Characteristics of severe thunderstorms studied with the aid of VLF atmospherics over North–East India

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Electromagnetic waves from lightning activity, commonly known as atmospherics or sferics serve as an effective tool for studying the lower ionosphere as well as thunderstorm activity. It is also useful for locating lightning strokes regionally and globally. In this paper, we present the analysis of the Integrated Field Intensity of Sferics (IFIS) at six discrete VLF frequencies for 30 lightning-associated overhead thunderstorms in Tripura, within the period from August 2009 to October 2010. An ingeniously developed well calibrated GPS locked software VLF receiver, located at the Department of Physics, Tripura University (23.5°N, 91.25°E), is used for the present study. Two distinct types of variations of IFIS, (i) single peak and (ii) dual peak are found characterizing each thunderstorm and their occurrence show nearly inverse character. The spectral character of IFIS rise rate, fall rate and rate of enhancement for each type is studied searching for suitable frequencies in the VLF range to forecast a thunderstorm. It is concluded that VLF sferics from 3–10 kHz are the most effective in terms nowcasting an incoming thunderstorm well before 3–4 hours of its peak occurrence, when there may not be any visual indication of the thunderstorm.

1. Introduction

North–East India, being one of the most intense lighting-prone regions on the globe, requires special attention to study its characteristic features. Lightning radiates an electromagnetic pulse which contains energy over a wide bandwidth, ranging from just a few Hertz (Burke and Jones 1992; Bluestein and MacGorman 1998) up to tens of Mega Hertz (Weidman and Krider 1986; Nagano *et al.* 2006; Romatschke and Houze 2010). The electromagnetic pulses from lightning at ELF–VLF frequencies are known as radio atmospherics, more often referred to as sferics. Most of the energy in the radiated spectrum is contained in the Extremely Low Frequency (ELF, 3–3000 Hz) and Very Low Frequency (VLF, 3–30 kHz) bands (Inan and Carpenter 1987; Carey *et al.* 2003; Collier *et al.* 2006). This sferics in VLF range propagates long distance even up to several thousand km within the earth-ionosphere waveguide with very little attenuation compared to other higher radio frequencies and are received by sensitive receivers as sferics. In every second, hundreds of cloud to ground and several thousand intra cloud lightning occurs all over the globe. The Integrated Field Intensity of Sferics (IFIS) is the resultant of a large number of individual impulses originating from different lightning flashes. The integrated sferics arrive at the receiver directly and also through reflections from the ionospheric layers for long distance propagation inside the earth-ionosphere waveguide. To study the radio wave in ELF and VLF range, it is essential to conduct scientific research on lightning activity as well as the earth-ionosphere wave guide. Intensive investigation is going on to understand the

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characteristics of global electric circuit (Williams 1994, 2005; Guha and De 2009) as well the characteristics of thunderstorm and the earth-ionosphere wave guide. But studies on the basis of long term VLF atmospheric data, i.e., long term IFIS data are very few over the region of North–East India. To understand the seasonal variability, long term data analysis is required. In this paper, we perform the analysis on 16 month's data. Here we are reporting the preliminary result of enhancement of the sferics 3–4 hours before the peak activity of the overhead thunderstorms over Tripura (latitude ∼23.5°N, longitude ∼91.25°E), located at the southernmost part of North–East India. The propagation effect on the VLF waves from the lightning activity within the earth-ionosphere waveguide is minimized as we consider only the case of overhead thunderstorms and we mostly get the contribution from the source inside the thunderstorms, producing the electrical discharge leading to the emission of sferics. This information is very useful in forecasting the overhead thunderstorm event before the thunderstorm becomes detectable by weather radar. Many developed countries have radar network to track storms but the major portion of the globe is not covered by such observation systems. The temporal and spatial resolutions provided by various satellite systems are also not sufficient to study the small scale thunderstorm systems. The real time analysis of Doppler weather radar data along with satellite imaging is one of the best methodologies to study the thunderstorm characteristics. But these methods are highly expensive and need enormous computational power and also infrastructural facilities. Since intense thunderstorms can develop in less than an hour, especially in case of Nor-wester in the coastal areas of Bay of Bengal and in North–East India and last only a few hours, there is a need to develop a network of VLF stations to monitor such hazardous storms continuously, especially in undeveloped regions of the globe where other observation systems are lacking. In order to study the temporal evolution of a thunderstorm and its strength with the help of IFIS, it could become a feasible method, especially for North–East India. The observation shows North–East India is a highly thunderstorm intense region (www.thunder.msfc.nasa.gov). The reason behind this is not yet totally understood but the topographical features might be an important criterion for enhanced lightning activity in this region.

