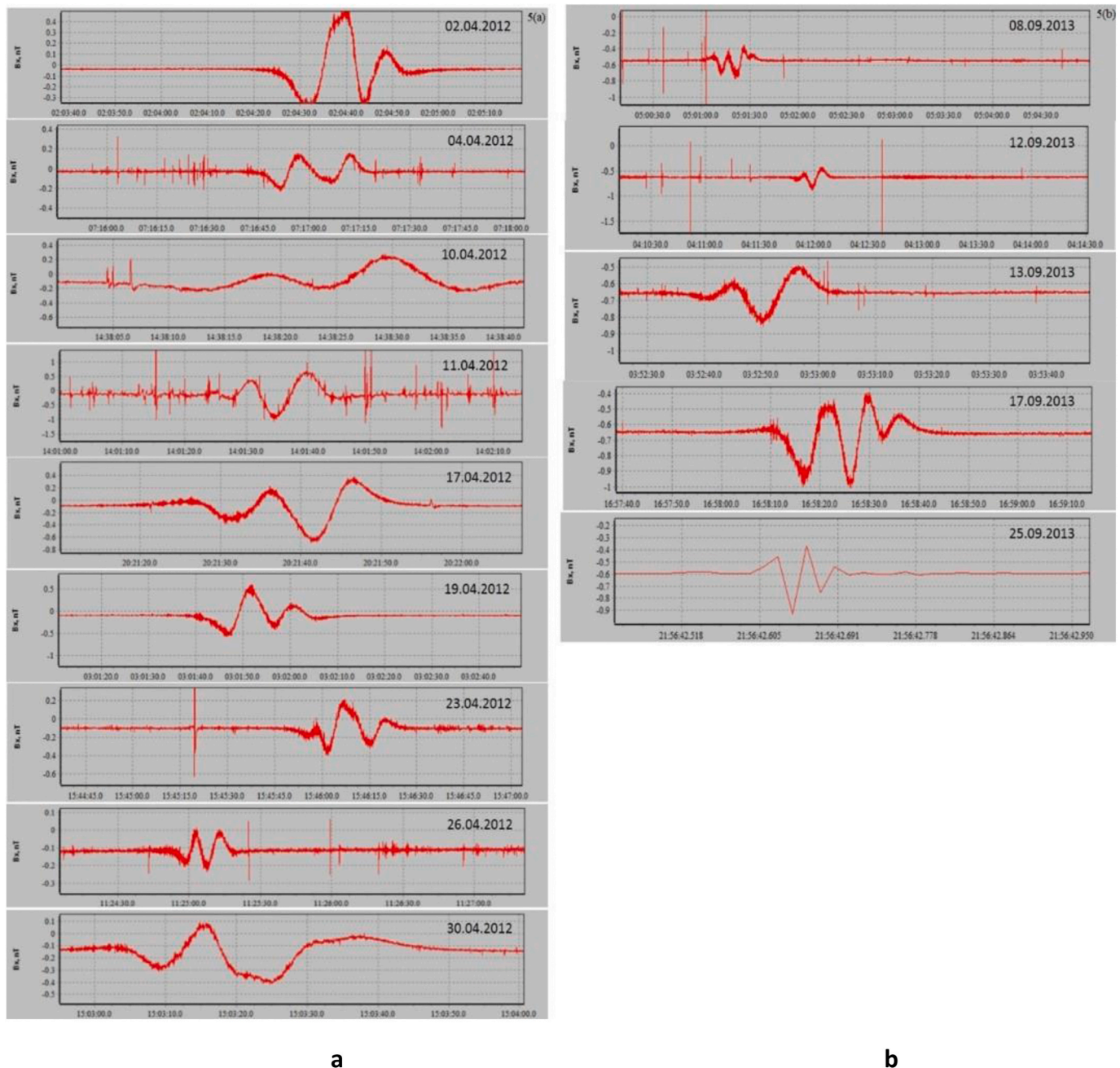


Fig. 4. (a) Short period electromagnetic pulses in the anomalous bursts recorded in the month of April 2012. (b) same as (a) but for the month of September 2013.

The months of April and September are totally free from lightning activity in North India including the observation site Agra. However, we show in Fig. 8a the variation of such activity in the month of April 2012 and September 2013 using the WWLLN data (obtained through the courtesy of Dr. Anirban Guha of Tripura University) collected within a block over Indian region formed by latitude and longitude ranges of 25° – 30° N and 60° – 100° E respectively. The figure shows occurrence of lightning strokes by histograms and on the days of occurrence of bursts shown by solid stars.

The polarization analysis of the ULF data is useful to ascertain the source of the signal whether in lithosphere or in ionosphere. It is for this reason that we have also carried out this analysis on the ULF data available with us. Fig. 8b shows the variation of polarization parameter Z/X for a period of three months, March–May 2012 and August–October 2013. Here Z is the vertical and X is the horizontal components of the ULF signal. Downward arrows indicate the days of the earthquakes.

Recently, our group (Swati et al., 2020) has done fractal analysis of the September 2013 data using Burlaga–Klein method. This month is chosen because there was no magnetic storm in this month. Since their results are relevant to our present analysis we reproduce Fig. 6 of their paper in Fig. 9 which shows the variation of fractal dimension and fractal exponent (solid curves) using statistical method of mean and standard deviation around the mean approach.

