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Key Points:

- First wave-like signatures in *D* region ionosphere by total solar eclipse
- WLS reported are important to current understanding of ionospheric dynamics
- Results of coordinate observations from five VLF sites covering full eclipse path

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Low-mid latitude *D* region ionospheric perturbations associated with 22 July 2009 total solar eclipse: Wave-like signatures inferred from VLF observations

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Abstract We present first report on the periodic wave-like signatures (WLS) in the *D* region ionosphere during 22 July 2009 total solar eclipse using JJI, Japan, very low frequency (VLF) navigational transmitter signal (22.2 kHz) observations at stations, Allahabad, Varanasi and Nainital in Indian Sector, Busan in Korea, and Suva in Fiji. The signal amplitude increased on 22 July by about 6 and 7 dB at Allahabad and Varanasi and decreased by about 2.7, 3.5, and 0.5 dB at Nainital, Busan, and Suva, respectively, as compared to 24 July 2009 (normal day). The increase/decrease in the amplitude can be understood in terms of modal interference at the sites of modes converted at the discontinuity created by the eclipse intercepting the different transmitter-receiver great circle paths. The wavelet analysis shows the presence of WLS of period ~16–40 min at stations under total eclipse and of period ~30–80 min at stations under partial eclipse (~85–54% totality) with delay times between ~50 and 100 min at different stations. The intensity of WLS was maximum for paths in the partially eclipsed region and minimum in the fully eclipsed region. The features of WLS on eclipse day seem almost similar to WLS observed in the nighttime of normal days (e.g., 24 July 2009). The WLS could be generated by sudden cutoff of the photo-ionization creating nighttime like conditions in the *D* region ionosphere and solar eclipse induced gravity waves coming to ionosphere from below and above. The present observations shed additional light on the current understanding of gravity waves induced *D* region ionospheric perturbations.

1. Introduction

The solar eclipses (SEs) are of great scientific interest as they provide a unique opportunity to study photochemical, optical, and radio-physical processes in the Earth's environment under the sudden reduced solar radiation conditions. There are several investigations on the Earth's atmospheric and ionospheric effects of SEs [e.g., *Boyd*, 1966; *Anderson et al.*, 1972; *Antonia et al.*, 1979; *Srivastava et al.*, 1982; *Chimonas and Hines*, 1970; *Chimonas*, 1970; *Clilverd et al.*, 2001; *Babakhanov et al.*, 2013 and references therein]. Further studies on SEs ionospheric effects (particularly in lower ionosphere) are warranted because of the fact that each eclipse is different from others based on the occurrence time of the year, time of the day, degree of the solar disk occultation, state of the space, and atmospheric weather and location (latitude and longitude) of observations on the Earth [*Baran et al.*, 2003].

Apart from wide range of implications of SEs on the near Earth's atmosphere and ionosphere, the two most important consequences of SEs are ionospheric variability due to sudden cutoff of solar radiation for a short duration and generation of gravity waves (GWs) [*Chimonas*, 1970; *Zerefos et al.*, 2007; *Babakhanov et al.*, 2013]. The passage of solar terminator is another main in situ source of GWs. Several studies have shown wave-like signatures (WLS)/GWs in *E* and *F* regions of ionosphere during SEs using Ionosonde and GPS total electron content (TEC) measurements [*Liu et al.*, 1998; *Altadill et al.*, 2001; *Zerefos et al.*, 2007; *Kumar et al.*, 2013; *Yadav et al.*, 2013], but very few studies have attempted WLS/GWs in the Mesosphere/*D* region ionosphere [*Bošková and Laštovička*, 2001; *Chernogor*, 2010; *Ratnam et al.*, 2012]. The probing of *D* region ionosphere is difficult as its altitude is too low for satellites and too high for balloons and due to low electron

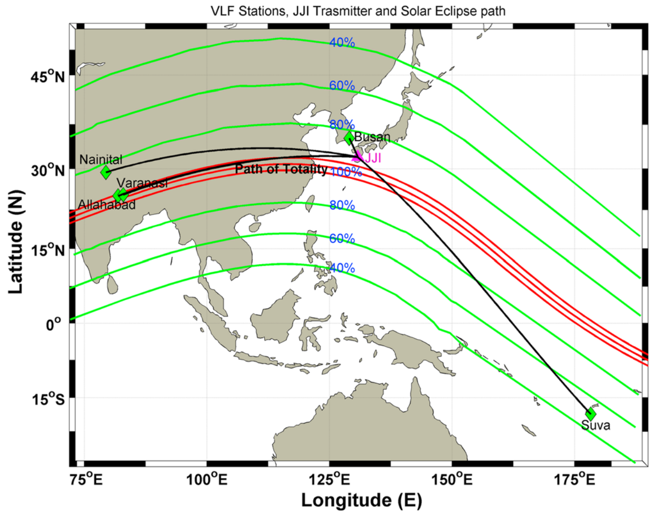

Figure 1. The 22 July 2009 solar eclipse totality path in the Indian and Asia-Oceania regions. The locations of very low frequency (VLF) receiving sites (Allahabad, Varanasi, Nainital, Busan, and Suva) are represented by green diamond and location of JJI transmitter by pink triangle.

density ionosonde cannot receive echoes; hence, the *D* region remains the least explored region of the Earth's ionosphere. Fixed very low frequency (VLF) narrowband signals from various VLF transmitters located across the world propagate by multiple reflections through the waveguide formed by the Earth and the lower ionosphere called Earth-ionosphere waveguide (EIWG) and form the novel tools for continuous monitoring of the *D* region ionosphere [*Clilverd et al.*, 2001].

The 22 July 2009 total SE was the longest SE of the century. The totality was seen in a narrow belt of ~230 km wide but partial eclipse was seen in much wider path in East and South Asian region (Figure 1). The detailed information about this eclipse can be found on http://eclipse.gsfc.nasa.gov/SEmono/TSE2009/TSE2009.html. There are several studies on 22 July 2009 SE effects on the *D* region ionosphere using broadband and narrowband VLF signals generated by lightning discharges and navigational transmitters, respectively [*Guha et al.*, 2010; *Singh et al.*, 2011; *Zhang et al.*, 2011; *Ohya et al.*, 2012; *Phanikumar et al.*, 2014], but none of these studies focused on the possibility of WLS in the *D* region ionosphere.