2. Experimental arrangement

We take observations from the roof of the Department of Physics, Tripura University (23.75°N, 91.25°E) at a height of 30 m from the ground. The experimental set-up consists of a loop antenna having an area of 1 m^2, a pre-amplifier of bandwidth 30 kHz and Spectrum Lab (V2.7b14) software VLF receiver. The 24-bit sound card of a P-IV 2.66 GHz clock frequency computer records analog data at a sampling rate of 48 kHz. The internal clock of the computer is synchronized with the help of a GPS receiver. Fast Fourier Transform (FFT) of the pre-amplified signal is performed online at 65,536 points per second using 'Hann FFT window function'. The sampled wide band waveform is then digitally filtered into six narrow band frequencies (4, 7, 9, 11, 14 and 16.5 kHz) with a Q-factor of 300. It is observed that the man-made interference for these frequencies is quite low compared to other frequencies at our site. The root mean square value of the signal at the desired frequency is recorded at a sampling rate of 1 second.

3. Methodology of work

For the present analysis, we considered IFIS data from 1st July 2009 to 31st October 2010 at our station. During this period, we recorded the several sferics at 4, 7, 9, 11, 14, 16.5 kHz for 30 lightning associated overhead thunderstorm events. We define some parameters like rise time, fall time, dB enhancement for characterizing the sferics to study the thunderstorm features. The rise time of sferics is defined as the time during which IFIS is enhanced from reference/ambient level to its peak value and fall time is defined as the time required getting back to its reference/ambient level from the peak level of IFIS. Enhancement of IFIS from reference/ambient level is termed as dB increment. The scheme is depicted in figures 1 and 2. Further, we classify

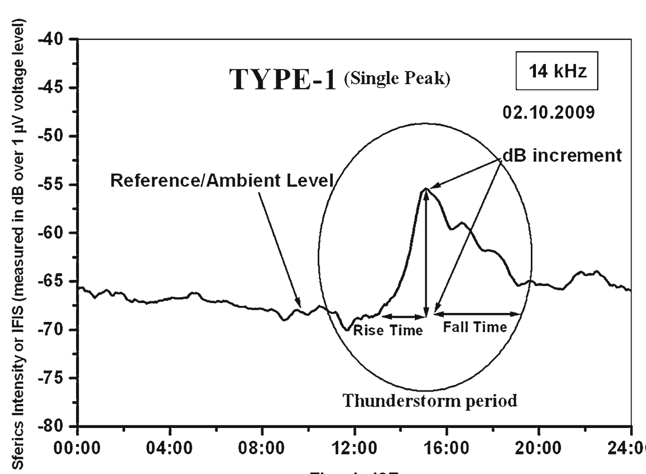

Figure 1. Enhancement pattern of Integrated Field Intensity of Sferics (IFIS) for Type-1 at 14 kHz.

the thunderstorm events in two time zones, time zone-1 (12 midnight to 12 noon) and time zone-2 (12 noon to 12 midnight) according to their occurrence times in a period of 24 hrs in a day. There are several types of IFIS patterns which are observed but two types of variations of IFIS are most prominent at all frequencies, Type-1 (single peak) and Type-2 (dual peak) as shown in figures 1 and 2, respectively. Rise rate and fall rate are observed to be different for the two time zones and it provides valuable information about the formation of thundercloud charging and its recovery mechanism.

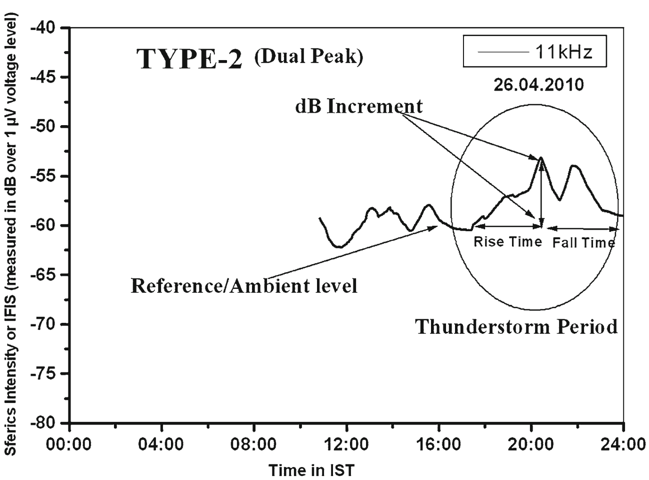

Figure 2. Enhancement pattern of Integrated Field Intensity of Sferics (IFIS) for Type-2 at 11 kHz.

4. Observational results

The daily records of IFIS have been analyzed in relation to 30 overhead thunderstorms at our location. The record of IFIS during thunderstorms exhibit an initial gradual rise and gradual fall in case of Type-1, and 1st gradual rise followed by a 1st sudden recovery and again 2nd gradual rise followed by 2nd gradual recovery in case of Type-2. The sferics intensity or IFIS is calculated in dB measured above 1 μV induced voltage level.

4.1 *Diurnal occurrences*

The occurrence of Type-1 and Type-2 IFIS at different frequencies at time zone-1 and time zone-2 are shown in figure 3. It is observed that the variation of Type-1 and Type-2 occurrences show almost inverse character at all the frequencies (4, 7, 9, 11, 14 and 16.5 kHz) in both time zones. Type-1 occurrence shows maximum count of 7 and 10 at 16.5, 9 kHz in time zone-1 and time zone-2 respectively, whereas Type-2 count has maximum value of 5 and 4 at 14, 16.5 kHz for time zone-1, and time zone-2 respectively. It appears from figure 3 that over North–East India, majority of the cases the occurrences of Type-1 IFIS in both time zones dominate Type-2 IFIS.

