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**Key Points:**

- First correlation study of very low latitude whistlers with lightning activity
- Diurnal and seasonal variations of various whistler parameters are studied
- Ducted mode of propagation for low-latitude whistlers is suggested

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# Very low latitude ($L = 1.08$) whistlers and correlation with lightning activity

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**Abstract** We present analysis of more than 2000 lightning-generated whistlers recorded at a low-latitude station, located at Allahabad (geographic latitude, 25.40°N; geographic longitude, 81.93°E; $L = 1.081$), India, during December 2010 to November 2011. The main focus of this work is on the correlation between observed low-latitude whistlers and lightning activity detected by the World-Wide Lightning Location Network near the conjugate point (geography 9.87°S, 83.59°E) of Allahabad. Whistler occurrence is higher in the postmidnight period as compared to the premidnight period. Whistlers were observed in the daytime only on 2 days that too before 8:30 LT (morning). Seasonally, occurrence is maximum during winter months, which is due to more lightning activity in the conjugate region and favorable ionospheric conditions. About 63% of whistlers were correlated with lightning strokes in the vicinity of the conjugate point within spatial extent of 1000 km (conjugate area). Most (about 53%) whistlers were found to be associated with lightning strokes that were offset to the southeast of the conjugate point. The results indicate that an energy range of 7.5–17.5 kJ of lightning strokes generate most of whistlers at this station. The $L$ shell calculations show that propagation paths of the observed whistlers were embedded in the topside ionosphere. Based on these results we suggest a possibility of ducted mode of propagation even for such very low latitude whistlers.

## 1. Introduction

A cloud-to-ground (CG) lightning stroke emits an electromagnetic pulse over a very wide spectrum from a few Hz to several MHz, but the most intense energy released lies in the extremely low frequency (30–3000 Hz) and very low frequency (VLF: 3–30 kHz) range [*Uman*, 1987, p. 118] with peak around 5–10 kHz [*Prasad and Singh*, 1982; *Ramachandran et al.*, 2007]. The lightning impulse, known as a "sferic," can travel long distances within the Earth-ionosphere waveguide (EIWG) with a very low attenuation [*Davies*, 1990, p. 389]. However, under favorable conditions some fraction of the energy passes through the ionosphere which can travel through the magnetospheric (plasmaspheric) plasma, guided along the magnetic field lines due to field-aligned density gradients in the magnetosphere called ducts, and is received in the opposite hemisphere with a distinct frequency-time signature [*Helliwell*, 1965]. Due to dispersion, the higher-frequency components arrive first, which in audio playback sounds like a descending tone with whistling sound; hence, they are called "whistlers." The frequency-time signature is often characterized by a long sweeping arc defined by $D(f) = T\sqrt{f}$, where $D$ is called dispersion and $T$ is the time delay of the signal at frequency $f$ [*Helliwell*, 1965]. The whistler time delays depend on the integrated electron density of the medium and on the geomagnetic field strength. This property of whistlers has been applied by several researchers around the globe as a remote sensing tool to probe the magnetospheric plasma [*Crary et al.*, 1956; *Carpenter*, 1963; *Hayakawa and Tanaka*, 1978; *Sazhin et al.*, 1992; *Singh et al.*, 1998, 2004; *Singh and Hayakawa*, 2001; *Lichtenberger et al.*, 2013].

Whistlers have been predominantly observed at middle ($\sim 1.4 < L < \sim 2.3$), higher ($\sim 2.4 < L < \sim 3.5$), and high latitudes ($\sim 3.5 < L < \sim 4.5$). However, significant whistler activity at low-latitude ($L < \sim 1.4$) stations, e.g., China [*Ohta and Hayakawa*, 1990], Japan [*Hayakawa et al.*, 1973], and India [*Singh et al.*, 2012], has also been observed during past several decades. Unlike middle- and high-latitude whistlers, low-latitude whistlers do not escape the topside of the ionosphere to the plasmasphere due to their origin in the low latitude.

Low-latitude whistlers in India are particularly interesting because the conjugate region, where the causative lightning discharge would be located, lies in the ocean, which in general has about 10 times less lightning activity [*Christian et al.*, 2003] as compared to land area. On the other hand, the radiated VLF energy from oceanic lightning on average appears to be higher [*Said et al.*, 2013].

Although whistlers at low latitudes have been observed, it is not known whether they also require ducts for the propagation as is the case with high- and middle-latitude whistlers. The propagation mechanism of whistlers requires the angle between wave normal direction and the geomagnetic field (wave normal angle) to lie within the transmission cone defined by wave normal direction and vertical direction [*Helliwell*, 1960], which is substantially wider when a duct is present. On the other hand, the ducted propagation of low-latitude whistlers appears to be improbable due to sharp curvature of the magnetic field lines at low latitudes. Consequently, there has remained some doubt that low-latitude whistlers even can exist. Some researchers have proposed a nonducted mode of propagation for low-latitude whistlers [*James*, 1972; *Ceisier*, 1973; *Singh and Tantry*, 1973; *Hayakawa and Iwai*, 1975; *Tanaka and Cairo*, 1980; *Kumar et al.*, 2007], while others have suggested ducted propagation based on ground data and direction-finding measurements [*Somayajulu and Tantry*, 1968; *Hayakawa et al.*, 1973, 1985; *Ohta et al.*, 1989; *Singh et al.*, 2012].

An analysis of the lightning activity in the conjugate region of the receiving station has been missing in past studies on low-latitude whistlers, which has the potential to answer the fundamental question on propagation mechanism of low-latitude whistlers. *Singh et al.* [2012] presented the first observations of low-latitude whistlers in India (Allahabad) alongside precise lightning locations and their peak current measured by new Global Lightning Data (GLD) 360 lightning location network [*Said et al.*, 2010] on a particularly whistler-heavy night of 26 January 2011. They showed that low-latitude whistlers could be unambiguously linked with their causative lightning strokes and suggested the possibility of ducted mode of propagation for low-latitude whistler. *Srivastava et al.* [2013] extended this analysis on correlation between lightning events and whistler for a month of data (April 2011).

We present here the first long-term observations of low-latitude whistlers with measurements of lightning activity in the conjugate region, over 1 year period between December 2010 and November 2011. The diurnal and seasonal occurrence of whistlers and their parameters at this low-latitude station, Allahabad (geomagnetic latitude, 16.79°N; geomagnetic longitude, 155.34°E; $L = 1.08$), India, have also been presented and discussed.

