Chapter 9

Ionosphere Variability in Low and Mid-Latitudes of India Using GPS-TEC Estimates from 2002 to 2016

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Additional information is available at the end of the chapter

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Abstract

Continuous Global Positioning System (cGPS) observations spanning 14 years at 24 cGPS sites located in low and mid-latitudes (5–35° N) in the Indian subcontinent are analyzed to extract the ionosphere delay from one-way residuals for each satellite. Absolute integrated electron content (IEC) is the integral of electrons per m^2 along the line of sight between the satellite and receiver. Total electron content (TEC) is determined from IEC using elevation mapping function to normalize the variation of the ray path length through the ionosphere based on the GPS satellite elevation angle. In this study, GPS TEC estimates temporally cover two solar cycles (23 and 24) and spatially cover equatorial ionization anomaly (EIA) region and beyond, thus depicting the ionosphere variability in space, time and geographical location. Results capture different phases of solar cycle, EIA, annual, daily, diurnal and seasonal variability of ionosphere in northern hemisphere. This chapter gives significant insights in to the high and random variability of TEC associated with the changes in solar activity, intensity of the sun radiation, zenith angle at which they impinge the earth's atmosphere, equatorial electrojet (EEJ) and plasma flow.

Keywords: global positioning system (GPS), ionosphere, total electron content (TEC), solar radiation, equatorial ionization anomaly (EIA)

1. Introduction

Ionosphere consists of layers of earth's atmosphere containing free electrons as a result of ionization of the atoms in this region by high energy from sun and cosmic rays. These layers of free electrons surrounding the earth from 60 to 1100 km altitude influence the GPS signal propagation, causing errors in positioning. Total electron content (TEC) is estimated from the dual frequency GPS receiver signals by extracting the phase advances and code delays caused by ionosphere. Precise TEC estimates give significant insights into the variability of ionosphere in space, time, geographical location and solar and cosmic activity. GPS based ionosphere research was initiated globally [1–6] for large scale studies, local earthquakes, mine blasts, and so on. Spatial and temporal variability of ionosphere based on GPS-TEC estimates was studied by several researchers [7–18] using GPS data in different regions of the world giving insights into the response of ionosphere due to the variations in solar activity, geomagnetic storms, and so on. Ionosphere maps for few regions were prepared from the GPS-TEC estimates from a network of stations.

In India, GPS based ionosphere studies were initiated after the establishment of dual frequency GPS stations in 2003 by Indian Space Research Organization and Airport Authority of India as a part of the GAGAN (Geo And GPS Augmented Navigation) program. For the first time in India, spatial and temporal variability [19] of equatorial ionosphere is studied using GPS-TEC estimates for a 16-month period (March 2004–June 2005) with low sunspot activity (LSSA) using 18 GPS station data covering a geomagnetic range of 1° S to 24° N. Using the same GAGAN network GPS data [20], estimates of GPS TEC were compared with the International Reference Ionosphere (IRI) predicted TEC values. They have also investigated diurnal, seasonal and annual variability of ionosphere over Indian subcontinent during the 16-month LSSA period. For a low latitude station Rajkot located near the equatorial ionization anomaly crest region in India [21], ionosphere variability during LSSA period (2005–2007) was investigated to give insights into solar activity dependence and effects of geomagnetic storm on GPS-TEC. Variability of GPS-TEC at a single station Udaipur in Rajasthan for a period of 2005–2010 was studied [22] and the result of seasonal variations are compared with IRI-2007 Model. Similarly diurnal and seasonal variation of GPS-TEC at a single station Agra, for the LSSA period (2006–2009) was studied [23]. GPS-TEC estimates for Surat GPS station [24, 25] were compared with model predictions from IRI-2007 and IRI-2012 and the ionosphere variability was investigated. GPS-TEC derived [26, 27] from a chain of Indian stations for a 1 year period (2011–2012) was used to study the diurnal, seasonal and latitude variability and its relation to geomagnetic storms, solar eclipse, and so on. They gave comparison of GPS-TEC with IRI-2012, Standard Plasmasphere-Ionosphere Model (SPIM) and Global Ionospheric Maps (GIM).

All the above studies so far reported in the Indian subcontinent were for a period of 1–2 years over single and network of GPS stations. For the first time we report the GPS-TEC estimates for a period spanning 14 years (2002–2016) covering solar cycle 23 (1996–2008) and 24 (2008–2019) from a network of about 24 cGPS stations (**Figure 1**; **Table 1**) with geodetic latitude ranging from 5 to 35° N and longitude ranging from 70 to 95° E in Indian subcontinent. New set of cGPS station data is used for the present study compared to majority of earlier ionosphere studies which use GAGAN network data and hence give an independent estimate of ionospheric TEC in this region. The geomagnetic latitude and longitude of these GPS stations (**Table 1**) is 0–26° N and 145–168° E which is very important for the study of ionosphere variability as equatorial region has the high ionosphere activity compared to the rest of the regions in the world. In addition, for the first time TEC estimates are reported for region beyond the EIA region in the Indian subcontinent using cGPS data. Annual, spatial, seasonal, diurnal variability of ionosphere is presented using these TEC estimates and its relation to solar activity, EEJ, EIA is investigated.

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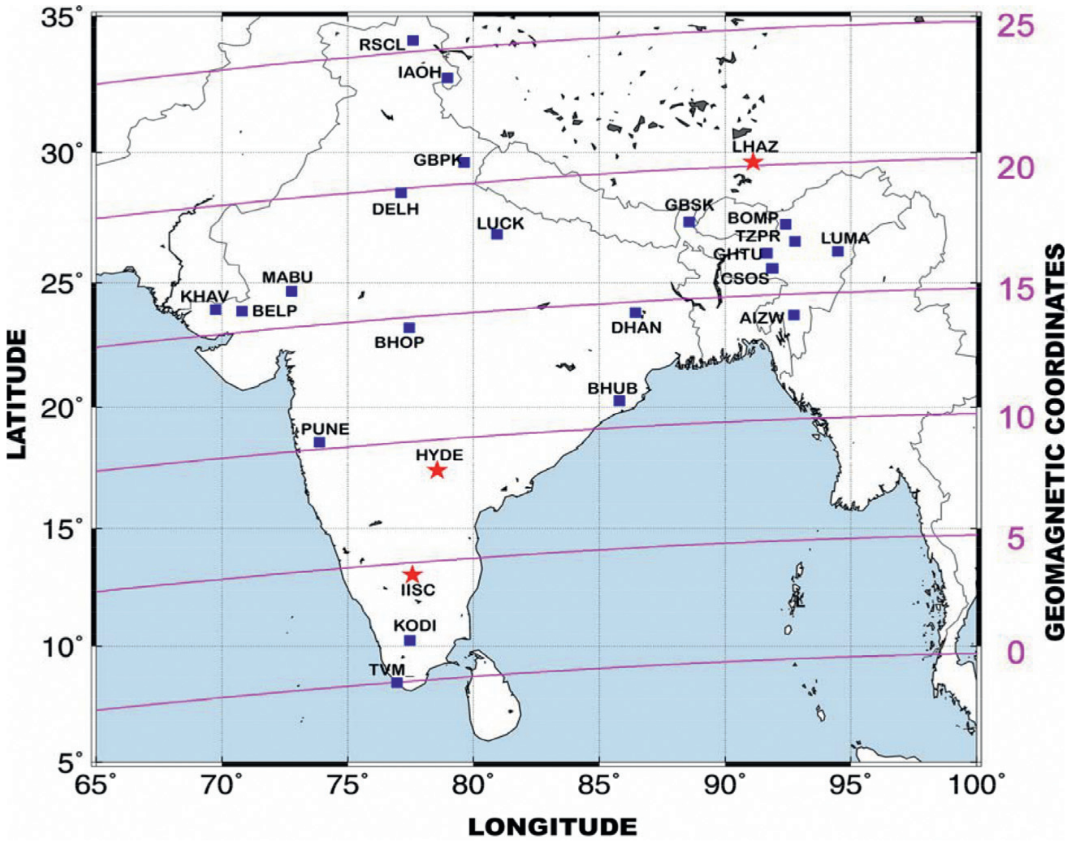

Figure 1. cGPS stations used in the study with geomagnetic latitude lines. Geomagnetic equator (0° N) passes through the bottom tip of Indian subcontinent and northern crest of EIA is located at geomagnetic latitude of 15° N. Red stars are IGS (International GNSS service) sites and blue squares are cGPS sites.

