**Annual and Semi-Annual Variations of TEC over Nepal During the Period of 2007 to 2017 and Possible Drivers**

**Abstract**

The satellite signal delay recorded at GPS stations provides a means of estimating TEC of ionosphere. The fluctuation of the ionospheric TEC is primarily influenced by Geomagnetic and solar activities. In this study, we identify Annual Oscillation (AO) and Semi-annual Oscillation (SAO) in the day-time and night-time TEC over Nepal from three nearby stations (CHLM, BMCL, LMJG) for about 11 years period from 2007 to 2017. We also investigate the possible relationship between the indicators of geomagnetic and solar activities. For detail analysis, wavelet transform, global wavelet power spectrum, cross wavelet transform, and wavelet coherence were computed for daily averages of day-time and night-time TEC~~.~~ Our results computed from the long-term observations show the significant periods of the AO (356-days) and SAO (178-days) of TEC. We find that SAO is the most dominating periodicity in the day-time TEC, while the AO is the most dominating periodicity in the night-time TEC. Similarly, geomagnetic indices, AE and AU are seen to vary in phase and most consistently with both day-time and night-time AO, which illustrates these indices are to be the possible drivers of these periodicities in TEC. On the other hand, Dst index is seen to be the most prominent driver of SAO in both day-time and night-time TEC.

**Keywords: TEC, AO, SAO, wavelet techniques,**

**1. Introduction**

Dual frequency Global Positioning System (GPS) satellites use radio waves of wavelengths 19.05 cmand24.45cm (Hofmann-Wellenhof et al., 2001) for triangulation and thereby determine the precise location of places (Liu & Lachapelle, 2002). These waves travel in the ionosphere and are therefore affected by various phenomena then get delayed(Yu et al., 2014).From delay information, electron content of ionosphere can be calculated. The ionosphere is a complex layer in the upper part of the atmosphere which undergoes both spatial and temporal change mainly because of the ionization effect of high-energetic solar radiation (i.e. extreme ultraviolet (EUV)) and solar-related ionospheric disturbances (Marov & Kuznetsov, 2015). Besides, Geomagnetic storms are accompanied by the modulation of ionosphere content during which changes can be seen in the total electron content (TEC) (Pedatella et al., 2009; Rama Rao et al., 2009; Wang et al., 2010). From different studies changes in the electron precipitation, solar flux, geomagnetic storms, as well as regional dynamics during the day and the night time were noticed the fluctuation in ionospheric height from 80-450 km and 80-300 km in the day and night time, respectively (Huang et al., 1995; Bergeot et al., 2013;Shinbori et al., 2014; Liu et al., 2017; Amaechi et al., 2018; Ogwala et al., 2019; Macotela et al., 2019). One of the other parameters that we observe differently in the day-time and night-time is the value of the TEC in the ionosphere.

TEC is the sum of the number of electrons in the ionosphere(Yu et al., 2014). We can calculate the value of TEC from the difference between the expected and observed time taken by the radio wave signals to reach their ground station after they are propagated from GPS satellites, which are at the altitude of 20,200 km from the Earth’s surface (Hofmann-Wellenhof et al., 2001). The values of TEC are subject to diurnal, monthly, and seasonal variations (Bagiya et al., 2009; Chauhan et al., 2011; Rao et al., 2006; Pundhir et al., 2016; Ogwala et al., 2019). Recent studies have also shown that TEC undergoes annual and semi-annual oscillations (Silber et al., 2015; Guharaya et al., 2009; Bagaya et al., 2009; Karia & Pathak 2011; Liu et al., 2017 and Sharma et al., 2017).