## 2. Experimental Setup and Data

We record whistler wave data continuously using the Atmospheric Weather Electromagnetic System for Observation, Modelling and Education (AWESOME) receiving system operating at Allahabad (geographic latitude, 25.40°N; geographic longitude, 81.93°E; $L = 1.08$). The conjugate point of the Allahabad VLF station lies in the Indian Ocean at the location of geographic latitude, 9.87°S; geographic longitude, 83.59°E. Figure 1 shows the locations (blue stars) of Allahabad site and its magnetic conjugate point wherein and $L$ value lines have been drawn to indicate the low-latitude region. The observational site (Allahabad) was established as a part of global AWESOME network under the auspices of International Heliophysical Year [*Scherrer et al.*, 2008; *Singh et al.*, 2010] in the year 2007. The details of the AWESOME VLF receiver, antenna, and related hardware can be found in the paper by *Cohen et al.* [2010].

In tandem with the AWESOME receiver we also apply the Automatic Whistler Detector (AWD) algorithm [*Lichtenberger et al.*, 2008]. AWESOME shares a continuous stream of VLF data with AWD, which can detect the times of whistlers. The detector algorithm is based on image correlation where the target image is a preprocessed spectrogram of raw VLF signals and the pattern is a modeled whistler wave derived from Bernard's approximation [1972] [*Lichtenberger et al.*, 2008]. The AWD operates in two stages. In the first stage, broadband VLF data are inspected using a sliding window. If the window contains a whistler trace then it is fed to the second stage which more carefully scrutinizes and validates the candidate whistler. If a whistler is identified, then its time of arrival is recorded as the time at which the trace crosses 6 kHz scale. The estimated efficiency of the two stages for whistler detection is around 95%. The AWD for low latitudes comprises of dispersion values in the range of 5–15 $s^{1/2}$. We have used AWD as primary detection system.

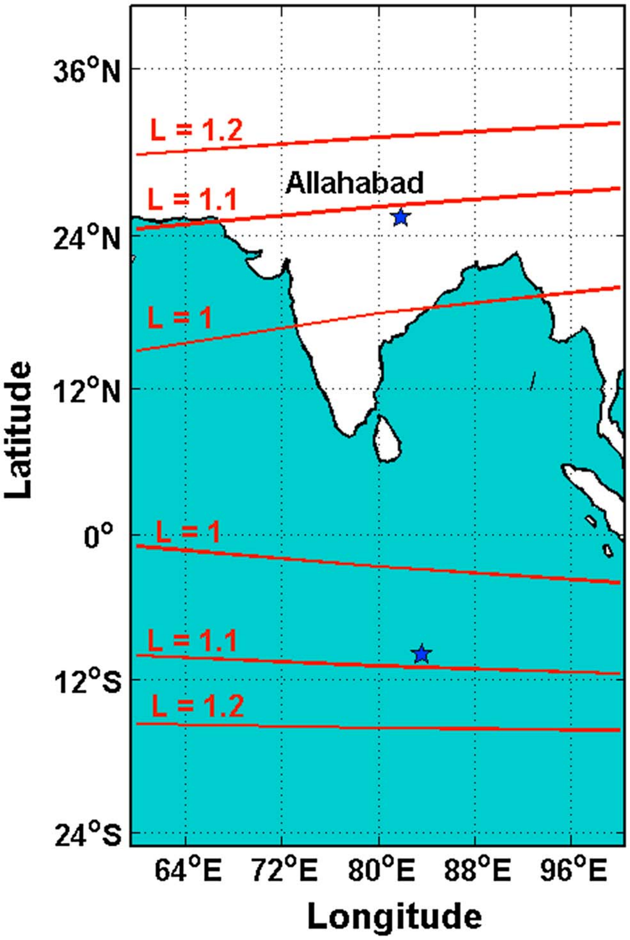

**Figure 1.** Locations of Allahabad, Indian low-latitude VLF recording station and its conjugate point along with *L* shell values.

Once AWD detects whistler, we check the continuous data for that particular day to avoid the possibility of any false or missing detection.

Lightning occurrence data are taken from the World Wide Lightning Location Network (WWLLN), which geolocates lightning discharges using the VLF sferics [*Dowden et al.*, 2002]. WWLLN works on Time of Group Arrival technique. WWLLN provides time and location of lightning discharges with the temporal and spatial accuracies of ~30 μs and ~10 km, respectively [*Rodger et al.*, 2009]. Of the strongest lightning discharges (with peak current above 50 kA), WWLLN detects ~5–10% of them. Since 2009, WWLLN also includes the energy values associated with lightning discharges along with the uncertainty in the measured values.

The geomagnetic indices, *Kp* and *Dst*, have been obtained from World Data Center for Geomagnetism, Kyoto, Japan (http://wdc.kugi.kyoto-u.ac.jp/).

## 3. Occurrence Statistics of Whistlers

The whistlers presented here were recorded at Allahabad, India, at low latitude ($L = 1.081$) for 1 year period (December 2010 to November 2011) which includes 15 whistler activity days: 17 December 2010; 24 and 26 January 2011; 02, 04, and 27 February 2011; 19, 30, and 31 March 2011; 01, 04, 05, 06, and 07 April 2011; and 03 September 2011 with total of 2006 whistlers. Figure 2 shows sample traces of whistlers observed on the night of 27 February 2011 at 20:00 UT. Three whistler traces can be seen clearly in the spectrogram designated as W1, W2, and W3, associated with three dispersed sferics (tweeks) indicated by S1, S2, and S3. The time difference between three tweeks indicates that three strokes were part of a single lightning stroke consisting of multiple return strokes. Total of 356 whistlers were recorded during 3 h from 19:00 to 22:00 UT, on the night of 27 February 2011.

Table 1 presents the details of whistlers recorded on all 15 days with their occurrence number, number of lightning discharges detected by the WWLLN network in the conjugate region, storm center locations, number of lightning discharges associated with whistlers, whistler dispersion values, and magnetic activity index *Dst*. Out of 15 days, 2 days (04 February 2011 and 06 April 2011) were associated with moderate geomagnetic storms having *Dst* values of −59 nT and −65 nT, respectively, but the whistler occurrence on these days is not different than that on the geomagnetically quiet days, so we could not establish a connection between geomagnetic activity and low-latitude whistler occurrence. However, the geomagnetic storms of such intensity may not be able to affect the whistler propagation paths in the low-latitude region. *Kumar et al.* [2007] observed whistlers at a low-latitude station, Suva (18.4°S), Fiji, in the South Pacific region, only during recovery phases of a moderate storm of 17–19 July 2005 (*Dst* −72 nT) and a super intense storm of 20–21 November 2003 (*Dst*—422 nT). Whistler occurrence is higher in the nighttime than in the day which can be attributed to the lower attenuation of the wave in the ionosphere