Station	Site code	Data span	Geodetic latitude (° N)	Geodetic longitude (° E)	Geomagnetic latitude (° N)	Geomagnetic longitude (° E)
Trivandrum	TVM_	2002–2005	8.42	76.97	−0.02	149.95
Kodaikanal	KODI	2002–2015	10.23	77.47	1.73	150.59
Bengaluru	IISC	2002–2015	13.02	77.57	4.49	150.93
Hyderabad	HYDE	2002–2015	17.42	78.55	8.76	152.24
Pune	PUNE	2002–2005	18.56	73.88	10.29	147.85
Bhubaneswar	BHUB	2002–2012	20.26	85.79	11.09	159.39
Aizwal	AIZW	2003–2006	23.72	92.73	14.18	166.17
Dhanbad	DHAN	2004–2005	23.82	86.44	14.58	160.24
Bhopal	BHOP	2004–2005	23.21	77.45	14.59	151.68
Bela Temple	BELP	2010–2011	23.87	70.80	15.84	145.46
Khavda	KHAV	2010–2011	23.92	69.77	15.98	144.48
Shillong	CSOS	2002–2008	25.57	91.86	16.05	165.43
Mount Abu	MABU	2010–2011	24.65	72.78	16.42	147.41
Lumami	LUMA	2003–2015	26.22	94.48	16.60	167.92

Station	Site code	Data span	Geodetic latitude (° N)	Geodetic longitude (° E)	Geomagnetic latitude (° N)	Geomagnetic longitude (° E)
Guwahati	GHTU	2003–2012	26.15	91.66	16.64	165.28
Tezpur	TZPR	2002–2013	26.62	92.78	17.06	166.35
Bomdilla	BOMP	2004–2013	27.27	92.41	17.72	166.04
Lucknow	LUCK	2002–2005	26.89	80.94	17.98	155.29
Panthang	GBSK	2003–2014	27.37	88.57	17.99	162.45
Delhi	DELH	2003–2005	28.48	77.13	19.85	151.87
Lhasa	LHAZ	2002–2015	29.66	91.10	20.15	164.94
Almora	GBPK	2002–2014	29.64	79.62	20.81	154.30
Hanle	IAOH	2002–2015	32.78	78.97	23.97	153.99
Leh	RSCL	2002–2012	34.13	77.60	25.42	152.91

Table 1. Details of cGPS stations used in the present study.

2. Data and methods

cGPS data, during 2002–2016, of about 24 cGPS stations (**Table 1**; **Figure 1**) located in the Indian subcontinent with data span ranging from 2 to 13 years with sampling interval of 30 s has been used. The dataset span is more than any previous study till date and spatially covers the length and breadth of the Indian subcontinent. Details of the cGPS sites and the data used are listed in **Table 1** and the data is analyzed using GAMIT software [28]. Data sampling interval of 30 s and elevation cut-off angle of 20° is used for the analysis. The quality check of GPS data at each station was done using TEQC software [29] to remove data with several cycle slips, multipath and span of less than 18 h. The daily data of all the stations after quality check is analyzed using GAMIT to extract the ionospheric delays suffered by GPS signals in L-band with frequency f_1 (1.57542GHz) and f_2 (1.2276GHz) from the one-way residuals of each satellite at 30 s interval. These one-way residuals for each satellite are output after cleaning the observables for cycle slips, multipath, outliers during the analysis. The *IEC* along the line of sight (LOS) between the satellite and receiver are calculated from the carrier phase delays L_1 and L_2 and the group delays P_1 and P_2 (code pseudo-ranges) in range units obtained from GAMIT analysis as detailed earlier. The absolute *IEC* [30] is given by

$$IEC = \frac{\lambda_2}{A} \frac{\left(f_1^2 f_2^2\right)}{\left(f_1^2 - f_2^2\right)} (B - L_G) \tag{1}$$

where, ambiguity constant B is given by

$$B = \frac{1}{n} \sum_{i=1}^{n} (P_{Gi} - L_{Gi}) \tag{2}$$

$$L_G = \frac{(L_1 - L_2)}{\lambda_2} \tag{3}$$

$$P_G = \frac{(P_2 - P_1)}{\lambda_2} \tag{4}$$

where, n is number of phase measurements in a given arc [1]. L_G and P_G are linear combinations as given above whereas L_G is precise and smooth with unknown phase ambiguity constant and P_G is noisy and less precise and not ambiguous [2, 31]. To estimate the absolute and precise estimate of *IEC*, we fit L_G on P_G using ambiguity constant B. λ_1 and λ_2 are the wavelengths of the L-band GPS signals. *IEC* is given in TEC units where 1 TECU = 10^{16} electrons/m^2. To calculate vertical equivalent TEC along the satellite receiver path, elevation mapping function ($emf\theta$) is used to account for the variation in the ray path length (L_θ) based on GPS satellite elevation angle θ varies with the orbital pass of each satellite as given below:

$$emf\theta = \frac{H_{ion}}{L_\theta}. \tag{5}$$

$$L_\theta = \sqrt[2]{(R + H_t)^2 - R^2 \cos^2(\theta)} - \sqrt[2]{(R + H_b)^2 - R^2 \cos^2(\theta)} \tag{6}$$

where, H_{ion} is the mean ionosphere thickness, R is earth's radius and H_t and H_b are the top and bottom altitudes of the ionosphere layer. Vertical equivalent TEC along the satellite receiver path in TEC units is given by

$$\mathrm{TEC} = IEC \times emf\theta \tag{7}$$

TEC is computed at 30 s interval during the orbital pass of the each satellite at the each GPS station for all the 24 cGPS stations during 2002–2016. Two-sigma iterated average of TEC at 30 s interval is computed from the TEC of all the visible satellites at that epoch. GPS-TEC thus estimated is used to discuss the ionosphere variability over Indian subcontinent.

3. Ionosphere variability

Ionosphere is highly variable in space (geographical location) and time (solar cycle, seasonal, diurnal) and with solar-related ionospheric disturbances and earthquakes. About 15 cGPS sites are located in the equatorial ionization anomaly (EIA) region from geomagnetic equator to northern crest of EIA region (17° N) where the low latitude ionosphere exhibits annual, spatial, seasonal and diurnal variability. Nine cGPS sites are located in mid-latitude region beyond the EIA region in northern India and Himalaya. Using the GPS-TEC estimates, variability of ionosphere is discussed in the subsequent sections.

3.1. Inter-annual

There are about 12 sites with data span covering the two solar cycles. Daily mean value of GPS-TEC is plotted for these stations from 2002 to 2016 in **Figure 2** to study the annual variability of ionosphere over the 14-year period. The last solar cycle 23 lasted for 12.3 years starting in August 1996 and ending in December 2008 with peak solar activity between 2001 and 2005 at low- and mid-latitude regions. The current solar cycle 24 began on January 4, 2008 with minimal solar activity till early 2010 and had two peaks in 2011 and early 2014. TEC at almost all the stations indicate the peak (2002–2005) and descending phase (2005–2008) of solar cycle 23. This is followed by low values of TEC during 2008–2010 consistent with minimum solar activity of current solar cycle 24 and high values of TEC during 2011 to 2014 consistent with peak solar activity. The TEC variation is higher for the sites (KODI, IISC, HYDE, BHUB, CSOS) which are located in the EIA region with a peak TEC value of 100–120 TECU in 2002 and 60–80 TECU in 2003. For the rest of the sites (GBPK, IAOH, RSCL, GBSK, BOMP, TZPR, LHAZ) located beyond the EIA region, the TEC variability is low and depends upon the geographic location of these sites which is discussed in detail in the subsequent sections. Daily mean value of TEC plotted in **Figure 2** indicates significant semi-annual and annual cycles. Sensitivity of TEC to solar activity is stronger at low latitudes when compared to mid-latitudes in the northern hemisphere.

3.2. Spatial variability

For the Indian subcontinent, geomagnetic equator passes through the southern bottom tip and the northern crest of EIA (15° N geomagnetic latitude) lies in the middle (**Figure 1**) providing a unique opportunity for studying the ionosphere variability. Since we have several stations and a larger spread of data, we give detailed in-depth study of spatial variation of ionosphere from 5 to 35° N latitude (0–26° N geomagnetic latitude) and 70 to 95° E longitude. Also since the data covers different phases of two solar cycles, the results are given separately for each solar cycle.

