Climatology of ionosphere over Nepal based on GPS TEC data from 2008 to 2018

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17 Abstract

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19 In this study, we analyze the climatology of ionosphere over Nepal based on GPS derived VTEC observed from four stations: KKN4 (27.80° N, 85.27° E), GRHI (27.95° N, 82.49° E), JMSM 20 21 (28.80° N, 83.74° E), DLPA (28.98° N, 82.81° E) during years 2008 to 2018. The study illustrates the diurnal, monthly, annual, seasonal and solar cycle variations of VTEC during all 22 23 time of solar cycle 24. The results clearly reveal the presence of equinoctial asymmetry in TEC 24 which is more pronounced in maximum phases of solar cycle in year 2014 at KKN4 station 25 followed by descending, ascending and minimum phases. Diurnal variation of VTEC showed 26 short-lived day minimum which occurs between 5:00 to 6:00 LT at all the stations considered 27 with diurnal peak between around 12:00 to 15:00 LT. The maximum value of TEC is observed 28 during spring equinox than autumn equinox with a few asymmetries anomalies. Seasonal variation in TEC is observed to be a manifestation of variation of solar flux, particularly the level 29 30 of solar flux in consecutive solstices. Similarly, winter anomalies are noticed during increasing 31 and maximum phases of the solar cycle 2011 and 2014 from almost all stations taken in the 32 study.

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34 **1.** Introduction

Total electron content (TEC) is a crucial parameter of ionosphere comprising high concentration of electrons and ions, formed under the ionization of extreme ultraviolet (EUV) radiation and solar X-rays. The lower atmospheric disturbance also contributes to ionospheric variability

1 (Anderson and Fuller-Rowell, 1999; Prikryal et al., 2010). A numerous periodic and aperiodic 2 variability identified in the ionosphere makes impact on the applications involving radio link 3 between satellites and ground which play vital role in the communication, navigation and 4 surveillance with important consequences for the reliability and accuracy of the service (Guo et 5 al., 2015). Global positioning system (GPS) is widely used in recent appliances which encounter 6 largest errors in the path due to disturbed ionospheric free electrons which emphasizes to study 7 GPS-TEC variability. The application of GPS technology allows scientists insight into the shape 8 and behavior of ionosphere. List of factors affecting TEC are ionospheric electron density, ion-9 electron temperature, composition, dynamic vary with altitude, latitude, longitude, local time, 10 seasons, solar as well as magnetic activity. Equatorial ionosphere is being highly vulnerable 11 possess major threats to the communication signals. The ionosphere at mid latitude is less 12 variable hence the most of the observations and measurements are taken from this region where 13 as high latitude ionosphere is sensitive to outer space connected by geomagnetic field lines 14 (Akala et al., 2013; Parwani et al., 2019). Study of VTEC at low-mid ionosphere showed solar 15 activity dependence (Shimeis et al., 2014). TEC has been studied by large number of researchers, 16 Rama Rao et al. (1980) studied the diurnal variation in TEC at Waltair, India and found short 17 lived pre-dawn minimum, a steep early morning rise followed by broad mid afternoon maximum and a steep post sunset fall. The relation between TEC and SSN, F_{10.7}and EUV was studied by 18 19 Dabaset al. (1993) and pointed out that TEC has nonlinear relation with SSN and linear relation with F_{10.7} and EUV. Ouattara and Amory- Mazaudier (2012) showed impact of solar activity on 20 21 diurnal variability during different phases of solar cycle. Analogous study was carried around the 22 globe using various methods on TEC such as diurnal, monthly, seasonal and solar cycle and solar 23 activity dependency e.g. in South Asia (Chauhan et al., 2011; Walker et al., 1994); in South 24 America (Sahai et al., 2007; Natali and Meza, 2011; Akala et al., 2013; de Abreu et al., 2014); 25 over North America (Huo et al., 2009; Perevalova et al., 2010); in Africa (Shimeis et al, 2014; 26 D'ujanga et al., 2012; Ouattara and Fleury, 2011; Zoundi et al., 2012); over Brazil (Venkatesh et 27 al., 2014a, 2014b, 2015); over Japan (Zakharenkova et al., 2012; Mansoori et al., 2016); over 28 China (Guo et al., 2015; Zhao et al., 2007; Liu et al., 2013).

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TEC studied at Jet Propulsion laboratory for the year (1998-2008) found stronger annual TEC variation in southern hemisphere and variation in phase and amplitude is more in conjugate

1 hemisphere (Liu et al., 2009). Galay et al. (2010) found semiannual periodicity in daytime TEC, 2 and the spring equinox shows highest TEC and winter solstices the lowest in India. The winter 3 anomaly, semiannual anomaly and annual anomaly are described in paper by Liu and Chen 4 (2009); Rishbeth and Garriott (1998). Global scale TEC research found that the effect on TEC 5 was stronger on day than at night and also at low latitude than in high latitudes. The effect on 6 TEC is seen more on the either side of dip equator than at dip equator (Liu et al., 2009). Dashora 7 and Suresh (2015) analyzed the characteristics of low latitude TEC data of solar cycle 23 and 24 8 over Indian sector using global ionospheric data. A double hump structure in solar flux as well 9 as in TEC was identified at low latitude station Varanasi, India in ionospheric response using GPS TEC, IRI and TIE-GCM TEC of solar cycle 24 by Rao et al., (2019a). Parwani et al. (2019) 10 11 studied latitudinal variation of ionospheric TEC at northern hemispheric region and found that 12 the diurnal TEC has higher value in low than in mid and high latitude and in seasonal variation 13 maximum in Spring and autumn than in summer and winter.

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Many studies on TEC have been conducted in Asia, however no result for the climatology of 15 16 TEC over Nepal for a long-time series, about one solar cycle has been reported up to now. In this 17 paper, we present for the first-time characteristics of ionosphere in Nepal such as the diurnal, 18 annual, seasonal and solar cycle dependence of TEC on the local ionospheric conditions using 19 GPS TEC data obtained from four GPS stations: KKN4, GRHI, JMSM and DLPA. Our study 20 includes GPS TEC data from 2008 to 2018 of the solar cycle 24, including all four phases of this solar cycle, the minimum phase of year 2008-2009; ascending phase of year 2010-2013, 21 22 maximum phase of year 2014 and descending phase of year 2015-2018. The second section of 23 this paper includes the dataset and methodology, the third for the results and discussion. The 24 concluding remark is discussed in the last section.

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27 **2. Dataset Data sets and data analysis**

Total electron content (TEC) is total number of electrons integrated along the path from receiver to each GPS satellites which orbits the Earth at altitude of 20,200 km. It measures in TECU, $1\text{TECU} = 10^{16} \text{ electron/m}^2$. The TEC is obtained as (Hofmann-Wellenhof et al., 1992)

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$$\operatorname{TEC} = \int_{R}^{S} N_{e}(h) dh \tag{1}$$

Where, N_e is electron density, R is the receiver altitude and S the satellite altitude. The dual frequency GPS receiver in two L-band of frequency: $f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz provide the carrier phase and pseudo-range measurements. The TEC is calculated from these L1 and L2 pseudo-range and carrier phase (Hofmann-Wellenhof et al., 1992). Using pseudo-range and phase data, TEC is calculated as

TEC =
$$\frac{1}{40.3} \left(\frac{f_1^2 f_2^2}{f_2^2 - f_1^2} \right) (P_1 - P_2)$$
 (2)

8 Where, P_1 and P_2 are the pseudo-ranges for frequencies f_1 and f_2 , respectively.

9 The TEC obtained by this method is called slanted TEC (STEC) which is a measure of the total 10 electron content of ionosphere along the ray path from the satellite to receiver has to be 11 converted to vertical TEC (VTEC) using equation (Titheridge, 1972).

