

Atmospheric Electricity Research in Indian Subcontinent during Solar Eclipses

S. Paul^{1,2}

¹Centre of Advanced Study in Radio Physics and Electronics,
University of Calcutta, Kolkata 700009, India

²Department of Physics, Rishi Bankim Chandra Evening College,
Naihati, 24 Parganas (N), PIN 743165, India

Received 9 April 2017

Abstract. Solar eclipse (SE) gives researchers a unique opportunity to observe and analyze the dynamics of the Earth's space-environment throughout the globe. In India, excellent studies of atmospheric electricity parameters and observations of metrological parameter changes during the past SEs have been made. Various experiments, viz., measurement of surface O₃, NO, NO₂, NH₃ and CO, detection of short-period coronal oscillation, vertical electrical potential gradient, Very Low Frequency (VLF), Point Discharge Current (PDC) measurement, measurement of temperature, relative humidity, wind speed, Ultra Violet (UV) radiation, performed in different places of India during SE periods and the outcome of those investigations are documented in brief in this review.

PACS codes: 95.10.Gi; 92.60.Pw.; 92.70.Cp

1 Introduction

Solar eclipse is one of the most spectacular astronomical phenomenon which occurs when the Moon covers the Sun, casting its shadow on the Earth and it inspires researchers to conduct special investigations. Eclipses are connected with the rapid and short time, impulse-like decrease of solar energy flux reaching the area of its visibility [1,2]. It also provides a unique opportunity for meteorologists to study the temporal response of the atmosphere to the sudden switch off-on of the incidental solar radiation during and after the SE. There are a number of studies and observations made during the SEs which include observations of meteorological parameters, viz., wind speed and direction, air temperature, atmospheric pressure, humidity [3-8], gravity waves [9-11], ozone measurements [12-14] and heat & momentum fluxes within the boundary layer [6]. Researchers have the opportunity to study the behavior of typical electrodynamic coupling between different layers of the ionosphere and magnetosphere during a short duration nighttime conditions made by eclipse period [3,15-17].

Also, studies of the ionospheric response to SE have been made with various experimental techniques, such as ionosondes, incoherent scatter radar, rockets, Faraday rotation measurements, global positioning system and satellite measurements [18-28] as well as theoretical modeling [29]. The majority of the studies are devoted to the behavior of the ionosphere at altitudes above 100 km [17,29-31]. Moreover, SE gives the opportunity to investigate a great number of parallel phenomenon at different environments, e.g., atmosphere, marine environment, ecosystems etc. as well as meteorological variables [8,32-34]. The effects of SE on total O₃ column and stratospheric O₃ have also been reported [13]. Similarly, the studies concerning SE induced effects on troposphere/surface O₃ and other photo-oxidants i.e., NO₂, NO etc. are reported by several researchers at different parts of the globe [14,33-39].

In India, excellent studies of atmospheric electricity parameters and observations of metrological parameter changes during the past SEs have been made [6,10,40-56]. There are very few studies about the effects of solar eclipse on the propagation of Very Low Frequency (VLF) waves especially over the Indian subcontinent and its connections with lower ionosphere [57,58]. The effect of total SE on surface O₃, NO, NO₂, NH₃, CO mixing ratio and the meteorological parameters on 15 January 2010 at Thiruvananthapuram, India was investigated [59]. Faraday rotation data obtained at Delhi, Kurukshetra, Hyderabad, Bangalore, Waltair, Nagpur and Kolkata during the total SE of 16 February 1980 and at Delhi during the total SE of 31 July 1981 have been analyzed to detect the gravity waves generated by a total SE as hypothesized by Chimonas and Hines [60]. It has been found that gravity waves can be generated by a total solar eclipse but their detection at ionospheric heights is critically dependent on the location of the observing station in relation to the eclipse path geometry. The distance of the observing station from the eclipse path should be more than 500 km in order to detect such gravity waves [10].

In this review, various experiments performed in different places of India during SE periods and the outcomes of those investigations are compiled in brief. The results are also discussed.

2 Instrumentation and Data Handling

2.1 Measurement of Surface O₃, NO, NO₂, NH₃ and CO

Sharma et al. [59] used an UV-based Ozone analyzer for measuring the surface O₃ during the SE on 15 January 2010 at Thiruvananthapuram (8.55°N, 76.77°E). Precision was 1 ppb and it was calibrated before and after the eclipse events using zero air generator and mass flow calibrator. Mixing ratio of NO and NO₂ were measured using NO_x-Analyzer with Photo-catalytic Converter operating based on chemiluminescence method with an accuracy of ±50 ppt and was calibrated before and after eclipse events using zero air generator and National

Institute of Interdisciplinary Science and Technology (NIIST) certified NO span gas (500 ppb $\pm 5\%$). NH₃ mixing ratio was measured using NH₃-Analyzer operating based on chemiluminescence method. CO was measured using non-dispersive infrared (NDIR) gas filter correlation analyzer with lowest detection limit 20 ppb. Mixing ratio of O₃, NO, NO₂, NH₃ and CO at 1 min time resolution during the study period had been collected. Statistical analysis of all the data sets was done using standard methods.