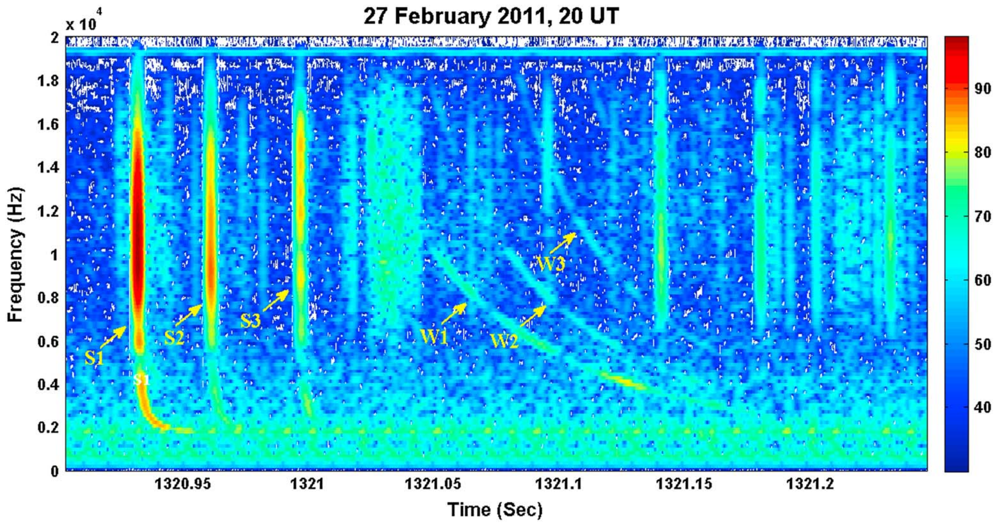

**Figure 2.** Example of whistlers (W1, W2, and W3) recorded at Allahabad on the night of 27 February 2011 at 20:00 UT. The causative sferrics are indicated by S1, S2, and S3.

at nighttime [*Helliwell*, 1958]. During summer months of southern hemisphere, lightning activity is enhanced in the conjugate areas of northern hemisphere, and hence, the whistler activity at the receiving station is enhanced [*Storey*, 1953] in the northern hemisphere. The average dispersion of whistlers observed at Allahabad is found ~$12.4 \pm 3\ \mathrm{s}^{1/2}$, which is consistent with the empirical relationship, $D = 1.22(\varnothing - 0.72)$, given by *Hayakawa and Tanaka* [1978], where $\varnothing$ is the geomagnetic latitude in degrees, which for Allahabad is 16.25°N.

## 4. Results and Discussion

### 4.1. Source Region Identification of Whistlers

Although *Helliwell* [1966] suggested a method to use the dispersion to estimate the source lightning time, there remains some uncertainty with this method for low-latitude whistlers. At midlatitudes, the interhemispheric propagation time of whistlers is of the order of 1 s, so a 10% error in the estimate of arrival time leads to a window of 100 ms during which time the causative lightning may have occurred. It is not unusual for there to be many sferics in VLF data over a 100 ms window. Arrival azimuth determination of the sferics can help reduce the uncertainty in identifying the source lightning discharges

**Table 1.** Details on Whistlers Observed at Allahabad During December 2010–November 2011 and WWLLN-Detected Lightning

| Date | Hour String (UT) | No. of Whistlers Observed at the Site | Total No. of Lightning in Conjugate Region | No. of Lightning Associated With Whistlers | WWLLN Storm Center (Geographic Latitude, Longitude) | Dispersion ($\mathrm{s}^{1/2}$) | *Dst* Index (nT) |
|---|---|---|---|---|---|---|---|
| 17/12/2010 | 03:00 | 2 | 46 | 2 | −7.44, 81.86 | 19.4 | −13 |
| 24/01/2011 | 20:00–24:00 | 129 | 1133 | 100 | −14.17, 85.61 | 11.9 | −11 |
| 26/01/2011 | 19:00–23:00 | 1060 | 1294 | 576 | −11.56, 85.31 | 11.1 | −5 |
| 02/02/2011 | 15:00 | 7 | 217 | 4 | −11.76, 82.97 | 15.4 | −15 |
| 04/02/2011 | 12:00 | 92 | 295 | 61 | −5.44, 81.45 | 18.2 | −59 |
| 27/02/2011 | 19:00–22:00 | 356 | 3077 | 295 | −12.58, 87.14 | 12.9 | 1 |
| 19/03/2011 | 22:00–24:00 | 70 | 174 | 46 | −12.71, 84.00 | 12.7 | −8 |
| 30/03/2011 | 20:00 | 116 | 494 | 69 | −8.26, 87.58 | 15.7 | −2 |
| 31/03/2011 | 22:00–24:00 | 109 | 384 | 74 | −9.28, 89.62 | 13.8 | −5 |
| 01/04/2011 | 18:00 | 05 | 67 | 03 | −9.75, 91.57 | 16.1 | −14 |
| 04/04/2011 | 21:00 | 10 | 104 | 09 | −10.81, 88.73 | 13.4 | −30 |
| 05/04/2011 | 19:00 | 01 | 6 | 01 | −10.90, 86.31 | 17.5 | −19 |
| 06/04/2011 | 22:00–24:00 | 22 | 939 | 13 | −9.87, 83.59 | 16.2 | −65 |
| 07/04/2011 | 01:00 and 20:00 | 07 | 364 | 05 | −9.90, 78.83 | 20.7 | −43 |
| 03/09/2011 | 19:00–21:00 | 19 | 144 | 11 | −3.82, 88.25 | 15.7 | −13 |

in the conjugate region. There may be multiple strokes within 100 ms from the same lightning flash, so there still remains some ambiguity in determination of stroke which excited the whistlers. This is not a problem with low-latitude whistlers, because the interhemispheric propagation time is much smaller because the whistler station and causative lightning stroke are much closer. As an example, consider Figure 2 showing whistlers and their causative sferics. Because the delay time is much smaller, the three whistlers, W1, W2, and W3, can be unambiguously associated with causative sferics labelled as S1, S2, and S3. Furthermore, since lightning flash rate is typically lower over the ocean as compared to land, the odds of other lightning occurring nearby by chance are quite small.