3.2.1. Solar cycle 23

TEC variability for all the available days of December 2004, March, June, September and December 2005 representing the solstice, equinox, summer and winter seasons are plotted in **Figures 3–5** for cGPS stations with geomagnetic latitude of 0–10° N, 10–17° N, >17° N to study the spatial, diurnal and seasonal variability in EIA region, northern crest of EIA and beyond. To study in detail the variability along the latitude, 10 sites were chosen with approximately same longitude (TVM_, KODI, IISC, HYDE, BHOP, DELH, GBPK, IAOH, RSCL) starting from geomagnetic equator covering the EIA region and beyond for the descending phase of solar cycle 23 from December 2004 to 2005. The peak value of diurnal TEC increases with latitude from geomagnetic equator (Trivandrum, 50 TECU) to Northern crest of EIA region (Bhopal, 80 TECU) and then decreases gradually from Delhi (50 TECU) to Leh (40 TECU) station located beyond the EIA region. Moreover, the maximum value of diurnal TEC (**Figure 3**) is for a longer duration for the stations (TVM_, KODI, IISC, HYDE) close to the geomagnetic equator when compared to the

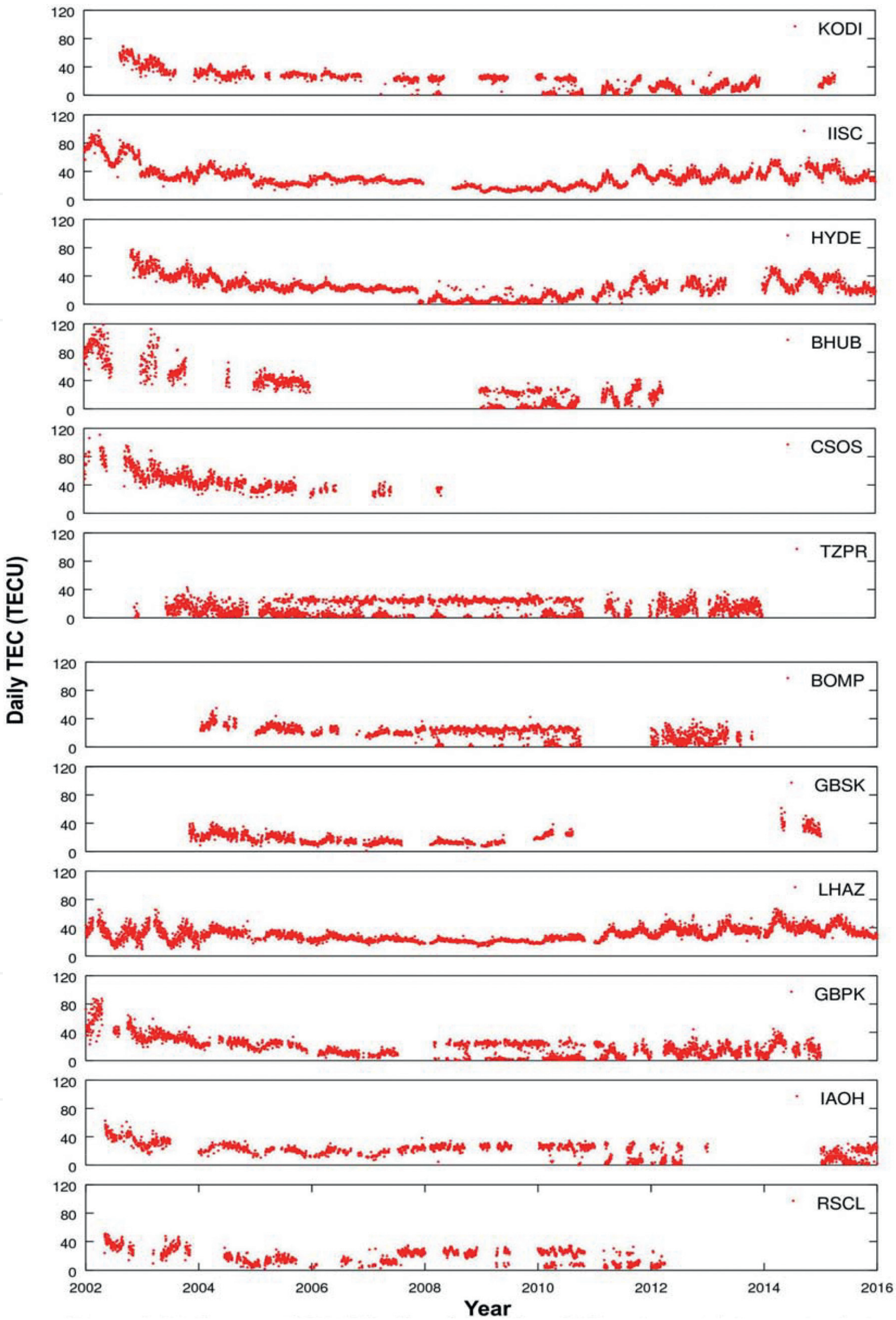

Figure 2. Daily mean GPS TEC values for 12 cGPS stations with increasing latitude.

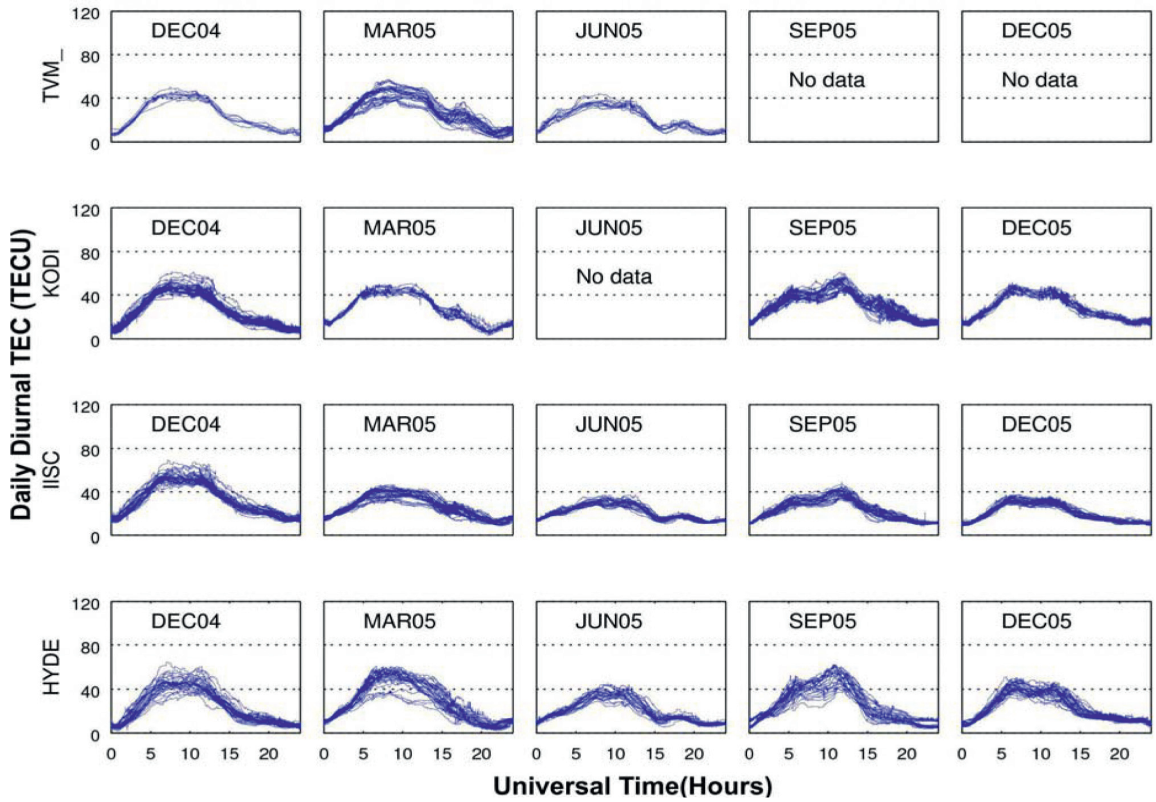

Figure 3. Daily diurnal GPS TEC during solar cycle 23 (2004–2005) for cGPS stations located between 0 and 10° N geomagnetic latitude.

stations located in crest of EIA region and beyond (**Figures 4** and **5**) which have more pronounced diurnal peaks. Conversely, the diurnal minima have longer duration and broad spread for the stations located in crest of EIA region and beyond as compared to the stations located close to geomagnetic equator. Day-to-day variability of diurnal TEC is more pronounced for the stations located in EIA region (**Figure 4**) when compared to the rest of the stations.

Pune and Bhubaneswar, Bhopal and Aizwal stations with 12 and 15^{o} E longitude difference located in the northern crest of EIA region do not indicate any consistent variability related to longitude. Beyond EIA region DELH and BOMP, GBPK and LHAZ with 12 and 15^{o} E longitude difference also do not show any significant longitude related variability during this period.

3.2.2. Solar cycle 24

The current solar cycle started in January 2008 and had minimum solar activity between the year 2008 and early 2010 followed by ascending solar activity. GPS TEC for March, June, September and December for 3 years (2009, 2010, 2011) for all available station data are plotted in **Figures 6–8** to study the spatial and temporal variability of the ionosphere during the low and ascending phase of current solar cycle. During the minimum solar activity year of 2009 stations (**Figure 6**)with increasing latitude (IISC, GHTU, GBSK, LHAZ) indicate marginal increase of TEC value (35–40 TECU) in EIA region from IISC to GHTU and marginal decrease beyond EIA region (GBSK, LHAZ). In 2010 (**Figure 7**), TEC value gradually increases from 40