2.2 Short-Period Coronal Oscillation Detection

In search of the suspected brightness oscillations in the solar corona during the eclipse of 24 October 1995, photometric observations were performed at Kalpi (26.08°N, 79.45°E), Uttar Pradesh by Singh et al. [61]. A stepper motor-driven coelostat of 30 cm aperture was used to collect the light from the Sun which in turn was reflected horizontally with the help of a second mirror of 15 cm aperture. Photons were detected using a photomultiplier tube (PMT) with the cathode kept at 1.6 kV. Pulse amplifier discriminator was a Thorn EMI Type AD 100 with a dead time of 100 ns. The data acquisition was made with a PC-based, locally developed photon counting system. The digital counter used had a bandwidth of 100 MHz.

2.3 Atmospheric Electric and Meteorological Parameters Measurement

2.3.1 Vertical Electrical Potential Gradient

De et al. [50] measured the vertical electric field with an ac field-mill at Kolkata (22.56°N, 88.30°E) during eclipse of 1 August 2008. Signal from the field-mill was amplified using a signal processor with 1 sec time constant. IC LF356N was used at the input stage because of its high input resistance ($\sim 10^{12} \Omega$) and good signal to noise ratio. Sensitivity of the field-mill was $(0.33 \pm 0.03) \text{ Vm}^{-1}$. Output was recorded by PCI 1050, 16-channel 12-bit digital data acquisition system (DAS) with 12-bit A/D converter, 16 digital input and 16 digital outputs. The data were recorded at a sample rate of one record per second. An electric field monitor (EFM-100) of around 30 km field of view was used by Anil Kumar et al. [62] to measure the height integrated electric field variation over wide area on the eclipse path of 15 January 2010 eclipse at Tirunelveli (8.07°N, 77.08°E). The outputs from the sensors, after proper signal conditioning, were fed to a highly sensitive 8 channel windows based data logger [63,64].

2.3.2 Point Discharge Current (PDC)

During the eclipse of 22 July 2009, PDC was measured by using a steel wire having diameter of 3 mm and length of 8 cm, one end of which was made tapered to a sharp edge, at Kolkata (22.56°N, 88.30°E) by De et al. [54]. The tip of the

sharp edge was about 0.02 mm. The other end was soldered to a co-axial cable which was made perfectly insulated by Teflon. The total junction was tightly covered by Teflon insulated wire. The cable was surrounded by thermoplastic polystyrene which was coated by very thin honeycomb winding copper wire. The external surface was kept within the cylindrical plastic cover. This process ensured efficient heat insulation. The other end of the cable was connected to the receiving system. The transient responses from the tip were amplified with overall gain around 40 dB. Anil Kumar et al. [62] measured the current using Wilson's plate [65], horizontal long wire antenna [66,67], and spherical shell in the form of two hollow hemispheres [68]. Corresponding electric field was indicated by the electrometers with OP-AMP, AD 549. A buffer stage (LM308) was connected to the electrometer outputs which were filtered by a low-pass filter (3 dB) at the input of an A/D converter. The filtered signal was fed to a high-resolution Windows-based data logging system. 1 min averaging of the data is carried out during the analysis.

2.3.3 Meteorological Parameters

The meteorological parameters, viz., temperature, relative humidity (RH), wind speed, wind direction and solar radiation were recorded using calibrated Portable Weather Logger stationed at 6 m height above the ground at Thiruvananthapuram site [59]. Temperature of near-Earth surface and RH at an interval of 15 min were measured by Kestrel[®] 4500 pocket weather tracker at Kolkata [54]. Well-sealed, precision thermistor was mounted externally and thermally isolated for rapid response to measure temperature with $\pm 0.5^\circ\text{C}$ and 0.1°C resolution and operational range -29° – 70°C . RH was measured with $\pm 3.0\%$ accuracy and with high resolution. Operational range was 0–100%. Temperature, RH and air pressure were measured during the solar eclipse on 22 July 2009 at Kalyani University Campus (22.97°N , 88.47°E) by Bhattacharya et al. [69]. A 3 m high tower was installed at the ground of Space Application Centre, Ahmedabad (23.35°N , 72.60°E) to measure both mean and turbulence parameters during 11 August 1999 eclipse [6]. The fluctuations in wind, humidity and temperature were measured by collocated Gill propeller anemometer (range $\pm 30\text{ ms}^{-1}$; accuracy 0.1 ms^{-1}), capacitor based humidity sensor (accuracy of 2% in the range from 0 to 90% RH and 3% accuracy from 90% to 100% RH) and fast response platinum resistance thermometer (range 0 – 50°C ; accuracy 0.2%), respectively. Also, slow response measurements of wind, temperature and soil temperature were made using cup anemometer, platinum resistance thermometer and four level soil temperature sensor (5, 10, 20 & 40 cm), respectively. Prior to the experiment, all the sensors were calibrated. The automated weather instruments at Tirunelveli (8.07°N , 77.08°E), and manual observations of wet and dry temperatures, visual scanning of cloud coverage, and visibility checking were used [62].