In this work we present first observations of WLS in the *D* region ionosphere associated with 22 July 2009 total SE using JJI (22.2 kHz) VLF navigational transmitter signal recorded at five VLF sites uniquely located under full to partial eclipse conditions along the transmitter-receiver great circle paths (TRGCPs) (Figure 1). The diurnal conditions at receiving stations were such that *D* region ionosphere was partially developed (early morning time in the Indian Sector), almost developed (late morning time at Busan, Korea), and had varying conditions at Suva (late afternoon at the time of shadow intercept of TRGCP to evening time of partial passage of SE). The observations of WLS and their probable sources of generation are discussed.

2. Experimental Setup and Data

Coordinated observations for 22 July 2009 total SE were made using JJI (22.2 kHz) signal at five VLF receiving sites: Allahabad (25.40°N, 81.93°E), Varanasi (25.30°N, 82.93°E) and Nainital (29.35°N, 79.45°E) in the Indian Sector, Busan (35.23°N, 129.08°E) in Korea, and Suva (18.2°S, 178.4°E) in Fiji located in low to low-mid latitude region. The locations of the receiving sites, transmitter, the TRGCPs, eclipse totality path, and partial eclipse regions are shown in Figure 1. The eclipse magnitude at the stations varied from 1.015 to 0.54 as given in Table 1. The recording

Table 1. The Locations of Very Low Frequency (VLF) Stations, Transmitter-Receiver Great Circle Path (TRGCP) Path Lengths, Eclipse Magnitude, and Parentage Decrease in the Electron Density Estimated Using Two Methods[a]

VLF Stations	Coordinates Lat., Long.	Eclipse Magnitude	Maximum Eclipse LT (UT) (hh:mm:ss)	TRGCP (km)	% Decrease in Electron Density: Method 1	% Decrease in Electron Density: Method 2
Allahabad	25.4, 81.9	1.001	06:25:31 (00:55:31)	4785	95	100
Varanasi	25.3, 83.0	1.015	06:25:42 (00:55:42)	4686	97.21	100
Nainital	29.4, 79.5	0.845	06:27:18 (00:57:18)	4867	71.31	60
Busan	35.2, 129	0.853	10:52:49 (01:52:49)	393	80.80	60
Suva	−18.2, 178.4	0.54	16:16:16 (04:16:16)	7540	20	26
JJI	32.0, 130.8	0.945	10:57:38 (01:57:38)	–	N/A	80

[a]Method 1: *Guha et al.* [2010]; Method 2: *Ratnam et al.* [2012].

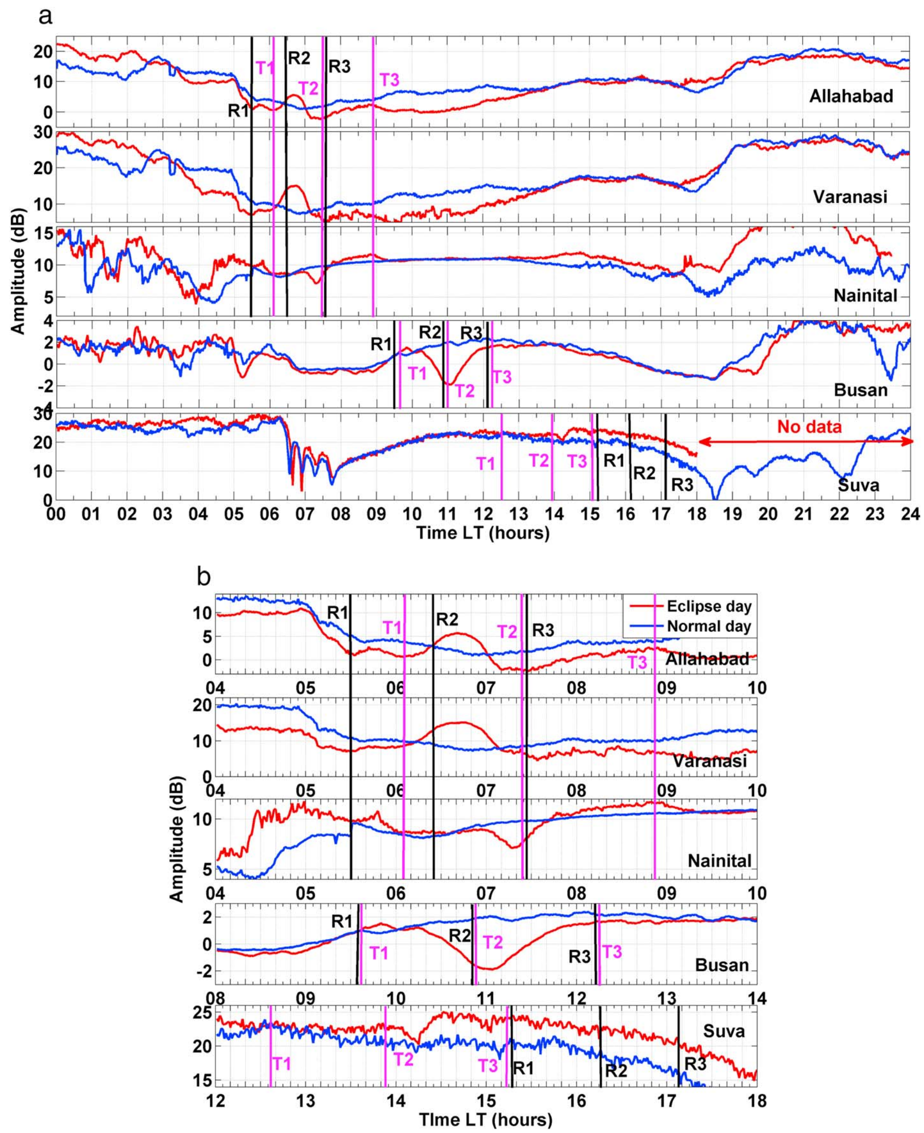

Figure 2. (a) The JJI signal amplitude variation for 24 h local time (LT) observed at the VLF stations on 22 July eclipse day (red line) and on a normal day (24 July 2009) (blue line). The vertical lines R1, R2, and R3 (pink line) and T1, T2, and T3 (black line) represent begin, maximum, and end times of eclipse at receivers and transmitter, respectively. The local time (LT) for Allahabad, Varanasi, and Nainital = Universal Time (UT) + 5.5 h, for Busan = UT + 9 h, and for Suva = UT + 12 h. (b) The JJI signal amplitude variation for 06 h local time (LT) interval surrounding eclipse timing observed at the VLF stations on eclipse day (red line) and on a normal day (24 July 2009) (blue line). The vertical lines R1, R2, and R3 and T1, T2, and T3 represent begin, maximum, and end times of eclipse at receivers and transmitter, respectively.