Moreover, VLF narrowband measurements (Macotela et al., 2019; Silber et al., 2015; Rawer k. 1993; Cheng & Cummer, 2005) have reported the influence of the annual and semi-annual oscillation of the D-layer of the ionosphere. In addition to these oscillations, which are of the order of 360 and 180 days, several other periodicities such as 241 days, 27 days, and other transient periodicities of 30-120 days (Mukhtarov et al., 2010); were reported. The 27-day periodicity was linked to solar rotation cycle, periodicities of the order of 30-120 days were possibly linked to planetary waves, while the origin of 241-day periodicity reported by Silber et al. (2015) is still not clear. In all of these studies, Lomb-Scargle analysis was used to identify the periodicities associated with the waves.However, the Lomb-Scargle method is unable to point out any temporal change in signals that are in a time-series(Vaishnav et al., 2019). The same is true of fast Fourier Transform. This is where the wavelet analysis reigns superior to either of these methods as it specifies how the dominant modes of time series change in time. Therefore, Macotela et al. (2019) used the wavelet technique to establish that AO in day-time VLF amplitudes is in antiphase with respect to the mesospheric temperature variation. In addition, Vaishnav et al. (2019) used wavelet technique in GTEC maps to show that VTEC variation is maximum for seasonal timescale followed by 16-32 days period.

The main purpose of this study is to find out how the ionospheric TEC oscillates in the day-time and night-time in the solar cycle 24. We also wish to find out the factors that affect these oscillations. We transformed the time-series ionospheric TEC data into time-frequency domain by using the wavelet technique (Tangborn et al., 2011; Kessler et al., 2003; Vidakovic, 1985; Cohen, 2018). We calculated the Global Wavelet transformation (GWT) to obtain the most dominant oscillations. We then used Continuous Wavelet Transform (CWT), Cross-Wavelet Transform (XWT) and Wavelet coherence (WTC) to find out which space weather parameters were responsible for such types of oscillations.

**2. Data and Methodology**

**2.1 TEC Data**

In this study, we used the data obtained primarily from a GPS station in Nepal located at CHLM (28.20**°**N, 85.31**°**E). We also took the data from other stations BMCL (28.65**°**N,81.71**°**E) and LMJG (28.17**°**N, 84.57 **°**E) to fill the data gaps (will be discussed further in later sections). The TEC data are compiled from University NAVSTAR Consortium (**UNAVCO**) ([https://www.unavco.org/data/gps-gnss/data-access-methods/dai2/app/dai2.html#](https://www.unavco.org/data/gps-gnss/data-access-methods/dai2/app/dai2.html))in Receiver Independent Exchange Format (RINEX) Hantanaka archive files from the UNAVCO website. The RINEX file was processed in order to calculate vertical TEC (VTEC) with the help of the calibration algorithm implemented in GOPI-software (Seemala&Valladares, 2011) which is available from the author’s website [https://seemala.blogspot.com](https://seemala.blogspot.com/).

GOPI-software computes the values of VTEC using a thin shell model as shown in figure 1. This software is set up with the value of the zenith angle (Z') as 10 degreeo and the maximum height from the surface of earth (hmax) as 400 km. As the density of electrons in the ionosphere is maximum when hmax ranges between 350-450 km (Pulinets and Boyarchuk, 2004; Oikonomou et al., 2016), the use of hmax as 400 km in GOPI-software is a suitable one. The American Standard Code for Information Interchange (ASCII) files processed in this way is devoid of any TEC bias error. GOPI-software eradicates TEC bias errors by making use of the mathematical expressions below (Bagiya et al., 2009).

Since the GPS satellite may not always be directly overhead, the number of electrons in a square unit area between a satellite and receiver is obtained in the form of Slant TEC (STEC) which is given by equation (1) is to be obtained by the relation (2) (Bagiya et al., 2009; Chen et al., 2016).