2.4 Very Low Frequency (VLF) Measurement

De et al. [50] used an inverted L-type antenna made from 8 SWG copper wire of 120 m in length to receive vertically polarized atmospheric VLF signals from near and far sources. It was installed horizontally at a height of about 30 m above the ground. The signal processor was tuned to the desired frequencies. The overall Q-factor of the tuning circuit was around 300. The signals from the tuning stage were fed to a log amplifier. The data were recorded by DAS. Measurements of sferics were taken for noting the ionospheric irregularities by a sensitive tuned radio frequency receiver at 27 kHz [69]. The recording of several VLF transmitted signals and atmospheric VLF signals were continued round the clock at Tripura University site (23.75°N, 91.25°E) by Guha et al. [70] during the eclipse of 22 July 2009. The experimental setup consisted of a loop antenna of 1 m², a 30 kHz bandwidth preamplifier, and a SpectrumLab V2.7b14 software VLF receiver. The 24 bit sound card of a P-IV 2.66 GHz computer, which records analog data at a sampling frequency of 48 kHz, was used as data acquisition. The r.m.s. value of the signal at the desired frequency was recorded at a sampling rate of 1 s. Coordinated observations for 22 July 2009 total eclipse 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 by Maurya et al. [71]. The recording system at Allahabad, Varanasi, and Nainital was the Stanford University designed AWESOME VLF system [72, 73]. The data were recorded at 1 Hz sampling frequency but for the analysis 1 min average data were used.

2.5 Ultra Violet Radiation Measurement

During the SE on 22 July 2009, the penetrating solar radiation was observed on the ground of Kalyani University campus (22.97°N, 88.47°E) by Bhattacharya et al. [69]. The sensor had an extremely precise structure with UV photo diode and UV colour correction filter. The direct solar irradiance was measured in 290-390 nm band width with sample time about 0.4 sec. The UV sensor was designed to measure UV light values up to 199.90 Wm⁻². The luminosity was measured using a sensitive Lux meter. The measurements were taken at 1 min interval on an average. The photo detector was faced to light source in a horizontal position and the value of illuminance was taken from the LCD display.

3 Results and Discussions

To explore the effect of SE, the surface O₃, NO, NO₂, NH₃, CO mixing ratio and meteorological parameters (temperature, relative humidity, wind speed and solar radiation) had been measured at NIIST, Thiruvanthapuram during the annular

SE on 15 January 2010 by Sharma et al. [59]. The ambient temperature and wind speed were found to decrease while RH to increase. The experimental data demonstrated that SE phenomenon has prominent effects to the mixing ratio of surface O_3 , NO, NO_2 , NH_3 , CO. The decrease in mixing ratio of surface O_3 and NO_2 was observed after the beginning of the SE events and lasted for four hours, probably due to decreased efficiency of the photochemical ozone formation, whereas, the increase in mixing ratio of NO, CO and NH_3 might have followed the night time chemistry. After the end of the eclipse period, all the above mentioned parameters exhibited a tendency to re-gain their earlier pattern on the same day.

During the eclipse of 24 October 1995, from the photometric observations at Kalpi, Singh et al. [61] examined coronal intensity oscillations of periods ranging from 5.3 to 56.5 s. The recorded data revealed that most of the power was contained in 6 frequencies below 0.2 Hz and the periods of 6 frequency components were found to be 56.5, 19.5, 13.5, 8.0, 6.1 and 5.3 s said earlier. These oscillations were sinusoidal, and their amplitudes were found to lie in the range 0.2–1.3% of the coronal brightness. Thus, in the solar corona there is enough flux for the heating as the observed oscillations were fast magnetosonic modes. Further study may be continued to investigate, if any, the oscillations with enough resolution to delineate the size of the oscillating region and to observe at different solar radii to detect changes in oscillations with radius.

From the temporal variation of the vertical potential gradient recorded on 1 August 2008 at Kolkata together with its normal trend obtained from the average of five days adjacent to the eclipse day, De et al. [50] found that the vertical potential gradient enhanced from prior to the occurrence of the SE over Kolkata and reached maximum during the eclipse at 17:15 IST. The peak value was around 490 Vm^{-1} . Then it progressively decreased until local midnight registering values below the normal ones. The corresponding maximum value of the normal variation was around 275 Vm^{-1} , i.e., the observed increase was well beyond the standard deviation. During the balance of the eclipse day, the observed variation lied within the standard deviation range. The increase in vertical potential gradient suggests a decrease in ionization during the period of SE. This provides a good coupling between the Earth's near-surface atmosphere and the lower ionosphere. The removal of electrons from the lower part of the ionosphere due to recombination mechanism during the SE might give rise to an increase in vertical potential gradient as suggested by De et al. [50]. Moreover, during the eclipse period, ions from the lower regions were carried out somewhat due to convection current and became neutralized to some extent by the recombination process, thereby reducing the conductivity of the medium. This was another probable reason for the potential gradient to increase.

On the contrary, Anil Kumar et al. [62] found about 65% decrease in the ambient electric field during the eclipse of 15 January 2010 in comparison to control-day data in and around 30 km height integrated area. They explained the decrease as

a result of the micrometeorological changes within the air, the small ions, which are more mobile than heavier ions, usually might get attached to newly formed water droplets. This coalescences process ends in free space charge reduction that could result in a large drop in the electric field centered at around the peak of the eclipse, and recovers toward normal level by the end of the eclipse.

Diurnal variation of PDC over Kolkata was reported by De et al. [54] during the day of SE on 22 July 2009 w.r.t. the same variation on two control days, i.e., 21 and 23 July 2009, respectively. The value of PDC prior to the eclipse was slightly higher than the average of the adjacent days and found to decrease from about 05:30 IST with the commencement of the eclipse and attained the minimum value at about 08:00 IST. After 08:00 IST, PDC gradually increased to follow the nature of the variation similar to that of the two adjacent control days. In the absence of solar radiation during eclipse, because of the want of ionization, PDC drop down suddenly and maintains nearly a plateau with almost fixed value during the period of eclipse and as soon as eclipse seized, solar radiations enhance the causality background rapidly showing the signature of approaching the ambient magnitude of PDC. Total process is highly quasi-static. Wind velocity during the eclipse period took part in the way of transportation of space charges surrounding the antenna wire-tip causing conductivity of the adjoining medium to fall. As a result, value of PDC decreases.