system at Allahabad, Varanasi, and Nainital is the Stanford University designed AWESOME VLF system [*Cohen et al.*, 2010; *Singh et al.*, 2010]. At Busan, the VLF data were recorded using Sudden Ionospheric Disturbance (SID) monitor [*Scherrer et al.*, 2008] and at Suva VLF recording system SoftPal [*Kumar et al.*, 2008] were used to record the amplitude of JJI transmitter signal. The VLF data were recorded at Allahabad, Varanasi, Nainital, and Suva at 1 Hz sampling frequency and at Busan at 12 Hz, but for the analysis we used 1 min average data for all the stations.

3. Results and Discussion

3.1. Solar Eclipse Time Variation of JJI VLF Signal Amplitude

Figure 2a shows the local time (LT) variation of JJI signal amplitude for 24 h at five sites on eclipse day (22 July 2009, red line) and on normal day (24 July 2009, blue line). The amplitude variation for 6 h period surrounding eclipse time is shown in Figure 2b to indicate the solar eclipse effect more clearly. The LT of Allahabad, Varanasi, and Nainital is universal time (UT) + 5.5 h, of Busan LT = UT + 9 h, and of Suva LT = UT + 12 h. Vertical lines R1, R2, and R3 correspond to the start, maximum, and end times of eclipse at receiver sites, and lines T1, T2, and T3 correspond to the same times at transmitter site. Allahabad (Figure 2b) was in 100% totality where the JJI signal amplitude change started at 06:11 LT with a maximum increase of about 6 dB at 06:41 LT which returned to its normal level at 07:06 UT as compared to 24 July amplitude values. The SE shadow first touched Allahabad at 05:30 LT (00:00 UT) and propagated almost along TRGCP ending at 07:26 LT (01:56 UT). At Varanasi (Figure 2b), which was also under 100% totality with highest eclipse magnitude (1.015), a similar increase in the amplitude of about 7 dB was observed. At Nainital (Figure 2b) where totality was 85%, the amplitude first increased by about 2.5 dB at 05:45 LT and returned to its normal value at 06:07 LT then slowly decreased to a maximum of 2.7 dB at 07:18 LT. Busan-JJI GCP (Figure 2b) with 85–95% of totality showed a decrease in the amplitude of ~3.5 dB at 11:02 LT. The SE totality intercepted Suva-JJI GCP (Figure 2b) at about 14:12 LT and amplitude decreased by 2.6 dB with respect to pre-SE values and by 0.5 dB with respect to normal day values. Following the intercept of totality, Suva-JJI GCP was under varying SE conditions (54–95%) starting at 12:37 LT and ending at 17:08 LT and showed increase in the amplitude over the normal day values due to reduced attenuation of the signal associated with partial SE. The amplitude values at different stations are different due to constructive/destructive interference of modes at stations, different orientations of antennas with respect to wave arrival, different background noise at systems used to record the VLF signals, and different gains tuned even for same recording system at different sites [*Morfitt*, 1972]. The eclipse day was accompanied with a moderate geomagnetic storm with the main phase at 02:00 UT, and D_{st} index had its minimum value of -83 nT at 07:00 UT and Σ Kp index reached the value of 25 (source: http://wdc.kugi.kyoto-u.ac.jp/) on 22 July 2009. Thus, at Allahabad, Varanasi, and Nainital, geomagnetic storm started after eclipse had passed but at Busan and Suva both eclipse and storm progressed almost simultaneously. However, moderate magnetic storms of such intensity are unlikely to have any effect on the low-mid latitude *D* region ionosphere [*Peter et al.*, 2006; *Kumar and Kumar*, 2014] so changes seen in JJI VLF signal amplitude are due to eclipse. The time delays varying 10–15 min have been estimated between the first encounter of eclipse shadow at different TRGCPs with respect (w. r.) to start of change in the amplitude of signal at different stations, e.g., at Allahabad and Varanasi the time delay was ~ 17 min and at Busan it was ~10 min. *Clilverd et al.* [2001] estimated time delays varying ~4–12 min for four VLF transmitters in the frequency range of 10–24 kHz measured at five receiver sites (four in Europe and one in Antarctica) during the SE of 11 August 1999.

During a SE, the decrease in solar flux due to moon's shadow causes sudden changes in the *D* region physical and chemical processes. The primary ionizing source at *D* region altitudes is Lyman-α (1215 Å) radiation from Sun, which is blocked by moon during total SE, causing a decrease in the *D* region electron density and hence an increase in the *D* region reflection height. The 22 July 2009 total SE effect on the *D* region VLF reflection height was estimated by *Singh et al.* [2011] using tweek radio atmospherics recorded at Allahabad and Nainital stations. They found a gradual decrease in *D* region electron density and an increase in reflection height following the eclipse conditions at Allahabad and Nainital. The eclipse creates nighttime like situation due to blockage of Lyman-α radiation, but still electron density is higher than nighttime due to some of the ionization produced by the soft X-ray and EUV radiations originating from the limb solar corona [*Curto et al.*, 2006; *Singh et al.*, 2011]. The overall effect of SE is to increase the *D* region VLF reflection height and create discontinuity in the total eclipse region of TRGCPs and hence changes in the VLF propagation conditions that result in the increase/decrease in the received VLF signal amplitude at the receiver. The increase in the *D* region reflection height of ~5–8 km associated with SE of 22 July 2009 has been reported by *Guha et al.* [2010] and *Singh et al.* [2011]. The TRGCPs for five selected stations in the study vary between ~ 400 and 7600 km (Table 1) and can be classified as short ($<$1000 km) and medium (1000–10,000 km) paths [*Clilverd et al.*, 2001]. *Clilverd et al.* [2001] for 11 August 1999 total SE observed both positive (increase) and negative (decrease) VLF amplitude changes (and in some cases both) which for majority of short paths were positive and negative for long paths. During 22 July 2009 total SE, *Guha et al.* [2010] from the observations taken in the eastern part of India observed a decrease in VLF (18.2 kHz) signal amplitude for the path length of ~2000 km. For the same SE, *Pal et al.* [2012] from the observations taken in north-eastern India reported an increase in VLF (18.2 kHz) amplitude for path length of ~2000 km and decrease at other stations with path lengths $>$2000 km. The increase/decrease in the VLF singnal amplitude is due to the constructive/destructive interference of modes at the receiver sites generated at the