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$$VTEC = (STEC - B_s - B_u) \left(\sqrt{1 - \left(\frac{(R_e \times cos\varepsilon)^2}{(R_e + h)^2}\right)} \right)$$
(3)

14 B_s and B_u are the biases of instruments of satellites and receivers respectively, ε is the elevation 15 angle of satellite and $R_e = 6371$ km is the mean radius of the Earth.

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17 For this study data was carried out with GPS data taken from four GPS stations: DLPA, JMSM, 18 KKN4 and GRHI from Nepal. The details of the stations including their geographical and 19 geomagnetic coordinates are shown in table 1 and Universal time is considered as all-time 20 references. The GPS data of the four stations were downloaded from www.unavco.org which is 21 freely available to all users. This data is available in RINEX (Receiver Independent Exchange 22 format) v2.1 which is a standard ASCII format. The temporal resolution of this data is 15 min. 23 The raw data is then processed using software developed by Rolland Fleury (Rolland Fleury, 24 July 19, 2018, on the website www.girgea.org) from Lab-STICC, UMR 6285, Institut Mines-25 Telecom Atlantique, site de Brest, France which runs on a window operating system to get 26 required TEC.

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The data for solar indices sunspot number (SSN) and solar flux index (F10.7) to study long term solar activity are taken from Royal Observatory of Belgium, Brussels, through website: sidc.oma.be/silso/home and OMNI website http://omniweb.gsfc.nasa.gov/.SSN is most consistent solar indices effectively describes solar activities and are valuable mode in forecasting
 space weather phenomena. The solar flux index provides the information about the total emission
 produced by the Sun at the wavelength of F10.7 cm at the Earth.

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5 In this study, we use GPS derived TEC from RINEX file using this method to obtain TEC 6 calibrated at 15 minutes for all measures. Between 30s VTEC sequences, the elevation may vary. 7 This leads to variation in the VTEC depending on the constellation and not just the variation of 8 the content over that period. We have chosen to do the regression over a period 15 minutes with 9 the VTEC obtained displayed in the middle of this period. This makes it possible to have 4 points over 1 hour and therefore to have an evolution of the VTEC 4 times more precise than that of 10 11 GIM maps which are currently in steps 1 or 2 hours depending on the organization. So, it is 12 better possibility to see and characterize finer local structures in RINEX derived TEC than in 13 GIM.

This study analyzes variations of VTEC during different phases of solar cycle 24 along with annual, seasonal and diurnal variation. For this local season classified as winter (November, December, January and February), spring (March and April), summer (May, June, July and August) and autumn (September and October). The classifications of selected years as per solar cycle phases are presented in table 2.

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3. Results and Discussion

21 In this section, we present the diurnal, monthly, seasonal, solar cycle and geomagnetic variation 22 in GPS TEC over Nepal during the solar cycle-24. Figure 1 represents the position of chosen 23 GPS stations in Nepal for this study and Figure 2 represents the variation of sunspot number and 24 solar flux during the period 2008-2018. In this section, we present the signatures of diurnal, 25 monthly, seasonal, solar cycle and geomagnetic variation on GPS VTEC over Nepal which is 26 calculated using Rolland software (as described in sec. 2). Figure 1 represents the position of 27 GPSTEC stations in Nepal used for this study and Figure 2 represents the variation of sunspot number and solar flux for the year 2008 to 2018. 28

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30 **3.1 Diurnal variation**

1 Figure 3a exemplify diurnal variation of VTEC in LT time observed during February 2, 2009, 2 2012, 2014, 2016 and 2017 during the minimum, inclining increasing, maximum and declining 3 decreasing phases of solar cycle 24 at KKN4 station in Nepal. The plot shows before sunrise 4 ~5:00 LT, VTEC becomes minimum and reaches a maximum around 11:00-14: 00 LT and later 5 decreases in the evening and night. The diurnal peak is noticed between 11:00 to 14:00 LT 6 though the peak values change every month. The VTEC plots reveal a growth from dawn to a 7 highest value about 5 to 98 TECU after the hours of daylight, it decreases to the lowest value 8 prior to dusk with time difference of ± 1 to 2 hours. A flat curve with minor peaks is identified 9 during minimum and descending phases whereas dome shape is noticed during maximum phase, 10 multiple peaks and trough at varying position is observed during ascending phases. In overall, 11 the VTEC shows a normal trend of diurnal behavior with the lowest value in dawn and dusk and 12 the highest value during the midday. The maximum VTEC in diurnal curve noticed during 13 maximum phases of the solar cycle 2014 then in 2012 the ascending phases and minimum in 2016, 2017 and 2009 during descending and minimum phases. Diurnal variation of VTEC was 14 15 studied by plotting similar curves for all the days from year 2008 to 2018 for all chosen four 16 stations. Diurnal variation of VTEC was studied by plotting similar curves for all the days from 17 year 2008 to 2018 for all chosen four stations. In general, the diurnal VTEC behavior exhibits the 18 solar cycle dependency. The diurnal variability of VTEC for all the day is not presented due to 19 constraint of space. In our study the mean diurnal curves for KKN4 station of years 2008, 2009 20 and 2010 exhibits wave like profile whereas the mean diurnal curves of years 2011, 2012, 2013, 21 2014, 2015, 2016 and 2017 show parabolic nature which is shown in Figure 3b. The similar 22 diurnal profile was noticed for all the stations considered. The diurnal graphs (Figure 3) show 23 better synchronization of VTEC with SSN and solar flux (Figure 2).

The observed diurnal VTEC pattern reflects the different solar events signature. The noon bite out profile with asymmetric peaks, parabolic profile and wave profile with morning, evening and night peaks and few complex structures are noted in diurnal profile. The quiet day activity at minimum phase, the fluctuating activity during increasing phase, shock activity during maximum phase and recurrent activity during declining phase was noticed in the study of ionospheric parameters at Ouagadougou ionosonde station data in West Africa by Ouattara et al. (2009).

30 The upward $\vec{E} \times \vec{B}$ drift velocity plays an important role in producing the nighttime post sunset

31 enhancement. The average plasma flux required for the enhancement in equatorial latitude found

 $(2.2 \pm 0.9) \times 10^{12} \text{ m}^{-2} \text{s}^{-1}$ by Jain (1987) in India. In 2015 Tariku, studied pattern of GPS-TEC over 1 2 African sector during 2008 to 2009 and 2012 to 2013 and found small enhancements in the 3 VTEC in the nighttime ~ between 21:00 to 23:00 LT especially for equinoctial months and then 4 drops again mostly after 23:00 LT. The enhancement was mostly found in equinoctial months during high solar activities and during low solar activities phase in solstice the pre-reversal 5 6 enhancement was much smaller. A diurnal plot (Figure 3) of ionosphere over Nepal shows 7 similar result of pre-reversal enhancement during high solar activities 2012 and 2014 but not 8 during low solar activities of 2009 and 2017.

9 Mountains generate relief waves which propagate to stratosphere and lower thermosphere 10 (Martin Leutbecher and Hans Volkert, 2000). Studies on these waves have been made in Nepal 11 in the lower atmosphere (Regmi, R.P. and S. Maharjan, 2015; Regmi et al., 2017). Other studies 12 have shown the impact of relief waves on the ionosphere in the Andes (Torre et al., 2014) and 13 Tibet (Khan A., S. Jin, 2018). In the figure 3a we see oscillations which cannot be interpreted 14 directly as the signature of the waves. In fact, for the processing of GPS data, we use pseudo-15 range signals which can be affected by reflections on surrounding reliefs as well as by waves.