From the measurements of different atmospheric current components recorded at Tirunelveli on the 15 January 2010 eclipse day, Anil Kumar et al. [62] reported that following the onset of the eclipse the currents started to fluctuate. The displacement current exhibited two large cyclic fluctuations within about 5 h from the start of the eclipse until about an hour after the end of the eclipse (sunset); and the period and amplitude of the fluctuations increased with the progress of the eclipse. Similar fluctuations were also observed in Maxwell current, and to a lesser extent in conduction current. The second cycle of fluctuation in the Maxwell current indicates that the surface air is uplifted through upward convection generated by solar heating after maximum eclipse. The convection current can occur in different directions and intensities; it also depends on the space charge density, air movements, stability of atmosphere, and gravity acting on charged particles' suspension. The fluctuations in the conduction current were weak and might be because this current component generally depends on the global thunderstorm activity rather than on local generators.

Ambient temperature close to the surface decreased from 33.3°C to 29.5°C during the total eclipse event and after the full phase of eclipse, it began to increase abruptly. Temperature dropped by 3.8°C with a time lag about 20 min after the full phase of eclipse. Relative humidity started to increase at 11:15 IST as the decrease in temperature reaching a maximum at the end of the SE. Also, wind speed started to decrease after the beginning of eclipse and reached at minimum during totality. It might be due to cooling and stabilization of the atmospheric boundary. After the end of eclipse period, all parameters exhibited a tendency

to re-gain their earlier pattern [59]. The variations of temperature and RH on the day of 22 July 2009 eclipse were reported by De et al. [54]. At the start of eclipse, temperature was 28.4°C that gradually decreased to 26.2°C when the eclipse attained its greatest phase. RH was 84.8% at the start and reached 87.2% at the greatest phase. For the same eclipse, Bhattacharya et al. [69] also reported the decrease of temperature and increase in RH measured at Kalyani University Campus. Krishnan et al. [6] conducted experiments at Ahmedabad during the period from 4th to 17th August 1999 continuously. The fast measurements were made only for the selected time period during daytime, but round the clock measurements of fast data were made during 10th to 13th August 1999. The air temperature showed a variation in the range 24–30°C and RH varied in the range 70–90% till 11 August 1999, the eclipse day. The air temperature showed an increase from 12th August onwards and RH varied between 40 and 80%. The wind speed was found to be low with a value ranging up to 2 ms⁻¹ and the wind direction indicated the south-westerly flow over land which is characteristic of the south-west monsoon period. Anil Kumar et al. [62] manually observed meteorological parameters at three nearby stations and reported that detectable changes started about an hour from the first contact of 15 January 2010 annular eclipse, and peak changes also occurred about an hour after annularity. Except air density and air pressure, all other meteorological parameters recovered back to normal level soon after the end of the eclipse. Surface temperature decreased by up to 4°C. The level of humidity on control days was low, but on the eclipse day humidity as a whole was low. Over the low level, as a consequence of the cooling, humidity raised by about 35%. The wind speed was nearly zero before the start of eclipse compared to a speed of up to 2 ms⁻¹ on control days. During the eclipse, wind speed increased from 0 to about 1 ms⁻¹.

Observations of VLF sferics and subionospheric propagation during the SE on 1 August 2008 showed similar trends of the observed effects of earlier works [44,74,75]. Amplitude of the sferics at the observed frequencies 1, 3, 5, 9 and 12 kHz was increased, while the maximum normalized amplitude decreased for higher frequencies [50]. Reduction of the ionization and the conductivity of medium during the eclipse were probably responsible for such enhancements. The D-layer of the ionosphere was mostly responsible for signal absorption. It is also most sensitive to the loss of sunlight during SE. This is because it is the lowermost of the layers and is quickly overwhelmed by the neutral air around it once the active ionizing source of radiation is removed. The change in phase of 25 kHz signal ascertained that the reflection height increased due to the ionization reduction at the D-layer. At the new altitude, the reflection coefficient relatively increased. The absorption of radio waves in the region below the reflection zone decreased. The formation of shadow in the ionospheric D-region transferred energy from first mode to the second mode. This is due to discontinuities raised around the shadow region. Detail discussion is available in their work [50]. Round the clock records of sferics at 27 kHz during 22 July 2009