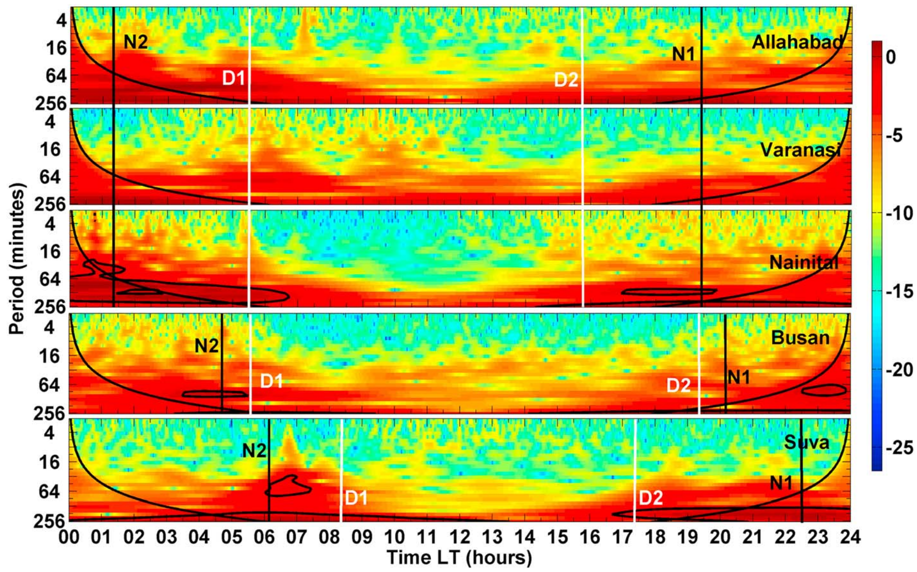

Figure 3. The wavelet spectra of JJI amplitude signal observed at five stations on 24 July 2009 obtained from the Morlet wavelet analysis. The time duration between D1 and D2 vertical lines corresponds to the complete daylight and between lines N1 and N2 to the complete dark conditions. The time duration between D2 and N1 gives day/night transition time and between N2 and D1 the night/day transition time. The black thick contour shows 95% confidence line of the period, and the bowel shape contour shows the cone-of-influence, anything below is dubious. Hence, the period lying between two curves is significant.

discontinuty created by SE shadow [*Clilverd et al.*, 2001] which depends mainly on the TRGCP length, path direction, topography of receiver sites, SE conditions, and ionospheric conditions along the TRGCP. The sudden increase in the *D* region reflection height due to SE causes some more significant modes reaching to receving stations and resulting in a complex interference pattern [*Clilverd et al.*, 2001] of modes at the receiver sites.

3.2. Normal Day Wave-Like Signatures

The main aim of this study is to explore whether the wave-like signatures (WLS) were induced in the *D* region ionosphere by 22 July 2009 total SE for which we have applied Morlet wavelet technique [*Grossmann and Morlet*, 1984; *Sauli et al.*, 2006] for the normal day (Figure 3) and eclipse day (Figure 4, section, 3.3) JJI amplitude data. The wavelet transform of the signal $X(u, z)$ is defined as [*Sauli et al.*, 2006]:

$$T_X(a,t,z) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} X(u,z)\Psi_0\left(\frac{u-t}{a}\right)du \tag{1}$$

where $X(u, z)$ is the amplitude time series, $T_X(a,t,z)$ is wavelet transform of $X(u, z)$, and Ψ_0 is the mother wavelet. For details on introduction to wavelet transforms, the reader is referred to *Mallat* [1998].

Figure 3 shows the wavelet spectra based on Morlet wavelet analysis of JJI amplitude on 24 July 2009 (normal day). The time duration between vertical lines D1 and D2 corresponds to the time when TRGCPs were in the complete daylight and between lines N1 and N2 corresponds to the time when TRGCPs were in complete dark. The time duration between lines D2 and N1 gives day/night transition time for TRGCPs and between N2 and D1 the night/day transition time. The black thick contour in the Figure 3 shows 95% confidence limit, and the bowel shape contour shows the cone-of-influence. Hence, WLS within the period lying between two curves are significant and considered in the present work. It is evident from Figure 3 that quasi-periodic WLS with period varying ~30–120 min were present on normal day during the dark conditions along TRGCPs and during night/day and day/night transition time at all five sites. The intensity of wavelet power spectra and period of WLS are different at different stations; at Allahabad (Figure 3) and Varanasi significant intensity WLS were not present during 24 h duration, at Nainital the WLS with period ~ ~30–128 min were present in the interval 00–06 LT (during night and night-day transition time) and in the interval 17–20 LT (during day/night transition and night times), at Busan the WLS with period