Using visual observation of the spectrograms, we matched 1269 out of 2006 (or 63%) whistlers with lightning discharges detected by WWLLN within a widow of ~10 ms which is within accuracy of WWLLN lightning location time measurement and propagation time of sferics from causative lightnings. It is likely that the remaining 37% of whistlers had causative lightning discharges in the conjugate region of Allahabad station, but they were missed by WWLLN due to its low-detection efficiency. Figure 3 shows the total lightning activity (during whistler activity period) for the 15 days, grouped according to different seasons. WWLLN-detected lightning events are indicated with cyan circles. WWLLN lightning events that are correlated with whistlers are indicated with circles of other colors. We find that the most probable region of lightning events producing whistlers is around the conjugate point within a radius of ~1000 km. *Collier et al.* [2009] reported causative lightning events within a few hundred kilometers of conjugate point for the whistlers observed at Tihany, Hungary. From the study of whistlers observed in south China, *Ohta and Hayakawa* [1990] concluded that the causative sferics of whistlers are widely distributed in a range over 1000 km from the conjugate point of the ionospheric exit region. Also, *Singh et al.* [2012] observed an intense thunderstorm between 200 and 450 km from the conjugate point for the whistlers observed on the night of 26 January 2011 at Allahabad. *Srivastava et al.* [2013] for whistler observations on five nights during April 2011 found the source region within a circle of ~700 km radius to the conjugate point of Allahabad. Our results are consistent with these earlier studies but with the addition of larger database of 1 year. From Table 1 and Figure 3, it is apparent that whistler occurrence at Allahabad is well correlated with total lightning activity in the conjugate region. We did not observe any instances of two-hop whistlers from storms that were near the receiver, although it is possible that some may have occurred and were simply obscured by the much higher VLF noise level at the site when there is a nearby storm.

However, there were many nights when there was lightning activity in the conjugate region, but no whistlers were observed at Allahabad. This means that not all the lightning discharges in the conjugate region can produce whistlers. To account for the lightning-to-whistler causal relationship we have counted the number of lightning events per hour within 1000 km of the conjugate region and within 1000 km of the receiving station for the entire year. We have considered only local postmidnight hours, 00:30–05:30 h LT (19:00–24:00 UT) when ionospheric absorption is much more favorable to whistler propagation (LT = UT + 5:30 h). The results presented in Figure 4 show that whenever there is comparatively high lightning activity in the vicinity of the receiving station, fewer whistlers are recorded. In this situation, the whistlers may be present but simply below the noise level. Hence, the lightning activity near the receiving station acts as a limiting factor for identification of whistlers. It does not mean that a whistler is not present at that time but it is more likely to be masked by the closely spaced sferics in the spectrogram and the noise due to surrounding lighting discharges.

To account for this limitation, we adopted a methodology as follows. For the night of 24 January 2011, we calculated average amplitude of the observed whistlers, also the average background amplitude of the entire spectrogram containing whistlers. The average-amplitude difference of these two was found ~19 dB, which we take as a measure of signal-to-noise ratio (SNR) for whistler observations. We then calculated the background amplitude of spectrograms during June 2011, which is peak of monsoon season and associated lightning activity. The average-amplitude difference of spectrograms during June 2011 was found ~25 dB. This increase of background amplitude from 19 dB to 25 dB is likely to make detection of whistler traces more indistinguishable as compared to nonmonsoon background noise level. In addition to SNR, selectivity of AWD also depends on other factors like bandwidth and sharpness of the whistler trace. The smaller the $L$ value, the larger is the bandwidth required to detect the whistler trace [*Lichtenberger et al.*, 2008]. This selectivity of AWD may exclude swishy and short whistler traces.

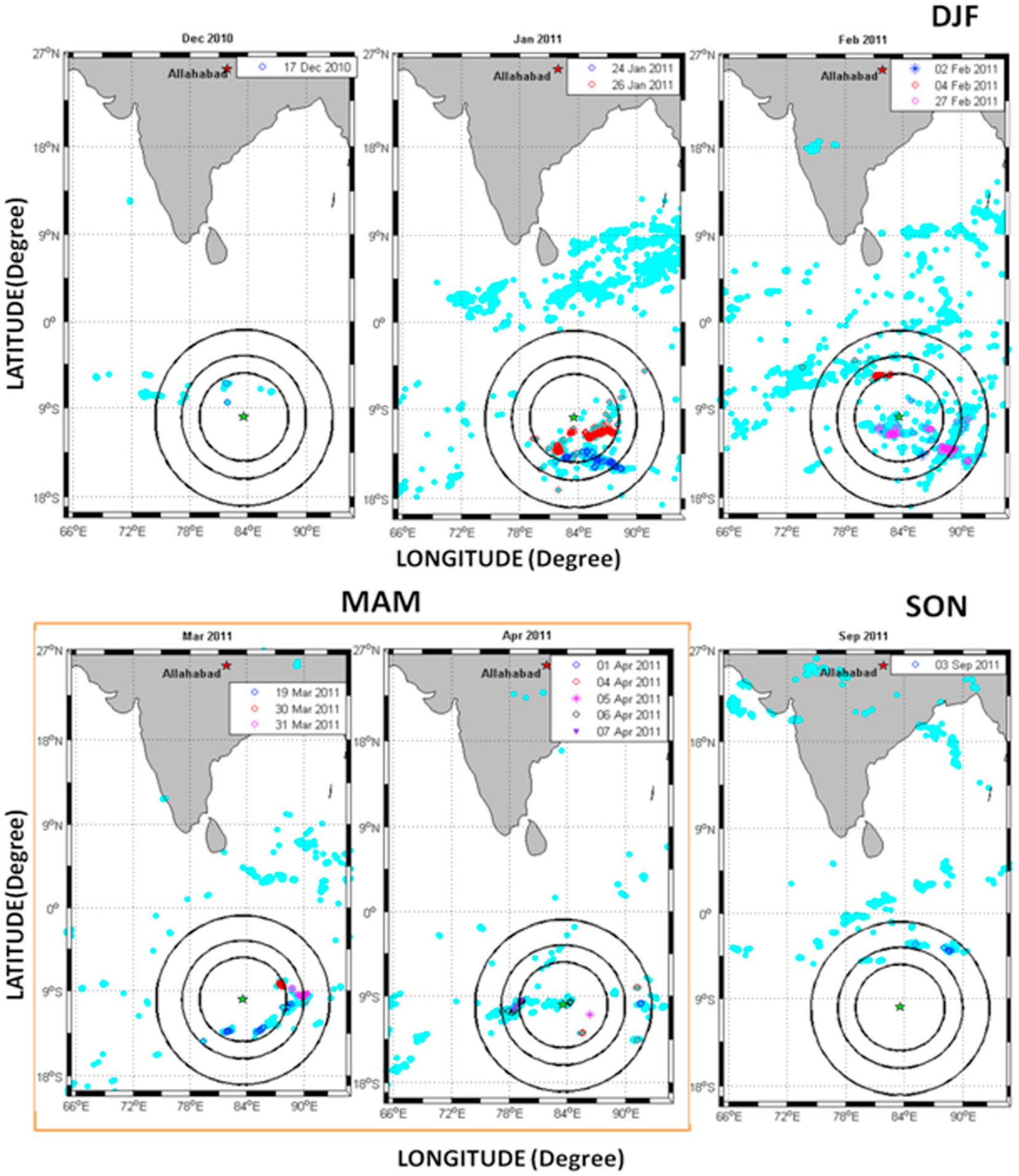

**Figure 3.** Maps showing lightning activity in the vicinity of conjugate region within circles of radii 500 km, 700 km, and 1000 km, with the conjugate point of Allahabad as the center, for different seasons. DJF represents, December, January, and February; MAM, March, April, and May; JJA June, July, and August; and SON, September, October, and November.