eclipse showed a fading pattern presumably caused by ionospheric irregularities. It exhibited a typical short period fading in the sferics level during eclipse. Normal day record exhibits all regular variations, viz., the sunrise effect, first minimum, recovery effect, morning minimum, afternoon maximum, late afternoon minimum and night maximum. On the eclipse day, just after the sunrise effect, variational characteristics of the sferics totally differ and also reveal that there are a number of fade-outs prior to the peak activity of the eclipse. The pattern vanishes and amplitude level returns to the normal value at the end of the eclipse almost within an hour. The decrease of the electron density (ED) at the lower ionosphere caused by the occurrence of the eclipse appears to be associated with the short period fading pattern [69]. King and Eccles [76] also reported that the structure of ionosphere returns to normal value within two hours at the end of the eclipse. The decrease in the UV component at sunlight is significant as the ionosphere was eclipsed for an important part of the developmental phase and it is possible that during this period, the behavior of the ozone layer might be abnormal [12,48,77]. Main observations during SE of 22 July 2009 were a decrease in the amplitude of the 18.2 kHz VLF signal [70]. The decrease in the VLF signal was primarily due to the decrease in ED in the lower ionosphere as the solar obscuration increased and a corresponding increase in the reflection height of the VLF wave caused more attenuation. The model estimate showed an increase in virtual reflection height and increase in Wait inverse scale height parameter. The model ED height profile of the lower ionosphere depicted non-linear variation of change in ED with respect to solar radiation. Maurya et al. [71] reported the first observations of wave-like signatures (WLS) in the D region ionosphere associated with 22 July 2009 SE from the analysis of amplitude of 22.2 kHz VLF transmitted signal. The wavelet analysis showed the presence of WLS with period $\sim 16\text{--}40$ min at the station under total eclipse and with period $\sim 30\text{--}80$ min at stations under partial eclipse (85–54%). The WLS are probably generated by the ionospheric ED changes due to partial/total SE conditions along the transmitter receiver great circle paths (TRGCP). 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 was also estimated that the decrease in the ED is well correlated with solar radiation obscuration.

The response of down welling solar radiation fluxes in the covered UV wavebands between 290 and 390 nm to the SE events is interesting particularly when the optical properties are cross-examined with the meteorological parameters during 22 July 2009 eclipse [69]. UV component of the sunlight reaching the Earth's surface diminished together with luminosity, when there was a reduction of surface air temperature but an enhancement of the RH. The effect of cloud cover on the amount of solar UV exposure under tree canopies was remarkably

different in variational pattern exhibiting a reduction of one tenth from that under clear skies.

Some of the observations carried out in India during SE have been presented in Table 1 showing explicitly their scientific results in brief.

Table 1. Observations of solar eclipse in India

Date	Location	Coverage in %	Parameters	Results
16.02.1980	Raichur (16.37°N, 77.37°E) [46]	100	Potential gradient, conductivity	Diminution in the potential gradient and increase in conductivity about 60% and 200% during next 45 min after the totality.
	Pune (18.53°N, 73.87°E) [43]	85	Potential gradient	Enhanced at 2 m altitude
18.03.1988	Pune (18.53°N, 73.87°E) [44]	24.1	Atmospheric electricity	All the parameters showed remarkable changes
24.10.1995	Budge Budge (22.45°N, 80.17°E) [77]	100	UV radiation, intensity of radio signal, atmospheric	Remarkable change of all the parameters from regular pattern
	Ahmedabad (23.05°N, 72.62°E) [12,78]	79.3	11.8 MHz transmitted signal, ozone column	Increase in the received signal strength; variation was noted
	Hyderabad (17.37°N, 78.48°E) [48]	67.4	Wind speed, temperature	No appreciable change in wind speed; maximum cooling by 9–10°C
	Roorkee (29.85°N, 77.89°E) [79]	92	Electrical conductivity	Negative conductivity was larger than positive conductivity at maximum phase
	Kalpi (26.13°N, 79.75°E) [61]	100	Coronal intensity, oscillations of periods between 5.3 and 56.5 s	Oscillations are sinusoidal, and amplitudes lie in the range 0.2–1.3% of coronal brightness
11.08.1999	Space Application Centre, Ahmedabad (23.35°N, 72.60°E) [6]	99.7	Fluctuations in wind, humidity and temperature	Wind speed and temperature decreased, humidity increased
01.08.2008	Kolkata (22.56°N, 88.50°E) [50]	55	Fair weather electric field	Enhancement of sferics during eclipse and it was frequency dependent

Table 1. Continued

Date	Location	Coverage in %	Parameters	Results
22.07.2009	Kolkata (22.56°N, 88.50°E) [54]	91	Point discharge current, meteorological parameters	Significant fall of PDC during eclipse was observed; temperature decreased and RH increased
	Kalyani (22.97°N, 88.47°E) [69]	90.2	UV radiations, sferics	Diminution of UV intensity, short period fading in sferics
	Allahabad (25.40°N, 81.93°E) [71]	100	22.2 kHz transmitted signal amplitude	Increased by maximum 6 dB
	Varanasi (25.30°N, 82.93°E) [71]	100	22.2 kHz transmitted signal amplitude	Increased by maximum 7 dB
	Nainital (29.35°N, 79.45°E) [71]	85	22.2 kHz transmitted signal amplitude	Increased by maximum 2.5 dB, then slowly decreased by maximum 2.7 dB
15.01.2010	Thiruvananthapuram (8.55°N, 76.77°E) [59]	94	Mixing ratio of O ₃ , NO, NO ₂ NH ₃ and CO and meteorological parameters	Remarkable variations are noted; ambient temperature decreased, RH increased, wind speed decreased
	Tirunelveli (8.07°N, 77.08°E) and Braemore Hill (8.41°N, 76.59°E) [62]	90	Atmospheric electric parameters and meteorological parameters	Marked deviations observed; ambient electric field dropped by up to 65% during the eclipse; Potential gradient showed epochs of enhancements.

