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

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**Abstract**

The ionospheric TEC fluctuation is primarily influenced by Geomagnetic and solar activities. The satellite signal delay recorded at GPS stations provides a means of estimating TEC of ionosphere. In this study, wavelet transform, global wavelet power spectrum, cross wavelet transform, and wavelet coherence are computed for TEC over Nepal using data from three nearby stations (CHLM, BMCL, LMJG) of about 11 years period from 2007 to 2017. Annual Oscillation (AO) and Semi-annual Oscillation (SAO) are identified in the daytime and nighttime TEC over Nepal using data from three nearby stations (CHLM, BMCL, LMJG) of about 11 years period from 2007 to 2017. The possible relationships with the indicators of geomagnetic and solar activities were investigated. SAO is found to be the most dominating periodicity in the daytime TEC, while the AO is the most dominating periodicity in the nighttime TEC. Similarly, geomagnetic indices AE and AU are seen to vary in phase and most consistently with both daytime and nighttime AO, which illustrates these indices are 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 daytime and nighttime TEC.

**Keywords**: Solar indices, TEC, Annual oscillation (AO), Semi-annual Oscillation (SAO), wavelet techniques

**1. Introduction**

Dual frequency Global Positioning System (GPS) satellites use radio waves of wavelengths 19.05 cm and 24.45cm (Hofmann-Wellenhof et al., 2001) for triangulation and thereby determine the precise location of places (Liu & Lachapelle, 2002). These waves travel in the ionosphere are therefore affected by various phenomena and then get delayed (Yu et al., 2014). From such 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). In addition, 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 nighttime were noticed the fluctuation in ionospheric height from 80-450 km and 80-300 km in the day and nighttime, 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).

The ionospheric TEC can be estimated from the time lag experienced by the radio wave signals to reach their ground receivers as they are propagated from GPS satellites. The values of TEC are significantly varied diurnally, monthly, and seasonally as well (Pundhir et al., 2016). Several previous studies have also reported that TEC undergoes annual and semi-annual oscillations (Silber et al., 2015; Liu et al., 2017 and Vaishnav et al., 2019) and that can be determined from the time lag experienced by the radio wave signals to reach the ground receivers as they are propagated from GPS satellites. The values of TEC are significantly varied diurnally, monthly, and seasonal as well ( Pundhir et al., 2016). Several previous studies have also reported that TEC undergoes annual and semi-annual oscillations (Silber et al., 2015; Liu et al., 2017 and Vaishnav et al., 2019). Similarly, VLF narrowband measurements have been reported to respond to of the annual and semi-annual oscillation of the D-layer of the ionosphere (Rawer, 1993; Cheng & Cummer, 2005; Silber et al., 2015; Sharma et al., 2017; Macotela et al., 2019). 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 were reported (Mukhtarov et al., 2010). The 27 days periodicity was linked to the solar rotation cycle, periodicities of the order of 30-120 days were possibly linked to planetary waves, while the origin of the 241-day periodicity as studied 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) as is the case with Fourier Transform. This is where the wavelet analysis is superior to either of these methods as it also shows the evolution of dominant modes in the time-series. So, Macotela et al. (2019) used the wavelet technique to determine the annual oscillation (AO) in daytime VLF amplitudes remains antiphase with respect to the temperature variation of the mesosphere. In addition, Vaishnav et al. (2019) used the wavelet technique in GTEC maps to indicate that VTEC variation is maximum for seasonal timescale followed by 16-32 days period.

This study focuses to investigate the day-to-day oscillations of ionospheric TEC in the daytime and the nighttime period during the solar cycle 24. We also wish to find out the factors that affect such oscillations and their relationships. For this purpose, we transformed the time-series ionospheric TEC data into a time-frequency domain by using the wavelet technique (Kessler et al., 2003; Tangborn et al., 2011; Cohen, 2018). We calculated the Global Wavelet Transform (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 two 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 a later section). 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 can be obtained 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 degrees and the maximum height from the surface of the 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 ASCII files processed in this way are devoid of any TEC bias error. GOPI-software eradicates TEC bias errors by making use of the mathematical expressions as shown 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).