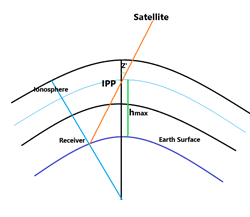
STEC = (1)

STEC = (2)

Where N is the ambugity number with in the path S, = 1575.42 MHz,  = 1227.60 MHz,   1 is the pseudo range at 1 and 2 is the pseudo range at 2 and l is the bias error calculation. The pseudo-ranges are calculated in units of kilometres. The bias error is calculated from the combination of both receiver and satellite biases. The Vertical TEC (VTEC), which is an overhead projection of STEC (as shown in figure 1) was obtained from the relation (Klobuchar, 1987):

VTEC=STEC × cos (3)

Where R is the radius of the Earth, Z’= elevation angle at the ground station



***Figure: 1*** *Geometry for the conversion from STEC to VTEC by using ionospheric prices point (IPP).*

The International GNSS Station (IGS) provides the calculation of the bias errors beforehand. The monthly biases values for satellites and IGS stations can be accessed from website <ftp://ftp.unibe.ch/aiub/CODE/>.

We have also used the night-time data to perform the analysis of equatorial ionospheric anomaly (EIA) as the study location lies close to the EIA region. The data of various geomagnetic parameters are taken from OMNIWEB (give the website here ?????????). .

The value of ionospheric TEC is obtained at a resolution of 15 seconds. We took the plateaus of VTEC data in the day-time and the night-time portion as shown in the figure 2b to be the representative of day-time VTEC and night-time VTEC. The data obtained during 6-8 UT is taken to be the day-time data, while the data from 16 - 20 UT taken as night-time data to compute the day-time and night-time daily values of TEC. For all the years during our study period, we have fixed the aforementioned time period as day-time and night-time data. The computed day-time and night-time data for 11 years period from 2007 to 2017 have been plotted in Figures 3a and 3b, respectively to show the temporal evolution of the TEC.

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| *Figure: 2 (a) The red dots in map of Nepal in left side figure show the location of the TEC stations considwered in this study and (b) right side figure shows sample TEC data of May 2, 2014.* |
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In order to apply the wavelet technique , we need constant time space between the data. However, no single station had complete data spanning one solar cycle. To overcome the data gap during the study period and obtain the continuous data set, we have taken the data from three nearby stations (CHLM, BMCL, LMJG) in Nepal during the 2007-2017. The location of the stations considered in this study is overlaid in the map of Nepal in figure 2(a). The data from these stations are averaged with equal weights i.e. all stations contribute equally to the average whenever the data are available. Nepal doesn’t span too much in latitude and longitude and the correlation between the data recorded at stations across Nepal have been found to be perfectly correlated as reported by Ghimire et al. (2020). So taking averages data from three stations doesn’t distort the long-time periodicities significantly.

However, this still leaves some minor gaps in the time series of the data. Although the time scales of the gap are largely inconsequential to our analysis, the missing data might leave behind some unexplained features in the wavelet analysis. For this reason, the minor gaps were filled with the help of linear interpolation. Figures 3(a) and 3(b) show the times series for both night and day-time TEC before the interpolation, while figures 3(c) and 3(d) are the times series after linear interpolation of the data.

**2.1 Space Weather Data**

Solar Lyman alpha radiation heavily influences the activities in the ionosphere (Laštovička, 1974). The D-region of the ionosphere is created by the Solar Lyman alpha radiation, and its absence marks the disappearance of D-layer in the night-time (Williams & Sátori, 2007). In addition, Solar Lyman alpha radiation also helps in the maintenance of the lower ionosphere (Correia et al., 2010). This is the reason why we have sought to study the relationship between TEC and Lyman alpha in this study.

The chemistry of the ionosphere is also heavily affected by the geomagnetic conditions (Wang et al., 2010; Heelis & Maute, 2020). As heavier electron precipitation in the ionosphere directly affects the value of TEC, we used various geomagnetic indices such as AE index, AU index, Dst. index, F10.7 cm flux, Kp index, and RMS BZ index. The data for all these solar indices were obtained from OMNI data set (<https://omniweb.gsfc.nasa.gov/form/omni_min.html>) maintained by NASA/Goddard Space Flight Center.