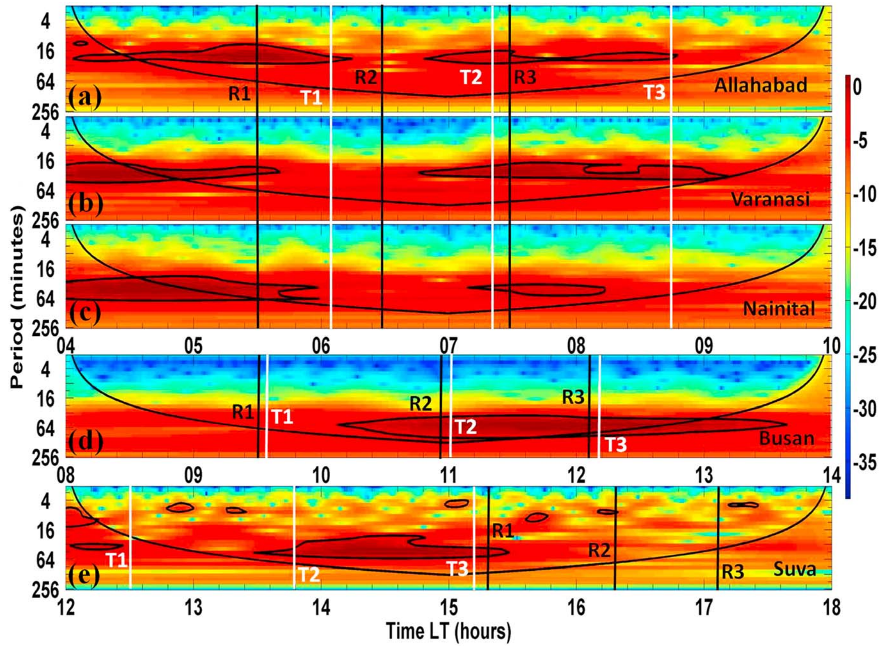

Figure 4. The wavelet spectra based on the Morlet wavelet of JJI filtered amplitude signal in two period range 10–50 min for totality stations (Allahabad and Varanasi) and 30–80 min for partially eclipsed stations (Nainital, Busan, and Suva) observed on 22 July 2009 eclipse day for 6 h duration at each station. The vertical lines R1 and R3, and T1 and T3 represent the eclipse begins and end time at receivers and transmitter, respectively.

~80–120 min were present in the interval 3:30–5:30 LT (during night and night/day transition times), and at Suva WLS with period ~32–64 were present in the intervals 06–7:30 LT (during night/day transition time) and with period ~120–200 min in the interval 17–20 LT during day/night transition time. There were no WLS present during completely daylight conditions of TRGCPs at any station.

Figure 3 shows that WLS with period ~30–120 min are mainly present in the dark conditions (nighttime) of TRGCPs and are more prominent in the night/day and day/night transition times. The nighttime observations of WLS are possibly due to high variability of nighttime *D* region ionosphere [*Maurya et al.*, 2012] due to absence of main source of ionization (Lyman-α) and presence of various other sources of ionisation as discussed by *Ohya et al.* [2011]. The variations in the electron density gradients of various scales in the *D* region parameters as reported by *Maurya et al.* [2012] and *Ohya et al.* [2011] produce WLS with different periods as seen at different stations. The daytime *D* region ionosphere is very stable with almost no temporal variability in the electron density gradients; therefore, we did not see WLS in the daylight conditions of any TRGCP. The night/day and day/night transition times are known as dawn and dusk terminators, respectively. Since passage of solar terminator is main source of GWs, the observed WLS during these intervals are probably caused by GWs [*Somsikov and Ganguly*, 1995; *Chernogor et al.*, 2002]. There is a possibility that WLS during these periods are generated by sudden change in solar radiation flux, temperature, electron density, plasma conductivity, and plasma instability due to night/day and day/night transitions at the *D* region altitudes. The review by *Somsikov and Ganguly* [1995] has experimentally and theoretically summarized the generation of WLS by the moving solar terminator which causes discontinuity/irregularities/gradients in temperature, electron density, etc. The electron density variation in the lower ionosphere due to solar terminator was studied by *Somsikov* [1983] who found that variation in the electron concentration due to solar terminator has seasonal and latitudinal dependences with maximum variation near equator during equinoxes. The previous studied have shown the solar terminator (ST) associated WLS of variable periods. *Nina and Cadež* [2013] using DHO, France, transmitter signal at 23.4 kHz recorded at Belgrade Serbia, reported WLS of period 1 s to 90 min during ST passes. *Afraimovich* [2008] reported GPS TEC oscillations with periods of about 1 h at 100 km altitude. Our results also show similar and also higher period WLS than reported in previous works. The WLS of higher period (>100 min) at respective stations are probably due to ST associated duration of amplitude change which is naturally visible in the wavelet analysis. However, the possibility of WLS due to gravity waves cannot be denied completely as period also falls within the period rage of gravity waves. There is a possibility of day-to-day, seasonal, local, and geographical variability of ST associated WLS. The ST is the regular source of irregularities and wave phenomena in the atmosphere, but its effects are not fully understood as it requires simultaneous continuous measurements of various parameters both vertically and horizontally at any location [*Somsikov and Ganguly*, 1995]. The present work is mainly focused on the eclipse generated WLS, but we also suggest further studies on ST generated WLS for better understanding of this phenomenon.

3.3. Eclipse Day Wave-Like Signatures

To examine the WLS in the *D* region ionosphere on eclipse day, Morlet wavelet analysis of JJI amplitude recorded at five sites on 22 July 2009 has been carried out. For the wavelet analysis of JJI amplitude we have subtracted monthly mean amplitude values from instantaneous amplitude values of 22 July 2009 which essentially removes the contribution of UV associated electron density changes from the WLS in the amplitude. Figure 4 shows wavelet analysis of the filtered amplitude data in two period ranges: 10–50 min for totality stations and 30–80 min for partially eclipsed stations. We have filtered these two period ranges from VLF signal amplitude recorded at five stations on eclipse day for 6 h duration (Figure 4) with respect to eclipse duration at each station. It is observed that (not shown here) the short period WLS are masked because of strong high period perturbations (~100–120 min) due to cycle of amplitude change and eclipse duration at respective stations. For example, the SE effect over Busan started approximately at 10:00 LT and ended at about 12:00 LT making a cycle of about 120 min. Similarly ~120 min eclipse duration is seen over Indian stations. Hence, we have filtered the VLF amplitude data to separate out the eclipse generated short period ($<$100 min) WLS from long period ($>$100 min) WLS associated with duration of the SE effect on the amplitude. The period ranges have been chosen based on the period of WLS reported by *Kumar et al.* [2013] and *Yadav et al.* [2013] for 22 July 2009 total solar eclipse over Indian stations and other reports on past SEs [*Altadill et al.*, 2001; *Ratnam et al.*, 2012; *Babakhanov et al.*, 2013].