4 Concluding Remarks

The geophysical conditions of any SEs never become exactly equal. Thus, each SE provides us a unique opportunity to study the behavior of the medium of the equatorial ionosphere. There are several papers that report contradictory results (increase as well as decrease) in the Earth's near-surface vertical electric potential gradient during SEs [41,43,44,80]. There are very few studies about the eclipse's effects on the equatorial lower ionosphere in the scientific literature. Some of those studies involving VLF signal during eclipse period showed both increases and decreases in their amplitude on different occasions [50,81-83]. Also, more focused observations of VLF signals during future SE events are required for the better understanding of generation mechanism of WLS under SE conditions. Thus, it is highly necessary to continue studying already detected

effects in more detail and to search for other manifestations of the solar eclipse in the atmosphere, especially at altitudes of the lower ionosphere. Next solar eclipse could be followed from India and neighboring regions on 26 December 2019 and researchers in this field will no doubt observe it through scientific eye and knowledge regarding unresolved nature of the ionospheric medium may be enriched further.

Acknowledgements

Author is grateful to Dr. S. S. De to initiate this review work and for his constructive suggestions to prepare the manuscript.

References

- [1] A. Stoev, P. Stoeva, D. Valev, N. Kishkinova, T. Tasheva (2005) *Geophys. Res. Abstr.* **7** 10209.
- [2] A.H. Krumov, D.D. Krezhova (2008) *J. Atmos. Sol. Terr. Phys.* **70** 407.
- [3] E.F. Nymphas, M.O. Adeniyi, M.A. Ayoola, E.O. Oladiran (2009) *J. Atmos. Solar Terr. Phys.* **71** 1245.
- [4] R.C. Anderson, D.R. Keefer, O.E. Myers (1972) *J. Atmos. Sci.* **29** 583.
- [5] K. Szalowski (2002) *J. Atmos. Sol. Terr. Phys.* **64** 1589.
- [6] P. Krishnan, P.K. Kunhikrishnan, S. Muraleedharan Nair, S. Ravindran, R. Ramachandran, D.B. Subrahmanyam, M. VenkataRamana (2004) *Proc. Indian Acad. Sci. (Earth Planet Sci.)* **113** 353.
- [7] P. Kolarz, J. Sekaric, B.P. Marinkovic, D.M. Filipovic (2005) *J. Atmos. Sol. Terr. Phys.* **67** 1357.
- [8] D. Founda, D. Melas, S. Lykoudis, I. Lisaridis, E. Gerasopoulos, G. Kouvarakis, M. Petrakis, C. Zerefos (2007) *Atmos. Chem. Phys.* **7** 5543 doi:10.5194/acp-7-5543-2007.
- [9] G. Chimonas, C.O. Hines (1971) *J. Geophys. Res.* **76** 7003.
- [10] L. Singh, T.R. Tyagi, Y.V. Somayajuh, P.N. Vijayakumar, R.S. Dabas, B. Loganadham, S. Ramakirshna, P.V.S. Rama Rao, A. Dasgupta, G. Naneeth, J.A. Klobuchar, G.K. Hartmann (1989) *J. Atmos. Sol. Terr. Phys.* **51** 271.
- [11] C.S. Zerefos, E. Gerasopoulos, I. Tsagouri, B.E. Psiloglou, A. Belehaki, T. Herekakis, A. Bais, S. Kazadzis, C. Eleftheratos, N. Kalivitis, N. Mihalopoulos (2007) *Atmos. Chem. Phys.* **7** 4943 doi: 10.5194/acp-7-4943-2007.
- [12] D.K. Chakrabarty, N.C. Shah, K.V. Pandya (1997) *Geophys. Res. Lett.* **24** 3001.
- [13] C.S. Zerefos, D.S. Balis, C. Meleti, A.F. Bais, K. Tourpali, K. Vanicek, F. Capelani, U. Kaminski, C. Tiziano, R. Stubi, P. Formenti, A. Andreae (2000) *J. Geophys. Res.* **105** 26463.
- [14] C. Tzanis, C. Varotsos, L. Viras (2008) *Atmos. Chem. Phys.* **8** 425 doi: 10.5194/acp-8-425-2008.
- [15] K.H. West, G. Goldsmith, D. Campbell, S. Zandstra *J. Geophys. Res.* (2007) **113** A12308 doi: 10.1029/2007JA012997.