**2.2 The Wavelet Technique**

The Wavelet technique involves a class of analysis tools that can be used to not only resolve a time series into time and frequency space, but also to give qualitative and quantitative measure of degree of similarity in two times series in terms of their frequency of oscillations.

Wavelet transform is a technique to break a time series into time and frequency components that has been deemed better than windowed Fourier transform (WFT). It uses a template wave signal that is localized in time and frequency and it gets rid of the problem of dealing with a fixed length of window as is the case with WFT (Tangborn et al., 2011; Hartmann, 2016; Farouk, 2018). In wavelet transform, a template wavelet, also known as the mother wavelet, is taken which is shifted and scaled before dotting with the time series. The shift parameter populates the time axis and scale parameter corresponds the frequency axis in the resulting wavelet transform plot.

In addition, we have used the Morlet function (Morlet et al., 1982) with a frequency wo = 6 and 24 suboctave per octave to find the dominant modes (Yi & Shu, 2012; Russell & Han, 2016). Heisenberg’s uncertainty principle states that there is a trade-off between the resolution in time and frequency space in taking the Fourier transform of a time series (Feichtinger & Gröchenig, 1992). A Morlet wavelet function with the aforementioned values of frequency and suboctave per octave helps us strike a good balance between time and frequency localization (Grinsted et al., 2004). The errors associated with the wavelet computation are identified by the help of the cone of influence (COI). The edge effects associated with the cone of influence (COI) can be discarded. We should have healthy scepticism about the information in the wavelet that lies outside the COI.

Wavelet transform, therefore, is helpful in studying most powerful modes of oscillations (Daffer& Kaneko, 2005; Chen & Chu, 2017) in a signal and has also been used in various applications in geoscience. We used the WTC toolbox for MATLAB by Torrence and Compo (1998), which is available at <http://www.glaciology.net/wavelet-coherence>. These routines allow the computation of continuous wavelet transform (CWT), cross wavelet transform (XWT), and wavelet Coherence (WTC) (Grinsted et al., 2004). The relative strength of various periodicities in the TEC time series can be quantified by computing the wavelet power spectrum first and then averaging it to find the Global Wavelet Power Spectra (GWS) in time (Daffer & Kaneko, 2005; Zakaria et al., 2019).

Then, we employ the cross-wavelet transform, which is an analysis technique that locates regions where two time series show common power in the time-frequency domain(Grinstead et al., 2004). We also computed WTC as XWT is not normalized and therefore not fit for significance testing to determine the inter-relationship between two processes. The WTC coefficient gives us the inter-relationship between two processes quite similar to the way that correlation coefficient does: the value of 1 in WTC marks the strongest correlation between two processes while 0 indicates no relationship at all. A more detailed introduction to these techniques and their applications to time series in geophysics can be found in Grinsted et al. (2004).

**3. Results**

**3.1. Interrelationship Between Periodicities in Ionospheric TEC Data and Geomagnetic Indices**

In this section, we take a look at the most important periodicities in the ionospheric TEC data in the day-time and the night-time as obtained from the Continuous Wavelet Transform (CWT) and Global Wavelet Spectrum (GWS). We then analyse the relationship between the ionospheric TEC and solar parameters by computing the XWT and WTC. The results of the day-time periodicities and reactions with solar parameters are presented in section 3.2, while those of the night-time are presented in section 3.3.

**3.1.1 Periodicities in Ionospheric TEC Data**

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*Figure 4: Global wavelet power spectrum(GWS) of the day-time (a) and night-time (b)TEC. The dashed line is the 95% confidence level for the global wavelet spectrum. The horizontal lines indicate the peaks of the most significant periods. Contours of the real part of the wavelet transform of the daily day-time (c) and night-time (d) TEC in the time–period domain. The contours colors indicate the minimum (blue) and maximum (yellow) magnitude of the matches between the phases of the wavelet and the time series. The black curve is the cone of influence*.