On 22 July 2009 eclipse day, at Allahabad station (Figure 4a), WLS with period ~12–32 min were present in the interval ~04:00–06:10 LT (~22:30–00:40 UT) and with period ~16–32 min in the interval ~06:50–08:40 LT (01:30–03:10 UT). The WLS in the first interval (~04:00–06:10 LT) at Allahabad correspond to night-day transition time and the second interval ~06:50–08:40 LT correspond to eclipse duration at receiver and transmitter as indicated by the vertical lines in Figure 4a. At Varanasi (Figure 4b), WLS with period of ~16–50 min were present up to ~05:40 LT (night-day transition time) and then with period ~16–40 min in the interval 06:50–09:00 LT (01:20–03:30 UT) (during eclipse duration at receiver and transmitter). Similarly, at Nainital WLS with period ~20–64 min were present up to 06:00 LT and then with period ~30–60 min in the interval ~07:10–08:15 LT (01:40–02:45 UT). Busan station with similar eclipse conditions as at Nainital showed clear signatures of WLS with period ~35–80 min in the interval 10:10–12:40 LT (01:10–03:40 UT) (Figures 4c–4d). At Suva (Figure 4e), the WLS with period 30–60 min in the interval 13:40–15:20 LT (01:40–03:20 UT) were observed. We have observed WLS with varying periods and duration during night and night-day transition times (first interval) which clearly shows that these WLS are associated with passage of ST. The variable period and duration could be due to geophysical variability and local influence as discussed in section 3.2. However, at Busan and Suva, WLS were present only during the eclipse at receiver/transmitter. The WLS during eclipse duration at respective stations were delayed with respect to the eclipse start time at the receiver/transmitter. The delay time was ~80 min at Allahabad and Varanasi, ~100 min at Nainital, ~50 min at Busan with respect to the eclipse start time at the receiver, and ~60 min at Suva with respect to eclipse start time at the transmitter.

The important result of the present analysis is the presence of WLS with period ~16–40 min at totality stations and with period ~30–80 min at partial eclipsed stations with totality varying from ~85 to 54%. The delay times varying between 50 and 100 min at different stations were estimated. *Chimonas and Hines* [1970] showed that WLS were generated in the partial eclipsed region only with the period increasing at stations located gradually away from totality path. *Singh et al.* [1989] with multi-station study of total SE of 16 February 1980 over Indian region suggested that the receiving station should be more than 500 km from the totality path in order to detect any GWs associated effect with SE. However, *Ratnam et al.* [2012] for the annular SE of 15 January 2010 observed GW signatures with periods ~30–60 min at the station located at a distance of ~350 km from the totality path. Most of the previous studies [*Chimonas and Hines*, 1970; *Singh et al.*, 1989; *Ratnam et al.*, 2012] on GWs associated with SEs indicated that WLS can be observed at a station away from totality path. A recent study by *Kumar et al.* [2013] for 22 July 2009 total solar eclipse over Indian sector using the GPS TEC data has shown the presence of WLS at totality station Varanasi (100% totality) with period ~20–60 min and at partially eclipsed stations: Kanpur (95% totality) with period ~80–90 min, Hyderabad (82% totality) with period ~70–100 min and Bangalore (65% totality) with period ~100–120 min. They attributed these WLS to the GWs generated in the lower atmosphere during the total solar eclipse. *Yadav et al.* [2013] for 22 July 2009 SE using the ionosonde data recorded at Bhopal (100% totality), India, have shown the presence of WLS with periods ~16–20 and ~24–32 min at the sporadic *E* (*E*s) layer at maximum solar obscuration and end of eclipse, respectively. Our results from JJI amplitude observations for the 22 July 2009 SE at Allahabad and Varanasi which lie in the SE totality region show the WLS of nearly same period range as reported for totality stations by *Kumar et al.* [2013] and *Yadav et al.* [2013]. Interestingly, our observations further confirm that that WLS can also occur at the station in the totality region with a shorter period as compared to partially eclipsed regions. The plausible reason for the observed results could be interpreted because of ionospheric conditions at the time of intercept of eclipse to TRGCPs. The eclipse at Allahabad and Varanasi occurred in the early morning time (~05:30 LT) just after sunrise time when lower ionosphere was not fully developed [*Singh et al.*, 2011], which is a unique condition as compared to previous studies [*Chimonas and Hines*, 1970; *Singh et al.*, 1989; *Ratnam et al.*, 2012]. Hence, continuation of nighttime like conditions due to this SE in early morning sector would have created the variability in the *D* region parameters generating the WLS of short period at Allahabad and Varanasi. The WLS at Varanasi are of slightly longer duration than at Allahabad which could probably be due to longer totality period (~3.18 min) at Varanasi as compared to Allahabad (~45 s).

The stations Nainital, Busan, and Suva lie in the partial eclipse (~85% and 54% totality) and show the presence of WLS with period ~30–60, ~35–80, and ~30–60 min, respectively. Periods of WLS observed at stations under partial eclipse are of longer duration than those at the stations under totality (Allahabad and Varanasi). Our results for partially eclipsed stations seem to be consistent with the theory suggested by *Chimonas and Hines* [1970] according to which WLS period increases with the location of station away from SE totality path. Since Nainital and Busan with 85% totality are located ~540 and ~460 km away from the totality path, higher period WLS compared with fully eclipsed regions are observed. Nainital and Busan have similar eclipse conditions (~85% of totality), but WLS at Busan are of longer period than at Nainital. The observations at Busan indicate that the TRGCP path length may also play an important role in generating WLS at respective sites. Busan is located near the JJI transmitter (TRGCP distance for Busan is ~390 km, which is much shorter than for JJI-Nainital TRGCP with distance ~4800 km). Also, eclipse timing at Busan (late morning ~10:52 LT) might have contributed toward longer period of WLS as compared to Nainital (early morning ~06:27 LT).

