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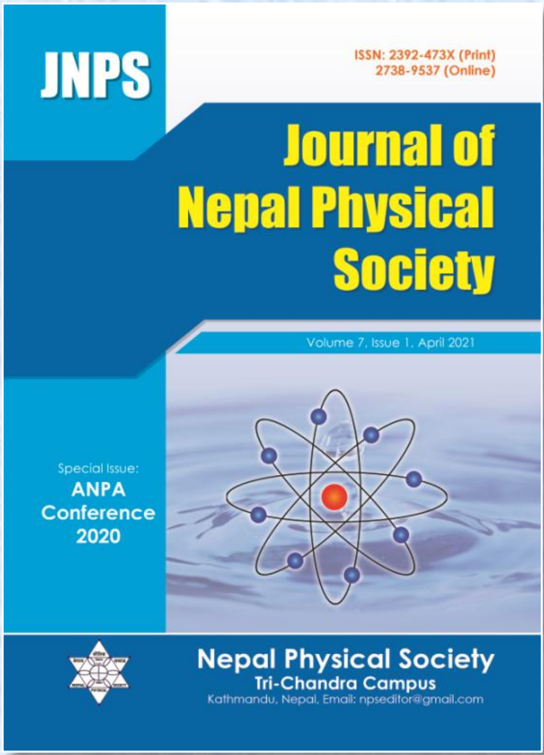

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Ionospheric Response over Nepal during the 26 December 2019 Solar Eclipse

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ABSTRACT

On 26th December 2019, during morning hours, an annular solar eclipse having a magnitude of 0.96 with a 118 km wide antumbra occurred and lasted for 3 minutes and 40 seconds at the point of maximum eclipse. The partial eclipse was visible in most of Asia, parts of North/East Africa, and North/West Australia. In the context of Nepal, only the partial eclipse was visible from ~ 8:34 LT (02:51 UT) and ended at ~ 11:40 LT (05:55 UT). It was 2 hours 47 mins and 54 secs long with the maximum visible eclipse time at ~ 10:01 LT (04:16 UT). Our study is based on Global Navigation Satellite System (GNSS) measurements from a widely distributed Global Positioning System (GPS) network over different places of Nepal on the day of the eclipse, a day before, and a day after the eclipse. We investigated the ionospheric behavior through the changes in Total Electron Content (TEC) during the partial eclipse by using the data archived at the five different GPS stations of Nepal. The result reveals that there is significant depletion of TEC, in some cases greater than 20% compared to other normal days. Observing the values of TEC before, during, and after the event, our study showed an apparent variation during the time of the eclipse, which agrees with previous studies on ionospheric responses to the eclipse as well as theoretical assumptions.

Keywords: Solar Eclipse, Total Electron Content, GPS, Ionosphere.

1. INTRODUCTION

The ionosphere is a dynamic layer of the upper part of the atmosphere, which generally changes according to radiation emitted by the sun and solar-related ionospheric disturbances. Different natural and artificial phenomena affect the physical and chemical behavior of the ionosphere [1]. Among these, the solar eclipse is a phenomenon that has a direct influence on the Earth's ionosphere. As a result of the solar eclipse, an apparent effect on the ionosphere can be witnessed. Investigation of the ionospheric variability during solar eclipse provides a great opportunity to study the effects of this phenomenon on the different parameters of the ionosphere and additionally temporal ionospheric responses to the eclipse events over a short period. The parameter of the ionosphere that produces most of the effects on radio signals is TEC. TEC is an integral of electron density along the path between the GPS satellite and the receiver [2], which is calculated as:

$$\mathrm{TEC}=\int n_e(s)\, ds \qquad (1.1)$$

Where n_e is location-dependent electron density. The TEC unit (TECU) is electron per square meter i.e., 1 TECU = 10^{16} electron/m^2 [3]. During a solar eclipse, the amount of solar radiation reaching the Earth diminishes. As a result, the production of the plasma in the ionosphere is reduced. Hence, compared to a normal day, during the solar eclipse, a lower electron density in the ionosphere is expected [4]. Since the TEC is the measure of integrated electron density, major variations in electron density are expected to be reflected in the TEC.