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3.2Monthly variation in TEC

18 Figure 4 shows the monthly variability of VTEC for the maximum phase of solar cycle year 19 2014 at KKN4 station. The plot is obtained using average of daily data. The plot shows 20 maximum in equinoctials months (March, April) and minimum in solstices (January, June). The 21 rise or fall of TEC in each curve follows the diurnal pattern, prominent peak in the midday with 22 different peak amplitude. The lowest VTEC peak observed during January and highest in March. 23 Late afternoon peak noticed in March, June and September whereas the peak centered ~ 2:00 LT 24 for rest of the months. A significant plat peak noticed in December whereas the steep rise in 25 VTEC is noticed in March, April and October. Monthly variation of VTEC was studied by 26 plotting similar curves for all the month from year 2008 to 2018 for all chosen four stations. The 27 plot shows clear wave's activity in mean diurnal curve for year 2008, 2009 and 2010 and from 28 the years 2011 to 2017 the stiff rise in VTEC was noticed and in 2017 the wave activity starts 29 again (plots are not included in this paper). In general, the sunrise time in summer and winter is 30 5:15 LT and 6:45 LT which are differ by 1.5 hours. During summer 2014, the maximum and 31 minimum TEC observed is 21 and 12 TECU tecu whereas in winter the maximum and minimum

TEC noticed is 25 and 15 TECU tecu respectively (Figure 4). It also seems that during sunrise
 time in summer the VTEC is linear but during the winter it is steep.

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3.3. Seasonal variation in TEC

5 Figures 5 show two dimensional diurnal plot of VTEC at JMSM station for all the four phases (I minimum-2009, II ascending-2011, III maximum-2014 and IV descending-2015) of the solar 6 7 cycle 24 which explains how diurnal VTEC varies hourly during four phases. In ionosphere over 8 Nepal the features of equinoctial asymmetry is distinctly noticed in 2D plots of year 2009, 2011, 9 2014 and 2015 in Figure 5a, 5b, 5c and 5d, respectively. From Figure 5a, 5b, 5c and 5d it is 10 observed that equinoctial asymmetry is not noticed in 2009, in 2011 autumn is more intense than 11 spring and in 2014 and 2015 spring VTEC is greater than autumn. In year 2009, equinoctial 12 asymmetry is not noticed during low solar activities. But in year 2011, the autumn is intense than 13 spring which is the features of equatorial ionization anomaly (EIA) crest latitude and in year 14 2014 the difference between equinoctial asymmetry is less (spring > autumn) which is again the 15 characteristics of the EIA trough station. And in 2015, the asymmetry very high (spring >16 autumn) which is the general feature of TEC at all latitude. Our study can conclude that 17 ionosphere Nepal sometimes show features of EIA crest latitude and sometimes EIA trough 18 station.

19 In the Figures 6a, 6b, 6c, 6d and 6e each panel separately represents the VTEC variation during 20 autumn, spring, summer and winter season for the year 2008, 2009, 2011, 2014 and 2015 at 21 KKN4, GRHI, JMSM and DLPA respectively. The plots show the maximum values of VTEC is 22 ~95 TECU teeu in spring 2014 the maximum year of sunspot cycle and minimum value 10 23 TECU tecu in 2009 winter the minimum year of sunspot cycle. In the increasing and decreasing 24 phases of solar cycle, the VTEC gradually increases and decreases depending to the amount of 25 UV that arrive the Earth. In general, the plots show that VTEC is maximum during spring 26 followed by autumn, summer and winter, except few cases. Similarly, previous study of GPS 27 TEC for the year 2014 over Nepal also reported the highest value of VTEC on March and lowest 28 on December with distinct the seasonal variations having higher values in spring and lower in 29 winter season (Ghimire et al., 2020). During the sunspot minimum years 2008 and 2009 and 30 2010, there are no semi-annual variations in the VTEC and it also seems the summer VTEC is as 31 strong as the Autumn VTEC. For the years 2011 to 2016 the semi-annual variations are noticed.

1 During the year 2017, we observed the same pattern as for the year 2008, 2009 and 2010, the 2 summer VTEC is as strong as the Autumn VTEC. At the station KKN4, the VTEC in autumn is 3 very weak in year 2015 and it is smaller than the VTEC in summer. In year 2011 winter anomaly 4 is noticed the VTEC is larger in Winter than in Summer at KKN4 whereas GRHI and JMSM the 5 Winter VTEC is observed smaller than the Summer one in year 2011 and 2014. Winter anomaly 6 is not observed At DLPA, the Winter VTEC is not larger than the Summer VTEC. In year 2008 7 spring VTEC identified more than autumn for GRHI, JMSM and DLPA but less than autumn is 8 observed KKN4. In year 2009 only at JMSM spring noticed greater than autumn. The autumn 9 VTEC is greater than spring for all station in 2011 except at JMSM it equal to spring. Large 10 asymmetry is noticed between spring and autumn in year 2014. In year 2015 the summer peak is 11 higher than autumn. In present study the VTEC larger in winter than VTEC in Summer winter 12 anomaly is noticed in 2011 and 2014. At KKN4 station the VTEC larger in winter than VTEC in 13 Summer winter anomaly is noticed in the year 2014; at GRHI 2014 and 2016; at JMSM 2014 14 and 2016. The VTEC larger in winter than Summer VTEC Winter anomaly is not noticed at 15 DLPA (Figure 6c and 6d).

16 Solar flux dependency of winter anomaly in GPS TEC has studied by Rao et al. (2019b). The 17 result showed that when the level of solar flux in winter month is greater than the corresponding 18 summer month winter anomaly is observed irrespective to the phases of solar cycle whether it is 19 high or low. Their study also pointed out that the winter anomaly in GPS-derived TEC may not 20 be a feature of any geophysical significance. The winter or seasonal anomaly introduced due to 21 temperature changes (Appleton, 1935), inter hemispheric transport of ionization (Rothwell, 22 1963), the significant changes in the Sun-Earth distance (Yonezawa, 1959), seasonal variation of 23 O/N2 concentration (Rishbeth and Setty, 1961; Wright, 1963; Rishbeth et al., 2000; Zhang et al., 24 2005) and the upward movement of energy flux (Maeda et al., 1986). The winter anomaly is 25 related to solar activity. Tyagi and Das Gupta (1990) and Bagiya et al (2006) have reported 26 absence of winter anomaly in low solar activities at low latitudes. The change in composition of 27 the constituents being identified as cause of the winter anomaly is coined by Rishbeth and Setty 28 (1961). The least VTEC in June solstice (in Northern hemisphere) during the low and high solar 29 activity phase may be due to the asymmetry heating and which result in transport of neutral 30 constituents from summer to winter hemisphere reducing the rate of recombination. The 31 reduction in recombination rate in winter causes the rise of VTEC in winter than in summer.