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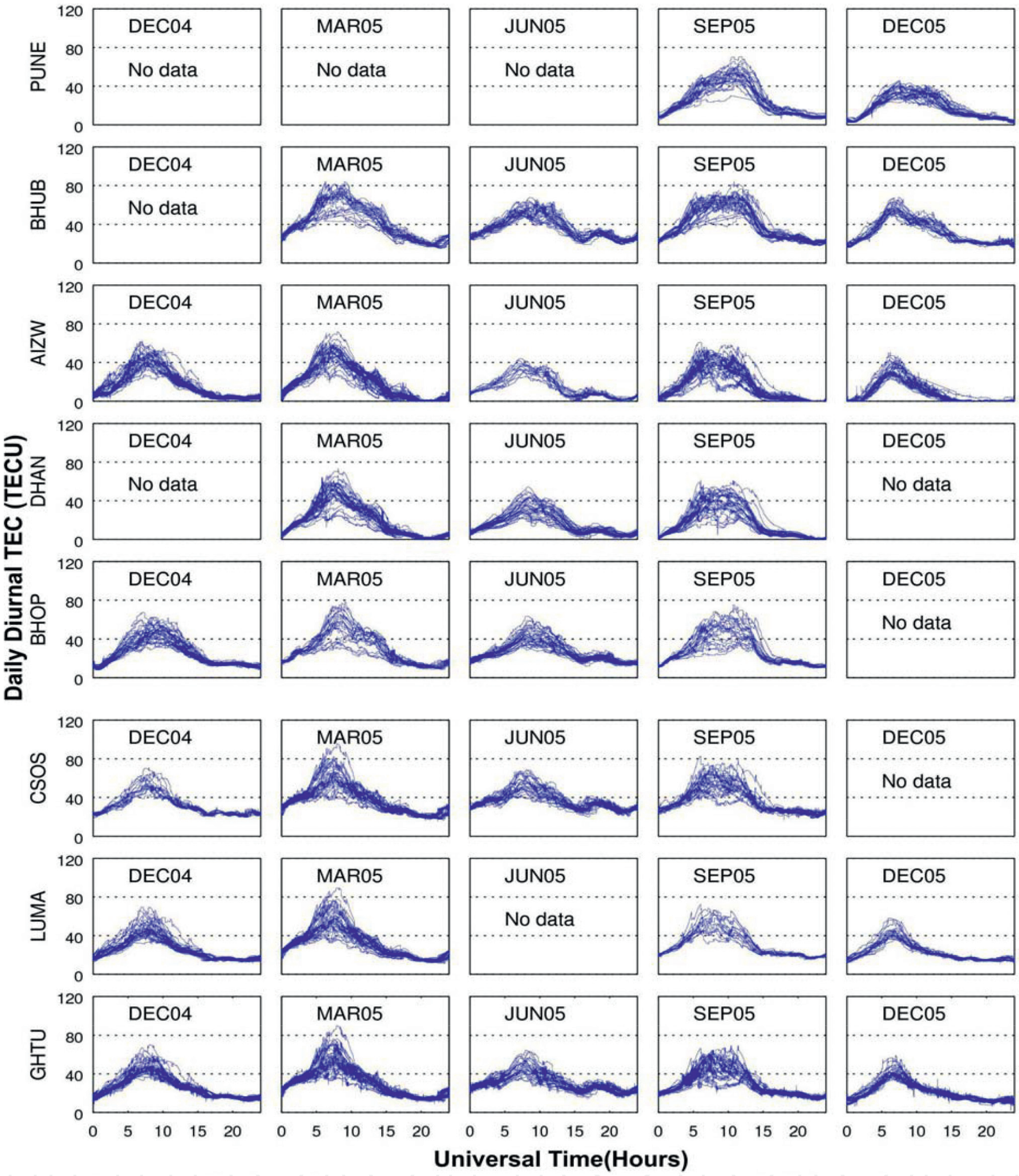

Figure 4. Daily diurnal GPS TEC during solar cycle 23 (2004–2005) for cGPS stations located between 10 and 17° N geomagnetic latitude.

to 60 TECU with increase in latitude in EIA region and marginal decrease beyond EIA region. In 2011 (**Figure 8**), peak TEC values ranging from 40 to 80 TECU are observed at IISC and the rest of the stations located in EIA with no consistent variation with latitude. Day-to-day variability of TEC is more pronounced in the EIA region during 2010 and 2011 when compared to 2009. Diurnal peak TEC value is for longer duration at Bengaluru and Hyderabad whereas pronounced peaks are observed in EIA region and beyond. Diurnal minima are for longer duration for the stations located in EIA region and beyond. Spatial variability of ionosphere between

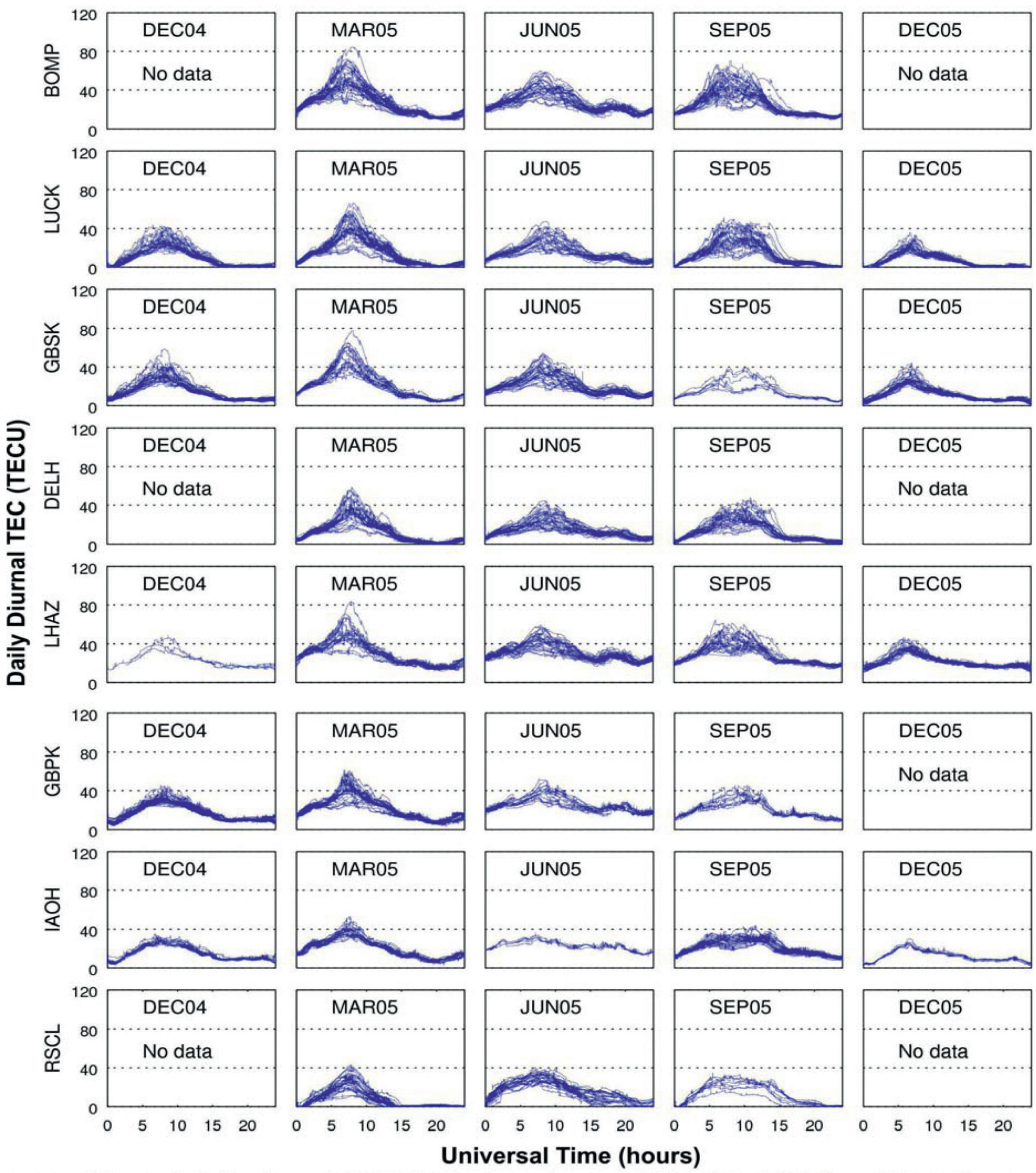

Figure 5. Daily diurnal GPS TEC during solar cycle 23 (2004–2005) for cGPS stations above 17° N geomagnetic latitude.

geomagnetic latitude of 0–17° N is not very pronounced during the current solar cycle when compared to the duration of diurnal peak and minimum TEC values.

During the ascending solar activity period of 2011, diurnal peak TEC values of 60 TECU are observed at KHAV, MABU and BELP stations (about 70° E longitude) when compared to diurnal peak TEC values of 80 TECU observed at GHTU and LUMA stations (90° E longitude). Distinct peaks are observed with increasing longitude. This indicates that during ascending phase of solar cycle the ionosphere increases with longitude difference of 19–25° E in the EIA region.