Atmospheric Electricity Research in Indian Subcontinent during Solar Eclipses

- [16] V.V. Belikov, V.D. Vyakhirev, E.E. Kalinina, V.D. Tereshchenko, S.M. Chernyakov, V.A. Tereshchenko (2008) *Geomagn. Aeron.* **48** 98.
- [17] N. Jakowski, S.M. Stankov, V. Wilken, C. Borries, D. Altadill, J. Chum, D. Buresova, J. Boska, P. Sauli, F. Hruska, L.R. Cander (2008) *J. Atmos. Sol. Terr. Phys.* **70** 836.
- [18] J.V. Evans (1965a) *J. Geophys. Res.* **70** 131.
- [19] J.V. Evans (1965b) *J. Geophys. Res.* **70** 733.
- [20] J.A. Klobuchar, H.E. Whitney (1965) *J. Geophys. Res.* **70** 1254.
- [21] H. Rishbeth (1968) *Space Sci. Rev.* **8** 543.
- [22] A.N. Hunter, B.K. Holman, D.G. Fieldgate, R. Kelleher (1974) *Nature* **250** 205.
- [23] W.L. Oliver, S.A. Bowhill (1974) *Radio Sci.* **9** 185.
- [24] E.A. Cohen (1984) *Radio Sci.* **19** 769.
- [25] J.E. Salah, W.L. Oliver, J.C. Foster, J.M. Holt (1986) *J. Geophys. Res.* **91** 1651.
- [26] K. Cheng, Y.-N. Huang, S.-W. Chen (1992) *J. Geophys. Res.* **97** 103.
- [27] T. Farges, J.C. Jodogne, R. Bamford, Y. Le Roux, F. Gauthier, P.M. Vila, D. Altadill, J.G. Sole, G. Miro (1999) *J. Atmos. Sol.-Terr. Phys.* **63** 915.
- [28] A.T. Tomas, H. Luhr, M. Forster, S. Rentz, M. Rother (2007) *J. Geophys. Res.* **112** A06303 doi: 10.1029/2006JA012168.
- [29] H. Le, L. Liu, X. Yue, W. Wan (2008a) *J. Geophys. Res.* **113** A08309 doi: 10.1029/2007JA013012.
- [30] Y.N. Korenkov, V.V. Klimenko, F.S. Bessarab, N.S. Nutsvalyan, I. Stanislawski (2003) *Adv. Space Res.* **31** 995.
- [31] H. Le, L. Liu, X. Yue, W. Wan (2008b) *Ann. Geophys.* **26** 107 doi: 10.5194/angeo-26-107-2008.
- [32] R.A. Antonia, A.J. Chambers, D. Phong-Anant, S. Rajagopalan, K.R. Sreenivasan (1979) *J. Geophys. Res.* **84** 1689.
- [33] P. Zanis, C.S. Zerefos, S. Gilge, D. Melas, D. Balis, I. Ziomas, E. Gerasopoulos, P. Tzoumaka, U. Kaminski, W. Fricke (2001) *Atmos. Environ.* **35** 4663.
- [34] C.S. Zerefos, D.S. Balis, P. Zanis, C. Meleti, A.F. Bais, K. Tourpali, D. Melas, I. Ziomas, E. Galani, K. Kourtidis, A. Papayannis, Z. Gogosheva (2001) *Adv. Space Res.* **27** 1955.
- [35] G.P. Srivastava, M.P.M. Pakkir, R.R. Balwalli (1982) *P. Indian Acad. Sci. A.* **48** 138.
- [36] J.P. Abram, D.J. Creasey, E.H. Dwayne, J.D. Lee, M.J. Pilling (2000) *Geophys. Res. Lett.* **27** 3437.
- [37] P. Fabian, B. Rappenglueck, A. Stohl, H. Werner, M. Winterhalter, H. Schlager, P. Stock, H. Berreshein, U. Kaminski, P. Koepke, J. Reuder, W. Birmili (2001) *Meteorol. Z.* **10** 187.
- [38] P. Zanis, E. Katragkou, M. Kanakidou, B.E. Psiloglou, S. Karathanasis, M. Vrekoussis, E. Gerasopoulos, I. Lisaridis, K. Markakis, A. Poupkou, V. Amiridis, D. Melas, N. Mihalopoulos, C. Zerefos (2007) *Atmos. Chem. Phys.* **7** 6061 doi: 10.5194/acp-7-6061-2007.
- [39] C. Tzanis (2005) *Int. J. Rem. Sens.* **26** 3585.
- [40] J. Eliot (1900) *Mon. Weather Rev.* **10** 449.
- [41] A.K. Kamra, N.C. Varshneya (1967) *J. Atmos. Terr. Phys.* **29** 327.