4. Discussion

The details of the three earthquakes considered from Table 1 show that one of them occurred at 08:38:35 h UT on 11 April whereas the other two occurred at 11:29:48 h and 07:34:10 h UT on 24 and 28 September respectively. If we consider the occurrence of amplitude bursts in relation to these earthquakes as considered by Kushwah et al. (2009) earlier who employed similar set of sensors and analysis

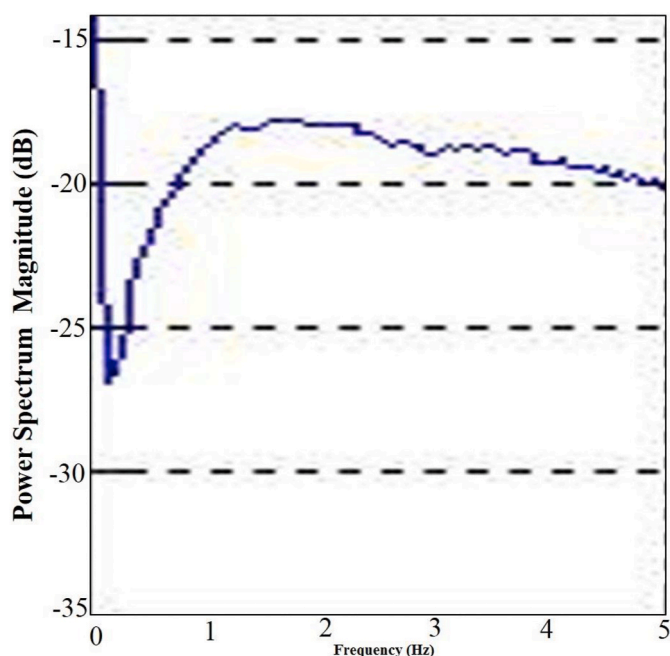


Fig. 5. Power spectrum magnitude for 11 April 2012.

Table 2(a)

The results of calculation of output power spectrum magnitudes and their variation with defined magnitude noise level.

S. No	Date	Frequency (Hz)	Power spectrum magnitude (dB)	Output magnitude (nT/ $\sqrt{\text{Hz}}$)	Gain
1.	April 10, 2012	0.701879	-34.356	3.10559×10^{-3}	31.06
2.	April 11, 2012	1.63187	-17.8402	4.169×10^{-4}	5.96
3.	September 24, 2013	0.779781	-31.6004	2.357×10^{-3}	23.57
4.	September 25, 2013	1.65927	-3.16259	9.6154×10^{-5}	1.374
5.	September 28, 2013	0.838323	-35.4545	3.472×10^{-3}	34.72

Table 2(b)

Same as Table 2(a) but for two unperturbed days.

S. No	Date	Frequency (Hz)	Power Spectrum Magnitude (dB)	Output Magnitude (nT/ $\sqrt{\text{Hz}}$)	Gain
1.	April 01, 2012	0.697017	-34.1349	3.0367×10^{-3}	30.367
2.	September 01, 2013	1.93548	-21.4573	5.988×10^{-4}	8.55

technique then the bursts occurred intermittently on 02 April, 09 days before the main shock of 11 April and during rest of the month as aftereffects, whereas on 08 September, 16 days before the earthquakes of 24 September and 20 days before that of 28 September. The burst occurring on 08 September may possibly be the combined effect of two earthquakes. However, it may possibly be due to earthquake of 24 September ($M = 7.4$) which is stronger than the other one. It is not clear whether the burst occurring on 25 September is precursor to the earthquake of 28 September or aftereffect of that occurring on 24 September or it may be the combined effect of these two earthquakes. The sources of these bursts lie in the corresponding earthquakes as

Table 3

Details of earthquakes considered in Fig. 6c.

S. No.	Date	Time	Lat.	Long.	Depth (km)	Mag.	Place
1	17-09-10	19:21:15	36.4	70.8	220	6.3	Hindu Kush region, Afghanistan
2	04-04-11	11:31:43	29.7	80.8	26	5.3	Nepal-India border region
3	10-04-11	9:02:47	31.4	100.8	43	5.4	western Sichuan, China
4	04-04-14	22:40:35	28.2	103.6	25	5.4	4 km SE of Xiluodu, China
5	25-09-14	2:31:57	27.3	65.8	52	5.4	100 km WSW of Khuzdar, Pakistan
6	26-09-14	4:21:24	12.5	95.2	20	5.5	285 km ENE of Port Blair, India
7	16-09-17	10:11:33	42.2	83.5	16	5.4	71 km NE of Kuqa, China
8	29-09-17	13:49:57	39.8	68.0	14	5.1	34 km SSE of Jizzax, Uzbekistan

depicted by the electromagnetic pulses inherited by them (shown in Fig. 4a and b).

From the Tables 2a and 2b we see that the power output magnitudes and hence the gains at $f \leq 1$ Hz are comparable to each other except on 24 September when it is attenuated due to strong emissions coming from the earthquakes of magnitude $M = 7.4$ at the input of the sensor amplifiers, whereas the same at $f > 1$ Hz are reduced as compared to that of the unperturbed day of September 1, 2013. The lowest value on 25 September is due to combined effects of the two earthquakes occurring on 24 and 28 September. The results presented in these tables show that breakup in panels in Figs. 2 and 3 is possibly due to changes in gains of the amplifier due to earthquakes. However, this result does not influence the precursory nature of ULF emissions as noted from Figs. 2 and 3. Here it may be mentioned that, although the measurements are on a wide frequency range (0.01–30 Hz) the peak frequencies and corresponding power amplitudes close to pre-seismic and seismic days shown in Table 2a as compared to those on undisturbed days of Table 2b are not due to the neighboring geo-system's pre-earthquake behavior but are associated with the main shocks of the earthquakes. This will be supported by the results of the study of self-organized criticality (SOC) for the month of September data using fractal analysis method the results of which will be presented later. The appearance of data in increased number of panels in the two months of April 2012 and September 2013 are due to seismic activities in these months only because in no other months such cases have been observed except, of course, in those months in which power supply was a problem.