Figures 4a and 4b (upper panels of figure 4) represent the GWS for the day-time and night-time normalized to their respective standard deviation. The dashed blue lines in these two figures (4a and 4b) are the 95% confidence levels. Only the powers above these lines are considered to be significant. The horizontal lines (in orange and green) in Figure 4 indicate the maxima of the significant peak periods that lie within the 95% confidence level. The peak periods are identified as 356.86 days and 178.44 days in the day-time ionospheric TEC and 356.87 days and 178.44 days in the night-time ionospheric TEC. In both of these cases, 178.44 days can be regarded as the semi-annual oscillation while 356.86 days can be regarded as an annual oscillation. As seen in the figure, during the day-time, power of SAO is seen to be almost twice that of the AO. However, during the night-time, power of AO is seen to be roughly 5 times that of SAO.

Figures 4(c) and 4(d), (lower panels of figure 4), show the real part of the Morlet wavelet transform for the day-time and night-time ionospheric TEC, respectively. The contour colours (maximum yellow) give us a measure of the TEC period as indicated in the colour bar. The portion of the figure outside of COI could feature artefacts that are not present in the data. Only the data within the COI of the wavelet transform should be given consideration in the study. Figures 4(c) and 4(d) reveal that day-time periodicity in AO is consistent from 2013-2017. The day-time AO is strongest in the year of 2013 to 2015 and weaker thereafter.  The night-time periodicity in AO is consistent throughout the years in our study. The strength of AO first steadily increases, being maximum in the year 2014 and decreasing thereafter (which conforms to visual inspection as the annual variation pattern can be seen prominently around 2014 as seen in figure 3(c) and 3(d). Day-time TEC is consistent in SAO from 2011 to 2015, while night-time TEC is consistent in SAO from the middle of 2013 to 2015.

The 356 day night-time period shows a narrow peak in the power spectrum but still includes the 365 day period. However, the variability broadens in period, also exhibiting greater periods during 2013–2016 as seen in figure 4(d). The night-time SAO peak in the power spectrum is relatively broader in comparison to day-time SAO, night-time AO, which includes the 182.5 days semi-annual oscillation. This period increased in 2013, becoming maximum in 2014 and decreased thereafter. To investigate more about the causes of periodicity due to other space weather parameters and physical parameters which affects are discussed in the following sections by using CWT, XWT and WTC method.

**3.1.2 Day-time Ionospheric TEC Variability**

Figure 5 shows the CWT for AE index (a), AU index (b), Dst index (c), F(10.7 cm) flux (d), Kp index (e), Lyman-alpha flux (f) and RMS-Bz-GSE flux (g). The colours indicate the common power of the two wavelet transforms analysed, ranging from low (blue) to high (yellow). The conical black curve represents the COI. Only the Information derived from the wavelet transform inside the COI is meaningful, as is the case with figure 4(c) and 4(d). We do not dwell upon all the periodicities seen solely in the indicators but we are concerned with the periodicities in these indicators that show similarity with that of day-time and night-time TEC seen in figure 4(c) and 4(d). For this, we employ XWT and WTC techniques whose results are shown in figure 6 and figure 7, respectively.

Figure 6 shows the XWT for the day-time TEC data when compared with the solar parameters used for CWT in figure 5 and shows overall relative phase differences between two time series represented by black arrows. Two time-series which are antiphase, or have a phase difference of 180° are represented by arrows pointing to the left while arrows pointing right indicate a phase difference of 0°. A downward pointing arrow represents TEC lagging the indicators that is being studied and an upward pointing arrow represents the indicators lagging behind TEC. Figure 7 shows the Wavelet coherence for these CWT, which as we discussed previously gives the normalized strengths between 0 and 1 (indicated by colours). Although figure 6 gives phase relation and the strength of correlation between the taken parameters at all ranges of time and periodicities, only those regions supported by figure 7 are significant enough to be explored for causal relations. In a manner similar to that of figure 5, COI is represented by the black curve. Solid black contours, on the other hand, are indicators of a confidence of 95%. In addition, when two different time series are related physically, a consistent or slowly varying phase lag is expected.