1 Gupta and Singh (2001) studied TEC over Delhi and concluded that winter anomaly in TEC 2 appears only during higher solar activity. This winter anomaly is due to the closer distance of the 3 Earth from the Sun and the direction of the wind from the summer season to the winter (Shimeis 4 et al, 2014). Krankowsky et al. (1968) and Cox and Evans (1970) separately pointed out that the 5 ratio of O/N₂ become twice in winter than in summer as a result of higher electron loss rate in 6 summer than in winter. Torr and Torr (1973) observed the winter anomaly in foF2 under different 7 solar activity at the mid latitude of northern hemisphere and similar result was observed in 8 southern hemisphere during high solar activity. Furthermore, they noticed lower solar activities 9 results lower winter anomaly. In general, June solstice anomaly is higher than the December 10 solstice but in earlier, study done at Agra GPS station noticed some abnormalities in the solstice 11 behavior demonstrating higher VTEC in the summer than autumn and winter anomaly with 12 higher VTEC than in summer (Bagiya et al., 2011).

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In Figure 7 top left panel represents the variation of VTEC during spring, down left during 14 15 autumn, top right during summer and bottom right during winter from year 2008 to 2017 at 16 KKN4. In spring the difference in VTEC between high and low solar activity is 65 TECU tecu, 17 in autumn 53 TECU tecu, in summer 45 TECU tecu and in winter 40 TECU tecu respectively. In 18 Figure 8 the top panel represents VTEC variability during minimum and increasing phases 19 whereas the bottom panel represents the maximum and decreasing phases of solar cycle 24 using 20 GPS station at GRHI. The plot shows that equinoctial asymmetry is not observable during 21 minimum solar cycle 2008 and 2009, it is clearly distinguishable during other phases of solar 22 cycle

23 The important parameter for semiannual variation of ionospheric ionization is the variation in 24 atomic/molecular ratio, i.e. concentration of O/N2 ratio. At solstice, there is circulation of 25 meridional wind of about 25 m/s in middle and low latitudes from summer to winter hemisphere 26 (Rishbeth et al., 2000). These winds carry nitrogen-rich air produced in summer hemisphere into 27 lower latitudes by upwelling in higher latitudes, reducing O/N2 ratio. At equinox, there is no 28 prevailing meridional circulation. The ratio O/N2 depends specially on the horizontal circulation, 29 and its seasonal changes accompany the change in global thermospheric circulation between 30 summer-to-winter pattern around the solstices to a symmetrical pattern at equinoxes. The six possible reasons of seasonal and semiannual variations in F2 layer discussed by Rishbeth (1998) 31

are: a) The compositional changes due to large-scale dynamical effects in the thermosphere b)
 Variations in the geomagnetic activities c) Energy of solar wind d) The inputs from lower
 atmospheric phenomena such as waves and tides e) change in atmospheric turbulence and f)
 Anisotropy of solar and EUV emission in solar latitude (Burkard, 1951).

In 2020, Ansari et al. found the minimum value of TEC in January and that becomes maximum in April then decreases in June-July and followed by increase in magnitude of second maximum in September-October and later decrease down till December at CHML and JMSM GRHI of year 2017. Referring Figure 8, our result of semiannual variation shows the minimum value of VTEC is found in January and that becomes maximum in March-April then decreases in June-July and followed by increase in magnitude of second maximum in October-November and later decreases down till December at GRHI of year from 2009 to 2018.

The asymmetry between the two equinoxes is due to geophysical parameters as magnetic indices related to geomagnetic activity (Triskova, 1989) and the IMF Bz the interplanetary component of magnetic field (Russell and McPherron, 1973). The equinoctial asymmetry observed in VTEC is explained by i) the axial hypothesis ii) the Russell McPherron (RM) effect and iii) the equinoctial hypothesis (ChamanLal, 1996; Shimeis et al., 2014).

Ouattara and Amory-Mazaudier (2012) made a statistical model of the F2 layer, at equatorial latitudes, based on data obtained during three sunspot cycles. This model shows the influence of the different type of geomagnetic activity defined by Legrand and Simon (1989) and the asymmetry of equinoxes due to the magnetic activity. The asymmetry between the two equinoctial peaks is also due to asymmetry of the thermospheric parameters that influence ionosphere as neutral wind and change in composition (Balan et al., 1998)

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24 **3.4Solar cycle variation of TEC**

Figure 9 shows the annual mean values of VTEC, solar flux index and sunspot number during the solar cycle from year 2008 to 2018. The black, blue, green and red color line represents VTEC variation on station KKN4, GRHI, JMSM and DLPA whereas pink and light green color line represents variation in SSN and solar flux index, respectively. The plot shows VTEC gradually begins to increase in 2009 and reaches a maximum in 2014. Then it begins to decrease till 2018 which agrees with the sunspot number and solar flux variation in the same plot. The figure shows that the maximum value of peak of ionization in 2014 about 37 TECU tecu in maximum phase of solar cycle and the minimum value in 2008 about 11 TECU tecu in the
minimum phase of solar cycle. The observed VTEC variation corresponds to the amount of UV
reach to the Earth.

Similarly, the solar flux increases from 2011 onward; the measured VTEC also exhibits highest
magnitude for the year 2014. The maximum VTEC value shows a decreasing trend since year
2015 to 2018 at all the stations used for this study. It is observed from the graph that average
annual VTEC shows better synchronization with SSN and solar flux index.

8 The patterns of the solar cycles play a major role in the solar variability: solar radiation and 9 sunspot number and consequently influence the ionosphere. The solar cycle 24 is the smallest 10 solar cycle since the spatial era (1957), in which peak is noticed in 2014, some few major solar 11 flares were erupted from the Sun in February and October 2014 (Kane, 2002) so the maximum 12 VTEC is noticed in February, October shown in Figure 8. Again from Figure 8, higher value of 13 sunspot and solar flux was reported in February 2011 corresponding to X-class solar flare at 14 which higher value of VTEC noted in station considered. Sharma et al. (2012) studied VTEC 15 variation at Delhi lies near equatorial crest region during year 2007 to 2009 low solar activities 16 and found TEC has a short-lived day minimum between 5:00-6:00 LT and gradual increase and 17 reaches its peak value between 12:00 to 14:00 LT. The day minimum was found flat during most 18 of the nighttime hours (22:00 to 06:00 LT). Their results show magnitude of daily maximum 19 TEC decreases since 2007 to 2009 due to decrease in solar flux. They also found TEC seasonal 20 behavior depends on the solar cycle and the largest daily TEC is observed during equinoctial 21 month at Delhi. In 2020, Ghimire et al, studied diurnal variation of TEC at JMJG (Lamjung, 22 Nepal) station for the year 2015 found the minimum in pre-dawn, a steady increase in the early 23 morning followed by afternoon maximum then gradual decrease after sunset the similar pattern 24 is also observed our study.

In African sector, Tariku (2015) observed from 2008 to 2009 and high 2012 to 2013 values of VTEC during the low and high solar activity phases. According to their finding, the diurnal VTEC values attained maximum in the time interval of 13:00 to 16:00 LT and the least values are mostly at around 06:00 LT. The similar result is noticed in all considered Nepalese GPS stations during the low solar active phases of solar cycle 24 in Nepal. The maximum diurnal variability in VTEC in 2014 is caused by solar active period confirmed by maximum sunspot number (SSN) and solar flux index (shown in Figure 2), VTEC greater in 2012 due to second

1 maximum in SSN and solar flux and minimum VTEC in 2009 and 2017 supported by minimum 2 SSN and solar flux which is confirmed by synchronization of VTEC with SSN and solar flux 3 (Figure 9). In the ionosphere over Nepal the diurnal VTEC maximum occurs approximately 4 between 12:00 to 14:00 LT. Similar to Delhi station in Nepal, the day minimum was found flat 5 during most of the nighttime hours (22:00 to 06:00 LT). In general, the value of diurnal peak in 6 VTEC is maximum during the spring equinoxes except in 2011 in which autumn VTEC is 7 maximum. As the solar flux decreases from 2008 to 2009, the daily maximum VTEC values 8 show a decreasing trend.