It may be seen from Fig. 6a that occurrence pattern of bursts at Agra and Shillong stations are almost similar with small variations in amplitude and dates of occurrence, whereas it is not similar at Kachchh. There is no data at Kachchh station in the month of April 2012; the same in September shows only two clear bursts on 12 and 13 September before the earthquake of 24 September. On some other days, the data are not in the form of bursts as found at Agra and Shillong stations, but they show enhanced amplitudes for long period of many hours and appear similar to that short period data displayed in the panel of 24 September of Fig. 3c. This is possibly due to the fact that this station is nearer to the epicenters of the two earthquakes occurred in Pakistan region and detected strong emissions for a prolonged period of time. The data corresponding to the remote station of Kakioka, Japan also does not show occurrence of bursts as found at Agra and Shillong stations except

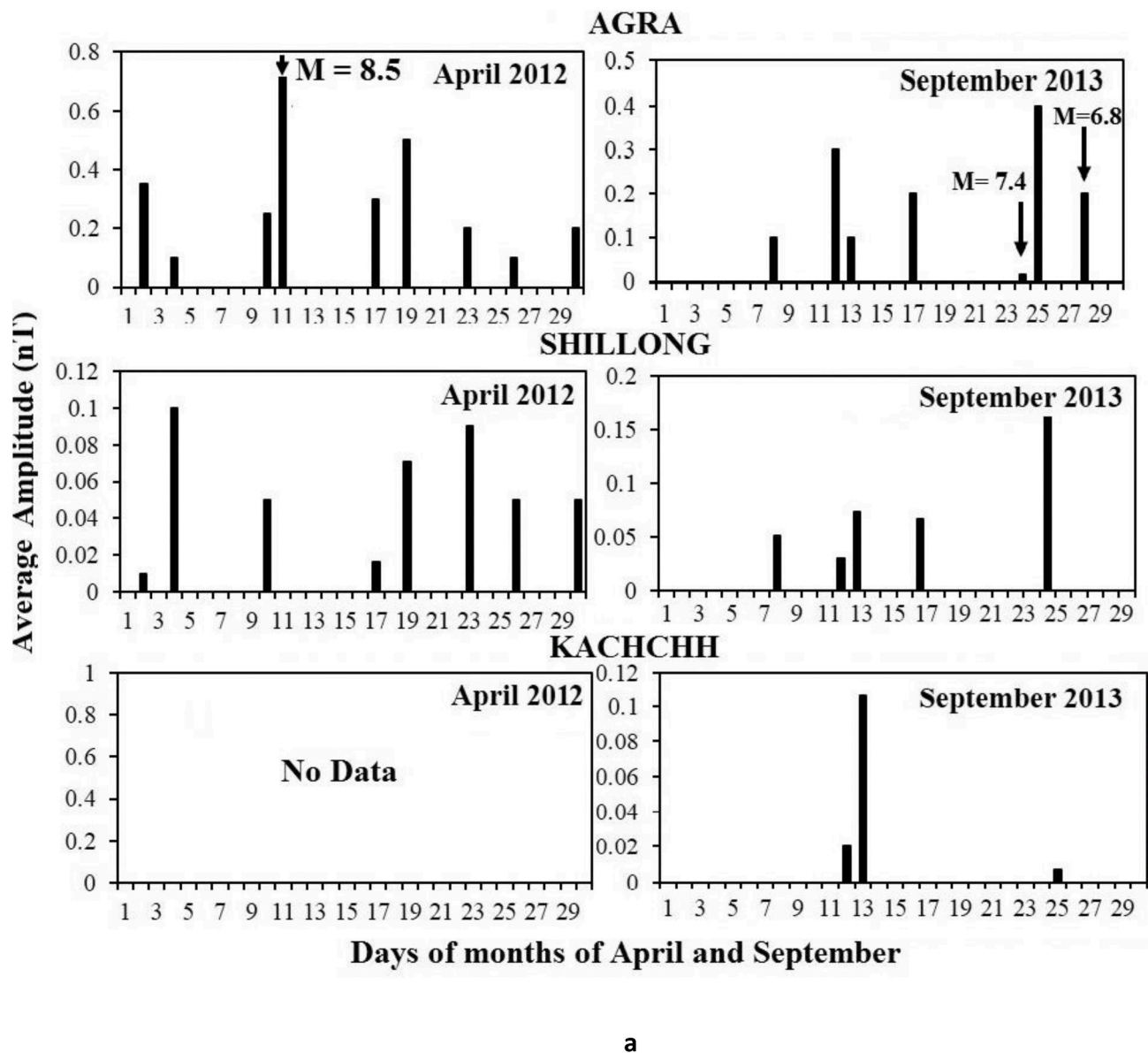


Fig. 6. (a) ULF data analysis at three stations of Agra, Shillong, and Kachchh for the months of April, 2012 and September, 2013. (b) ULF unprocessed and unfiltered data obtained from Kakioka station, Japan. (c) ULF data analysis for the month of April and September in four years between 2010 and 2017 at Agra station.

minor disturbances on the days of the earthquakes. The study of long period data at Agra station support the findings that large magnitude shallow depth earthquakes are indeed associated with ULF bursts. From the results presented in Fig. 6a–c it is clear that the ULF bursts observed in Figs. 2 and 3 are neither due to malfunctioning of sensors nor due to ULF emissions of magnetospheric origin (micropulsations) but they are associated with the major earthquakes in the months of April 2012 and September 2013.

The variation of magnetic storm and solar flux parameters for a period of three months including the months of April 2012 and September 2013 (Fig. 7a and b) show that our results are not at all influenced by geomagnetic disturbances due to solar terrestrial interaction. While the month of September is totally free from such disturbances, there was one large disturbance in the month of April, but it came 14 days (on 25 April) after the occurrence of the earthquake.

From Fig. 8a we find that the bursts occurred mostly on those days on which the number of lightning strokes was low and no bursts on days which were having intense lightning. Hence, the possibility that our data

were influenced by lightning activities is ruled out also.

The polarization ration condition (i.e. Z/X) determines the origin of the emissions in the lithosphere or ionosphere/magnetosphere (Hayakawa et al., 1996). However, the condition $Z/X > 1$ depends whether the earthquake occurred close to or far away from the observing station. In case the earthquake occurred close to the observing station the generated linear current will have a strong horizontal and weak vertical magnetic field. The condition is reversed in the case the earthquake occurred far away from the observing station because the horizontal magnetic field will be severely attenuated and the vertical magnetic field will be strong. Although the polarization parameters depend on the geomagnetic activity (Hayakawa et al., 1996), here, since the distances between the epicenter and observing station are large, the condition $Z/X > 1$ would apply (Hayakawa et al., 1996, 2011). We find from Fig. 8b that the ratios are significantly enhanced either on the same day or before the occurrence of the earthquake (marked by arrows). This figure confirms the association of anomalies with the earthquakes.