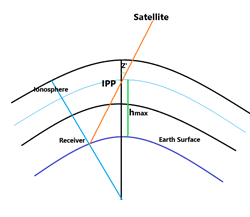
STEC = (1)

STEC = (2)

Where N is the ambiguity number within 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 receivers 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) keeps the archive of the bias errors. The monthly biases values for all satellites and IGS stations can be obtained from their file server at <ftp://ftp.unibe.ch/aiub/> [CODE/](ftp://ftp.unibe.ch/aiub/CODE/).

We have also used the nighttime 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 (<https://omniweb.gsfc.nasa.gov/form/omni_min.html>).

The value of ionospheric TEC is obtained at a resolution of 15 seconds. We took the plateaus of VTEC data in the daytime and the nighttime portion as shown in Figure 2b to be representative of daytime VTEC and nighttime VTEC. The data obtained during 6-8 UT is taken to be the daytime data, while the data from 16 - 20 UT taken as nighttime data to compute the daytime and nighttime daily values of TEC. For all the years during our study period, we have fixed the aforementioned time period as daytime and nighttime data. The computed daytime and nighttime data for the 11 years period from 1st January 2007 to 31st January 2017 have been plotted in Figures 3a and 3b, respectively to show the temporal evolution of the TEC.

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| mapGraph |
| *Figure: 2 (a) The black triangles in the map of Nepal in the left side figure show the location of the TEC stations considered in this study and (b) the right side figure shows sample TEC data of May 2, 2014.* |
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| https://lh3.googleusercontent.com/eeifRdU8j-k60G2YTIaNR9N1Uvf-PIJCRHZdA1IALqtgW9K1qgIiX0doBADJyRPC8xjNkqc3cpUIPaunj4bXXJ8dF0e3geq452neii2G_ifFWhayi04IX62dSWEm8vzGriPp3Ko_  https://lh5.googleusercontent.com/oBkKyMNQrkC0gfbyr5JQRm0uml3ZfpWpck0sff3l_K8T5H5u_iLNE0xS7yJrcbMGHAE39GzehH1Dj8pLLgTrWw7e4O47rjq8PSfJFJ2w9eBG_a7CURZ4p70dcUaJ80gSrCNGuhpS  *Figure 3: (c) Daytime and(d) Nighttime averaged TEC time-series with missing data filled by linear interpolation during2007-2017* |

In order to apply the wavelet technique, we need constant time space between the data. However, no single station had complete data spanning during 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, and LMJG) in Nepal during 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. Since Nepal doesn’t span too much in latitude and longitude and the correlation between the data recorded at stations across Nepal has 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. The time-series for both nighttime and daytime TEC before and after the linear interpolation of the data are shown in Figures 3(a) and 3(b), and in Figures 3(c) and 3(d), respectively.

**2.1 Space Weather Data**

Solar Lyman alpha radiation heavily influences the activities in the ionosphere (Laštovička, 1974). It gives rise to the D-region of the ionosphere during the day, and its absence marks the disappearance of the D-layer in the nighttime (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 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 the 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 a qualitative and quantitative measures of the 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 have 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 the 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 taking a point-wise product with the time series. The shift parameter populates the time axis and the scale parameter corresponds to the frequency axis in the resulting wavelet transform plot.

In addition to, we have used the Morlet function (Morlet et al., 1982) with a specific choice of frequency wo = 6 and 24 suboctaves per octave as the template wavelet(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). The optimal resolution in time and frequency localization is achieved in the case of Morlet wavelet function with the aforementioned values of frequency and suboctave per octave(Grinsted et al., 2004). Errors associated with the wavelet computation are identified with the help of the cone of influence (COI). The edge effects associated with the COI can be discarded. We should have a healthy scepticism about the information in the wavelet transform that lies outside the COI.