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10 **4 Conclusion**

This paper investigates the diurnal, monthly, seasonal and solar cycle variations of VTEC at four
mid low latitude stations: KKN4 (27.80° N, 85.27° E), GRHI (27.95° N, 82.49° E), JMSM

13 (28.80° N, 83.74° E) and DLPA (28.98° N, 82.81° E) in Nepal.

14 The following conclusions are found:

15 - The shape of mean diurnal variation of VTEC depends on the solar cycle phases: flat no diurnal
 16 peak is observed during minimum and descending phases of the solar cycle whereas a Gaussian

17 with different peak amplitude is noticed during ascending and maximum phases of the solar18 cycle.

19 - The study may reveal that diurnal TEC maximizes at around 11:00 LT to 14:00 LT, with20 minimum in the pre-dawn periods.

- Day to day variation in VTEC is significant in all the station. The maximum is noticed at
KKN4 and minimum at DLPA.

- The mean diurnal profile in the year 2008, 2009, and 2010 and 2017 exhibit wave like nature

- whereas the parabolic nature is observed in the year 2011, 2012, 2013, 2014, 2015, and 2016 and
- **25 2017**.
- The week ionospheric activities characterized by lower TEC values during minimum and
 strong activities by higher value of VTEC during maximum phase ie VTEC has shown proper
 synchronization with SSN and solar flux.
- The monthly plot shows during sunrise time in summer the VTEC is linear whereas during thewinter it is steep.

Equinoctial asymmetry is not noticed in 2009, in 2011 autumn is more intense than spring and
in 2014 and 2015 spring VTEC is greater than autumn.

3 - Equinoctial asymmetry in peak is noticed in spring (March, April) and autumn (September,

4 October) in which higher is observed during spring.

5 -The equinoctial asymmetry is noticed in all the available stations due to difference in the

6 F10.7cm for the two equinoxes.

7 -The spring-maximum is smaller than autumn-maximum mainly during years 2011, 2012, 2013

8 and also during year 2008 for one station, these years are years of minimum or increasing phase

9 of the sunspot cycle.

10 -The VTEC in winter is greater than VTEC in summer winter anomaly is observed in all the

available stations at the maximum of sunspot cycle 2014 and in one other station during the year2011.

-During the year 2009 of the sunspot minimum the VTEC in winter is greater than VTEC in
summer winter anomaly is not observed for all the stations. And there is no equinoctial
asymmetry i.e. very weak (compare to the year of the maximum) except at JMSM.

16 -It seems that in Nepal for some years there is no semiannual variation, as we observe sometimes

that the summer VTEC is larger than VTEC in the autumn. It is probably a characteristic of
Nepal.

19 The highest Himalayan mountains on earth in Nepal, are the source of landform waves that travel 20 through the stratosphere and the lower thermosphere where they deposit their energy and give 21 birth to secondary gravity waves that can affect VTEC. In our climatology study we analyze 22 average behaviors that do not allow the study of these waves. Another study analyzing 23 individually each day and using phase processing of GPS signals should be done in the future to 24 analyze the impact of the Himalayas on VTEC and the impact of the low atmosphere on VTEC.

25

26 Data availability

27 In this study data is available at www.unavco.org , http://aiuws.unibe.ch/ionosphere (CODG),

28 www.ngs.noaa.gov/CORS/Gpscal.shtml , http://www.isgi.unistra.fr/,

29 http://celestrack.com/GPS/almanar/Yuma/2017/, website: sidc.oma.be/silso/home and Omni data

30 site http://omniweb.gsfc.nasa.gov/ for GPS TEC data in RINEX , DCB file, Yuma file, sunspot

number and solar flux and data for solar wind parameters and geomagnetic indices respectively
 are used.

3

4 Authors' contributions

5 Drabindra Pandit = He developed the idea of this manuscript. He has major contribution to

6 prepare introduction, dataset and methodology and conclusions.

7 Basudev Ghimire = He has contributed in writing the results discussion.

8 Christine Amory-Mazaudier = She has contributed in data set and data analysis, conclusion and

9 in editing the manuscript and gave the shape of this paper.

10 Rolland Fleury = He has provided the software for this study, contributed in the methodology

11 and in editing the text.

12 Narayan Prasad Chapagain = He gave overall feedback on this paper. He reviewed this paper

13 thoroughly and gave a shape of complete manuscript.

Binod Adhikari = He has contributed in the result and discussion and reviewed the paperthoroughly.

16

17 Competing interests

18 The authors declare that they have no competing interests.

19

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22 www.ngs.noaa.gov/CORS/Gpscal.shtml, and http://www.isgi.unistra.fr/, 23 http://celestrack.com/GPS/almanar/Yuma/2017/, website: sidc.oma.be/silso/home and Omni data 24 site http://omniweb.gsfc.nasa.gov/ for providing RINEX data for TEC, DCB file, Yuma file and 25 data for solar wind parameters and geomagnetic indices for our calculations. The author would 26 like to acknowledge Nepal Academy of Science and Technology (NAST), Nepal for proving 27 PhD scholarship and ICTP, Italy for giving the opportunity to participate in a workshop on Space 28 weather effects on GNSS operations at low latitudes.

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1	References
2	
3	Akala, A. O., Rabiu, A. B., Somoye, E. O., Oyeyemi E. O., Adeloye A. B. (2013). The
4	Response of African equatorial GPS TEC to intense geomagnetic storms during the
5	ascending phase of solar cycle 24, Journal of Atmospheric and Solar-Terrestrial Physics,
6	98, 50–62, doi:10.1016/j.jastp.2013.02.006.
7	Ansari, K., Park, K. D., Panda, S. K. (2019). Empirical and orthogonal function analysis and
8	modeling of ionospheric TEC over South Korean region, ActaAstronautica, 161, 313-
9	324, doi:10.1016/j.actaastro.2019.05.044.
10	Anderson, D., Fuller-Rowell, T. (1999). The ionosphere, Space environment topics SE-14,
11	Space Environment Center, Boulder, Report.
12	Appleton, E. V. & Ingram, L. J. (1935). Magnetic Storms and Upper-Atmospheric Ionisation
13	<i>Nature</i> , 136 , 548–549.
14	Bagiya, M. S., Iyer, K. N., Joshi, H. P., Tsugawa, T., Ravindra, S., Sridharan, R., Pathan, B. M.
15	(2011).Low-latitude ionospheric-thermospheric response to storm time electro dynamical
16	coupling between high and low latitudes, J. Geophys. Res., 116, AO1303,
17	doi:10.1029/2010JA015845.
18	Balan, N., Batista, I. S., Abdu, M. A., Macdougall, J., Bailey, G. J. (1998). Physical mechanism
19	and statistics of occurrence of an additional layer in the equatorial ionosphere, J.
20	Geophys. Res., 103(A12), 29,169–29,181, doi:10.1029/98JA02823.
21	Breit, G., Tuve, M. A. (1926)., A Test of the existence of the conducting layer, <i>Phys. Rev.</i> , 28,
22 23 24 25	 Bremer, J. (2004). Investigations on long-term trends in the ionosphere with world-wide ionosonde observation, <i>Advances in Space Research</i>, 2, 253–258, doi:10.5194/ars-2-253-2004.
26 27 28	 Buonsanto, M. J. (1986). Possible effects of the changing Earth-Sun distance on the upper atmosphere, S. Pacific, <i>J. Nat. Sci</i>, 8, 58-65. Burkard, O. (1951). Die halbajahrige Periodic der F2-Schicht-Ionisation, <i>ArchivMeteorol</i>.
29 30 31 32 33	 BIOKIUM, WIEN, 4, 391-402 ChamanLal (1996). Seasonal trend of geomagnetic activity derived from solar-terrestrial geometry conforms an axial-equinoctial theory and reveals deficiency in planetary indices, <i>J. Atmos. Terr. Phys.</i>, 58, 1497-1506,doi: <u>10.1016/0021-9169(95)00182-4</u>. Chauhan V., Singh, O. P., Singh, B. (2011). Diurnal and seasonal variation of GPS-TEC during
34	a low solar activity period as observed at a low latitude station Agra, Indian Journal of
35	Radio and Space Physics, 40, 26-36.