4.2 *Rise and fall rate variation of Type-1 and Type-2 IFIS in time zone-1 and 2*

The average rise and fall rate variation of IFIS at different frequencies for Type-1 and Type-2 at

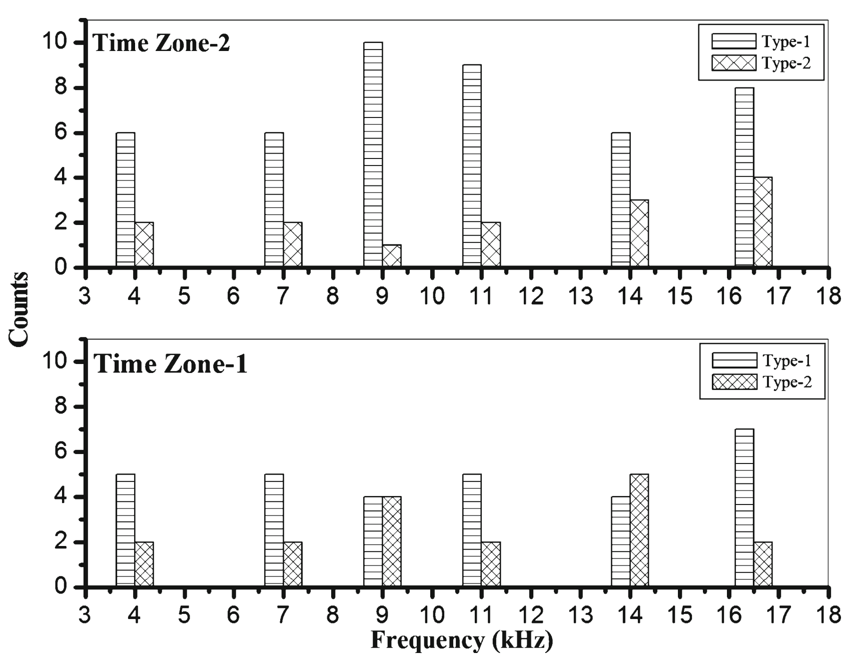

Figure 3. Variation of number of occurrence of Type-1 and Type-2 with frequency for both time zones.

both time zones are represented in figures 4 and 5. It is clearly observed from figure 4 that variation of average rise and fall rate of Type-1 shows similar character in cases of time zone-1 and almost inverse character in time zone-2. Moreover, in time zone-1, the average rate of rise and fall of Type-1 is maximum at 9 kHz around 8.5 and 6.5 dB/hour and the rise rate is minimum in case of 11 kHz, around 1.5 dB/hour. Whereas in time zone-2, the average rise rate of Type-1 shows a maximum of 2.4 dB/hour at 7 kHz, and minimum at 16.5 kHz with the rate of 1.6 dB/hour. In figure 5, average rise rate of Type-2 in time zone-1 shows almost same value at 4, 9, 11 kHz frequencies, and shows a peak of 3 and 2 dB/hour at 7 and 14 kHz, respectively. In case of time zone-2, the average

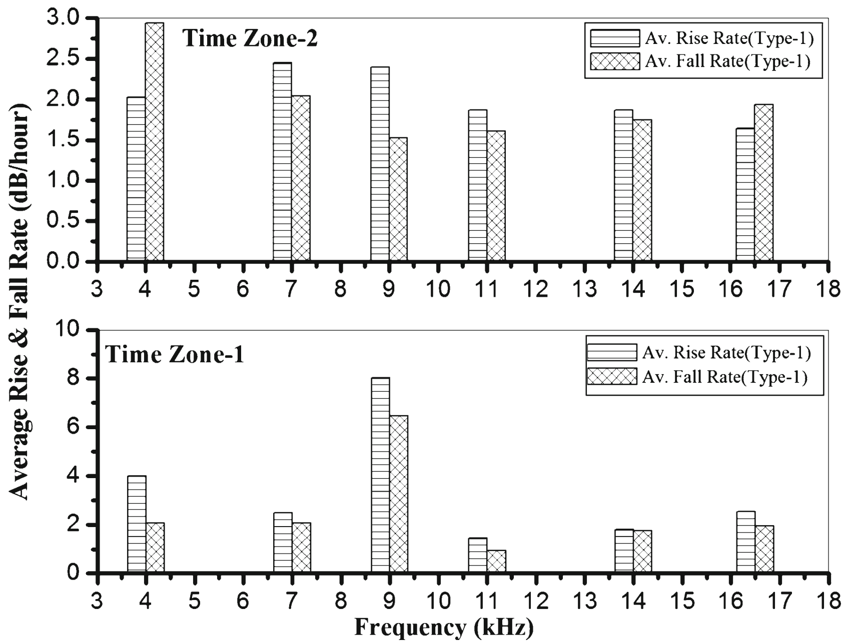

Figure 4. Average rise and fall rate variation of IFIS at different frequencies for Type-1.