Wavelet transform, therefore, is helpful in studying the 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 in the two-time series with common power in the time-frequency domain (Grinstead et al., 2004). We also computed WTC as XWT is not normalized and as such is not to be used for significance testing to determine the inter-relationship between two time-series. 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 daytime and the nighttime as obtained from the Continuous Wavelet Transform (CWT) and Global Wavelet Spectrum (GWS). We then analyze the relationship between the ionospheric TEC and solar parameters by computing the XWT and WTC. The results of the daytime periodicities and reactions with solar parameters are presented in section 3.2, while those of the nighttime is presented in section 3.3

**3.1.1 Periodicities in Ionospheric TEC Data**

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| attachment | https://lh6.googleusercontent.com/U5PqhlQ1ybVXn7hsxpruqFESioDfrRsSIXY4U5Hs7f7JmntYaZFH85uhmRJzdbejl_jsW9fsMlrTDY7OrwBu-L_E1HjQv3oC88DOHV_YRgfqVuytDTmbQt35ULXviwp7Xjw1NAGz |
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*Figure 4: Global wavelet power spectrum (GWS) of the daytime (a) and nighttime (b) TEC. The peaks appearing to the right of the vertical dashed curve in the global wavelet spectrum are within a 95% confidence level. The period values for the significant peaks are shown by the horizontal lines. Closed black curves are the wavelet transform (real part) contours of the daily daytime (c) and nighttime (d) TEC. The light black curve is the COI*.

Figures 4a and 4b (upper panels of figure 4) represent the GWS for the daytime and nighttime normalized to their respective standard deviation. The dashed blue lines in these two figures (4a and 4b) are the 95% confidence levels. Only the peaks crossing these lines are considered significant. The horizontal lines (in orange and green) in Figure 4 indicate the period maxima for each significant peak periods. The period maxima are identified as 356.86 days and 178.44 days in the daytime ionospheric TEC and 356.87 days and 178.44 days in the nighttime 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 daytime, the power of SAO is seen to be almost twice that of the AO. However, during the nighttime, the power of AO is seen to be roughly 5 times that of SAO.

Figures 4c and 4d show the real values of wavelet transform for the daytime and nighttime 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 4c and 4d reveal that daytime periodicity in AO is consistent from 2013-2017. The daytime AO is strongest in the year 2013 to 2015 and weaker thereafter. The nighttime 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 3c and 3d). Daytime TEC is consistent in SAO from 2011 to 2015, while nighttime TEC is consistent in SAO from the middle of 2013 to 2015.

The major periodicity in the nighttime TEC peaks around 356-day in the power spectrum but still includes the 365 day period. The period of variability broadens and also exhibits higher periods during 2013–2016 as seen in Figure 4d. The nighttime SAO peak in the power spectrum is relatively broader in comparison to daytime SAO, nighttime 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 affect are discussed in the following sections by using CWT, XWT and WTC method.

**3.2 Daytime 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 colors indicate the common power of the two wavelet transforms analzsed, ranging from low (blue) to high (yellow). Only the Information derived from the wavelet transform inside the COI is meaningful, as is the case with Figure 4c and 4d. 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 daytime and nighttime TEC seen in Figure 4c and 4d. 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 daytime 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 that 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 are being studied and an upward pointing arrow represents the indicators lagging behind TEC. Figure 7 shows the Wavelet coherence for this CWT, which as we discussed previously gives the normalized strengths between 0 and 1 (indicated by colors). 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. As in Figure 5, COI is represented by the black curve, and regions enclosed by solid black contour are within a confidence of 95%. In addition, when two different time series are related physically, a consistent or slowly varying phase difference is expected.

**Daytime AO and Its Drivers**

In terms of annual oscillation, the daytime TEC from 2009-2011 is most strongly correlated with both the AU and AE indices, which remain consistently in phase. The daytime TEC and AU are moderately correlated during 2011-2015. Daytime TEC remain in phase with RMS Bz in late 2013 and 2014. Further, the daytime 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.

**Daytime SAO and Its Drivers**

In terms of semi-annual oscillations, the Daytime 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 daytime TEC from 2014-2015.