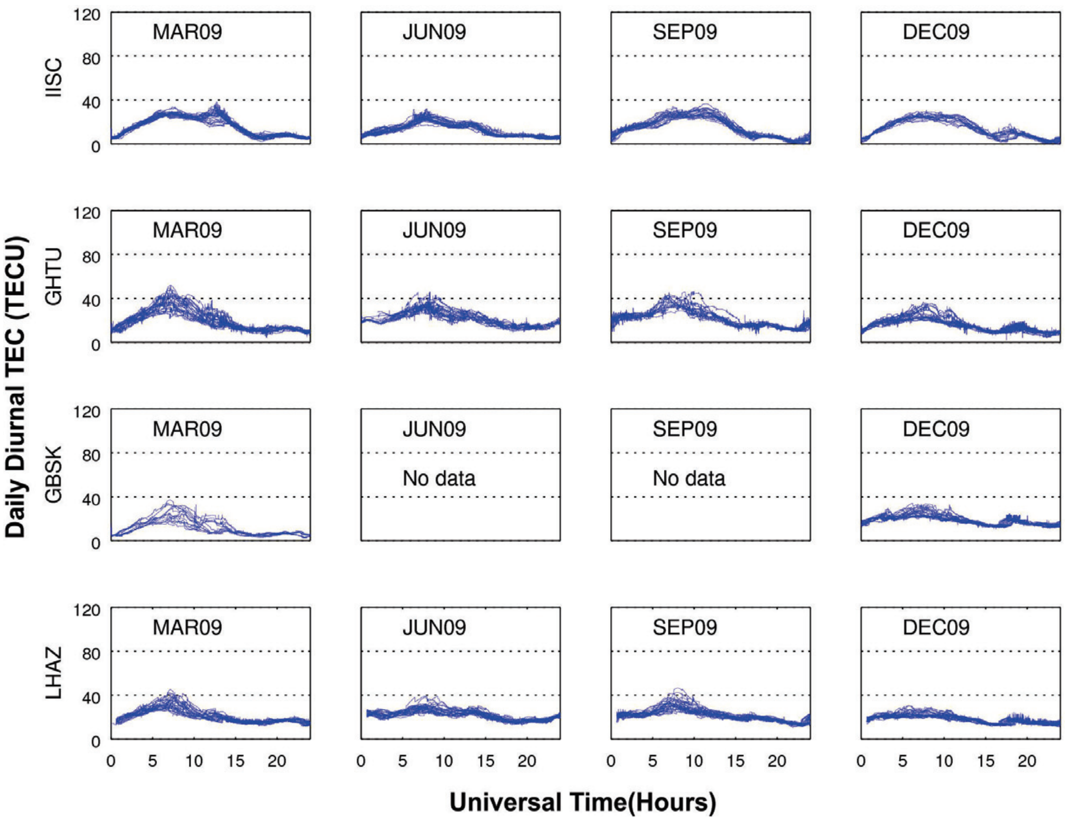

Figure 6. Daily diurnal GPS TEC during solar cycle 24 for cGPS stations with increasing latitude during minimum solar activity year 2009.

3.3. Diurnal variability

Diurnal variability of TEC depends on the Sun's orbit, changes in solar activity and intensity of radiance, earth's magnetic field and dynamics of neutral winds (diffusion of transported electrons from the equator). Plasma flow associated with the EIA effects the day-to-day variability of diurnal TEC for the stations located in EIA region. Geomagnetic and seismo-ionosphere disturbances also effect the day-to-day variability of diurnal TEC. Results of diurnal variability for two solar cycles is given below.

3.3.1. Solar cycle 23

Diurnal variability of TEC at all the stations in **Figures 3–5** shows the minima during the night hours between 17 and 24 h UT and increasing TEC from 0 h UT to peak at midday between 8 and 11 h UT. The highest peak value of diurnal TEC (80 TECU) is observed at stations (BHOP, BHUB, CSOS, LUMA, GHTU) located in northern crest of EIA region and the lowest peak (20 TECU) is recorded at RSCL and IAOH located in Ladakh Himalaya beyond the EIA region. Moreover, the maximum value of diurnal TEC has longer duration (5–12 h UT) for the stations (TVM_, KODI, IISC, HYDE) close to geomagnetic equator when compared to the stations located in EIA region and beyond which have more pronounced diurnal peaks. Conversely, the diurnal minima have longer duration (15–24 h UT) and broad spread for the stations

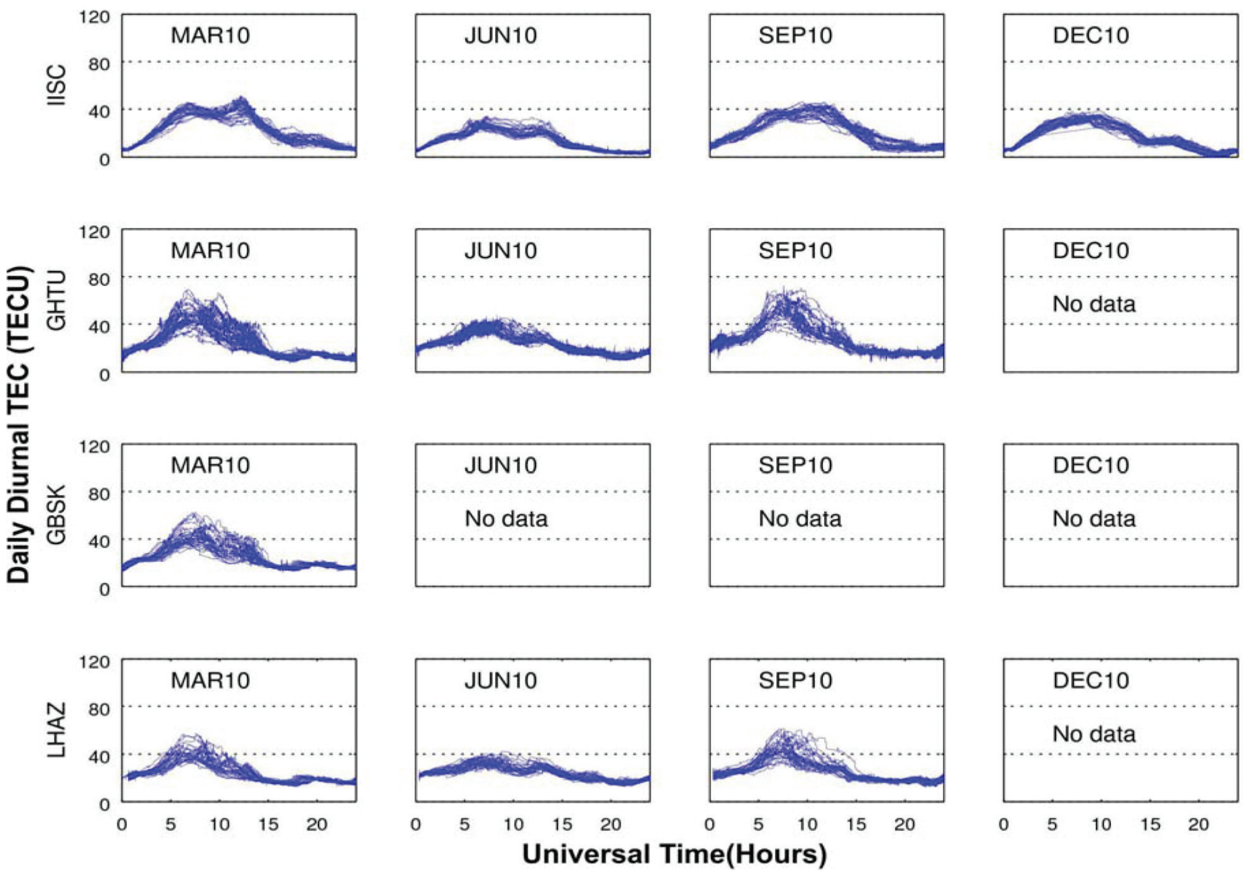

Figure 7. Daily diurnal GPS TEC during solar cycle 24 for cGPS stations with increasing latitude during low solar activity year 2010.

located in EIA region and beyond as compared to the stations located close to the geomagnetic equator. Day-to-day variability of diurnal TEC is more pronounced for the stations located in EIA region when compared to the rest of the stations.

Seasonal variability of diurnal TEC is clearly depicted in **Figures 3–5** with low TEC values during summer solstice (June) and high values for winter solstice and equinoxes for all the stations from geomagnetic equator to the northern crest EIA region. Beyond the EIA region, higher values of diurnal TEC with pronounced peaks were observed during the equinox month of March and lower TEC values during equinox month of September. For Trivandrum located on the geomagnetic equator, diurnal TEC values are the highest for March equinox whereas for Kodaikanal and Bengaluru the higher values of TEC are observed for December 2004 in winter. The lowest TEC was observed at Bengaluru during the solstice month of June. For the rest of the stations located in EIA region, the highest TEC value was observed during March and September equinox. Maximum spread of day-to-day variability of diurnal TEC is observed in the EIA region during the equinox months of March and September. Higher TEC values during December 2004 is due to the increase of electrons in winter caused by the transport of neutral constituents from summer to the winter hemisphere. This in turn increases the anomaly crest development in the winter. In addition, this may be also due to the seismo-ionospheric disturbance caused by Mw of 9.2, 26 December 2004 Sumatra earthquake [32] which affected the cGPS stations in southern India.