To quantify this effect, we have calculated the ratio of hourly lightning rate within 1000 km of the receiving station to the hourly lightning rate within 1000 km of the conjugate region, which we refer as *F*. Hence, *F* represents the amount of noise contributed by local lightning activity. When *F* is greater than 1, conditions are poor for identifying whistlers at Allahabad. From Figure 4 it is clear that April, May, June, July, August, and September are the months with a high value of *F*; hence, very small number of whistlers were recorded during these months. The remaining months with lightning activity in the conjugate region are considered to be sufficient for identifying whistlers from spectrograms at Allahabad. Even during these months, not all the days are masked with whistlers. The occurrence of whistlers strongly depends on lightning location, as the VLF energy is injected into the ionosphere within a certain distance of the lightning stroke from the conjugate point. We demonstrate this fact in Figure 5, which represents the distribution of lightning discharges with distance. Here the occurrence rate is normalized to unity. From

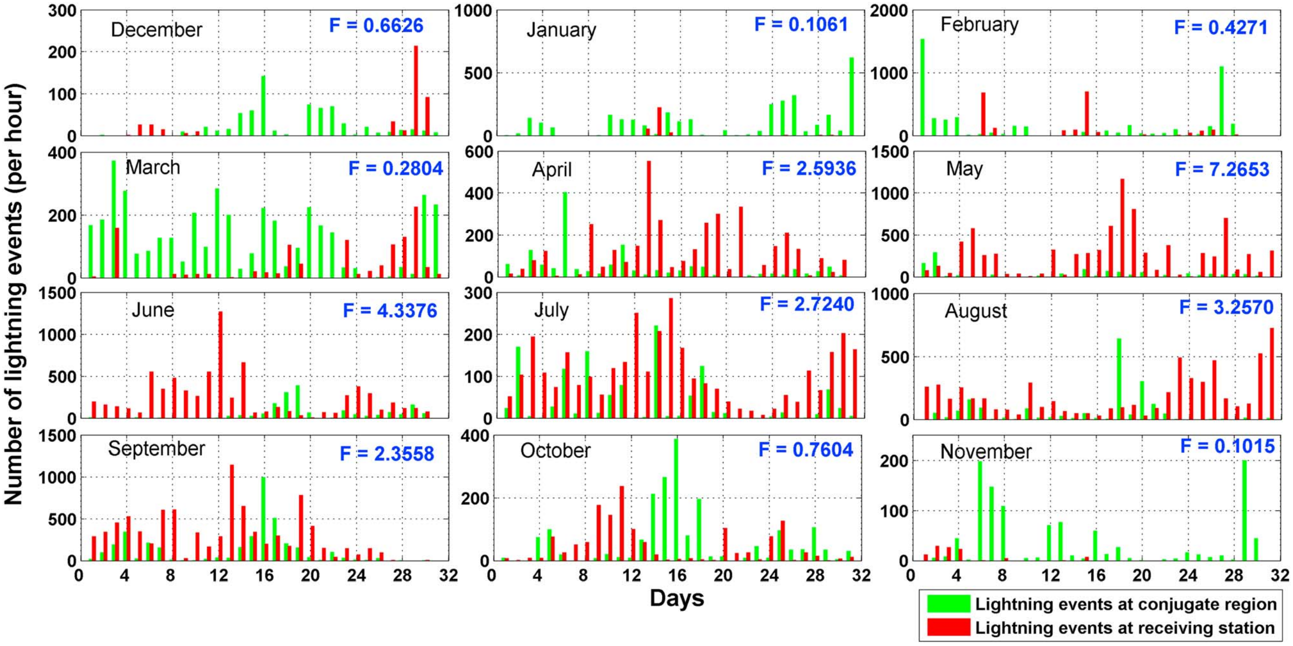

**Figure 4.** Comparison of number of lightning strokes per hour in the conjugate region and number of lightning strokes per hour at the receiving station that occurred in the postmidnight hours (19:00–24:00 UT) with spatial extent of 1000 km. *F* is defined in the text.

Figure 5, it can be seen that the lightning discharges that produced whistlers (blue bars) were located in the region of 200–800 km with a peak around 400 km with reference to the conjugate point. Whereas overall lightning activity throughout the year (red bars) has maximum occurrence in the region of 900–1300 km with a peak around 1100 km region with reference to the conjugate point. Hence, the days with clear sky at the receiving station and lightning activity within 200–800 km region around the conjugate point are more probable conditions for the whistler activity. In addition to this the type of lightning, the thunderstorm direction and the Earth's magnetic field lines alignment may also play a role in triggering, trapping, and propagation of whistler waves along the magnetic field lines [*Yoshino*, 1976; *Oster et al.*, 2009; *Collier et al.*, 2009]. CG flashes have a strong, low-frequency component associated with the initiation of the return stroke, with the peak in frequency around 10 kHz, whereas cloud-to-cloud (CC) flashes generate

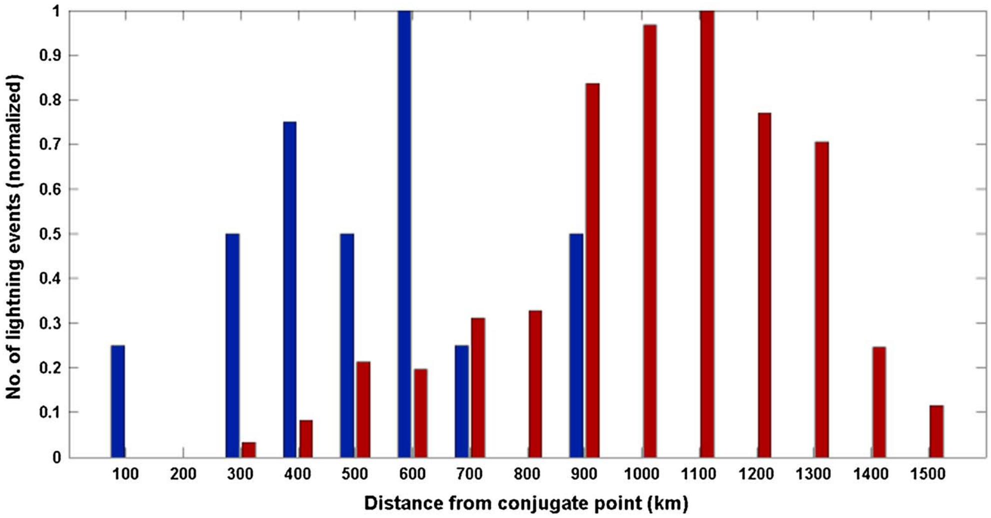

**Figure 5.** Number of lightning discharges that produced whistlers (blue bars) and total number of lightning discharges (red bars) in different regions during year 2011.