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| https://lh4.googleusercontent.com/xWwis_24CX81bOYYH2hPiTA5jexixeLTj7vU_Vm0fqKkGwbMhawudYl8genPNecPO89_r0ckm8TI3xSC2jUS9HVm80bNWUYCwxWzIqBv21dpjdRR9Hj6hePS5TcQ5j9Wil_IxBaw | *Figure 5: Continuous wavelet transform(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 faded regions are the region outside of the 95% confidence level i.e. outside the Cone of Influence (COI). Blue indicates low and yellow indicates high relative power of oscillation.* |

Among all the parameters taken, only the AU index and AE index showed some level of correlation with the daytime 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 years 2009 and 2010. In the years 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 and Skaumanich, 1983; Pap et al., 1990) is also seen in Figure 7f 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://lh5.googleusercontent.com/BBFRjQ3tiECUPoh8Ju1tU9OaQcn7BuvgKxufJaRKY6hSkdyOpMdqDjz_I0_wLU3jAvmpNIlNvW5G9UyDICU2wC1_-WM4agdO2pZoAvMK_Ds5xDMOEUOUynuh9twioILJi6VpFjDi | *Figure 6: Cross wavelet transform (XWT) for the daytime 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 faded regions are the region outside of the 95% confidence level i.e. outside the Cone of Influence (COI). Colors indicate the relative power of oscillation.* |

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| https://lh5.googleusercontent.com/Tv9UW9IUJiE_wxRwMGGV6JJxEnGtcY6vjxy527MRQXFzABQcy1X0JIpNtTzLHMVCHFOKIzrih6lNasZT4JFlyWvaq3Rx2mxWiiR8wGajAoxfjYUzg8kfP54d3oNS0q2UwFeqXpTu | https://lh5.googleusercontent.com/gECNj3HFy3vhrxB74GkdRp7qgbNhjHkDUSMIFBVouImu4LCqaNjNYYLxojaEKgCfee-rtCUepB8_0k6Kt0yrm3Ogz2KiuUsg_BWO1seWEutM9qBmO6D2YwM_5p-N-HfQypDo6cYk |
| https://lh6.googleusercontent.com/wJnQWvnslFeHGkhUuFmsDh54d8cvt2N8rECLTnSBQpTo9xa8cZkMSl6PPsZ576nydsX3RSKAkt88EejaWXb9Xb3GHtpVqFX1rxvdQBOaoichCnvWkde_S03ErhkxbDgPZIbJm1SE | https://lh5.googleusercontent.com/XqtWW8eL0eGjP30bHWxjLBXrbY_fZgSKiijLNRndDwjxfClHoq09i_qbQx6gso5I8QpWkyS1kHiTNuSSZUCXKvRiSSg1lH0ylN6HVYN4kLFDkpZ2h8zyEAVLTmgYc_0GM09gXXYu |
| https://lh3.googleusercontent.com/cRLWMF0GN1k1FLsbSxzYUA2RdQfLJ4xX1KO2UeZdGb4X9Oe38w0N_WpOR71xaLvDRVh90JDZKHTxcOoGyJkUfV_7zSmLA3e0IyNwCDGl4DOYygG48N4UDWmwHD033T9wu8G3-8jl | https://lh4.googleusercontent.com/dAvF5ws2xgzJQ4Sb7s6PswuEc1ZmMDRT3WbESsVybg9IjJzEou4NgMWm8JyW-tTyesBMiQQVkmZNcDqu3J5xjPgswELC-TEmC0qT03FdY7DeIe91RXZbIU_u9JCH6Plra9I5IKn6 |
| https://lh5.googleusercontent.com/4AMrMAkYP-GapNe75iz3LVQgGEHhVJGB-zNXDb_ms1E6B5oL8nhw6iQa1h8dMRxBhdSusrmH5Ho9GXn8iT_PoYcNOubPzh9yHP1_fTE92HQXF0aN9HSLwfaOM1eaHg209W7KxjAi | *Figure:7 Wavelet coherence (WTC) for the daytime 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 faded regions are the region outside of the 95% confidence level i.e. outside the Cone of Influence (COI). Blue indicates no correlation and yellow indicates a high correlation between the two wavelet transforms. The phase relationship is indicated by the arrows. Right-pointing arrows indicate an in‐phase relation and left-pointing arrows show antiphase relation.* |

**3.3 Nighttime Ionospheric TEC Variability**

Figures 8 and 9 show the XWT and WTC between the CWT of nighttime TEC data (figure 4d) and all the solar parameters used in the study (CWT of which are shown in Figure 5). Similar to that of daytime 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.