**Day-time AO and Its Drivers**

In terms of annual oscillation, the day-time TEC from 2009-2011 is most strongly correlated with both the AU and AE indices, which remain consistently in phase. The day-time TEC and AU are moderately correlated during 2011-2015. Day-time TEC remain in phase with RMS Bz in late 2013 and 2014. Further, the day-time TEC and Kp remain in phase from 2010-2011, while becoming antiphase from 2015-2017. The Dst index remained antiphase from 2012-2014 while becoming in phase from 2015-2017.

**Day-time SAO and Its Drivers**

In terms of semi-annual oscillations, the Day-time TEC was the most strongly correlated from 2011-2013 with the Lyman alpha, which remains in phase. The AU index as well as the Dst index remain antiphase from 2012-2014. The Kp index also exhibited a phase relationship with day-time TEC from 2014-2015.

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Among all the parameters taken, only AU index and AE index showed some level of correlation with the day-time TEC. TEC AO was seen to be in phase with both AE and AU index from the year 2008 till 2011. Dst., Kp index, F10.7 don’t show sustained correlation with TEC at any periodicities with smoothly varying phase relation. RMS BZ leads the TEC in AO period regions in the year 2009 and 2010. In the year 2013 and 2014, RMS BZ remains in phase with TEC in a broad range of periodicities near AO. Lyman-alpha, although shows no relation in yearly periodicities, shows some smoothly varying phase relations in the year 2011 to 2013 around the SAO regions. Lyman-alpha also shows some intermittent correlation with TEC in roughly 16 to 64 days periodicities. However, no consistent or smoothly varying phase relation is seen in this period range. 27 days variability in Lyman-alpha during solar maxima which is attributed to solar rotation (Lean & Skaumanich, 1983; Pap et al., 1990) is also seen in the figure 7(f) during the year 2014. The TEC seems to lag behind the indicators starting roughly in the year 2015 till the end of COI.

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| https://lh4.googleusercontent.com/1T9HnaJNWmS1GzXHEGaVJiMpbZujMt7j-cm2yTzwftzGZXoB3ZJiaW97QVVC5Kv72ZPvowdIR9Mo8_ScSIszFfcKEAzPQbIhT8UCHsiUlIDhKDbdWipnX0iZy1A017G8elu5TTxA | https://lh3.googleusercontent.com/13_tq1LyxGTk8zcJzwlgNK5XCyYeOzpGslxD3e9bHWSTml4G4Aub-UwRSma2kH0WWoXkWgtqGqK6tih9kPwHo4CYu8jyboca0Y-ISJbOsNzF9WGvTyrzSURVrXdKx4fDQiyItPDf |
| https://lh5.googleusercontent.com/BBFRjQ3tiECUPoh8Ju1tU9OaQcn7BuvgKxufJaRKY6hSkdyOpMdqDjz_I0_wLU3jAvmpNIlNvW5G9UyDICU2wC1_-WM4agdO2pZoAvMK_Ds5xDMOEUOUynuh9twioILJi6VpFjDi | *Figure 6: Cross wavelet transform (XWT) for the day-time TEC data and AE index (a), AU index (b), Dst index (c), F(10.7 cm ) flux (d), Kp index (e), Lyman-alpha flux (f) and RMS-Bz-GSE flux (g). The black curve is the cone of influence and the solid black contours indicate 95% confidence level. The contours colours indicate no correlation (blue) and high correlation (yellow) between the two wavelet transforms. The relative phase relationship is shown as arrows. Arrows pointing to the right or to the left mean in‐phase and antiphase, respectively.* |