much higher energy at higher frequencies than CG strokes. Therefore, whistlers are most likely produced by the CG strokes rather than CC strokes, but WWLLN detects both CG and CC flashes. Also, some ducted whistlers originate from lightning poleward of the field line foot point [*Helliwell*, 1965]. *Strangeways* [1981] suggested that the coupling from the neutral atmosphere into the ionosphere is more effective when the lightning occurrence is equatorward of the conjugate point. As reported by *Singh et al.* [2012] radiated peak current/energy of the lightning can also influence the whistler generation and is discussed in section 4.4. So overall, the whistler activity at low latitude depends on clear-sky condition at the receiving station, distance, type, direction, and energy/current of the source lightning discharge as well as the properties of the medium into which whistler waves propagate.

### 4.2. Propagation Path of Whistlers

In an effort to determine whether the whistlers followed ducted or nonducted paths, we calculated the *L* shell values for the locations of WWLLN-detected lightning discharges. The average *L* value found is ~1.14, which is higher than the 1.08 *L* shell of Allahabad. This shows that the path of observed whistler waves is embedded close to the topside ionosphere and reaching a height of about ~900 km. Also, most of the source lightning discharges for low-latitude whistlers were located southeast of the conjugate point. It is possible that there is a ducted mode of propagation at low latitudes. We intend to explore this in future work with longer-duration data at multiple stations in the Indian region since this is an area of further experimental and theoretical research.

### 4.3. Diurnal and Seasonal Variations of Whistler Occurrence and Parameters

We now present diurnal and seasonal variations of the whistler occurrence and parameters. For each day we have calculated number of whistlers (*n*), whistler dispersion (*D*), and sferic identification factor (*C*). Most of the whistler causative sferics are dispersed sferics called “tweeks.” But there are cases when causative sferics do not show any detectable dispersion. These sferics usually do not have any frequency component below 4 kHz. To account for this behavior of whistler causative sferics, factor *C* has been introduced which is given as

$$C = \frac{CS_s}{CS_s + CS_t} = \frac{CS_s}{CS} \tag{1}$$

where $CS$ is the total number of whistler causative sferics, $CS_s$ is the causative sferics without dispersion, and $CS_t$ is the causative sferics which are identified as tweeks. During morning hours, it is very difficult to see the sferic frequency components below 2 kHz which is attributed to the change in height of EIWG [*Maurya et al.*, 2012] and higher daytime attenuation of sferics. In other words, *C* is simply a proxy for daytime versus nighttime propagation. Ideally, the *C* is expected to be 1 in the daytime and 0 in the nighttime. The *C* remains almost constant with a value less than 0.2 throughout the year. This may be due to the fact that majority of whistlers were observed during nighttime when they are associated with tweeks as causative sferics. Only 2 days (17 December 2010 and 07 April 2011) were marked with the daytime whistlers when ~74% and ~85% of whistlers were found to be associated with $CS_s$. The reason behind this low daytime occurrence may be the high collision frequency of the charged particles with neutrals in the ionosphere in the daytime. WWLLN was able to detect lightning discharges closely matching with such sferics ($CS_s$) in the conjugate region. As these sferics ($CS_s$) are associated with the observed whistlers, the source region of daytime whistlers is also confirmed within the conjugate region. The results presented here are the first time observations of daytime (morning) whistlers at such low latitudes. *Burkholder et al.* [2013] showed that some of the energy lost by sferics within the EIWG can be gained by whistlers in the ionosphere, so that the sferics that experience more attenuation correspond to more energetic whistlers. Hence, it will be interesting to investigate properties of whistlers that are associated with such sferics in future.

Figures 6a and 6b show the diurnal variations of *n* and *D* of which statistics is given in Table 2. The time is divided in different periods: morning 5:30–9:30 LT (00:00–04:00 UT), noon 9:30–14:30 LT (04:00–09:00 UT), evening 14:30–19:30 LT (09:00–14:00 UT), premidnight 19:30–00:30 LT (14:00–19:00 UT), and postmidnight 00:30–05:30 LT (19:00–00:00 UT). From Figure 6a, it can be seen that the whistler occurrence is more prominent in the postmidnight hours having a peak around 20:00 UT with 968 whistlers. There are very few whistlers that were recorded in the morning on 17 December 2010 (03:00 UT) and 07 April 2011 (01:00 UT). No whistler activity was observed during rest of the daytime. By applying Full-Wave Method model, *Graf et al.* [2013] estimated waveguide attenuation at 2 kHz in the daytime and at the nighttime, respectively, which for geomagnetic latitudes of Allahabad (16.25°N) comes out to be ~20 dB and ~4 dB,