**Nighttime AO and its Drivers**

Figure 8 clearly shows that the nighttime TEC is strongly correlated with AE and AU indices similar to the daytime TEC. Likewise, WTC plot in Figure 9 also confirms the in-phase relationship between nighttime TEC and AE index during the years 2009-2014. Similarly, the AU index remains in-phase for a long time before slowly lagging behind the nighttime TEC starting in 2014. The phase relation with the 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 nighttime 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 years 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 the Dst index). F10.7 and Lyman alpha show similar arrow patterns in XWT throughout the solar cycle going from being antiphase to leading the nighttime TEC by 90 degrees. These indices, in the range of AO, lead the nighttime TEC by 90 degrees with the relation being supported by WTC in the years 2014 to 2016. RMS Bz remained in phase with nighttime TEC from roughly 2011 to 2014 when it started to lead the nighttime TEC. However, the phase relation remains significant only during the middle of 2012 in WTC where the normalized coefficient also reached its peak.

**Nighttime SAO and Its Drivers**

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

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| https://lh5.googleusercontent.com/fPcL3DVO3B78oG93tiiKkdaFJlQVc1OxoZLGaCA1bkrWfQfZTwam9FC2usquxpzbcWGblJ7zGLlR_0_r6Qgw-DX_L6__v64Bdz8xHPTMbEjw0SEDH2dFRhM0FEBKzzAe6SRWneAC | https://lh3.googleusercontent.com/YdaseE8L1huwCfIX9WIlzXJK390_BuxGElGNBoIcWqtfRD1feJr9D-bh9PXljCEdqZLxXtpMjPFvGtc5yS8EmL7w77tjLW0V3G5KOTLkkUifd5qEtN74b309JzQVzoCcRzRh7NfS |
| https://lh3.googleusercontent.com/IrPTjT5hzt7-hLj2gAIGlvbACKF8a19twHrqxTRiv2yQ7mWcbhFIk6Tc85Y8eEr46HMrflHEfIlLETSA4uRils8kGyzkww8Vcgc3pQ3dSa2432WGxXXuxFEJyALLXSIktLBCqAZ7 | https://lh6.googleusercontent.com/0fpc3cOWnS7Dx-sEcY_o49VAphUuyFU63JL_SqaKm81vrPJ5e4tzD_mtKP17yHyjpkm9aRjEq_WsbnO1fQAuXJXlja5iCZ0-LUaq6bqGbxtKPltOwj164qZ07OzeeuDKWeGGimnE |
| https://lh3.googleusercontent.com/KnRIPD3jTkJSqZIsVQkqYxzs8YmZJmYq7tCszxo54A0BDQyKR_SOBTfyjIUZPeStgnyEdBvvkjEwxhA8WjviArilnPD3TFl4ilxN_Q4-ZBnG2_HSAOkpjqiQpiDuCxFTa36TgC00 | https://lh6.googleusercontent.com/vtpVbBB1uSgJCjaZBn75uF4LiQmEdCdjBDJaSvA73-zq4hlrypiSN9O_t4MhwYybAyZr8_5vxaRH1OdT1ymrRQT6uQqgfpoGibLAPoGqY1KPjiLi8gSjctG8RBtjXWbn4am4usP1 |
| https://lh4.googleusercontent.com/nIm9oOkaGtGGXCioA_3A1mJwYRuYMV4DkuKwGBNTJKBChTaGcHOCMqnCJb9E8joZhoGY581CUTRo_Gx0fEvTQr_rgpXh9h24ZyPcPxKKJgasiElm0LZ_t7zPT5asSUibAodyaDYu | *Figure 8: Similar to Figure 6 but for the nighttime* |