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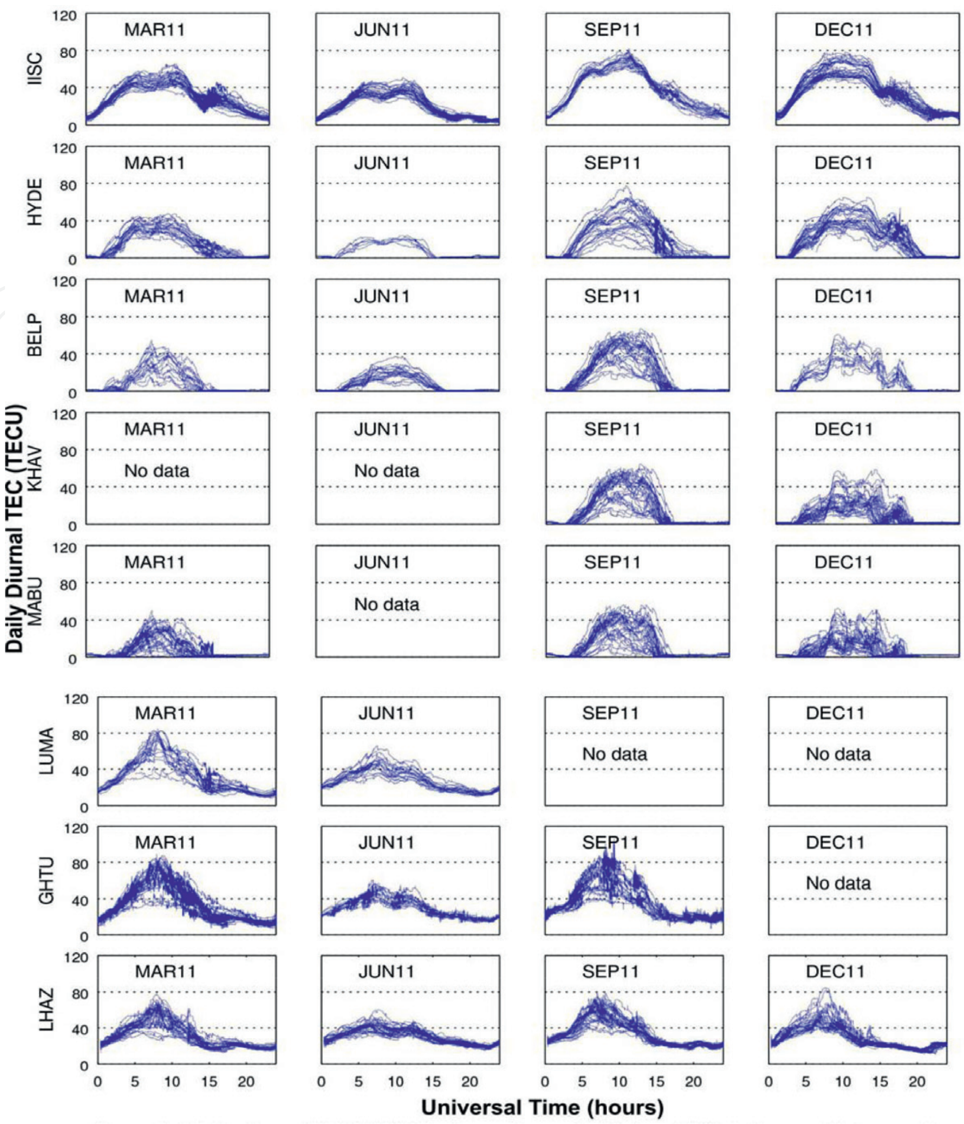

Figure 8. Daily diurnal GPS TEC during solar cycle 24 for cGPS stations with increasing latitude during ascending solar activity year 2011.

3.3.2. Solar cycle 24

Diurnal peak TEC values from 2009 to 2011 (**Figures 6–8**) increase with the increase in the solar activity from a minimum peak value of 30–40 TECU during 2009; 30–60 TECU in 2010; 40–80 TECU during 2011. Diurnal peak values occur for a long duration of 7–13 h UT for IISC located in the trough of EIA whereas for station located in the crest of EIA region pronounced diurnal peaks are observed between 7 and 10 h UT. Diurnal peak values are marginally higher for stations located in the crest of EIA regions. Diurnal minima for IISC occur during 20–24 h UT and for stations located in the crest of EIA region diurnal minima occur during 15–24 h UT. Gujarat stations (KHAV, BELP, MABU) recorded anomalous daily diurnal variation with very high day-to-day variability. For these three stations, diurnal peaks are not very distinct and the diurnal minima suddenly drops in the night hours and remains constant (15–24 and 0–2 h UT). Diurnal peak values are the highest with the maximum spread during equinox months of March and September for stations located in the northern crest (17° N geomagnetic latitude)

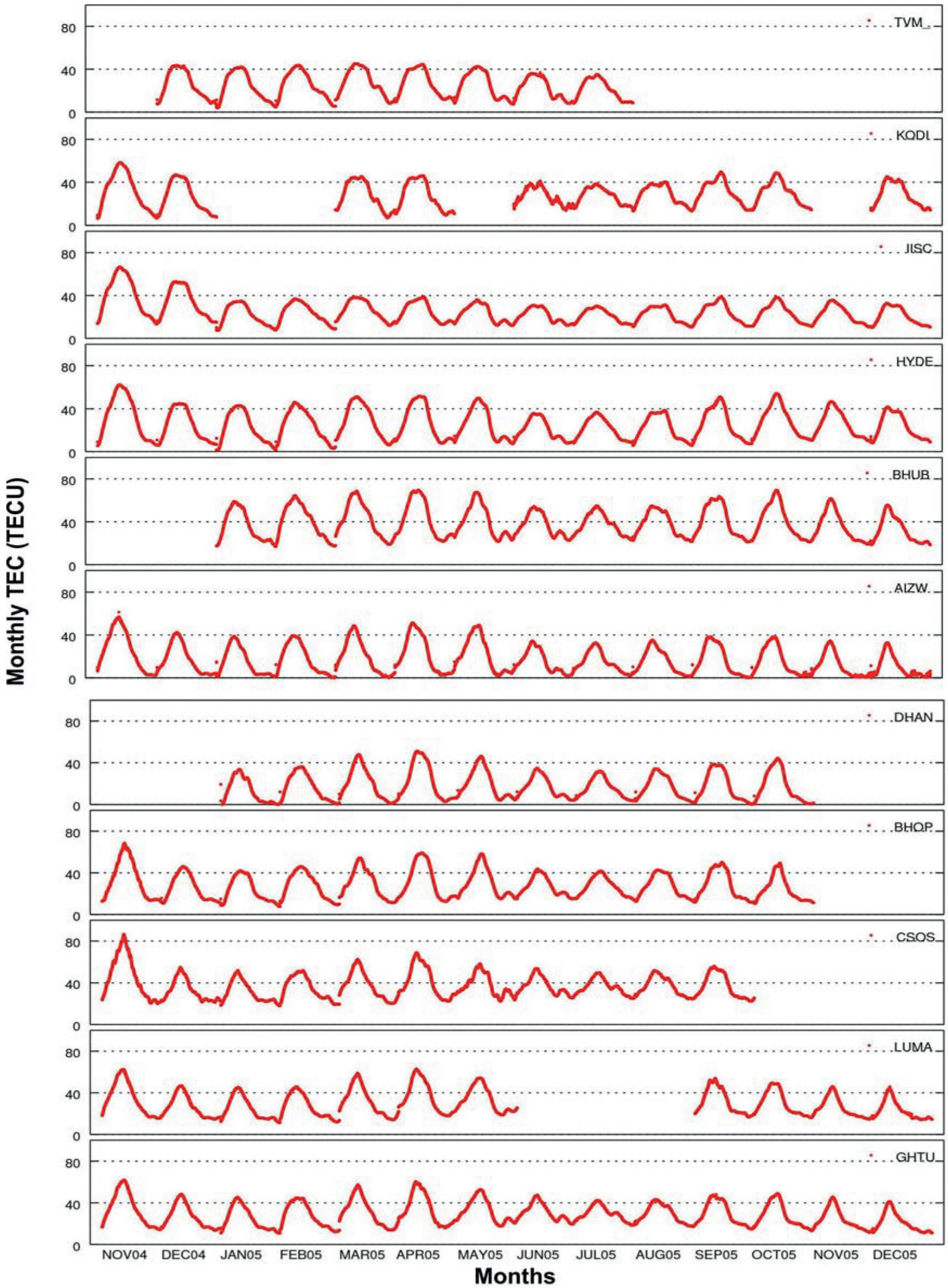

Figure 9. Monthly mean diurnal GPS TEC with increasing latitude for cGPS stations between 0 and 17° N geomagnetic latitude during solar cycle 23 from November 2004 to December 2005.