Solar eclipse effects on the ionosphere have been studied for more than a half-century, as they offer a naturally occurring "active" experiment with a great chance of studying the effect of solar radiation on the ionosphere-thermosphere-mesosphere (ITM) system [5]. In particular, eclipse studies for the December 26, 2019 event have benefited from several early research work by Chandra et al. (1997, 2007) [6, 7], Sharma et al. (2010) [4], Coster et al. (2017) [8], for example, show decrease in electron density of ionosphere during the solar eclipses and coverage of ground-based monitoring GPS segments. GPS data were also used in many studies to analyze the TEC variation during the solar eclipse, e.g., Baran et al. (2003) [9] accounted for the depression of TEC amounted to 2 - 8 TECU during the solar eclipse of August 11, 1999. Srigutomo et al. (2019) [10] has additionally shown that the rate of depletion of TEC is proportional to the magnitude of the eclipse, which is directly associated with the photoionization process.

We believe that this study would serve as a baseline for providing the crucial information on ionospheric variability, in case of rare events like solar eclipses since ionosphere range delay on GPS signals is a major error source in the continuous and smooth operation of satellite-based navigation systems.

2. MATERIALS AND METHODS

The present study has been carried out to observe the behavior of ionospheric TEC derived from ground-based dual-frequency GPS data obtained from the UNAVCO. UNAVCO is a non-profit university-governed consortium that facilitates geoscience research and education using Geodesy [11]. The GPS observation data of 1, 2, 5, and 10 Hz are provided freely by the UNAVCO website (https://www.unavco.org/) in RINEX format. The GPS RINEX data of UNAVCO has been calibrated to derive the TEC by using the technique described in Ciraolo et al. (2007) [12].

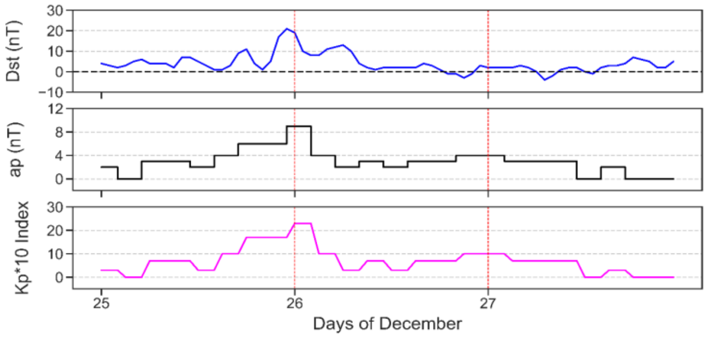

Fig. 1: Dst, Kp, ap indices on Dec 25-27, 2019

Figure 1 shows the kp*10, ap and Dst indices for the period of study and Figure 2 shows a network of the GPS receiver stations within the map of Nepal utilized in this study.

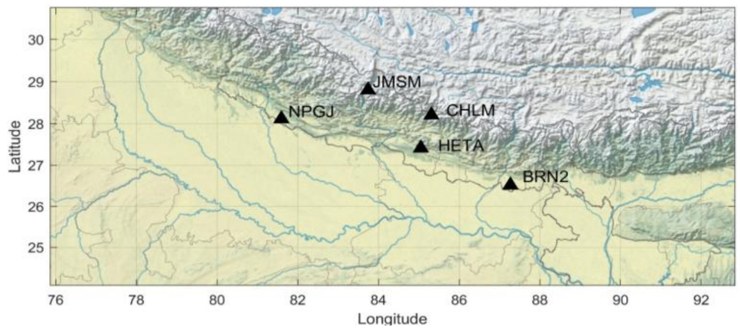

Fig. 2: Map of GPS receiver stations from which data was obtained.