The self-organized criticality (SOC) behavior of ULF data are studied

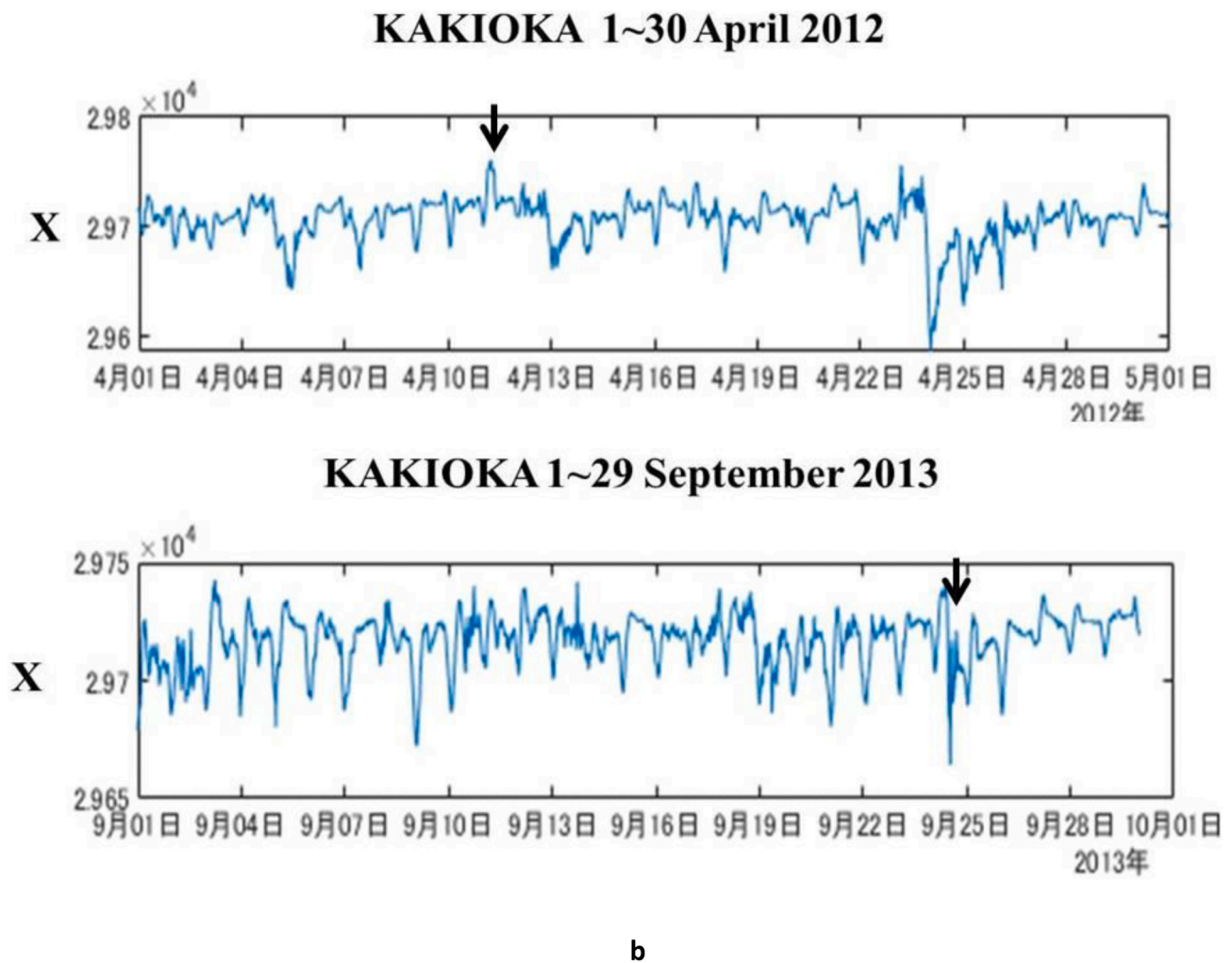


Fig. 6. (continued).