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| https://lh5.googleusercontent.com/4AMrMAkYP-GapNe75iz3LVQgGEHhVJGB-zNXDb_ms1E6B5oL8nhw6iQa1h8dMRxBhdSusrmH5Ho9GXn8iT_PoYcNOubPzh9yHP1_fTE92HQXF0aN9HSLwfaOM1eaHg209W7KxjAi | *Figure:7 Wavelet coherence (WTC) for the day-time TEC data and AE index (a), AU index (b), Dst index (c), F(10.7 cm ) flux (d), Kp index (e), Lyman-alpha flux (f) and RMS-Bz-GSE flux (g). The black curve is the cone of influence and the solid black contours indicate 95% confidence level. The contours colours indicate no correlation (blue) and high correlation (yellow) between the two wavelet transforms. The relative phase relationship is shown as arrows. Arrows pointing to the right or to the left mean in‐phase and antiphase, respectively.* |

**3.1.3 Night-time Ionospheric TEC Variability**

Figure 8 and 9 show the XWT and WTC between the CWT of night-time TEC data (figure 4(d)) and all the solar parameters used in the study (CWT of which are shown in figure 5). Similar to that of day-time, a major periodicity signal is seen in the annual oscillation regions with some level of period intensities being seen in semi-annual oscillation regions as well. The results seen in the figures are discussed in the following section.

**Night-time AO and Its Drivers**

From the figure 8, it is seen that the night-time TEC values correlate strongly with AE and AU index just like the day-time TEC. WTC (figure 9) confirms the in phase relation between night-time TEC and AE index during the year 2009 till 2014. Similarly, AU index remains in phase for a long time before slowly lagging behind the night-time TEC starting in 2014. The phase relation with AU index is significant all throughout the solar cycle in the AO regions with normalized coefficients in WTC remaining greater than 0.8. On the other hand, Dst and Kp index show a consistent antiphase relation with night-time TEC and abruptly shifting to in phase relation in the year 2014, the solar maxima year of the solar cycle 24. However, the WTC fails to show the significance of phase relation in this region of periodicity except briefly in the year 2011 and 2012. Kp index, however, started off being in phase and abruptly shifting to being antiphase in the year 2014. This is similar to the shift seen in Dst, however, going in the opposite direction. WTC supports the phase relations starting in mid 2009 till mid 2012 (which is longer than that of Dst index).  F10.7 and Lyman alpha show similar arrow patterns in XWT throughout the solar cycle going from being antiphase to leading the night-time TEC by 90 degrees. These indices, in the range of AO, lead the night-time TEC by 90 degrees with the relation being supported by WTC in the year 2014 to 2016. RMS Bz remained in phase with night-time TEC from roughly 2011 to 2014 when it started to lead the night-time TEC. However, the phase relation remains significant only during the middle of 2012 in WTC where the normalized coefficient also reached its peak.

**Night-time SAO and Its Drivers**

While looking at the semi-annual oscillations in the figure 9, during 2012-2013, Lyman alpha remained in phase with the night-time TEC values. Dst index was antiphase with the night-time TEC in 2015, while the Kp index was antiphase with night-time TEC during 2009 and 2010. The AE index was antiphase in 2014 while remaining in phase in 2015 with regards to the night-time TEC. In 2014, RMS Bz remained in phase while Dst index was antiphase. This, unlike that of day-time TEC, doesn’t show sustained periodicity relation with any indicators taken in the study.