Suman Paul

- [42] P.D. Agarwal, K.V. Janardhanan, B.V. Krishna Murthy, P.K. Kunhi Krishnan, P.R. Madhavaanicker, C. RaghavaRedyy, C.A. Reddy, K. Sen Gupta, V.V. Somayajulu, K.S.V. Subbrao (1980) SPD-SR-09-80.
- [43] A.K. Kamra (1982) *J. Geophys. Res.* **87** 4257 doi: 10.1029/JC087iC06p04257.
- [44] S. Dhanorkar, C.G. Deshpande, A.K. Kamra (1989) *J. Atmos. Terr. Phys.* **51** 1031.
- [45] C.G. Deshpande, A.K. Kamra (1992) *J. Atmos. Terr. Phys.* **54** 1413.
- [46] G.K. Manohar, S.S. Kandalgaoonkar, M.K. Kulkarni (1995) *J. Geophys. Res.* **100** 20805 doi: 10.1029/95JD01295.
- [47] K.S. Appu, K.S. Santhikumar, R. Padmanabha Pillai, V. Narayanan (1997) *Kodi-akanal Obs. Bull.* **13** 155.
- [48] G. Dutta, M.N. Joshi, N. Pandarinath, B. Bapiraju, S. Srinivasan, J.V. Subba Rao, H. AleemBasha (1999) *Indian J. Radio Space Physics* **28** 11.
- [49] S.S. De, S. Paul, D.K. Haldar, S. Barui, M. Sanpui, B. Bandyopadhyay (2009) *Indian J. Phys.* **83** 1245.
- [50] S.S. De, B.K. De, B. Bandyopadhyay, B.K. Sarkar, S. Paul, D.K. Haldar, S. Barui, A. Datta, S.S. Pal, N. Paul (2010) *Pure Appl. Geophys.* **167** 1273.
- [51] B.K. De, S.S. De, B. Bandyopadhyay, P. Pal, R. Ali, S. Paul, P.K. Goswami (2011a) *Terr. Atmos. Ocean. Sci.* **22** 435.
- [52] S.S. De, B.K. De, B. Bandyopadhyay, S. Paul, S. Barui, D.K. Haldar, M. Sanfui, T.K. Das, G. Chattopadhyay, P. Pal (2011b) *Bulg. J. Phys.* **38** 206.
- [53] S.S. De, B. Bandyopadhyay, S. Paul, D.K. Haldar, M. Bose, D. Kala, G. Guha (2013a) *Indian J. Radio Space Phys.* **42** 251.
- [54] S.S. De, S. Paul, S. Barui, P. Hazra, D. Kala, D.K. Haldar, A. Ghosh, G. Guha (2013b) *Earth Moon Planets* **111** 79 doi: 10.1007/s11038-013-9424-4.
- [55] A. Guha, B.K. De, A. Choudhury, R. Roy (2012) *J. Geophys. Res.* **117** A04305 doi: 10.1029/2011JA017498.
- [56] B.M. Vyas, S. Sunda (2012) *Adv. Space Res.* **49** 546.
- [57] P.S. Dixit, P.K. Rao (1980) *Bull. Astron. Soc. India* **8** 145.
- [58] H. Chandra, S. Sharma, P.D. Lele, G. Rajaram, A. Hanchinal (2007) *Earth Planets Space* **59** 59.
- [59] S.K. Sharma, T.K. Mandal, B.C. Arya, M. Saxena, D.K. Shukla, A. Mukherjee, R.P. Bhatnagar, S. Nath, S. Yadav, R. Gautam, T. Saud (2010) *Ann. Geophys.* **28** 1199 doi: 10.5194/angeo-28-1199-2010.
- [60] G. Chimonas, C.O. Hines (1970) *J. Geophys. Res.* **75** 875.
- [61] J. Singh, R. Cowsik, A.V. Raveendran, S.P. Bagare, A.K. Saxena, K. Sundararaman, V. Krishan, N. Naidu, J.P.A. Samson, F. Gabriel (1997) *Solar Physics* **170** 235.
- [62] C.P. Anil Kumar, R. Gopalsingh, C. Selvaraj, K.U. Nair, H.J. Jayakumar, R. Vishnu, S. Muralidas, N. Balan (2013) *J. Geophys. Res.* **118** 5098 doi: 10.1002/jgrd.50437.
- [63] C. Panneerselvam, C. Selvaraj, K. Jeeva, K.U. Nair, C.P. Anil Kumar, S. Gurubaran (2007) *Earth Planets Space* **59** 429.
- [64] C.P. Anil Kumar, R. Gopalsingh, C. Selvaraj, K. Jeeva, K.U. Nair, S. Gurubaran (2009) Scientific Report EGRL/IIGSR-01/2009 1.
- [65] H. Israel (1973) *Isr. Program for Sci. Transi.*, Jerusalem.
- [66] H.W. Kasemir (1955) *Geophys. Res. Pap. (Air Force Cambridge Res.)* **42** 91.
- [67] L.H. Ruhnke (1969) *J. Geomagn. Geoelectr.* **21** 453.

Atmospheric Electricity Research in Indian Subcontinent during Solar Eclipses

- [68] H.K. Burke, A.A. Few (1978) *J. Geophys. Res.* **83** 3093.
- [69] R. Bhattacharya, A. Bhoumick, A. Bhattacharya, P. Pal, A. Bhattacharya (2010) *Indian J. Radio Space Phys.* **39** 132.
- [70] A. Guha, B.K. De, R. Roy, A. Choudhury (2010) *J. Geophys. Res.* **115** A11302 doi: 10.1029/2009JA015101.
- [71] A.K. Maurya, D.V. Phanikumar, R. Singh, S. Kumar, B. Veenadhari, Y.-S. Kwak, A. Kumar, A.K. Singh, K. Niranjana Kumar (2014) *J. Geophys. Res.* **119** doi: 10.1002/2013JA019521.
- [72] M.B. Cohen, U.S. Inan, E.W. Paschal (2010) *IEEE Trans. Geosci. Remote Sens.* **47** doi: 10.1109/TGRS.2009.2028334.
- [73] R. Singh, B. Veenadhari, M.B. Cohen, P. Pant, A.K. Singh, A. K. Maurya, P. Vohat, U.S. Inan (2010) *Curr. Sci.* **98** 398.
- [74] P. Kaufmann, R.F. Schaal (1968) *J. Atmos. Sol.-Terr. Phys.* **30** 469.
- [75] P. Pant, H.S. Mahra (1980) *Indian J. Radio Space Phys.* **9** 134.
- [76] J.W. King, D. Eccles (1968) *J. Atmos. Terr. Phys.* **30** 1715.
- [77] A.B. Bhattacharya, S.K. Kar, R. Bhattacharya, J. Basak (1996) *Indian J. Radio Space Phys.* **25** 173.
- [78] P.D. Lele, K.G. Jani, A.P. Patel (1997) *Kodaikanal Obs. Bull.* **13** 213.
- [79] A.K. Singh, S. Nivas, A. Kumar, J. Rai, M.J. Nigam (1999) *Indian J. Radio Space Phys.* **28** 1.
- [80] H. Dolezalek (1972) *Arch. Met. Geoph. Biokl.* **21** 221.
- [81] B.K. De, S.K. Sarkar (1997) *Kodaikanal Obs. Bull.* **13** 205.
- [82] R. Fleury, P.L. Duchesne (2000) *IEE Conf. Publ.* **474** 391.
- [83] M.A. Clilverd, C.J. Rodger, N.R. Thomson, J. Lichtenberger, P. Steinbach, P. Cannon, M.J. Angling (2001) *Radio Sci.* **36** 773.