The Suva station represents the unique conditions due to the presence of WLS with period ~30–60 min when the eclipse passed over the transmitter in Japan whereas for other cases eclipse passed over the receiving sites. The JJI-Suva TRGCP is also unique in the sense that it was crossed by totality shadow and is longest TRGCP (~7540 km) as compared to other TRGCPs. The Suva station was ~1700 km away from the totality path at the time of SE shadow interception with TRGCP. Also, along the JJI-Suva TRGCP eclipse totality changed from 95% at the transmitter to 54% at the receiver. Since eclipse effect at Suva is dominated by eclipse occurrence at the transmitter, observations of WLS at Suva are discussed w. r. to eclipse timing at the transmitter. The period ~30–60 min of WLS at Suva is longer than that at Allahabad and Varanasi (totality stations) and is almost comparable with period of WLS at Nainital and Busan (partially eclipsed stations). It is also worth mentioning that partial eclipse at Suva occurred in the late afternoon (~16:16 LT) whereas it was late morning (~10:52 LT) at the transmitter. The delay time ~ 60 min w. r. to the eclipse start time at transmitter is comparable with delay time at other stations w. r. to eclipse start at the receiver stations.

The delay time of ~50–100 min observed in the present work is consistent with previous measurements [*Chernogor*, 2010; *Ratnam et al.*, 2012; *Yadav et al.*, 2013]. *Chernogor* [2010] for 1 August 2008 SE reported time delay of ~6 min at 70–80 km altitude using VLF measurements at Kharkov (50°N; 36.23°E). Moreover, *Ratnam et al.* [2012], for annular SE of 15 January 2010 observed time delay of ~ 68 min at the altitude range of 60–80 km at a low latitude station, in India. The longer delay times (~1–2 h) have also been reported by various workers at *E* to *F* region ionosphere heights [*Zhang et al.*, 2010; *Yadav et al.*, 2013].

The observations by *Kumar et al.* [2013] for 22 July 2009 total solar eclipse showed the presence of WLS with period ~40–100 min for partially eclipsed stations in Indian region under solar obscuration from ~95 to 72%. They attributed observed WLS to change/oscillations/gradient in the electron density caused by the SE generated GWs. *Chernogor* [2010] for 1 August 2008 solar eclipse using sub-ionospheric VLF signal recorded at Kharkov reported the detection of WLS at *D* region altitude and found short period (~10–18 min) WLS with the delay time ~6 min. *Altadill et al.* [2001] for the solar eclipse of 11 August 1999 showed the presence of WLS with period ~60 min at the altitude 150–250 km using Ionosonde data recorded at Observatori de l'Ebre station (40.8°N, 0.5°E) (~75% totality). *Babakhanov et al.* [2013] from the analysis of the critical frequency of F2 layer at Novosibirsk, Russia, located in the totality region of 1 August 2008 reported the WLS with period ~30–90 min. While comparing the present results of eclipse effect in the *D* region ionosphere with the results from *E* and *F* regions, it should be noted that the amplitude of WLS could be much weaker in the *D* region as compared to the *E* and *F* regions. This is probably due to the presence of stronger electron density gradients in the *E* and *F* regions as compared to the *D* region.

The electron density (ED) changes along the path of eclipse caused by the blockage of solar radiation in the *D* region ionosphere can disturb the balance state of upper boundary of EIWG, through which VLF waves propagate; hence, ED variation can be considered as one of the possible mechanisms for observed WLS along with the gravity waves coming from below the lower ionosphere. To estimate the ED changes (gradients) we have calculated percentage decrease in the ED (Table 1) using two methods. The method 1, as used by *Guha et al.* [2010], is based upon the change in the VLF signal amplitude as compared to normal day and is used to estimate the Wait ionospheric parameters (H' and β) which are used to estimate ED profile using relation $N_e(z) = 1.43 \times 10^7 \exp(-0.15H')exp[(\beta - 0.15)(z - H')]$ where $N_e(z)$ is the ED in cm^{-3} and H' is the *D* region reference height in km and β is the sharpness factor in km^{-1} [*Wait and Spies*, 1964]. The changes in ED due to the eclipse were calculated using normal daytime $H' = 71$ km and $\beta = 0.43\ \mathrm{km}^{-1}$ [*Clilvered et al.*, 2001] and eclipse time H' and β estimated using change in JJI signal amplitude for each TRGCP. As shown by *Clilverd et al.* [2001] for 11 August 1999 total SE, 1 dB change in the VLF signal amplitude corresponds to change in $H' = 1.1$ km and $\beta = 0.01\ \mathrm{km}^{-1}$. For the present work altitude (z) is taken 75 km as average daytime *D* region VLF reflection height. As shown in Table 1, using method 1 we estimated decrease in ED of about 95, 97, 71, 81, and 20 % at Allahabad, Varanasi, Nainital, Busan, and Suva, respectively, during SE. Using the method 2, as explained by *Ratnam et al.* [2012] we also estimated percentage change in ED depending on the solar radiation obscuration at different stations with respect to normal day. As explained by *Ratnam et al.* [2012], the ED for normal day can be taken to be proportional to $\sqrt{F \cos\chi}$, where F is solar flux and χ is solar zenith angle. But for eclipse day, the ED is proportional to $\sqrt{(1-\gamma)\cos\chi}$ where γ is obscuration rate of sun during the eclipse event. The ED decrease of 100, 100, 60, 60, and 26 percentages is estimated for Allahabad, Varanasi, Nainital, Busan, and Suva (Table 1) for solar obscuration of 100, 100, 82, 83, and 54, respectively, at the sites. The linear correlation coefficient (r) between solar radiation obscuration and decrease in ED is 0.836 and 0.947 using method 1 and method 2, respectively. Although there is some difference in ED changes by both the methods but significant change in ED associated with 22 July 2009 SE is evident from high "r" values between solar radiation obscuration and decrease in ED combined at the sites. The ED decrease/fluctuation seems to contribute to the WLS at different stations.