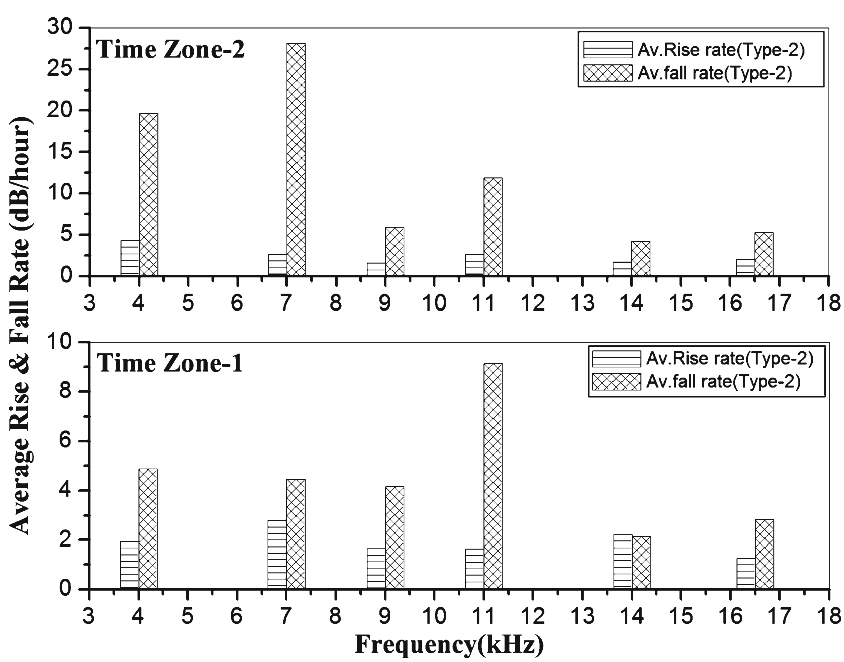

Figure 5. Average rise and fall rate variation of IFIS for Type-2 at different frequencies for both time zones.

rise rate of Type-2 peak occurs at 4 kHz with around 5 dB/hour rate. Rise rate of remaining frequencies settles around a value of 2 dB/hour. But one interesting feature in figure 4 for the time zone-1 is rise rate peak occurs at 4 kHz which might be the contribution from nearby lightning discharges (Sen 1967; Guha and De 2009) and the characteristics of afternoon thunderstorms in North–East India.

4.3 *IFIS variation with frequency in both time zones*

The distribution of various stages of enhancement of IFIS with respect to its ambient level lies within an amplitude level of 12 dB, figure 6 represents the variation of IFIS with respect to frequency for Type-1 and Type-2 for both time zones. In time zone-1, average dB increment of Type-1 and Type-2 shows almost inverse character at all frequencies. In both the time zones, maximum enhancement of Type-1 occurs at 4 kHz and it is around 11.5 dB. Type-2 variations in both time zones show almost similar nature except 4 kHz for time zone-2, several peaks occur around 4, 7, 11 and 16.5 kHz. The maximum value is near 10 dB for time zone-1 and near 12 dB for time zone-2. Minimum dB variation observed at 4, 9 and 14 kHz, values are around 6 dB for time zone-1. In time zone-2, IFIS of Type-1 decreases up to 9 kHz and after that, IFIS variation maintains almost same intensity level for other greater frequencies.

4.4 *IFIS rise time variation with frequency in both time zones*

In figure 7, the variation of average rise time of Type-1 and Type-2 with respect to frequency for time zone-1 and time zone-2 is depicted. In case of time zone-1, average rise time of 9, 11, 14, and 16.5 kHz sferics of Type-1 and Type-2 shows totally inverse character, whereas at 7 and 9 kHz, it has almost similar nature of variations. The Type-1 rise time peak occurs at 14 kHz, whereas Type-2 rise time peak occurs around 11 kHz. From both graphs, it is observed that in time zone-1, rise time of Type-2 is greater than the rise time of Type-1 and it is also observed that Type-1 sferics takes almost 5 hours to reach the peak level whereas for Type-2, it is around 7 hours in North–East India. In case of time zone-2, rise time of Type-1 and Type-2 shows reverse nature at 4, 7 and 9 kHz sferics, whereas 11, 14 and 16.5 kHz sferics shows similar nature. In time zone-2, Type-1 average rise time peak occurs at 4 kHz and its value is around 5 hours. For Type-2, the average rise time is maximum at 7 kHz and its value is around 4 hours.