1	Cox, L. P., Evans, J. V. (1970). Seasonal variation of the O/N ₂ ratio in the F ₁ region, J. Geophy.
2	Res., 75, 6271, doi:10.1029/JA075i051p06271.
3	D'ujanga, F. M., Mubiru, J., Twinamasiko, B. F., Basalirwa, C., Ssenyonga, T.J. (2012). Total
4	Electron Content Variations in Equatorial Anomaly Region, Advances in Space Research,
5	50 , No. 4, 441–449, doi: <u>10.1016/j.asr.2012.05.005</u> .
6	Dabas R.S., Lakshmi, D. R., Reddy, B. M. (1993). Solar activity dependence of ionospheric
7	electron content and slab thickness using different solar indices, Pure App. Geophys.,
8	140 , 721-728.
9	Dashora, N., and Suresh, S. (2015). Characteristics of low-latitude TEC during solar cycles 23
10	and 24 using global ionospheric maps (GIMs) over Indian sector, J. Geophys. Res. Space
11	Physics, 120, 5176–5193, doi:10.1002/2014JA020559.
12	deAbreu, A. J., Fagundes, P.R., Gende, M., Bolaji, O. S., de Jesus, R., Brunini, C. (2014).
13	Investigation of ionospheric response to two moderate geomagnetic storms using GPS-
14	TEC measurements in the South American and African sectors during the ascending
15	phase of solar cycle 24, Advances in Space Research, 53 (9), 1313-1328,
16	doi:10.1016/j.asr.2014.02.011.
17	Galav, P., Dashora, N., Sharma, S., Pandey, R. (2010). Characterization of low latitude GPS-
18	TEC during very low solar activity phase, J. of Atmospheric and Solar – Terrestrial
19	Physics, 72, 1309-1317, doi:10.10.1016/j.jastp.2010.09.017.
20	Ghimire,B.D, Chapagain, N.P., Basnet, V., Bhatt, K. and Khadka, B. (2020). Variation of Total
21	Electron Content (TEC) in the quiet and disturbed days and their correlation with
22	geomagnetic parameters of Lamjung Station in the year of 2015, Bibechana, 17, 123-132
23	DOI: https://doi.org/10.3126/bibechana.v17i1.26249
24 25 26 27	Ghimire,B. D., Chapagain,N. P., Basnet,V., Bhatta,K. and Khadka,B. (2020).Variation of GPS- TEC Measurements of the Year 2014: A Comparative Study with IRI - 2016 Model. <i>Journal of Nepal Physical Society</i> , 6 (1), 90-96, DOI: <u>http://doi.org/10.3126/jnphyssoc.v6i1.30555 90</u> .
28 29 30 31	Gonzalez, W.D., Joselyn, J.A., Kamide. Y.,Kroehl, H.W., Rostoker, G, Tsurutani, B.T.andVasyliunas, V.M. (1994). What is geomagnetic storm? J. Geophys.Res., 99, 5771-5792, https://doi.org/10.1029/93JA02867

- 1 Guo, J., Li, W., Liu, X., Kong, Q., Zhao, C., Guo, B. (2015). Temporal-spatial variation of 2 global GPS-derived total electron content, 1999-2013, *PloS ONE* **10**(7) e:0133378, 3 doi:10.1371/journal.Pone 0133378. 4 Gupta, J. K. and Singh, L. (2001). Long term ionospheric electron content variations over Delhi, 5 Ann. Geophys, 18, 1635-1644, doi: 10.1007/s00585-001-1635-8. 6 Hofmann-Wellenhof, B., Lichtenegger H., Collins J. (1992).GPS: Theory and Practice, Springer 7 Verlag/Wien, ISBN 978-3-211-82364-6 and 978-3-7091-3298-5 (eBook). 8 Huo, X. L., Yuan Y.B., Ou J.K., Zhang K.F., Bailey G.J. (2009). Monitoring the Global-Scale 9 Winter Anomaly of Total Electron Contents Using GPS Data, Earth Planets and Space, 10 61, 1019–1024, doi: 10.1186/BF03352952. 11 Jain, A.R. (1987). Reversal of EXB drift & post sunset enhancement of the ionospheric total 12 electron content at equatorial latitudes, Indian Journal of Radio and Space Physics, 16, 13 267-272. 14 Kane, R. P. (2002). Some implications using the group sunspot number reconstruction, Solar 15 Phys., 205, 2, 383-401, doi:10.1023/A:1014296529097. 16 Khan A., Jin, S. (2018). Gravity wave activities in Tibet observed by Cosmic GPS radio, 17 Geodesy and Geodynamics 9, 504-511, https://doi.org/10.1016/j.geog.2018.09.009 18 19 Kramkowsky, D., Kasprazak, W.T., Nier, A.O. (1968). Mass spectrometric studies of the 20 composition of the lower thermosphere during summer 1967, J. Geophys. Res. 73, 7291. 21 Legrand, J. P., Simon, P.A. (1989). Solar cycle and geomagnetic activity: A review for 22 geophysicists. Part I. The contributions to geomagnetic activity of shock waves and of the 23 solar wind, Ann. Geophys., 7(6), 565-578 24 Martin, L. and Volkert, H. (2000), The Propagation of Mountain Waves into the Stratosphere: 25 Quantitative Evaluation of Three-Dimensional Simulations, Journal of the Atmospheric 26 Sciences Volume 57(18), DOI: https://doi.org/10.1175/1520-27 0469(2000)057<3090:TPOMWI>2.0.CO;2, 3090-3108. 28 Liu, G., Huang, W., Gong, J., Shem, H. (2013). Seasonal variability of GPS-VTEC and model 29 during low solar activity period 2006-2007 near the equatorial ionization anomaly crest 30 location in Chinese zone, Advances in Space Research, 51, 366-376, doi: 31 10.1016/j.asr.2012.09.002.
 - 18