It is important to understand possible sources which might have produced ED gradient in the *D* region ionosphere and ultimately resulted in the observed WLS at different stations as revealed by wavelet analysis of JJI VLF signal amplitudes recorded on 22 July 2009. The potential candidate could be GWs generated in the stratosphere propagating upward and causing ED gradient variations which generated WLS in the *D* region ionosphere. The GW generation in the stratosphere during eclipse was proposed by *Chimonas and Hines* [1970] who suggested that the blockage of direct UV radiation from the Sun by moon stops heating of ozone in the stratosphere because of sudden cutoff of solar radiation by eclipse. This creates a cooling spot in the stratosphere which moves with the supersonic speed across the Earth and creates continuous GWs. The WLS can also occur due to traveling ionospheric disturbances (TIDs) caused by geomagnetic storm at high latitude which can travel to middle and low latitudes [*Francis*, 1975; *Hunsucker*, 1982; *Vlasov et al.*, 2011]. The TIDs are very unlikely to be the possible sources of WLS presented here as 22 July 2009 storm was a moderate geomagnetic storm. *Sauli et al.* [2006] for SE of 11 August 1999 using the electron density data recorded with classical ionosonde IPS 42 KEL Aerospace suggested the gravity and acoustic waves as possible sources of ED variations located in two regions. First region is located at 200 km which is the transition height between F1 and F2 regions where difference in solar radiation flux creates gradients of temperature, pressure, electron, and ion concentration. The GWs generated in this region propagate upward and downward simultaneously. The second source region is in the middle atmosphere due to cooling of ozone by the supersonic movement of moon's shadow. The GWs generated in this region propagate upward as suggested by *Chimonas and Hines* [1970]. *Zerefos et al.* [2007], for March 2006 total solar eclipse by using different measurement techniques for the troposphere, stratosphere, and ionosphere, showed the presence of GWs in the stratosphere and ionosphere with periods of ~ 30–40 min. *Zhang et al.* [2010], for the 22 July 2009 SE, using ionospheric back scatter sounding data recorded at Wuhan (30.5°N; 114.35°E), China, observed medium scales traveling ionospheric disturbances (MSTIDs) of a 40 min period from ED fluctuations in the *E*s and *F* regions. They suggested that GWs can be caused by differential heating of different regions of atmosphere due to SE and their downward and upward movements coupled with the ionosphere produce WLS in ionospheric parameters such as electron density and temperature in the *E*s and *F* regions. *Chen et al.* [2011] using ionosonde and radar data reported the WLS in the *E*s layer during 22 July 2009 SE with period of ~35 min at Wuhan. They concluded that SE generated GWs propagate upward to deform the *E*s layer and produce the observed WLS in the layer. Overall, various studies suggest the presence of WLS at different ionospheric altitudes possibly caused by eclipse generated GWs with sources located in the upper atmosphere (~200 km altitude) and lower atmosphere (~50 km altitude). Our VLF observations seem to confirm that similar WLS are also generated in *D* region ionosphere due to ED gradients created by blockage of *D* region ionization superimposed with GWs produced at ~200 km due to differential heating and the GWs produced in the stratosphere due to supersonic movement of moon's shadow.

In general, results presented here on WLS using the wavelet analysis of JJI VLF signal amplitude recorded at five VLF sites are in agreement with many previous studies on 22 July 2009 total solar eclipse [e.g., *Kumar et al.*, 2013; *Yadav et al.*, 2013] and many past SE using different measurements in different regions of atmosphere [e.g., *Altadill et al.*, 2001; *Ratnam et al.*, 2012; *Babakhanov et al.*, 2013]. For example, comparison of wavelet analysis on SE day (Figure 4) with control day (Figure 3) clearly shows WLS on eclipse day due to SE induced *D* region disturbances. The period of WLS (~16–80 min) reported in the present work is consistent with many previous studies [e.g., *Chernogor*, 2010; *Ratnam et al.*, 2012; *Yadav et al.*, 2013] on total and partial SEs. The delay times at each station indicate that WLS occur after the start of eclipse at the receiver/transmitter and are present during and after the eclipse totality at the receiver/transmitter which is in agreement with previous studies. It is important to note that due to limitations in our measurement technique, we could not provide clear evidence about the source of observed WLS, but we surmise that observed WLS in our work could be caused by SE generated GWs with sources located in the upper ionosphere (~200 km altitude) and stratosphere (~50 km altitude) and propagate both upward and downward. The observational evidence of WLS period occurrence duration and delay time provided in the past/present reports probably suggests that observed WLS are probably due to SE associated GWs and ED gradients changes. The observed variations in various parameters discussed above may be attributed to the complex nature of the wave generation and propagation from the source to the observational site, measurement techniques used in different studies, different local conditions, varying solar obscurations, and solar activity cycle. Overall, the observations of WLS at different stations seem to depend on the various factors such as location, day-night conditions, geometry of eclipse, eclipse magnitude, and time difference between transmitter and receiver.

4. Summary

The first observations of wave-like signatures (WLS) in the *D* region ionosphere associated with the 22 July 2009 solar eclipse have been reported from the analysis of amplitude of JJI VLF transmitter signal (22.2 kHz), Japan, recorded at five stations located in the low to low-mid latitude regions. The wavelet analysis shows the presence of WLS with period ~16–40 min at the station under total eclipse and with period ~30–80 min at stations under partial eclipse (85–54%) with the delay times (time difference between start of WLS at the station and start of eclipse) between ~50 and 100 min with respect to eclipse occurrence time at different stations and at transmitter in case of Suva. The WLS are probably generated by the ionospheric ED changes (gradient) due to partial/total SE conditions along the TRGCPs. Apart from ED changes in the *D* region ionosphere the upward propagating GWs generated due to supersonic movement of eclipse spot in the stratosphere and GWs generated at the altitude of about 200 km between F1 and F2 regions propagating downward to the *D* region are suggested as the potential candidates for the observed WLS at different stations. It is also estimated that the decrease in the electron density is well correlated with solar radiation obscuration. More focused observations of VLF signals during future SE events are required for the better understanding of generation mechanism of WLS under SE conditions.

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