4.5 *Average CAPE value and surface wind speed of thunderstorm active days for both type of storms*

We studied the average convective available potential energy (CAPE) value and average surface wind speeds with their standard deviations for

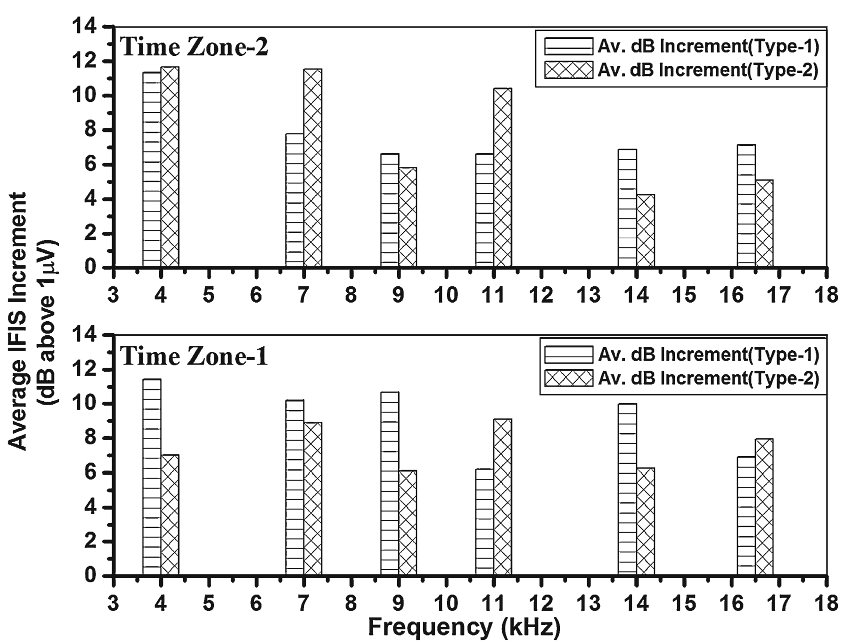

Figure 6. Variation of sferics intensity or IFIS (dB) above 1 μV voltage level with frequency for Type-1 and Type-2 for both time zones.

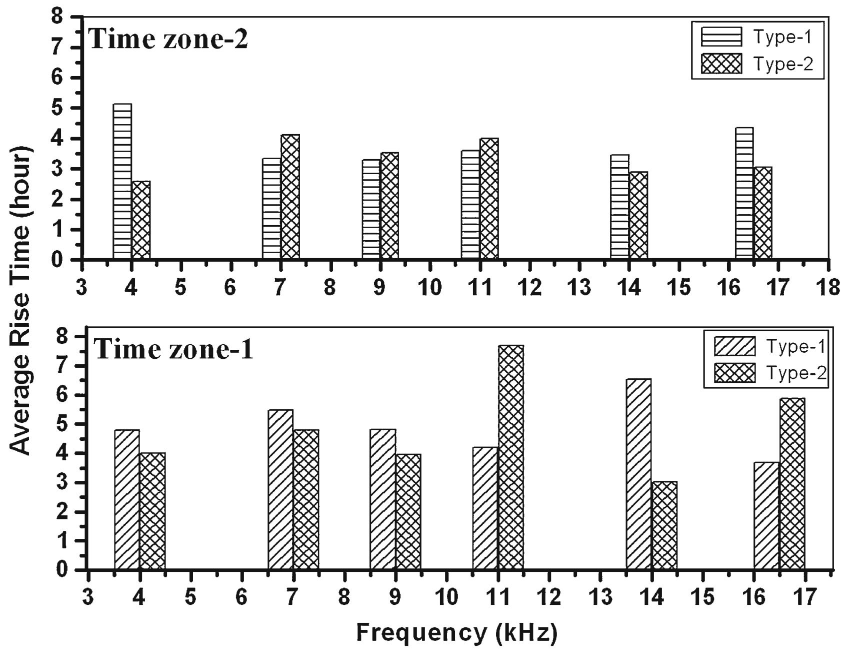

Figure 7. Variation of average rise time of Type-1 and Type-2 with frequency for both time zones.

Type-1 and Type-2 thunderstorms. All CAPE values were collected from University of Wyoming and surface wind speeds were collected from Weather Underground. Due to the unavailability of CAPE data for time zone-2, we considered only the CAPE data for time zone-1. It is observed that for Type-1 variations, the average CAPE value is 4581.77 J/kg with a standard deviation of 1540.29 J/kg and for Type-2 variations, the average CAPE value is 2245.61 J/kg with a standard deviation of 1615.96 J/kg. We also notice that the average surface wind speeds for both types of storms are quite different. For Type-1 storm, it is 5.78 km/hour with standard deviation 1.59 km/hour and for Type-2 storms, the average wind speed is 9.40 km/hour with standard deviation 1.96 of km/hour. It is observed that Type-1 storm is more active in terms of CAPE.

5. Discussion

The North-Eastern part of India is one of the major lightning-prone zones of the world, which lies between the Himalayan range and the Bay of Bengal. Usually, eastern sea-level depressions in the Bay of Bengal are responsible for the generation of severe thunderstorms over this region of India (Sarkar *et al.* 1980; Srivastava *et al.* 2007). They are closely related with the easterly wave trough line and its speed of travel is approximately 10–15 knots (Sarkar *et al.* 1980). In North–East India, the thunderstorms begin to develop gradually under the joint influence of the South–West monsoon current and upper easterly wave trough line (Sen 1967; Sarkar *et al.* 1980). The development of thunderstorms depends on the suitable conditions of low level convergence as well as high level divergence. Their combination together with the sufficient inflow of moisture in the lower layer and also favourable lapse rate in the lower and middle troposphere creates a very favorable condition for sudden growth of the thunderstorms.