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| https://lh4.googleusercontent.com/nIm9oOkaGtGGXCioA_3A1mJwYRuYMV4DkuKwGBNTJKBChTaGcHOCMqnCJb9E8joZhoGY581CUTRo_Gx0fEvTQr_rgpXh9h24ZyPcPxKKJgasiElm0LZ_t7zPT5asSUibAodyaDYu | *Figure 8:Similar to figure 6  but for the night-time* |

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**4. Discussion**

In this study, we examined the periodicities associated with day-time and night-time TEC values obtained from GPS stations in Nepal from 2007 to 2017 by using wavelet analysis. The dominant periodicities in day-time and night-time amplitudes of TEC were exactly identical with only annual and semi-annual periodicities of (356 and 178 days, respectively). Sharma et al. (2017), Silber et al (2016), and Macotela et al. (2019) reported some periodicities in the D region TEC other than the annual and semi-annual variations using VLF measurements.. High frequency periodicity of 14 and 32 days attributed to solar rotation oscillations were reported along with some other unattributed periodicities. Vaishnav et al. (2019) reported a 16-32 day period in all solar proxies as well as global mean TEC (GTEC). No such periodicities were associated in the TEC values of stations in Nepal chosen in our study. If complete sets of data were available from a single station, high frequency periodicities might emerge (as averaging data from multiple stations can smooth out such periodicities). Further, the number of day-time periodicities was comparatively lower than night-time, which is expected because the day-time TEC is dominated by the effect of solar illumination which decreases the sensitivity of Ionosphere to other external factors. During the night-time, however, the sensitivity to other drivers increases in absence of solar illumination. This is in agreement our result with what was obtained by Macotel et al. (2017).

We also computed the GWS of day-time and night-time TEC values and normalized them to the respective standard deviation. We found that the power of day-time SAO is two times more powerful than the night-time SAO. In contrast, night-time AO is ~5 times more powerful than day-time AO. These findings are exactly the opposite result than reported by Macotel et al. (2019) in the study of D region TEC by using VLF measurements.

Day-time AO showed the strongest relationship with AE and AU, both of which are in phase with TEC for several years except during the solar maxima. The most significant night-time AO drivers are seen to be AE and AU both of which show consistently in phase relation with TEC. The strength of these drivers is seen to be depleted during the solar maxima years. This effect could be due to an increase in the strength of drivers of solar origin such as sunspot numbers (SSN), and solar wind velocity. SAO, on the other hand, showed a consistent antiphase relation with Dst during the day, which is expected because a decrease in Dst indicates increase in the strength of geomagnetic disturbances which leads to increase in TEC (Pedatella et al. 2009; Kanaka et al., 2019).

Lyman-alpha remained in phase during the period from roughly 2010 to 2013 with both night-time and day-time SAO in TEC.  Day-time and night-time SAO relation to geomagnetic activity has been reported by Macotela et al. (2017), which they suggested could be attributed to the semiannual variation in geomagnetic activities in accordance with Russel-McPherron effect and equinoctial hypothesis.

**5. Conclusion**

In this paper, we obtained the annual oscillation (AO) and semi-annual oscillation (SAO) in day-time and night-time TEC using Global Wavelet Spectrum. The long-term data were computed from three nearby GPS stations in Nepal for about 11 years period from 2007 to 2017. We studied their relationship with seven geomagnetic and solar indices by using cross wavelet and wavelet coherence techniques. Our findings show that:

1. SAO is the most dominating periodicity in day-time TEC and AO is the most dominating periodicity in the night-time TEC.
2. Strength of AO in night-time is roughly five times higher than that in the day-time. However, the strength of SAO during day-time is roughly twice that during the night-time.
3. AE and AU indices are seen to vary in phase and most consistently with both day-time and night-time AO among all the indices taken in the study.
4. SAO in day-time TEC is consistently antiphase with Dst index.
5. Lyman-alpha shows a 27-day variability during the solar maxima attributable to solar rotation.

Absence of other periodicities in our study besides AO and SAO is most likely because we took vertical TEC of only three GPS stations with not much spatial distribution. A study using similar techniques but done to Global TEC could reveal more periodicities as seen in Vaishnav et al. (2019). Furthermore, lower atmospheric sensitivity to atmospheric parameters could warrant a detailed study of their contribution to Ionospheric TEC periodicities.

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