In order to show the variations of TEC around the eclipse hours, observations from the following ground-based monitoring GPS receivers were used, as listed in table 1. The local time at these stations is given by LT = UT + 5:45 h. We have considered Universal time as all-time references.

Table 1: Station information for TEC measurements

Station	Code	Geog. Longitude (° E	Geog. Latitude (° N)	Start of partial eclipse (UT)	End of partial eclipse (UT)
Nepalgunj	NPGJ	81.5953	28.1172	02:52:24	05:36:50
Jomsom	JMSM	83.7433	28.8053	02:57:08	05:40:47
Hetuada	HETA	85.0516	27.4149	02:57:17	05:45:55
Chilime	CHLM	85.3141	28.2072	02:59:03	05:45:23
Biratnagar 2	BRN2	87.2722	26.5197	03:00:13	05:53:03

One of the noteworthy features of our study has been based on the fact that the eclipse day was geomagnetically quiet, as seen from Figure 1. In Figure 1, the Dst index shows a minimum value of -5 nT at its least, and the kp*10 index lies between 3 to a peak value of 22. The ap index lies in between 3 to a peak value of 10 nT at most. Thus, the observed values of geomagnetic indices show low values, indicating a quiet condition of geomagnetic activity during this event. Being a geomagnetically quiet period, it provides us an opportunity to properly analyze the behavior of the ionosphere through TEC due to the effect of the eclipse. Thus, the main aim of this paper is to evaluate the effect of solar eclipse at five different geographical latitudes and longitudes. We have collected the data by dividing the study into three scenarios, i.e., one day before the eclipse (pre-event VTEC), during the day of the eclipse (main-event VTEC), and one day after the eclipse (post-event VTEC) in the first phase, and compared with quiet days as a reference for evaluating the deviation.

3. RESULTS AND DISCUSSION

Based on the methodology discussed above, the temporal variation of TEC before, during, and after the partial solar eclipse was studied. GPS measurements from all the satellites observed at stations (Table 1) during a 24-hr period were taken into account, and the results obtained are shown by plotting the graphs.

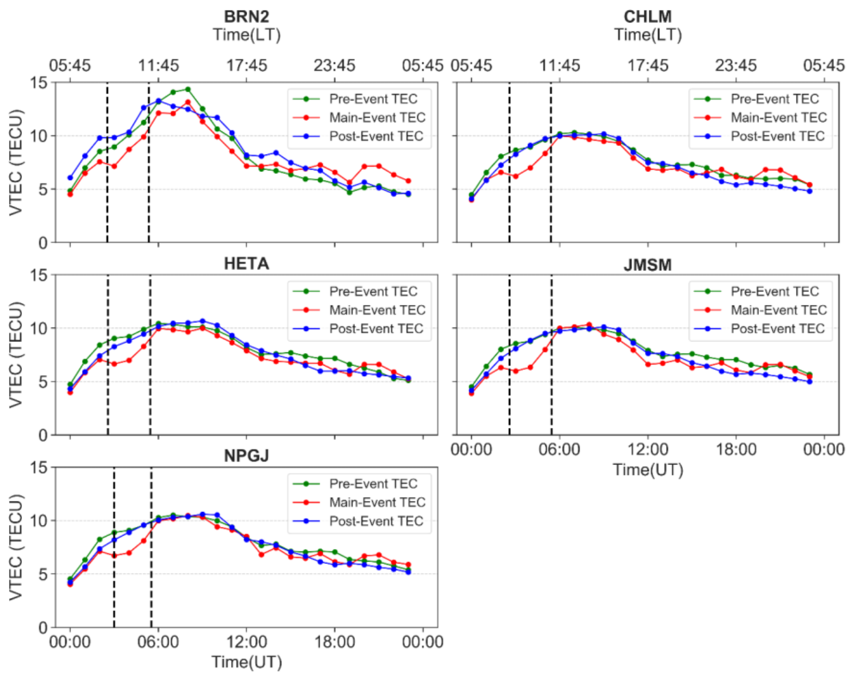

Fig. 3: Diurnal variations of TEC at five different stations, viz. BRN2, CHLM, HETA, JMSM, and NPGJ, before, during, and after the eclipse of December 26, 2019. The region between black dotted lines represents the eclipse hour.