To produce electrical charging inside a cloud, a process that leads to CG lightning production, MacGorman and Rust (1998) found that 'strong' updrafts associated with 'vigorous convective growth' should occur at the lower part of the mixed-phase region of the cloud. According to Nath *et al.* (2009), higher CAPE causes an increase of buoyancy of a parcel of air (Price 1993), which is responsible to create favourable condition for severe thunderstorms. Parcel theory predicts that $W_{\max} = (2{\cdot}\mathrm{CAPE})^{1/2}$, where $W_{\max}$ is the maximum vertical motion expected from the release of convective available potential energy (CAPE). Such a mixing would affect the CAPE in practice and it provides an estimate of the rough order of its magnitude. Bright *et al.* (2005) used three criteria to determine the likelihood of CG lightings. First, the lifting condensation level (LCL) must be warmer than $-10°$C, ensuring a low-level source of super-cooled cloud water into the convective line. Second, the equilibrium level (EL) must be colder than $-20°$C, ensuring ice nucleation. Third, CAPE must be greater than 100–200 J/kg in the $0°$C to $-20°$C layer, in order to provide the necessary ascent for electrification. We observed

Table 1. *Average CAPE and surface wind speed value of Type-1 and Type-2 storm for thunderstorm active days.*

Thunderstorm type	Average CAPE value over Tripura (J/kg)	Standard deviation	Peak wind speed (km/hr)	Standard deviation
Type-1	4581.77	1540.29	5.78	1.59
Type-2	2245.61	1615.96	9.40	1.96

that in all the thunderstorm active days, CAPE value were much higher than the minimum threshold for electrification which indicates strong convective activity during the thunderstorm. From table 1, it is clearly evident that the Type-1 storm had more CAPE compared to Type-2, i.e., in North–East India, thunderstorms showing Type-1 variation is convectively stronger compared to thunderstorms showing Type-2 variations.

The gradual rise of IFIS (Type-1) was associated with gradual development of the electrical activity inside the thundercloud and also due to its gradual approach towards the observing station. During its approach, the electromagnetic radiation from intense electrical activity inside the thundercloud was mainly responsible for the increment of IFIS level. Moreover, ground-based wind speed observation for both the thunderstorms reveal that the average peak wind speed during the Type-1 thunderstorm was quite lower than that for the Type-2 thunderstorm, as shown in table 1. It gives the idea that the whole convective thundercloud for the Type-1 approached slowly towards the observation site, whereas in case of Type-2, higher wind speed breaks up the whole cloud structure into several small structure and it approaches faster towards observation site. In case of Type-2 variation, the initial gradual rise of IFIS during thunderstorms could be associated with the gradual development of towering cumulus through detached cumuli (Sarkar *et al.* 1980) while it could also be related to the onset of marked instability during which the height of cloud is suddenly increased causing a sudden increase of electrical activity (Sarkar *et al.* 1980). On the other hand, the second enhancement in Type-2 variation could, most probably, be due to the vigorous charge separation during precipitation from cumulonimbus cloud. For that reason, it is possible to have creation and annihilation of multiple cells in the cloud. For Type-1 thunderstorms, greater CAPE values as well as lower wind speed indicate that the convective activity is higher and approaches towards the site as a single cell of thundercloud (Hughes *et al.* 1971; Knapp 1994).

The two types of variation in IFIS might be generated from single cellular and multi-cellular cloud structures. Each source contains some independent characteristics and as a result, the occurrence of Type-1 and Type-2 shows an inverse character. This could be also some unique feature of thunderstorms over North–East India as there are reports of some unique features by the previous from this region. Guha and De (2009) found different characteristics in Sferics Intensity and some distinct peaks in the VLF range between 1.5 and 6 kHz. So the inverse character of the occurrence of Type-1 and Type-2 variation could be a characteristic feature of thunderstorms storm over North–East India, which needs to be studied with more experimental data.