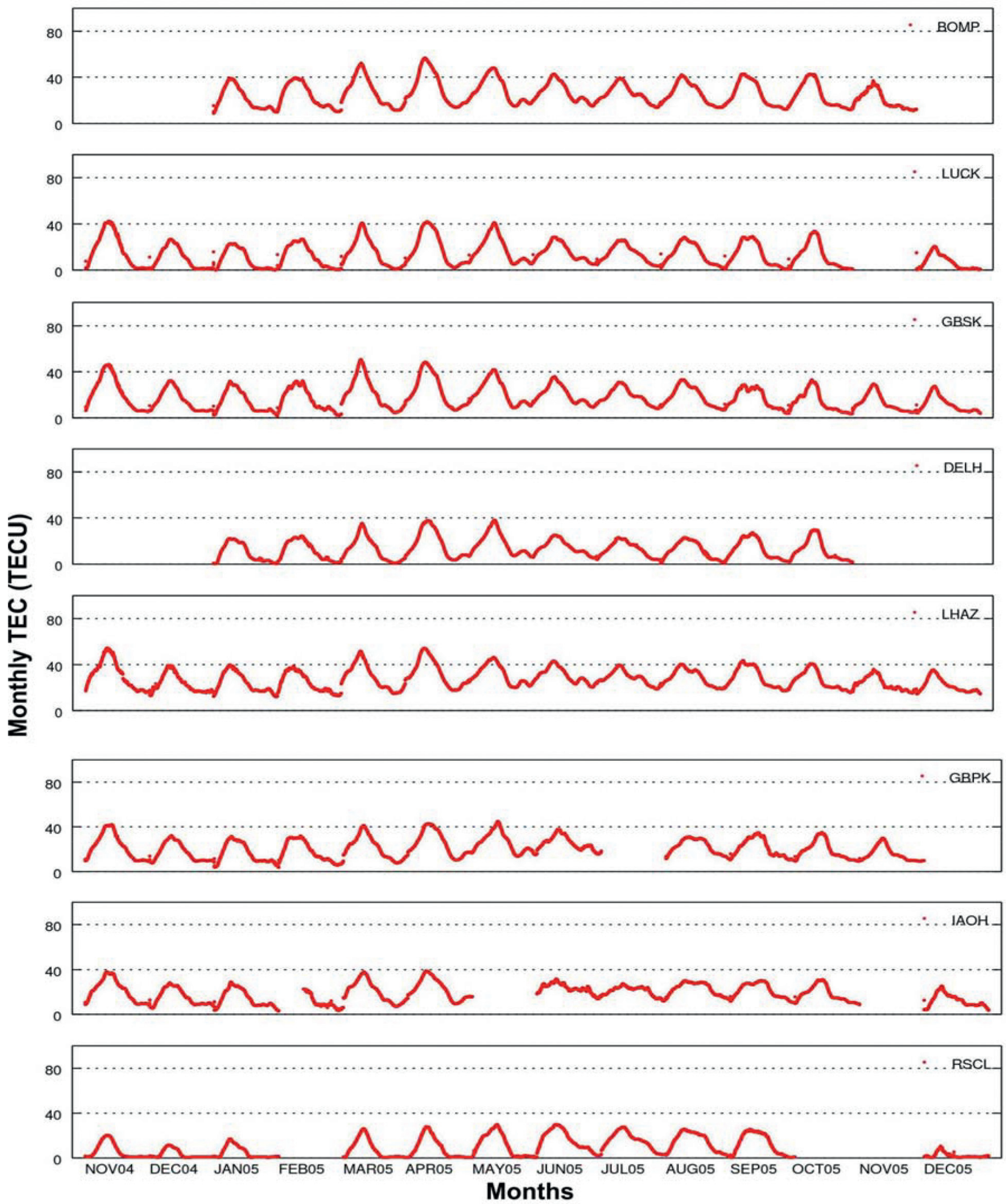

Figure 10. Monthly mean diurnal GPS TEC with increasing latitude for cGPS stations above 17° N geomagnetic latitude during solar cycle 23 from November 2004 to December 2005.

of EIA region. For Bengaluru and Hyderabad (5–9° N geomagnetic latitude) station high diurnal peak values are observed during equinox month of September and solstice month of December. Daily diurnal TEC values at LHAZ and GHTU stations (**Figure 8**) indicate very

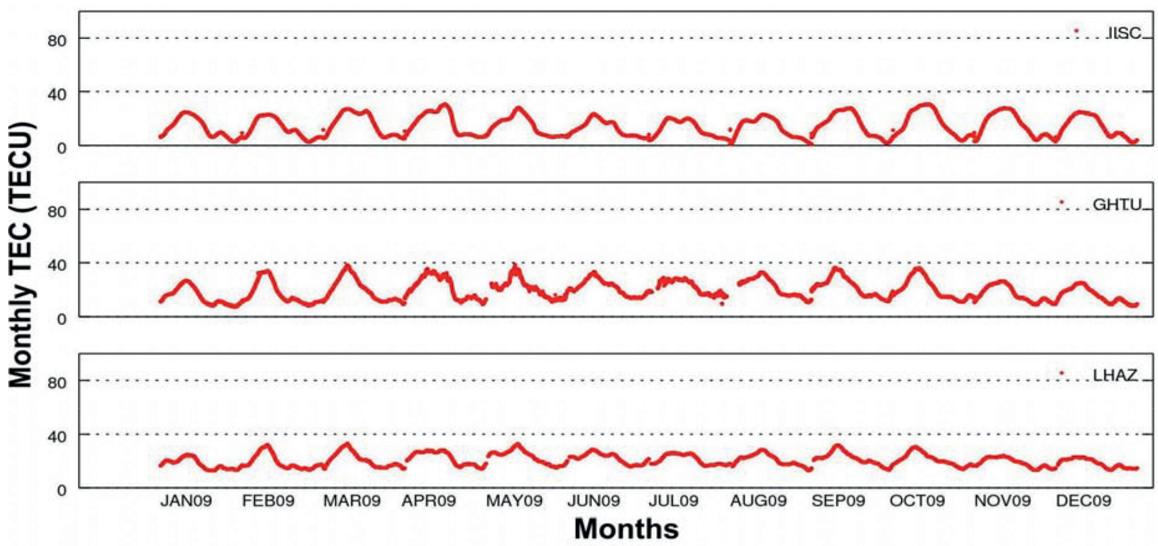

Figure 11. Monthly mean diurnal GPS TEC for cGPS stations with increasing latitude during solar cycle 24 for minimum solar activity year 2009.

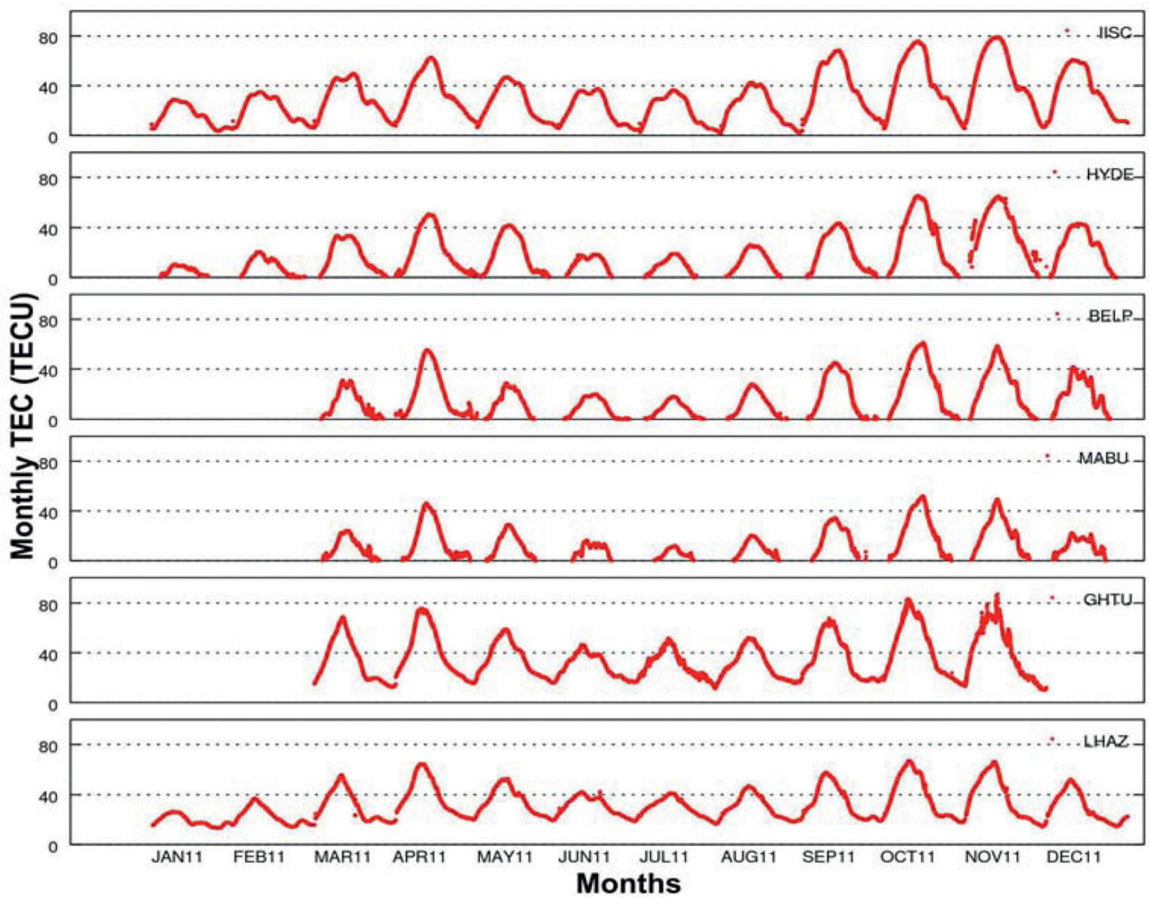

Figure 12. Monthly mean diurnal GPS TEC for cGPS stations with increasing latitude during solar cycle 24 for ascending solar activity year 2011.