1 Liu, L. B., Wan, W. X., Ning, B. Q., Zhang M. L. (2009). Climatology of the mean total 2 electron content derived from GPS global ionospheric maps, J. Geophys. Res., 114: 3 AO6308, doi: 10.1029/2009JA014244. 4 Liu, L. B., Chen, Y. D. (2009). Statistical analysis of solar activity variations of total electron 5 content derived at Jet Propulsion Laboratory from GPS observations, J. Geophys. Res., 114 :A10311, doi: 10.1029/2009JA014533. 6 7 Mansoori, A. A., Parvaiz A.K., Rafi A., Roshni A., Aslam A.M., Shivangi B., Bhupendra M., 8 Purohit P.K., Gwal A.K. (2016). Evaluation of long term solar activity effects on GPS 9 derived TEC, Journal of Physics: Conference Series, 759, 012069, doi:10.1088/1742-10 6596/759/1/012069. 11 Natali, M. P., Meza A. (2011). Annual and Semiannual Variations of Vertical Total Electron 12 Content during High Solar Activity Based on GPS Observations, Ann. Geophys., 29, 13 865-873, doi: 10.5194/angeo-29-865-2011. Ouattara, C., Amory-Mazaudier, C., Fleury, R., Lassudrie Duchesne, P., Vila, P., Petitdidier, M. 14 15 (2009). West African equatorial ionospheric parameters climatology based Ouagadougou 16 ionosonde station data from June 1966 to February 1998, Ann. Geophys., 27, 2503-2514, 17 doi: 10.5194/angeo-27-2503-2009. 18 Ouattara, F., Fleury R. (2011). Variability of CODG TEC and IRI 2001 Total Electron Content 19 (TEC) during IHY Campaign Period (21 March to 16 April 2008) at Niamey under Different Geomagnetic Activity Conditions, Scientific Research and Essays, 6, No. 17, 20 21 3609-3622. 22 Ouattara, F., Amory-Mazaudier, C. (2012). Statistical study of the equatorial F2 layer at 23 Ouagadougou during solar cycles 20, 21, 22 using Legrand and Simon's classification of 24 geomagnetic activity, J.Space Weather Space Clim., 2, A19, doi:10.1051/swsc/20122019. 25 Parwani, M., Atulkar, R., Mukherjee, S., Purohit, P.K. (2019). Latitudinal variation of 26 ionospheric TEC at northern hemispheric region, *Russian Journal of Earth Sciences*, 19, 27 ES1003, doi: 10.2205/2018ES000644. 28 Perevalova, N. P., Polyakova A.S., Zalizovski A.V. (2010). Diurnal Variation of the Total 29 Electron Content under Quiet Helio-Geomagnetic Conditions, Journal of Atmospheric 30 and Solar-Terrestrial Physics, 72, 997–1007, doi: <u>10.1016/j.jastp.2010.05.014</u>.

1	Prikryl, P., Jayachandran, P.T., Mushini S.C., Pokhotelov, D., MacDougall, J.W., Donovan E.,					
2	Spanswick E., St-Maurice J.P. (2010). GPS TEC, scintillation and cycle slips observed at					
3	high latitudes during solar minimum, AnnalesGeophysicae, 28, 1307-1316, doi:					
4	10.5194/angeo-281307-2010.					
5	Rama Rao P. V. S., Nru D., SriramaRao, M. (1980). Study of some low latitude ionospheric					
6	phenomena observed in TEC measurements at Waltair, India, Proc. Satellite Beacon					
7	<i>Symp.</i> , 57-65.					
8	Rao, S.S., Chakraborty, M., Kumar, S., Singh, A.K. (2019a). Low-latitude ionospheric response					
9	from GPS, IRI and TIE-GCM TEC to Solar Cycle 24, Astrophys Space Sci, 364:216,					
10	https://doi.org/10.1007/s10509-019-3701-2					
11	Rao, S.S., Sharma, S., Pandey, R. (2019b). Study of solar flux dependency of the winter anomaly					
12	in GPS TEC, GPS Solutions, 23(4) DOI: 10.1007/s10291-018-0795-x					
13	Regmi, R.P. and Maharjan, S. (2015). Trapped mountain wave excitations over the					
14	Kathmandu valley, Nepal, <u>Asia-Pacific Journal of Atmospheric Sciences</u> volume					
15	51, pages 303-309.					
16	Regmi, R.P., Kitada, T., Dudha, J., Maharjan, S. (2017). Large-scale gravity over the					
17	middle hills of the Nepal Himalayas: implication for aircraft accidents, Journal of					
18	applied meteorology and climatology, pp 371-389, DOI: 10.1175/JAMC-D-					
19	160073.1					
20 21 22	 Rishbeth, H., Garriott O.K. (1969). Introduction to Ionospheric Physics, International Physics Series, 14, New York: Academic Press. Rishbeth, H. (1998). How the thermospheric circulation affects the ionospheric F2- layer, Solar- 					
23	Terrestrial Physics, 60, 1385-1402, doi: 10.1016/S1364-6826(98)000062-5.					
24	Rishbeth, H., Muller-Wodarg, I.C.F., Zou, L., Fuller-Rowell, Millward, G.H., Moffett, R. J.,					
25	Idenden, D. W., Aylward, A. D. (2000). Annual and semiannual variations in the					
26	ionospheric F2-layer: II, physical discussion, Ann. Geophysicae, 18, 945-956, doi:					
27	<u>10.1007/s00585-000-0945-6</u> .					
28	Rishbeth, H., Setty, C.S.G.K. (1961). The F-layer at sunrise, J. Atmos. Terr. Phys, 20, 263-276,					
29	doi: <u>10.1016/0021-9169(61)90205-7</u> .					

- Rothwell, P. (1963). Diffusion of ions between F layers at magnetic conjugate points, in Proc.
 International Conference on the Ionosphere, *Institute of Physics and Physical Society*,
 London, 217-221.
- 4 Russell C. T., McPherron R. L. (1973). Semiannual variation of geomagnetic activity, J.
 5 *Geophys. Res.*, 78, 92-108, doi:10.1029/JA078i001p00092.
- Sahai, Y., Becker-Guedes F., Fagundes P.R. (2007). Response of Nighttime Equatorial and Low
 Latitude F-Region to the Geomagnetic Storm of August 18, 2003, in the Brazilian Sector,
 Advances in Space Research, **39**, 1325–1334, doi: <u>10.1016/j.asr.2007.02.064</u>
- 9 Sharma, K., Dabas, R.S., Ravindran, S. (2012). Study of total electron content over equatorial
 10 and low latitude ionosphere during extreme solar minimum, *Astrophs. Space Sci.*, doi
 11 10.1007/s10509-012-1133-3.
- Shimeis, A., Amory-Mazaudier, C., Fleury, R., Mahrous, A.M., Hassan, A. F. (2014). Transient
 variations of vertical total electron content over some African stations from 2002 to 2012,
 Advances in Space Research, 54, 2159-2171, doi: 10.1016/j.asr.2014.07.038.
- Tariku, Y.A. (2015). Patterns of GPS-TEC variation over low-latitude regions (African sector)
 during the deep solar minimum (2008 to 2009) and solar maximum (2012 to 2013)
 phases, *Earth Planet and Space*, 67; 35, doi: 10.1186/s40623-015-0206-2.
- 18 Titheridge, J. F. (1972). The total electron content of the southern midlatitude ionosphere, 1965-

19 1971, J. Atmos. Terr. Phys., **35**, 981-1001, doi: <u>10.1016/0021-9169(73)90077-9</u>.