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| https://lh5.googleusercontent.com/8cu907MxIMUOuOV5H0NV8teOBqs85jK8dSt0GOQQwgKeFfBHVi0zeOMZFB27efVNZFnnUcHEA-aYl-8lnuuwu-0QRIv0Xgo7rAAdrzW9xKqIj4mOP35UpjEKI13QHzNglbNuOIh6 | https://lh5.googleusercontent.com/5BJBy78SQNl3JsPE6OKyjfPYAGlEe6lSP_7ikfCTA9R7Gq2nm7AzTj8FtMxXENXso3ntmp2UmFBqSsy-c1RKR5v-Y0qCxbMJuFpA35HTs3w8QnsIQlYlmdHD0L5HuFEnkLP1Ay0g |
| https://lh5.googleusercontent.com/7gBou7hIVO3lc7DF3zRHe7aIk_EWSL3AZ2W1xxLpS9zqSuGTmKoSyGOjZJ4Ei3j0xpqDajPlsQHyMEUYlfJB8sezc560TbHr8b_eOrM32z9RvkURuQKw64CSje-v0cDW_TIWZsrB | https://lh6.googleusercontent.com/rcAS3rIBspvhTt82ghWdLVXDMTF96M6xXJR-mYt-0Et62yRVgeexD3pBZK_eorKBoHQW2EUYaq6xqTpyTrgFTLHuzmoy9Zq10C1C1A6qUsQ0yNWjU7tMqUhttb-FFxf5OaO0dR6d |
| https://lh6.googleusercontent.com/dOHfWx2Nhqay46UPLQ0JciW2h-jLlBGs5aDCS3QzqzKckGeKf51WvXm9nDq7duS1T47IBn32t5eZAfkZqBFxTCAa-GW-DPo69RKguvMGa2c0Lah2VWjXHoLBsDxnBBux6aY2eM8b | https://lh6.googleusercontent.com/5MuSkLI45W0ZoodnarTErUZ_eaNdrRWsFaqEvGAzBIXkirTZACIMZmGt0m9gTQ3ZAizeoMHZtrU-TQ1Z62OnM9pXIFtSvS3uHzwOZAWV8oTfTAdPloOqIo6poVghggjhy9BSk7Ig |
| https://lh4.googleusercontent.com/C7fFH0blospHoP4YiF-xmhHRIWjDCu69RkqlBOae0wEql61K08eDb8S4zHBgbV7dz6JER0u8zt43X0Nm03cOC1CENkKeFzYG5JAFg83_YCVVsguaFLN8Dk4jbVxCRfkzue3vjdlj | *Figure:-9 Similar to Figure 7 but for the nighttime* |

**4. Discussion**

In this study, we examined the periodicities associated with daytime and nighttime TEC values obtained from GPS stations in Nepal from 2007 to 2017 by using wavelet analysis. The dominant periodicities in the daytime and nighttime 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 was 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 with 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 daytime periodicities was comparatively lower than nighttime, which is expected because the daytime TEC is dominated by the effect of solar illumination which decreases the sensitivity of the ionosphere to other external factors (Guharaya et al., 2009). During the nighttime, however, the sensitivity to other drivers increases in absence of solar illumination. This is in agreement with what was obtained by Macotela et al. (2017).

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

Daytime 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 drivers of nighttime AO 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 an increase in the strength of geomagnetic disturbances which leads to an 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 nighttime and daytime SAO in TEC. Daytime and nighttime SAO relation to geomagnetic activity have been reported by Macotela et al. (2017), which they suggested could be attributed to the semiannual variation in geomagnetic activities in accordance with the Russel-McPherron effect and equinoctial hypothesis (Russel and Mcpherron 1973).

**5. Conclusion**

In this paper, we obtained the annual oscillation (AO) and semi-annual oscillation (SAO) in the daytime and nighttime 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 daytime TEC and AO is the most dominating periodicity in the nighttime TEC.
2. Strength of AO in nighttime is roughly five times higher than that in the daytime. However, the strength of SAO during the daytime is roughly twice that during the nighttime.
3. AE and AU indices are seen to vary in phase and most consistent with both daytime and nighttime AO among all the indices taken in the study.
4. SAO in daytime TEC is consistently antiphase with Dst index.
5. Lyman-alpha shows a 27-day variability during the solar maxima attributable to solar rotation.

The 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.

**Acknowledgements**

This work is partly supported by University Grants commission, Nepal. TEC data are compiled from **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)) and processed by GOPI software and the geomagnetic parameters are derived from Omni website (<https://omniweb.gsfc.nasa.gov/form/dx1.html>) . We would like express our sincere thanks to them.

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