Figure 3 presents the diurnal TEC variations over five different stations on Dec 25 (pre-event TEC), Dec 26 (main-event TEC), and Dec 27 (post-event) in the year 2019. Time series of TEC before, during, and after the solar eclipse provides an excellent basis to study the temporal effect of the solar eclipse on the TEC diurnal pattern. It can be seen that the mean values of VTEC during the eclipse hour are lower compared to the other days. It is worth noting that there is significant depletion in the level of TEC as an effect of the partial solar eclipse. The minimum level of TEC persists around 2 UT to 14 UT, and then it slowly recovers from the eclipse induced effect to its usual diurnal pattern after ~16 UT. As seen in figure 3, the depletion of the TEC level is different for each station, which is related to their geographic location.

We also compared the TEC level during the solar eclipse of Dec 26, 2019, with the mean TEC of top five quietest days of the month, provided by World Data Center for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/qddays/), which is shown by Figure 4 and the results revealed that there was a significant reduction in TEC during the eclipse hour which supports the previous results, depicted by Figure 3. The depression of TEC in terms of percentage during the day of the eclipse compared to the mean of the top five quietest days is presented in Figure 5.

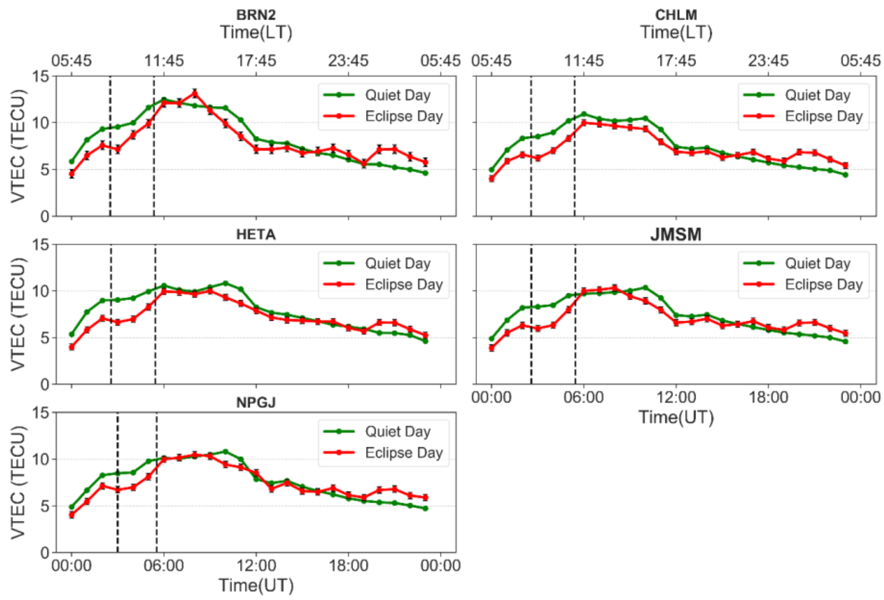

Fig. 4: Comparison of TEC level at five different stations with the mean TEC of most five quietest days of Dec 2019. (The vertical bar at eclipse day represents the standard error)