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high and random variability related to seismo-ionospheric disturbance due to Mw 6.9, 18 September 2011 Sikkim earthquake. It can be observed that the diurnal variability depends on the solar activity, solar radiance, geomagnetic field, latitude, longitude and plasma flow related to EIA effects.

4. Monthly and seasonal variability

4.1. Solar cycle 23

Monthly diurnal mean values of TEC are plotted from November 2004 to December 2005 for all the stations between geomagnetic equator and northern crest of EIA (0–17° N geomagnetic latitude) in **Figure 9** and beyond EIA region in **Figure 10**. The highest peak TEC values for all the sites in EIA region distinctly occur in November 2004 with a value of about 86 TECU for CSOS, 70 TECU for Bhopal to about 58 TECU for Kodaikanal. The lowest peak TEC values occur during the months of June, July, August for these sites with about 50 TECU at CSOS, 43 TECU for Bhopal to 35 TECU for Bengaluru. The highest peak TEC value during winter solstice and the lowest peak TEC value during summer solstice are due to seasonal anomaly prevalent in winter hemisphere due to increase in electrons caused by meridional neutral winds. For the sites beyond the EIA region (**Figure 10**), the highest peak TEC values (35–50 TECU) occur in the summer equinox months (March, April, May) and winter solstice month of November 2004 and the lowest peak TEC values (20–30 TECU) occur in January.

4.2. Solar cycle 24

Monthly diurnal mean TEC values are plotted from January to December for low solar activity period of 2009 (**Figure 11**) and ascending solar activity period of 2011 (**Figure 12**). Monthly and seasonal cycle is not very pronounced during the low solar activity period of 2009 with marginally higher peak values recorded during October for IISC (35 TECU) and March for GHTU (40 TECU) and lower peaks during January (20–30 TECU) in the EIA region. For the ascending solar activity period of 2011, the monthly and seasonal variation is distinct with the highest (80 TECU) in EIA region during October and November and the lowest during January (20–30 TECU) consistent with the winter anomaly observed in the northern hemisphere.

5. Summary

For the first time an in-depth study of ionosphere variability in low and mid-latitude region using TEC estimates from 24 cGPS stations for a 14-year (2002–2016) period is carried out. The cGPS data covers peak (2002–2004), descending phase (2005–2008) of solar cycle 23 and minimum (2008–2010), ascending phase (2011–2016) of current solar cycle 24.

Inter-annual variability of GPS-TEC depicts the peak, descending phase of solar cycle 23 and minimum, ascending phase of solar cycle 24. Maximum TEC values are observed during 2002–2004 and minimum TEC values are observed during 2008–2010. GPS TEC indicates a distinct daily, monthly, semi-annual and annual cycle. Sensitivity of TEC to solar activity is prominent in EIA region compared to mid-latitudes in northern hemisphere. TEC values recorded are consistent with large-scale electrodynamics associated with the equatorial electrojet (EEJ), plasma fountain, equatorial ionization anomaly (EIA), equatorial wind and temperature anomaly, which affect the ionosphere variability at equatorial and low latitude regions. The high variability of equatorial and low latitude ionosphere are due to the perfect horizontal alignment of the geomagnetic field lines at the dip equator and the shifting between the geographic and geomagnetic equator.

GPS-TEC values increase from geomagnetic equator to the crest of EIA region (17° N geomagnetic latitude) after which they gradually decrease toward mid-latitudes in the northern hemisphere. Latitude variability of ionosphere is more pronounced during the high solar activity years (2002–2004) when compared to low solar activity years (2008–2010). Diurnal peak TEC value has longer duration between 0 and 9° N geomagnetic latitude. Diurnal maxima have pronounced peaks and diurnal minima is observed for longer duration in the northern crest of EIA region and beyond. Ionosphere variability with longitude is observed for longitude difference of 19° E and above during the ascending phase of current solar cycle 24. Normally, solar radiation strikes the atmosphere more obliquely with increasing latitude decreasing its intensity and production of free electrons, whereas near the geomagnetic equator its strikes horizontally with eastward electric field during day and westward during night. This causes plasma diffusion along magnetic field lines at approximately ±15° geomagnetic latitudes forming crests on both the hemispheres (EIA region). Hence, TEC increases gradually from geomagnetic equator to the EIA crest, beyond which it decreases toward the mid-latitude regions. Intensity of EIA and its latitude of crest development vary with the strength of EEJ, season and solar activity. Our study indicates that the northern crest of EIA region extends up to about 17–18° N geomagnetic latitude in Indian region.

Diurnal variability of ionosphere depends on the intensity of solar activity, season and strength of geomagnetic field with high TEC values recorded in 2004 and 2011 and low values in 2009. Day-to-day variability is more pronounced for the high solar activity years when compared to low solar activity years. Maxima occurs during midday (7–13 h UT) with longer duration for geomagnetic latitudes between 0 and 9° N and pronounced peaks for greater than 9° N. *Minima* occurs after midnight (20–24 h UT) between 0 and 9° N geomagnetic latitude whereas it is for longer duration (15–24 h UT) for northern crest of EIA region and beyond. Day-to-day variability of maxima is more pronounced in the crest of EIA regions (9–18° N geomagnetic latitude). Day-to-day variability of diurnal TEC is high and random during December 2004 and September 2011 due to seismo-ionosphere disturbance caused by 2004 Sumatra and 2011 Sikkim earthquake. Also anomalous day-to-day TEC variability is observed for Gujarat stations (MABU, KHAV, BELP) in 2011 which needs further detailed study. Diurnal maxima and minima vary significantly during the equinox and solstice of summer and winter seasons with lower values during summer solstice in EIA region and higher values during equinox and winter solstice. Beyond EIA (>18° N), maxima with pronounced peak occurs in the equinox month of March. Maximum spread of diurnal maxima is observed in crest of EIA during the equinox month of September. The results indicate that the variability of diurnal TEC in low-latitude region is highly random as it is caused by several factors as detailed earlier.

Monthly diurnal mean TEC values are the highest in November and the lowest in the months June to August for solar cycle 23 and increase with latitude in the EIA region. This is due to the winter anomaly observed in the EIA region of northern hemisphere and is consistent with previous studies. Beyond EIA region, the high values are observed in the summer equinox months and November and minimum values occur during January. For the current solar cycle 24, the monthly and seasonal variability is marginal for the low solar activity year (2009) when compared to 2011. In the EIA region, the highest values are recorded during October-November and the lowest during January for ascending phase (2011) of current solar cycle 24. The seasonal and monthly variation is random depending upon the intensity of solar cycle and seasons in each year.

In summary, the temporal and spatial variability of equatorial, low and mid-latitude ionosphere reported using the GPS-TEC estimated from new GPS data during 2002–2016 are broadly consistent with previous studies globally and specific to the Indian subcontinent. When compared to previous studies, present study with longer data span and spatial spread gives significant insights into the randomness of day-to-day variability of ionosphere as detailed above. This high and random variability of TEC is due to the changes associated with solar activity, intensity of the sun radiation and zenith angle at which they impinge the earth's atmosphere. TEC variability on quiet days depends on the changes in Earth's magnetic field and EEJ strength. In equatorial and low-latitude region of Indian subcontinent there is intense east–west electric current (EEJ) due to neutral winds and the plasma flow associated with the EIA plays a significant role in the day-to-day variability of diurnal TEC. Ionosphere is also affected by solar and geomagnetic storms, solar eclipse, seismic disturbances, volcanic eruptions, tsunamis, and so on. Indian Space Research Organisation in collaboration with Airports Authority of India developed a model to predict TEC in the Indian region which can be used to provide TEC maps. They have used GAGAN (GPS Aided Geo Augmented Navigation) ground network of 18 stations for this model and predict TEC between 8 and 30° N latitude and 60–100° E longitude. Since the present study uses a new set of cGPS data for a 14 year period, benchmarking ISRO ionosphere model with the current data and combining with the current TEC estimates would give an opportunity to develop precise ionosphere models and maps for this region. In addition these GPS-TEC estimates can be used to model the spatial and temporal variability of the low and mid latitude ionosphere specific to Indian subcontinent. GPS TEC study has several applications in varied fields such as precise positioning, navigation, seismo-ionosphere coupling, propagation of radio waves and solar-terrestrial events.

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Conflict of interest

Authors declare that there is no conflict of interest.

Notes/thanks/other declarations

Notes: We used total of 55 cGPS stations data during 2002–2016 to estimate TEC. We have chosen about 24 cGPS data with common epochs to given the comparative study of ionosphere variability in this chapter.

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