- 20 Torr, M. R., Torr, D. G. (1973). The seasonal behavior of the F2-layer of the ionosphere, *J.* 21 *Atmos. Terr. Phys*, **35**, 22-37, doi: <u>10.1016/0021-9169(73)90140-2</u>.
- Torre, A., Alexander, P., Llamedo, P., Hierro, R., Nava, B., Radicella, S., Schmidt, T. and
 Wickert, J. (2014). Wave activity at ionospheric heights above the Andes Mountains
 detected from FORMOSAT3/COSMIC GPS radio occultation data, Journal of
 Geophysical Research: Space Physics, 119(3):2046-2051.
- 26 Triskova, L. (1989). The vernal-autumn asymmetry in the seasonal variation of geomagnetic
- 27 activity, J. Atmos. Terr. Phys., **51**, 111-118, doi: <u>10.1016/0021-9169(89)90110-4</u>.
- Tyagi T.R., Das Gupta, A. (1990). Beacon satellite studies and modeling of total electron
 content of ionosphere, *Indian J. of Radio Space Phys*, 424-438.
- Venkatesh, K., Fagundes P.R., de Jesus R., de Abreu A.J., Sumod S.G. (2014a). Assessment of
 IRI-2012 Profile Parameters by Comparison with the Ones Inferred Using NeQuick2,

1	Ionosonde and FORMOSAT-1 Data during the High Solar Activity over Brazilian					
2	Equatorial and Low Latitude Sector, Journal of Atmospheric and Solar-Terrestrial					
3	Physics, 121, 10-23, doi:10.1016/j.jastp.2014.09.014.					
4	Venkatesh, K., Fagundes P.R., Seemala G.K., de Jesus R., Pillat V.G. (2014b). On the					
5	Performance of the IRI-2012 and NeQuick2 Models during the Increasing Phase of the					
6	Unusual 24th Solar Cycle in the Brazilian Equatorial and Low-Latitude Sectors, J.					
7	Geophys. Res., 119, 5087-5105, doi :10.1002/214JA019960.					
8	Venkatesh, K., Fagundes P.R., Prasad D. S. V. V. D., DenardiniC.M., de Abreu A.J., de Jesus					
9	R., Gende M. (2015). Day-to-Day Variability of Equatorial Electrojet and Its Role on the					
10	Day-to-Day Characteristics of the Equatorial Ionization Anomaly over the Indian and					
11	Brazilian Sectors, J. Geophys. Res., 120, 9117–9131, doi:10.1002/2015JA021307.					
12	Walker, G. O., Ma J.H.K., Golton E. (1994). The Equatorial Ionospheric Anomaly in Electron					
13	Content from Solar Minimum to Solar Maximum for South East Asia,					
14	AnnalesGeophysicae, 12 , 195–209.					
15	Wright, J.W. (1963). The F-region seasonal anomaly, J. Geophys. Res., 68, 4379-4381, doi:					
16	<u>10.1029/JZ068i014p04379</u> .					
17	Yonezawa, T. (1959). On the seasonal and non-seasonal annual variations and the semiannual					
18	variation in the noon and midnight densities of the F2 layer in middle latitudes II, J.					
19	Radio Res. Labs. Japan, 6 , 651-668.					
20	Zakharenkova, I. E., Cherniak I.V., Krankowski A., Shagimuratov I.I. (2012). Analysis of					
21	Electron Content Variations over Japan during Solar Minimum: Observations and					
22	Modeling, Advances in Space Research, 52, 1827–1836, doi: 10.1016/j.asr.2014.07.027.					
23	Zhang, S.R., Holt, J.M., Anthony, P., Eyken, V., McCready, M., Amory-Mazaudier, C., Fucao,					
24	S., Sulzer, M., (2005). Ionospheric local model and climatology from long-term databases					
25	of multiple incoherent scatter radars, Geophys. Res. Lett., 32, L20102,					
26	doi.1029/2005GL023603					
27	Zhao, B., Wan, W., Liu, L., Mao, T., Ren, Z., Wang, M., Christensen, A.B. (2007). Features of					
28	annual and semi-annual variations derived from the global ionospheric maps total					
29	electron content, Annals Geophysicae, 25, 2513-2527, doi: 10.5194/angeo-25-2513-2007.					

1	Zou, L., Rishbeth, H, Muller-Wodarg, I. C.F., Aylward, A.D., Millward, G.H., Fuller-Rowell,				
2	T.J., Idenden, D.W., Mofett, R.J. (2000). Annual and semiannual variations in the				
3	ionospheric F2-layer I Modeling, Ann. Geophys., 18, 944.				
4	Zoundi, C., Ouattara F., Fleury R., Lassudrie-Duchesne P. (2012). Seasonal TEC Variability in				
5	West Africa Equatorial Anomaly Region, European Journal of Scientific Research, 77,				
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15	Tables Captions				
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18	Table 1. The selected GPS stations and their coordinates, the data of which are used in the study				
19	Table 2. Classification of selected years according to the solar cycle phases				
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15	List of figures
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17 18	Fig.1. A map of Nepal showing locations of GPS stations used in our study
20 21	Fig. 2 Display the variations of sunspot numbers and solar flux for the year 2008 to 2018.
22 23 24 25	Fig. 3a.Diurnal variation of vertical TEC in LT at KKN4 GPS station. The black, blue, light green, red and pink color line represent diurnal variation for the year 2009, 2012, 2014, 2016 and 2017 respectively.
23 26 27 28 29 30 31	Fig. 3b Diurnal variation of vertical TEC in UT at KKN4 GPS station. The first panel represents wave like mean diurnal curves of year 2008, 2009, 2010 and 2017 and the second panel represents parabolic nature of mean diurnal curves of the year 2011, 2012, 2013, 2014, 2015, 2016 and 2017. The plots are arrange following on their diurnal profile.
32 33	Fig. 4.Monthlyvariation of vertical TEC in LT for each month of year 2014 at KKN4 station.
34 35 36 37	Fig. 5 (a), (b), (c) and (d). Two dimensional (2D) variation of vertical TEC according to UT at JMSM stations for one of the year of minimum (2009), ascending (2011), maximum (2014) and descending (2015) phases of solar cycle 24.

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2 3 4	Fig. 6. Seasonal variability of VTEC during year 2008, 2009, 2011, 2014 and 2015 for KKN4, GRHI, JMSM and DLPA stations.								
5 6	Fig. 7. Mean yearly seasonal variation of VTEC for year 2008 to 2017 at KKN4								
7 8 9	Fig.8.Maximum VTEC variability at GRHI stations during minimum, increasing, maximum and decreasing phases of solar cycle 24								
10 11 12	Fig. 9. Annual mean VTEC variability at KKN4, GRHI, JMSM and DLPA stations with SSN and solar flux during year 2008 -2018								
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	SN	ID	Locations	Geog.	Geog.	Geom.	Geom.	Dip	Local Time
				Lat.	Long.	Lat.	Long.	Lat.	(LT)
	1	KKN4	Kakani, Nepal	27.80° N	85.27° E	18.62°N	159.41° E	43.86	UT+5:45h
	2	GRHI	Ghorahi, Nepal	27.95° N	82.49° E	18.94°N	156.82° E	44.25	UT+5:45h
	3	JMSM	Jomsom, Nepal	28.80° N	83.74° E	19.71°N	158.06° E	45.31	UT+5:45h
	4	DLPA	Dolpa, Nepal	28.98° N	82.81° E	19.94°N	157.21° E	46.03	UT+5:45h

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15	Table 2.		
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	Interval	Years	Solar cycle phases
	Ι	2008, 2009	The minimum of solar cycle 24
	II	2010, 2011	The increasing phase of solar cycle 24
	II	2012, 2013, 2014	The maximum phase of solar cycle 24
	IV	2015, 2016, 2017, 2018	The decreasing phase of solar cycle 24

- 16 Figure 1



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- 16 Figure 2



- 16 Figure 3a





- 3 Figure 3b



- 2 Figure 4









2 Figure 5a



2 Figure 5b



Figure 5c





2 Figure 5d



- 1.5

3 Figure 6a



2 Figure 6b









2 Figure 6c



2 Figure 6d



2 Figure 6e





2 Figure 7



2 Figure 8



- 3 Figure 9