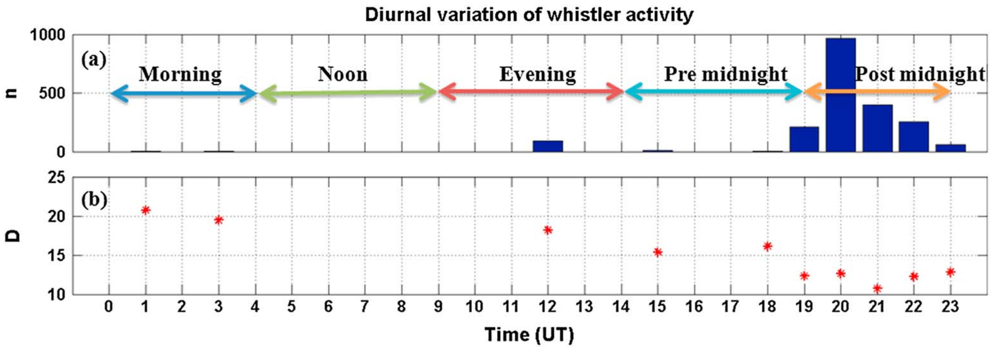

**Figure 6.** Diurnal variation of whistler parameters: occurrence number (*n*) and dispersion (*D*).

respectively. Waveguide attenuation for midlatitude regions at 2 kHz is in the range of 15–30 dB/Mm [*Wait*, 1962; *Chapman et al.*, 1966; *Bernstein et al.*, 1974], where the upper limit applies for the day and the lower limit for nighttimes [*Collier et al.*, 2010]. *Fiser et al.* [2010] estimated that for a given lightning peak current, the average whistler power at 700 km altitude in the nighttime is roughly 10 dB higher than that in the daytime. From their study on terrestrial VLF transmitter injection into the magnetosphere, *Cohen and Inan* [2012] showed that the total power injected by North West Cape VLF (19.8 kHz) transmitter in the daytime within 1500 km radius is 21.5 dB lower than that at the nighttime. Because of high absorption of whistler waves in the daytime, the whistler occurrence is seen to be low, although significant lightning activity is present in the conjugate region. Although earlier studies at midlatitudes reported relatively little change in dispersion from 1 h to the next [*Helliwell*, 1965], we found a decreasing trend in the dispersion of recorded whistlers as day progresses (Figure 6b). High dispersion with an average of ~20.1 $s^{1/2}$ was observed for morning whistlers which gradually decreased to 18.2 $s^{1/2}$, 15.7 $s^{1/2}$, and 12.1 $s^{1/2}$ with the progress of time until premidnight. This can also be attributed to relatively dense ionosphere in the morning period (daytime).

Similar parameters were analyzed to study the seasonal variation of low-latitude whistlers which are presented in Figures 7a and 7b and the statistics are given in Table 3. From Figure 7a it is clear that the whistler occurrence is higher during the winter months (December, January, and February) with 1647 whistlers. The seasons discussed in this section are referred with respect to receiving station. A total of 340 whistlers were recorded during the months of March, April, and May. No whistlers were recorded during summer months (June, July, and August), and very small number of whistlers (19) was observed during September, October, and November as shown in Figure 7a. This activity trend can be explained by the fact that the thunderstorm activity in the conjugate region is highest in winter. That is, during winter many sources are available for excitation of one-hop whistlers (which are common at low latitudes) and the atmospheric noise at the station is minimal [*Helliwell*, 1965]. From the study on the morphological features of whistlers at Varanasi station, India, *Singh et al.* [2007] showed that whistler occurrence is maximum during the January–March months. They concluded that whistler occurrence is highest in winter followed by equinox and summer seasons, respectively. Our results match well with the previous reports [*Storey*, 1953; *Helliwell*, 1965; *Singh et al.*, 2007]. The dispersion is low for whistlers observed during winter and high during equinoxes with an average value of ~12.0 $s^{1/2}$ and ~15.2 $s^{1/2}$, respectively. The monthly average dispersion trend in Figure 7b indicates that the dispersion can be maximum for whistlers observed during the summer months. This kind of behavior may be due to the high electron density during summer (for Allahabad latitudes) in the ionosphere, particularly at 200–400 km altitudes [*Tulasi Ram et al.*, 2009]. *Maurya et al.* [2012] calculated electron density of the ionosphere in the altitude range of 80–100 km using tweeks and showed that the electron density is higher during summer as compared to winter and equinox seasons.

**Table 2.** Diurnal Variation of Whistler Occurrence (*n*) and Dispersion (*D*)

| Time Period | *n* | *D* ($s^{1/2}$) |
|---|---|---|
| Morning | 8 | 20.1 |
| Noon | - | - |
| Evening | 92 | 18.2 |
| Premidnight | 12 | 15.7 |
| Postmidnight | 1863 | 12.1 |

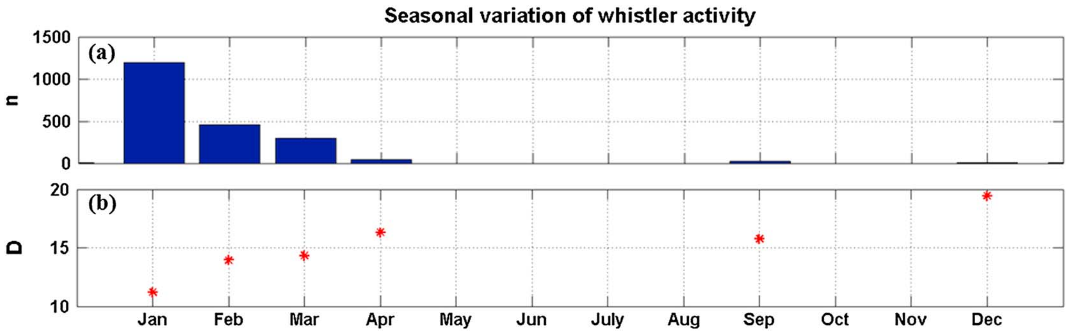

**Figure 7.** Seasonal variation of whistler parameters: occurrence number (*n*) and dispersion (*D*).

Figure 8 shows the seasonal spatial distribution of causative lightning discharges detected by WWLLN. During December, January, and February (DJF) months most of the lightning events occurred within a distance of 200–400 km from conjugate point which were responsible for generating whistlers (Figure 8b). The lightning-producing whistlers occurred farther to the conjugate point during March, April, and May (MAM) months (Figure 8c). The lesser occurrence of whistlers in September, October, and November (SON) months can not only be attributed to the less lightning activity in the conjugate region but also to the higher distance of thunderstorm occurrence, i.e., ~800–1000 km (Figure 8d) from conjugate point. In general, from Figure 8a, it is clear that the region within distance of ~200–400 km has the probable lightning discharges for generating whistlers.

### 4.4. Energy Determination of Lightning Strokes in and Around Conjugate of Allahabad

The only known characteristic of whistler causative lightning discharges that distinguishes them from ordinary lightning discharges is their relatively high energy [*Helliwell*, 1965]. In the present study an attempt has been made to examine any relationship between whistler occurrence and energy of associated causative lightning discharges detected by WWLLN in the conjugate region. To account for this, we have calculated the ratio of number of lightning discharges that produced whistlers with total number of lightning discharges for each energy bands in 500 J intervals. This ratio is designated as $L_f$ and plotted against energy bands as shown in Figure 9. The lightning discharges having energies higher than 20 kJ have been excluded from the analysis since the occurrence of such lightning discharges is very small. A Gaussian fit with $R^2$ (goodness of fit) ~45 is plotted to examine the behavior. From Figure 9, it can be seen that the lightning discharges having energies within the range of 7.5–17.5 kJ have higher rate of producing whistlers. It does not mean that the lightning discharges with lower energy cannot produce whistlers. Even though these lightning discharges have high occurrence probability, the probability of producing whistler is less. *Singh et al.* [2012] from the case study of whistlers observed at this station (Allahabad) and Global Lightning Detection (GLD) 360 data found that peak current of whistler causative lightning discharges lies in the range of ~30–100 kA. *Helliwell et al*. [1958] from a brief study on the relationship between the spectrum of the causative sferics and the resulting whistlers recorded at midlatitude station, Boulder and Stanford, found that the charge moment of a whistler producing lightning strokes was approximately 200,000 C m which is about 10 times higher than the average charge of lightning flashes. Hence, it becomes very important to study the dependence of whistler generation on the strength of the source lightning discharge. The detailed analysis on lightning parameters like type of lightning and its polarity may give better idea on the distinguishability of the lightning discharges that produce whistlers from that of ordinary lightning discharge.