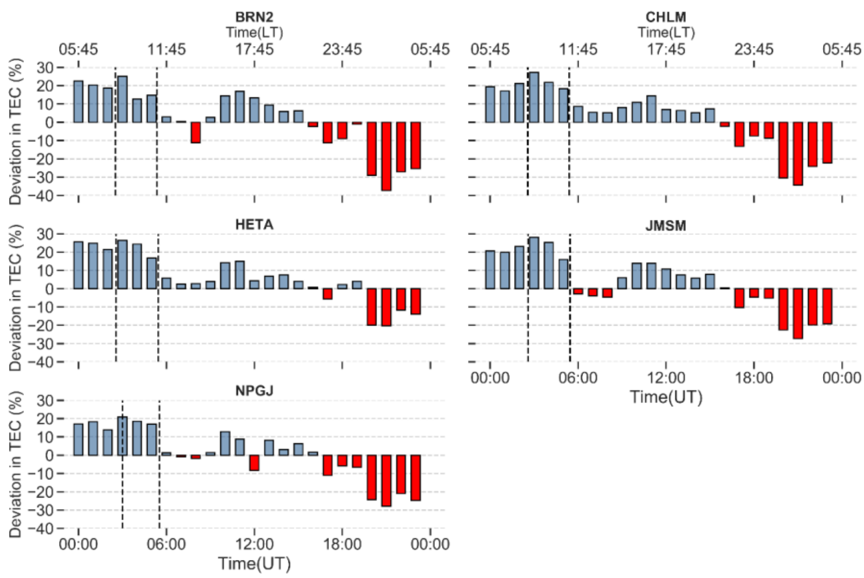

Fig. 5: TEC depletion column charts of (a) BRN2 station (b) CHLM station, (c) HETA station (d) JMSM station (e) NPGJ station. The region between black dotted lines represents the eclipse hour.

To get a better understanding of depreciation of TEC, the percentage decrease and increase were depicted in two respective parts, i.e., depreciation of TEC level during the solar eclipse hours in comparison to the same hour of the quiet day and growth of TEC level in the proceeding hours after the eclipse event. These two respective parts are presented in Figure 5. As it can be seen, the VTEC difference between the day of the solar eclipse and the quiet day exceeds by ~20% (~2-3 TECU) during the time 02:50 UT to 03:00 UT in all the stations. However, the rise in the TEC level for hours after the eclipse event exceeds roughly 10% (~1.2 TECU) during 16:00 UT to 19:00 UT, and greater than 30% (~ 4 TECU) during the night time, which we called the recovery phase after the occurrence of an event, as witnessed from Figure 5. The scale of the reduction is specifically associated with the obscuration rate [13]. Changes in spectral solar irradiance during the eclipse resulted in reduced photoionization production in the ionosphere. In addition, this method of investigation was used by Hoque et al (2016) [14]. The complex pattern of the Spatio-temporal TEC response is evidence of the important role in the dynamic processes in the ionosphere during the eclipse.

4. CONCLUSION

In this study, GPS observations over five different locations on the day of the eclipse, before the eclipse and after the occurrence of the eclipse were processed to investigate the ionospheric response to this event. Regarding TEC values, the results at different stations showed a reduction between 1-4 TECU approximately during the occurrence of the eclipse, which confirms previous studies and theoretical assumptions. This reduction corresponds to 10% - 30% TEC depletion during the eclipse event. Some of the earlier work had also shown that the level of TEC was depreciated by more than 60% as well [8]. However, only partial eclipse with less obstruction rate occurred in Nepal. This is the reason behind the depletion of TEC in a lesser amount during the eclipse hour. The importance of our work lies in the fact that comparable reductions in TEC were seen for a few more hours, even after the early morning eclipse. This study would serve as an essential reference to carry out further studies about the ionospheric response during a total solar eclipse with more obstruction rate. In the future, we will investigate the eclipse induced effects on the ionosphere and its correlation with solar parameters to obtain information on both the solar input and corresponding ionosphere response which will enable us to study the mechanisms underlying ionospheric changes better than ever before. Ultimately, future researchers can use these data to improve models of ionospheric dynamics.

AUTHOR CONTRIBUTIONS

There is an equal effort of all the authors at all stages. All authors have read and agreed to the published version of the manuscript.

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Geomagnetic indices (Kp, ap, Dst) data are obtained from the OMNI (http://omniweb.gsfc.nasa.gov/form) site. GPS Data is obtained from the UNAVCO (https://www.unavco.org/). We would like to thank staff members of NASA and UNAVCO for making the data available.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

EDITOR'S NOTE

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