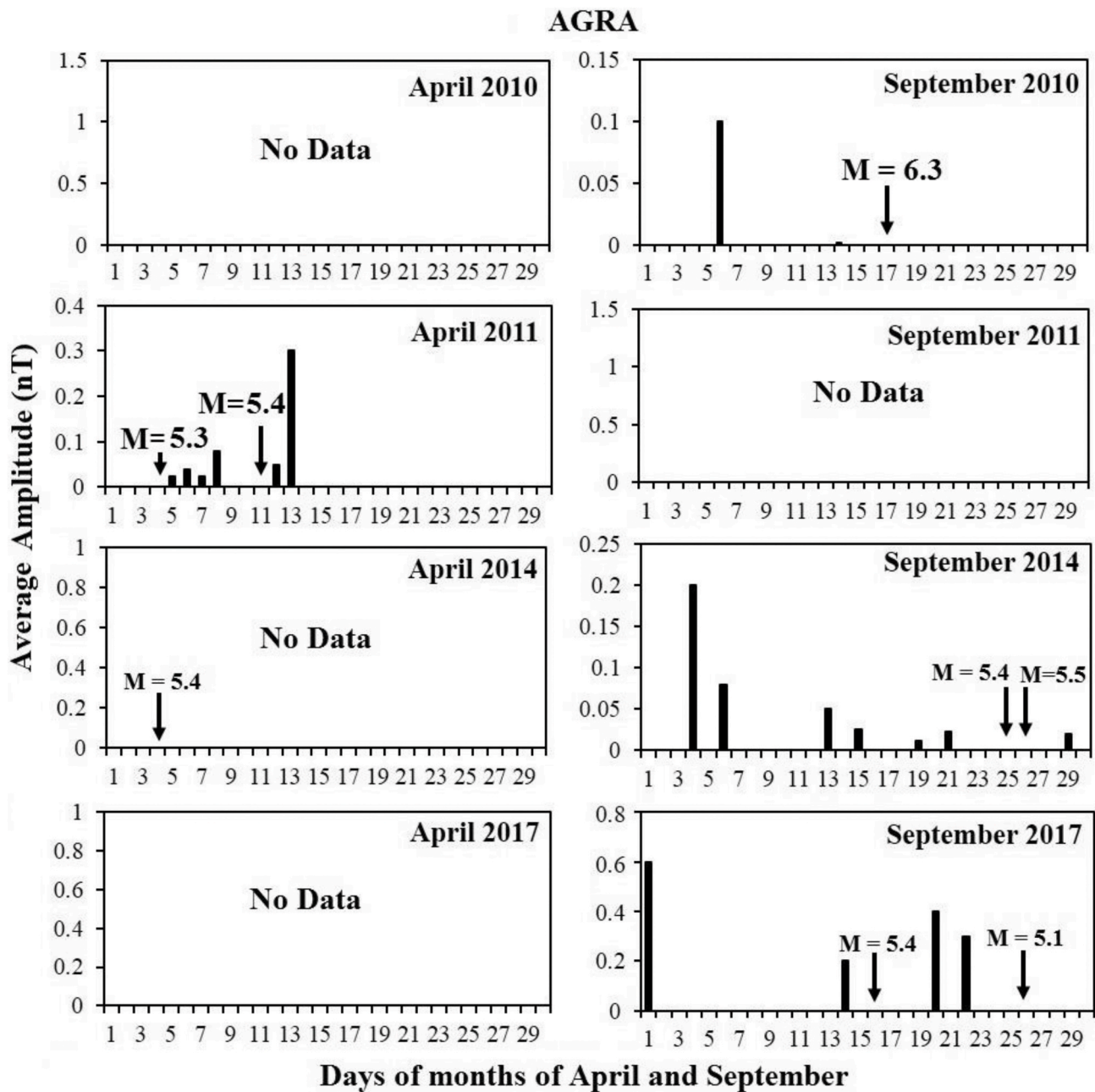
normally using two methods i.e. fractal analysis or natural time analysis (Hayakawa et al., 2015). We have studied such behavior using fractal analysis method of Burlaga-Klein (1986) applied on September data of Agra station because there was no magnetic storm occurred in this month (Swati et al., 2020). Here we reproduced Fig. 6 of this paper in Fig. 9. The figure shows the variation of fractal dimension and fractal exponent by solid line curve whereas horizontal straight lines show the mean and standard deviation. The variation shows clearly anomalous enhancement in fractal dimension above $m + \sigma$ line and corresponding dip in fractal exponent below $m - \sigma$ line on 15 September, 9 and 13 days before main shock of two earthquakes of 24 and 28 September, respectively. Although the precursory days differ by a week as compared to those in Fig. 3, the analysis justifies the occurrence of precursors in much advance period from the main shocks of earthquakes.

It is worthwhile to mention here that, although we have employed Burlaga-Klein method to carryout fractal analysis on ULF September 2013 data, there are two more methods which have been employed extensively. These are spectral slope of power frequency spectra (Hayakawa et al., 1999) and Higuchi method (Higuchi, 1988). Fractal analysis has been applied not only to the ULF frequency range (Smirnova et al., 2004; Gotoh et al., 2004; Ida et al., 2012 and references therein) but also to different frequencies ranges (DC, VHF etc.) (Eftaxias et al., 2002; Varotsos, 2005; Yonaguchi et al., 2007). Although Higuchi method was found better when compared to the other two methods in specific test-data sets of fractal Brownian motion with white noise (Gotoh et al., 2004) the Higuchi and Burlaga-Klein methods yielded

similar behavior for the fractal dimension, although absolute values differ from each other (Smirnova et al., 2001). Gotoh et al. (2003) and Smirnova et al. (2004) studied the fractal characteristics of ULF time series data related to Guam earthquake and seismic swarm of Izu peninsula in Japan employing all the three methods mentioned above and found common features in the variation of fractal dimension and fractal exponent. It is for this reason that we have employed Burlaga-Klein method only in our analysis.

As far as the increase in fractal dimension (D) ranging up to 3 is concerned, we mention here that we have used unfiltered data in our analysis. Smirnova et al. (2004) have used filtered data and found spectrum slope β varying between 0 and 2.5 with mean value around 1.8. In some frequency bands D goes as high as 3 to 4. In the light of these results our result in Fig. 9 may not be questionable.

The question of generation and propagation of ULF emission is still not solved exactly. While some workers (Fenoglio et al., 1995) have proposed electrokinetic effect in which fluid flows non-uniformly due to pore pressure changes in the rupture zone of the earthquake generating electromagnetic radiations, the others emphasize microfracturing of rocks or opening of an ensemble of cracks in the focus zone of the earthquake (Molchanov and Hayakawa, 1998). Microfractures have sizes in the range of 10^{-4} - 10^{-1} m² and the number of cracks is estimated in the order of 10^6 - 10^7 m⁻³ generated at the time scale of approximately microseconds. The velocity of opening is approximately 10^3 m/s which is in the range of seismic waves. The electrokinetic effect may hold good for certain distances only as compared to microfracturing