All types of lightning discharges produce electromagnetic signals with peak energy density in VLF range (3–30 kHz), and especially between 5 and 10 kHz when observed at distances beyond 50 km or so (Rakov and Uman 2003). The complex process of breakdown of lightning producing channel is still not known completely. We believe, the peak activity at those frequencies might be related to the physical mechanism of breakdown process of lightning channel and might also be due to numerous small discharges occurring during the formation of new channels. The occurrence of sharp peaks in a narrow VLF bandwidth might indicate the fact that these frequencies are characteristics of this particular tropical thunderstorm (Guha and De 2009). From North–East India, Guha and De (2009) reported preliminary results of observation of the lightning electrical characteristics during tropical summer thunderstorms, locally known as ‘Nor-wester’ and reported some distinct characteristics in VLF spectra between 1.5 and 6 kHz, which is likely to be the characteristic of VLF sferics over North–East India. Moreover, Roy *et al.* (2013) observed the gradual rise–gradual fall events in VLF sferics and showed that it was mostly effective for the monsoonal thunderstorm activity over North–East India. In analogy with the previous works, we also observed the average rise rate of IFIS for Type-2 variation reaches a remarkable rate of around 5 dB/hour around 4 kHz for time zone-2 thunderstorms, i.e., at the afternoon period. It is observed from IFIS rise time analysis that thunderstorms become electrically active 6–7 hours before its peak activity in time zone-1 and 3–5 hours in time zone-2 times even before the thunderstorm becomes detectable by weather radar. It also appears that development of electrical activity in time zone-2 requires lesser time compared to time zone-1. In case of time zone-2, high CAPE continental tropical storm develops a deep mixed phase region at temperatures well below the non-inductive charge reversal temperature, thereby effectively producing a normal polarity dipole which is consistent with high observed lightning flash rates (Hughes *et al.* 1971; Takahashi 1978; Branick and Doswell 1992; Randell Scot 1992; Pawar *et al.* 2010). Deep mixed phase regions are also developed in case of time zone-1, but it has lesser energy to carry the ice mass to cold enough temperatures to produce a dipole structure as in the case of the high CAPE continental tropical storms (Srinivasan *et al.* 1973; Doswell and Rasmussen 1994; Knapp 1994; Pawar *et al.* 2011). From our analysis, we observed that probability of occurrence of severe storms is maximum in case of time zone-2. It is related to large dynamic updraft leading to large CAPE of time zone-2 thunderstorms in North–East India (Koteshwaram and Srinivasan 1958; Deierling and Petersen 2008; Bourscheidt *et al.* 2009; Goswami *et al.* 2010). The comparative study shows that the number of single enhancement (Type-1) is predominant almost at all frequencies during time zone-2 as well as time zone-1, while double enhancement (Type-2) is mostly found in case of time zone-1. It appears that over North–East India, Type-1 thunderstorms are dominating when observed through VLF IFIS. Enhancement of IFIS during thunderstorms in this region seems to closely relate to the initial stage of its development of thunderstorms while in the final stage, the observed steady recovery associated with local heavy rainfall may be due to the weakening of the bipolar structure of thunderclouds due to the effect of charged rain (Sarkar *et al.* 1980).

6. Concluding remarks

The present observation points to the fact that different characteristics of VLF sferics are intimately related to the vertical development of thunderstorm activity. Our present analysis is significant in forecasting the arrival of thunderstorm from the appearance of the gradual rise in the record of the IFIS. The good positive correlation between lightning and CAPE over North–East India also indicate that CAPE plays an important role in convective thundercloud development over this region (Koteshwaram and Srinivasan 1958; Goswami *et al.* 2010; Pawar *et al.* 2011). The IFIS rise-rate and CAPE analyses significantly distinguished the different types of cloud structures, i.e., single and multiple cells, which are effectively active for the particular thunderstorm. It appears that along with VLF sferics, more meteorological parameters and as well as ice nuclei and cloud particle concentration data must be processed in parallel to determine additional information regarding the development of violent thunderstorms and classify them in different groups. This advance information might be more effective if the current VLF measurements of enhancements are supplemented by directional observations of sferics (Wang and Burns 1975; Sarkar *et al.* 1980; Pawar *et al.* 2010). From the current study, it appears that the time series analysis and pattern recognition techniques can be very useful methods in the study of severe thunderstorm activity and especially to build-up a low cost thunderstorm forecasting and warning system (Price 2008). It is evident that the study of sferics data shows real promise for building a forecasting system capable of providing useful information prior to the occurrence of a severe storm.

References

Bluestein H B and MacGorman D R 1998 Evolution of cloud-to-ground lightning: Characteristics and storm structure in the Spearman, Texas, tornadic supercells of 31 May 1990; *Mon. Weather Rev.* **126** 1451–1467.

Bourscheidt V, Juniora O P, Naccarato K P and Pintoa I R C A 2009 The influence of topography on the cloud-to-ground lightning density in South Brazil; *Atmos. Res.* **91** 508–513.

Branick M L and Doswell C A III 1992 An observation of the relationship between supercell structure and lightning ground-strike polarity; *Wea. Forecast.* **7** 143–149.

Bright D R, Wandishin M S, Jewell R E and Weiss S J 2005 A physically based parameter for lightning prediction and its calibration in ensemble forecasts. Preprints, *Conf. on Meteorological Applications of Lightning Data*, San Diego, CA, *Am. Meteorol. Soc.*, 4.3.CD-ROM.

Burke C P and Jones D L 1992 An experimental investigation of ELF attenuation rates in the earth-ionosphere duct; *J. Atmos. Terr. Phys.* **54** 243–250.

Carey L D, Rutledge S A and Petersen W A 2003 The relationship between severe storm reports and cloud-to-ground lightning polarity in the contiguous United States from 1989 to 1998; *Mon. Weather Rev.* **131** 1211–1228.