**Table 3.** Seasonal Variation of Whistler Occurrence (*n*) and Dispersion (*D*)[a]

| Months | *n* | *D* ($s^{1/2}$) |
|---|---|---|
| DJF | 1647 | 11.9 |
| MAM | 340 | 14.6 |
| JJA | - | - |
| SON | 19 | 15.7 |

[a] Where DJF represents December, January, and February; MAM, March, April, and May; JJA, June, July, and August; and SON, September, October, and November.

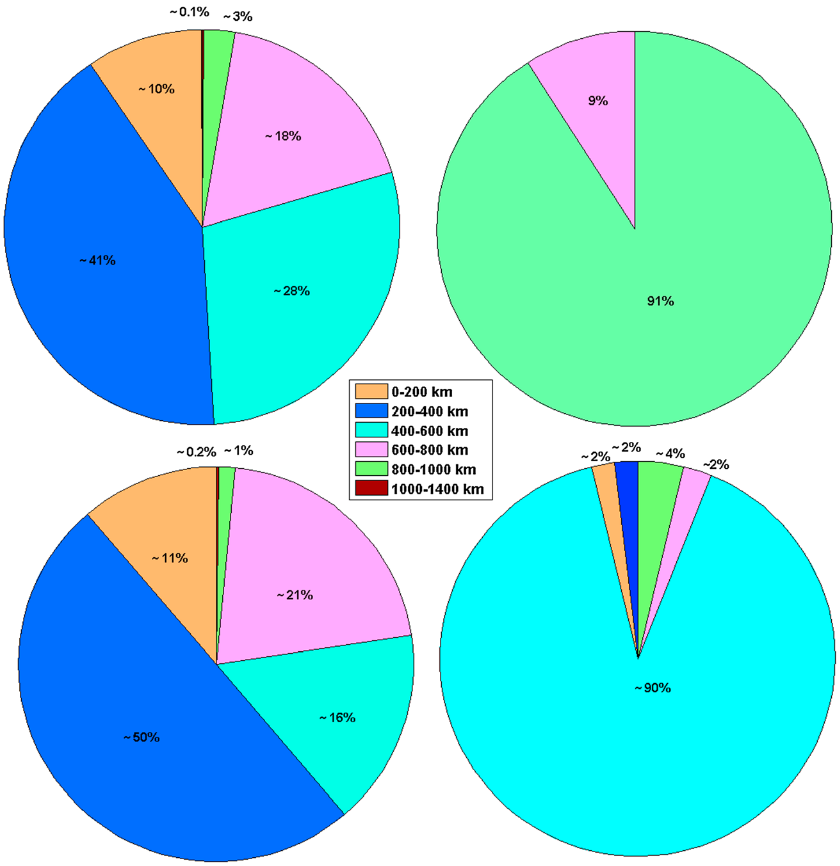

**Figure 8.** Spatial distribution of lightning discharges with respect to the conjugate region that produced whistlers during different seasons at Allahabad. DJF represents December, January, and February, MAM, March, April, and May; and SON, September, October, and November.

## 5. Summary and Conclusions

The correlation between the whistlers observed at Allahabad, a low latitude station in India, and lightning activity in the conjugate area is analyzed by matching arrival time of causative sferics with that of WWLLN-detected lightning discharges. The analysis showed that about 63% of whistlers were associated with the

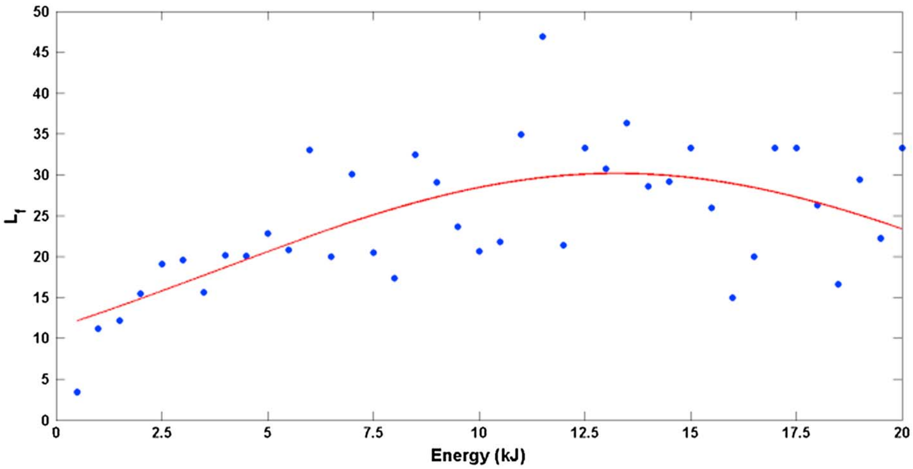

**Figure 9.** Distribution of fraction of lightning discharges that produced whistlers in different energy bands.

lightning within the radial extent of 1000 km from the conjugate point. Lightning discharges with energy in the range of 7.5–17.5 kJ were found to have high probability of producing whistlers. The statistical study on diurnal and seasonal variations of whistler occurrence and its parameters such as whistler occurrence number (*n*), whistler dispersion (*D*), and sferic identification factor (*C*) is also carried out. The occurrence of whistlers is clustered in the postmidnight hours. The diurnal variation of *D* indicates that the ionospheric conditions during whistler activity period are controlling factors for whistler occurrence apart from energy of the lighting discharges. The winter months (December, January, and February) showed relatively high whistler activity (*n*) which can be due to the higher occurrence of lightning in the conjugate area as well as the low atmospheric noise at receiving station. The average value of *L* shell parameter for the WWLLN-detected lightning is found ~1.14. The results obtained from diurnal and seasonal variations along with the *L* values of causative lightning in the conjugate area suggest that the propagation path of observed whistlers was embedded in the topside ionosphere. Hence, the study of real-time ionospheric conditions during whistler activity is of much interest to validate the ducted propagation proposed for such very low latitude whistlers in future.

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