c

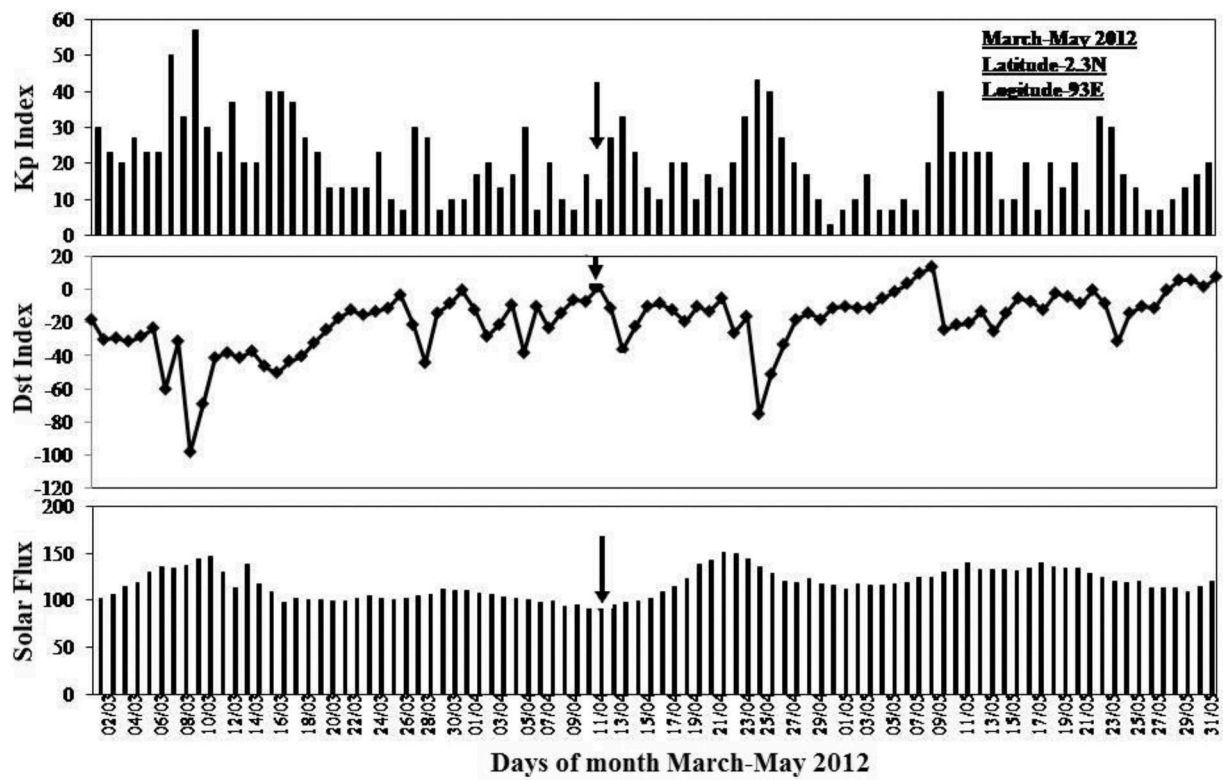
Fig. 6. (continued).

electrification which may account for long distance propagation of emitted radiation.

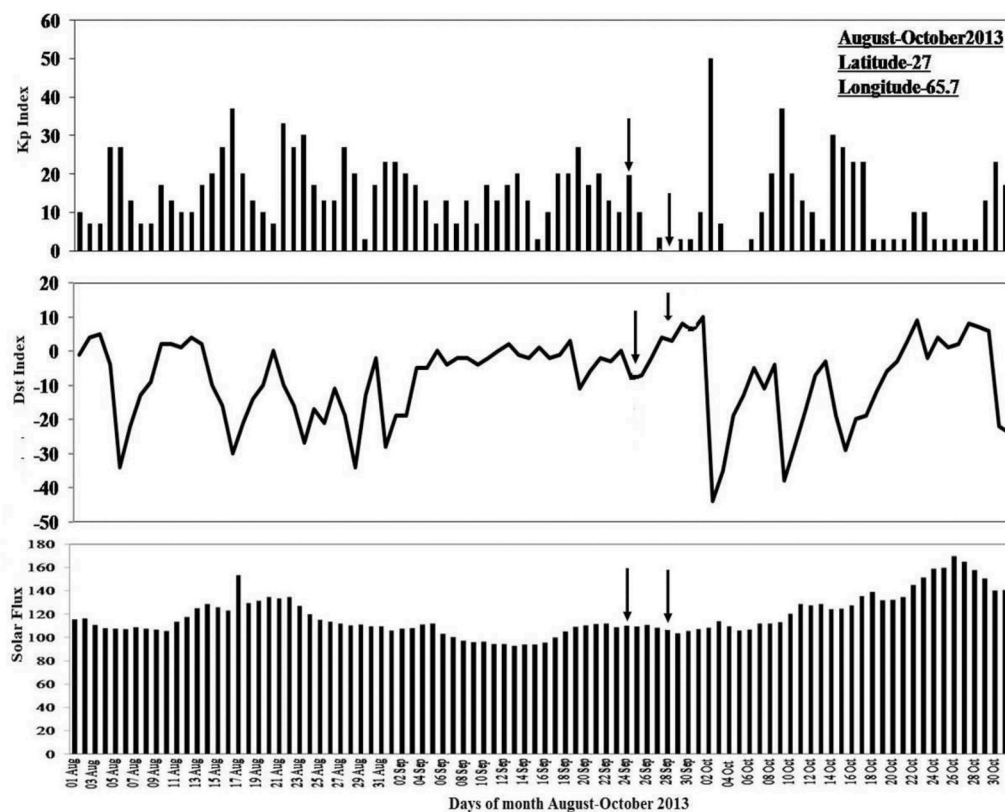
Many workers (Hattori et al., 2004; Hayakawa et al., 2007; Molchanov and Hayakawa, 2008) have inferred from two decades of their ULF observations that the ULF anomalies can be detectable in an area of radius 100 km for earthquakes of magnitude $M = 7.0$ and 70–80 km for magnitude $M = 6.0$. In the light of these results the anomalies observed by us may be questionable because we observed them at large distances ranging from 1196 km – 3196 km (see Table 1). In order to answer this we may submit here that firstly, the earthquakes considered by us are of large magnitude ($M = 6.8$ – 8.5) so that our observing station may be under the influence zone of these earthquakes. Secondly, while the short distance propagation may be true for homogenous earth in which electromagnetic signal may decay exponentially, it is not true in real

sense because the earth is highly inhomogeneous in which ULF signals can propagate to long distance (Varostos et al., 1998; Huang and Ikeya, 1998). It is for this reason that several authors have reported ULF anomalies at long distances of 500 km and more (Du et al., 2002), more than 600 km (Kushwah et al., 2009) and 2000 km (Ohta et al., 2002). Hence the distance factor in observing ULF anomalies in present studies does not arise.