Collier A B, Hughes A R W, Lichtenberger J and Steinbach P 2006 Seasonal and diurnal variation of lightning activity over southern Africa and correlation with European whistler observations; *Ann. Geophys.* **24** 529–542.

Deierling W and Petersen W A 2008 Total lightning activity as an indicator of updraft characteristics; *J. Geophys. Res.* **113** 1–11.

Doswell C A III and Rasmussen E N 1994 The effect of neglecting the virtual temperature correction on CAPE calculations; *Wea. Forecast.* **9** 619–623.

Goswami B B, Mukhopadhyay P, Mahanta R and Goswami B N 2010 Multiscale interaction with topography and extreme rainfall events in the north-east Indian region; *J. Geophys. Res.* **115** 1–12.

Guha A and De B K 2009 Lightning electrical characteristics during tropical summer thunderstorm in north-east India; *J. Atmos. Sol.-Terr. Phys.* **71** 1365–1373.

Hughes W L, McCollum P A, Pybus E J and Shanmugam K 1971 A center for the description of environmental conditions weather phenomena; *Ecom.* **12** 1–158.

Inan U S and Carpenter D L 1987 Lightning-induced electron precipitation events observed at L$\sim$ 2.4 as phase and amplitude perturbations on subionospheric VLF signals; *J. Geophys. Res.* **92** 3293–3303.

Knapp D I 1994 Using cloud-to-ground lightning data to identify tornadic thunderstorm signatures and nowcast severe weather; *Natl. Wea. Dig.* **19** 35–42.

Koteshwaram P and Srinivasan V 1958 Thunderstorm over Gangetic West Bengal in the presmonsson season and the synoptic factors favourable for their formation; *Indian J. Meteorol. Geophys.* **9** 301–312.

MacGorman D R and Rust W D 1998 *The Electrical Nature of Storms*; Oxford University Press, 422p.

Nagano I, Yagitani S, Ozaki M, Nakamura C and Miyamura K 2006 Estimation of lightning location from single station observations of sferics; *Wiley Periodicals, Inc.* **90** 22–29.

Nath A, Manohar G K, Dani K K and Devara P C S 2009 A study of lightning activity over land and oceanic regions of India; *J. Earth Syst. Sci.* **118** 467–481.

Pawar S D, Murugavel P and Gopalakrishnan V 2010 Anomalous electric field changes and high flash rate beneath a thunderstorm in northeast India; *J. Earth Syst. Sci.* **119** 617–625.

Pawar S D, Lal D M and Murugavel P 2011 Lightning characteristics over central India during Indian summer monsoon; *Atmos. Res.* **106** 44–49.

Price C 1993 Global surface temperatures and the atmospheric electric circuit; *Geophys. Res. Lett.* **20** 1363.

Price C 2008 Lightning sensors for observing, tracking and nowcasting severe weather; *Sensor.* **8** 157–170.

Rakov V A and Uman M A 2003 *Lightning: Physics and Effects*; Cambridge University Press, 6p.

Randell Scot C 1992 Non-inductive charging of tropical convection in high and low cape environments; *Fort Collins, Colo. Dept. of Atmos. Sci.* **499** 1–190.

Romatschke U and Houze Jr R 2010 Characteristics of precipitating convective systems in the premonsoon season of south Asia; *J. Hydrometeorol.* **12** 157–180.

Roy R, Guha A, De B K and Choudhury A 2013 Studies on VLF atmospherics during the tropical cyclone 'AILA' and several monsoon period thunderstorms over North East India; *Mausam* **64** 83–88.

Sarkar S K, Bhattacharya A B and Sen A K 1980 Characteristics of VLF atmospherics during tropical thunderstorm; *Arch. Met. Geoph. Biokl., Set. A* **29** 131–141.

Sen A K 1967 Enhancement of atmospherics in relation to premonsoon and monsoon thunderstorms; *Indian J. Meteorol. Geophys.* **18** 447–458.

Srinivasan V, Ramamurthy K and Nene Y R 1973 Summer-Nor'westers and Andhis and large scale convective activity over peninsula and central parts of the country; *Forecasting Manual Part iii, India Meteorological Department* **5** 1–145.

Srivastava S, Ray P K C, Shakya B, Joshi D, Kumar D R and Dhar P G 2007 South Asian Disaster Report (SAARC Disaster Management Center, New Delhi).

Takahashi T 1978 Riming electrification as a charge generation mechanism in thunderstorms; *J. Atmos. Sci.* **35** 1536–1548.

Wang P P and Burns R C 1975 Signatures analysis and recognition of severe weather patterns; *IEEE* **75** 1–12.

Weidman C D and Krider E P 1986 The amplitude spectra of lightning radiation fields in the interval from 1 to 20 MHz; *Radio Sci.* **21** 964–970.

Williams E R 1994 Global circuit response to seasonal variations in global surface air temperature; *Mon. Weather Rev.* **122** 1917–1929.

Williams E R 2005 Lightning and climate: A review; *Atmos. Res.* **76** 272–287.

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