Many workers have suggested generation of atmospheric gravity waves (AGW) from the variation of meteorological parameters (temperature, pressure, humidity etc.) over the epicenters of the earthquake and causing perturbations in the ionosphere (Molchanov et al., 2003; Schekotov et al., 2006; Nakamura et al., 2013). In fact, AGWs are taken as important tool for lithosphere-atmosphere-ionosphere (LAI) coupling (Kopytenko et al., 2009). Such waves propagate upward in atmospheric

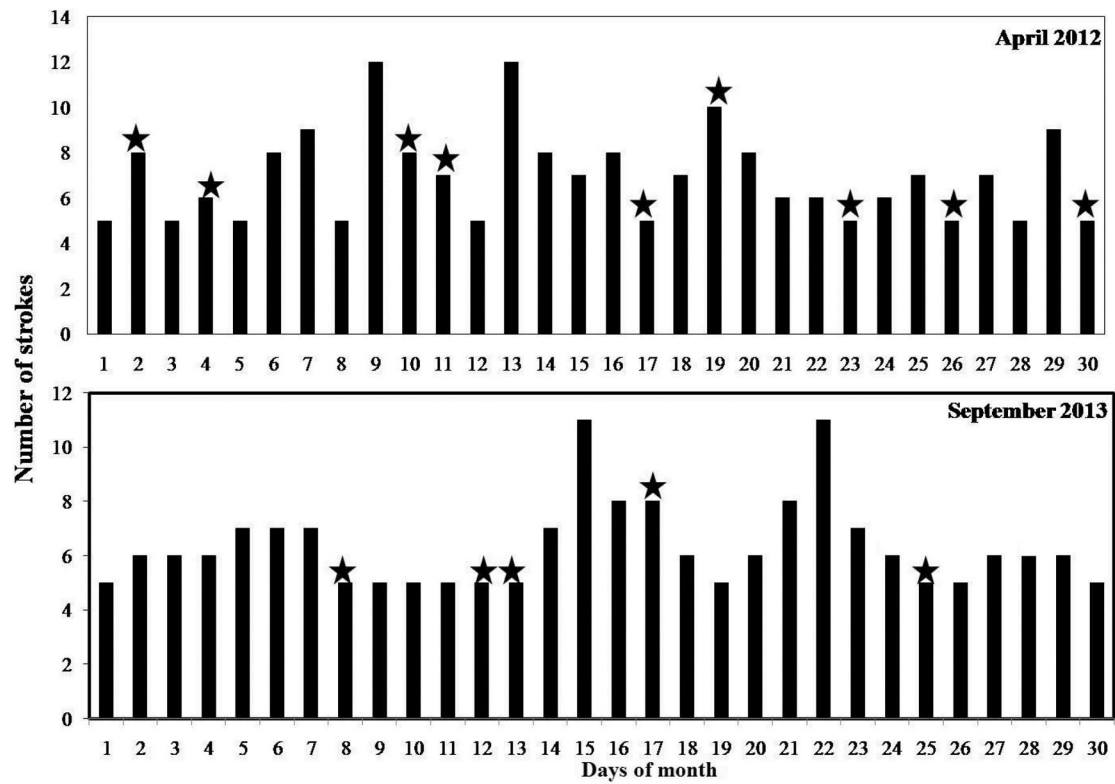


a

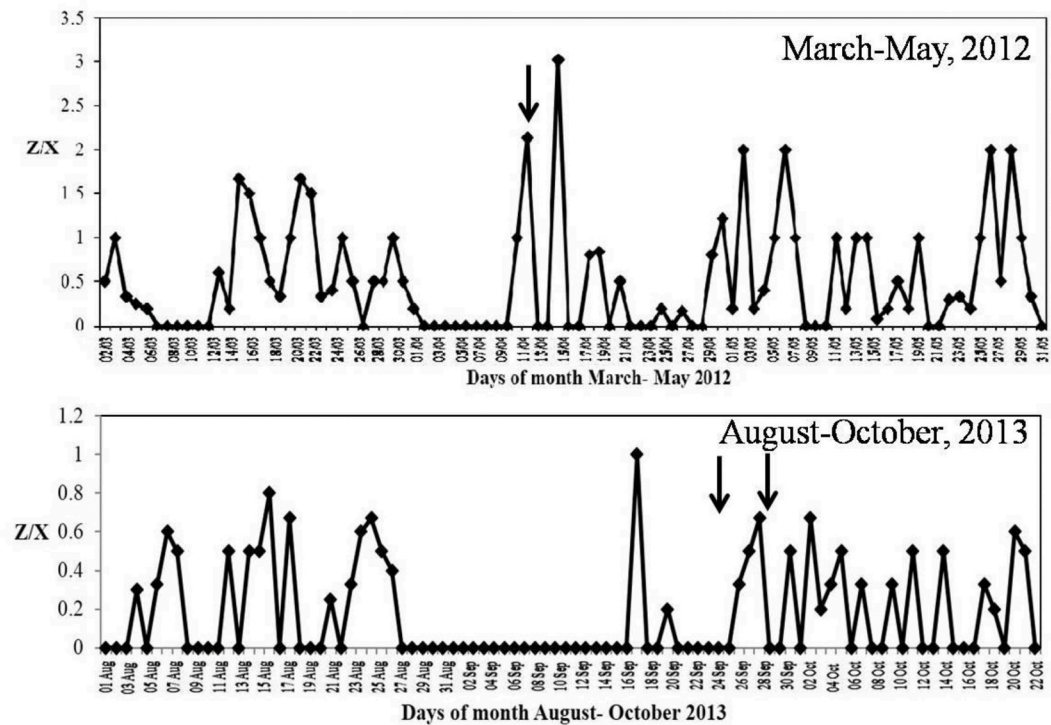


b

Fig. 7. (a) Dst and Kp index variation for the months of April 2012 and September 2013. (b) The same as Fig. 7a but for the month of September, 2013.



a



b

Fig. 8. (a) Variation of lightning activity over India during April, 2012 and September, 2013 (shown by histograms) and occurrence of ULF bursts (solid stars). (b) Variation of polarisation ratio (Z/X) for the months of April 2012 and September 2013.

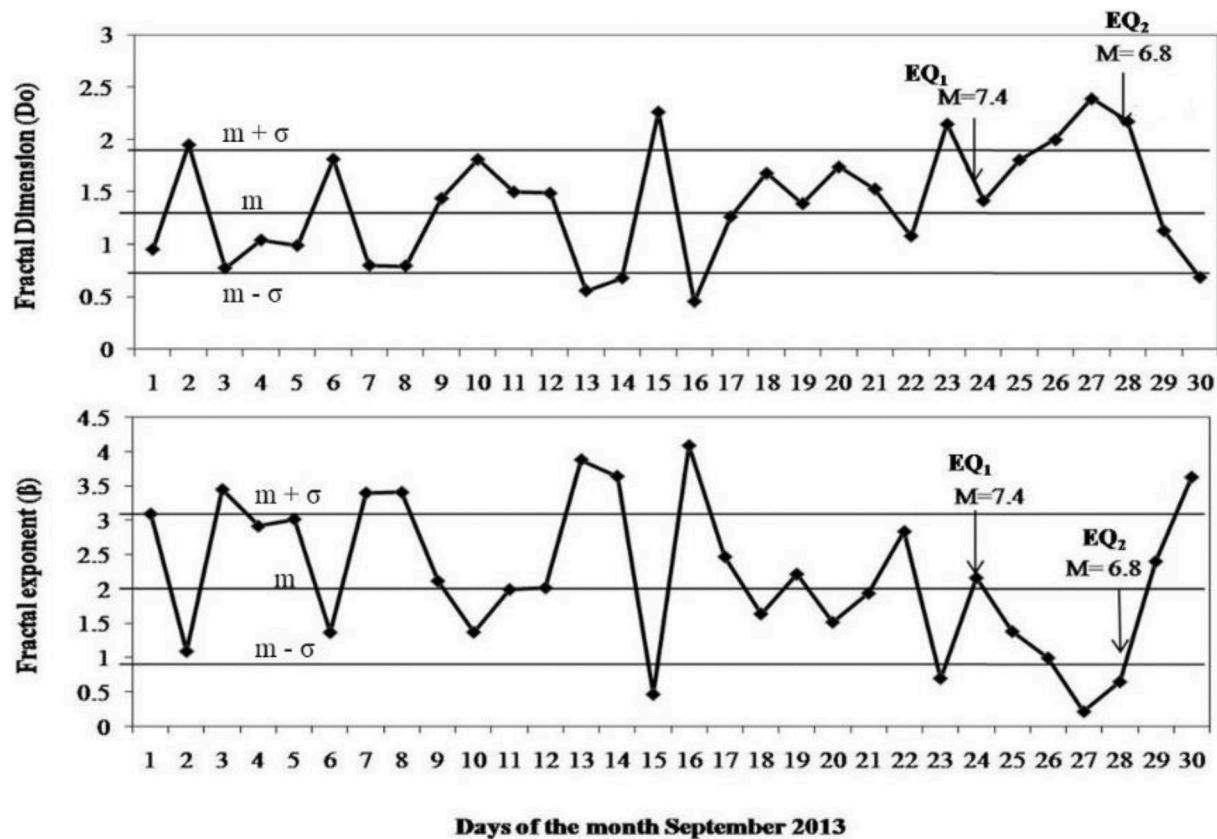


Fig. 9. Variation of fractal dimension (top) and fractal exponent (bottom) in the month of September, 2013 (reproduced from Swati et al. 2020).

dynamo region where they induce ionospheric perturbation and modulation causing simultaneous change in ground based ULF emission (Nakamura et al., 2013). Singh et al. (2018), have also emphasized the influence of AGW in lower and upper ionosphere which they studied using VLF and TEC methods. Recently Phanikumar et al. (2018) and Yang et al. (2019) have studied in detail and confirmed the propagation of AGW from seismic region to mesosphere via stratosphere.

5. Conclusion

Agra station is well equipped for the measurement of the ULF magnetic field emissions with the help of 3-component search coil magnetometer. The ULF data recorded for the months of April 2012 and September 2013 have been analyzed in the light of three major earthquakes occurred in these months, one of magnitude $M = 8.5$ in April and two of magnitudes $M = 7.4$ and 6.8 in September. The examination of the data for each month shows occurrence of ULF bursts containing electromagnetic pulses of period ranging 10–15s ($f = 0.06$ – 0.1 Hz). These ULF data are not influenced by lightning and magnetic storms. The polarization analysis of the data confirms the sources of these bursts in the lithosphere. In order to ascertain that ULF anomalies observed by us are not caused either by malfunctioning of sensors or by global geomagnetic disturbances (magnetic storms) we compare our data with those observed at two other stations of Shillong and Kachchh in India and a remote station Kakioka in Japan and also analyze long period data of Agra. We find that our results are not influenced by these factors.

The ULF response to above mentioned earthquakes shows consistency with the VLF and TEC data analysis in precursory periods of occurrence of anomalies which were reported 11–15 days (Singh et al., 2018). The suggestion of Singh et al. (2018), based on analytical analyses of the data that ionospheric perturbation is caused by acoustic gravity waves generated over epicenter region of these earthquakes is supported by the results of lithospheric emissions and ionospheric

perturbations taking place almost simultaneously.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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