GPS based TEC measurements for a period August 2008–December 2009 near the northern crest of Indian equatorial ionospheric anomaly region

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In recent years, measurements of total electron content (TEC) have gained importance with increasing demand for the GPS-based navigation applications in trans-ionospheric communications. To study the variation in ionospheric TEC, we used the data obtained from GPS Ionospheric Scintillation and TEC monitoring (GISTM) system which is in operation at SVNIT, Surat, India (21.16°N, 72.78°E) located at the northern crest of equatorial anomaly region. The data collected (for the low sunspot activity period from August 2008–December 2009) were used to study the diurnal, monthly, seasonal semi-annual and annual variations of TEC at Surat. It was observed that the diurnal variation at the region reaches its maximum value between 13:00 and 16:00 IST. The monthly average diurnal variations showed that the TEC maximizes during the equinox months followed by the winter months, and are lowest during the summer months. The ionospheric range delay to TEC for the primary GPS signal is 0.162 m per TECU. The diurnal variation in TEC shows a minimum to maximum variation of about 5 to 50 TECU (in current low sunspot activity periods). These TEC values correspond to range delay variations of about 1 to 9 m at Surat. These variations in the range delay will certainly increase in high sunspot activity periods. Detected TEC variations are also closely related to space weather characterizing quantities such as solar wind and geomagnetic activity indices.

1. Introduction

The GPS has become an efficient tool for studying the ionospheric variability in past few years. The GPS signal propagating through the ionosphere are advanced in phase and delayed in time. This time delay being a function of electron density when measured by using a dual frequency receiver can compute the TEC (the total number of electron encountered along a particular line-of-sight by the propagating wave). From the difference between the two frequency measurements, the TEC along the signal path between GPS and the receiver can be calculated. Unit of TEC is TECU = 10^{16} electrons per square meter. The ionospheric delay constitutes the main source of error for single-frequency GNSS operation. The sensitivity of the ionospheric range delay to TEC for the primary GPS signal is 0.162 m per TECU. Hence, the range delay for this signal can reach as much as 90 m for a low-elevation satellite (e.g., Langley 1996).

The ionization in the equatorial and Polar regions is known to be high compared to relatively moderate levels of electron content in the mid-latitude ionospheric regions (Kane 1980). TEC at the mid-latitudes are relatively small compared to the equatorial and low-latitude regions (Davies 1980). The studies on the latitudinal variation of

the electron density in the Indian sector have been carried out with the availability of the orbiting satellites, such as BE-B and BE-C, INTASAT and the geostationary satellites, such as ATS-6, ETS-2 and SIRIO; several researchers have made significant contributions by making individual measurements of TEC from various locations in India (Rastogi and Sharma 1971; Dasgupta and Basu 1973; Rastogi *et al* 1975; Iyer *et al* 1976; Rama Rao *et al* 1977; Davies *et al* 1979) and the broad features in the behaviour of the equatorial ionization anomaly (EIA) are brought out. It is known that the equatorial ionization anomaly is a result of the 'fountain effect', which is the consequence of the effect of the equatorial electrojet interaction with the horizontal (N–S) Earth's magnetic field at the equator which gives rise to a lifting of the equatorial plasma to higher altitudes, during most of the daytime hours. This plasma subsequently diffuses along the geomagnetic field lines to either side of the magnetic equator owing to the effects of ambipolar diffusion, gravity and pressure gradients, giving rise to an accumulation of ionization at the F-region altitudes around ±15° geomagnetic latitudes, resulting in the formation of crests of ionization.

2. Data and analysis for TEC measurement using Global Positioning System

The GSV 4004 Ionospheric Scintillation Monitor receivers (GISM) collect the TEC and scintillation data (Van Dierendonck *et al* 1996). Each GISM can track up to 11 GPS C/A-code signals at the L1-frequency of 1.575 GHz. The data is collected at one minute, which do not include the 50-Hz sampled raw data, but the reduced TEC and S4 index and other parameters are included. To extract TEC from the GPS observation file, the pseudo-range measurements on L1 (1.5754 GHz) and L2 (1.2276 GHz) frequencies have been considered. The ionospheric delay can be expressed in terms of the signal carrier frequency as follows:

$$\delta_{\mathrm{ion}}\left(f_c\right) = \frac{40.3 \cdot TEC}{f_c^2} \qquad (2.1)$$

where $\delta_{\mathrm{ion}}(f_c)$ is the signal propagation delay at a given carrier frequency.

$$STEC = \int_0^S N\, dr = \left(\frac{f_2^2}{f_1^2 - f_2^2}\right)\frac{2f_1^2}{K}\Delta P_{1,2} \quad (2.2)$$

where $\Delta P_{1,2}$ = difference between time delays measured by the L1 and L2, $K = 40.3$ m^3 s^{-1}, f_1 = frequency of the L1 wave, and f_2 = second frequency (L2 wave).

In the above equation (2.2), there is a bias error correction which is different for different satellite–receiver pairs. Sardon *et al* (1994) reported that if accurate estimates of the ionospheric TEC are to be obtained, the differential instrumental biases must be removed. Many scientists have developed technique to derive GPS-TEC (Coco *et al* 1991; Leick 1995; Liu *et al* 1996). In the present study, the receiver part of the above bias is corrected by taking the value supplied by the manufacturer by calibrating the receiver against wide area augmentation system (WAAS). As we are mainly concerned with variations of TEC, the above approach is satisfactory. This procedure gives the corrected slant TEC. The slant TEC measurements made are the sum of the real slant TEC, the GPS satellite differential delay b_S (satellite bias) and the receiver differential delay, b_R (receiver bias). Except when at the zenith, the GPS satellite transmits the signal to the reference station through the ionosphere at some oblique angle. To remove the effect of the increased path length due to obliqueness, the *STEC* needs to be multiplied by a slant factor, $S(E)$.

Therefore, the vertical TEC can be expressed as:

$$VTEC = \left(\frac{STEC - [bR+bS]}{S\left(E\right)}\right)$$

$$S\left(E\right) = 1/\left(\cos\chi'\right)$$

where

$$\cos\chi' = \sqrt{1 - \left(\frac{R_x\cos\chi}{R_x + h_m}\right)^2} \qquad (2.3)$$

R_x = mean earth radius, 6371 km, h_m = altitude of the IPP, χ = elevation angle, and $\chi' = (90° - \chi)$ (Mannucci *et al* 1993; Langley *et al* 2002).

The ionosphere puncture point (IPP) is where the GPS signals travel through the maximum electron density layer of the ionosphere. The mean ionospheric height of 350 km is used for the determination of IPP locations, which is found to be valid for elevation > 50° in a low latitude sector (Rama Rao *et al* 2006). To obtain a good average diurnal variation plot of TEC, all TEC > 50° elevation are filtered so as to eliminate the low elevation effects, due to multipath and tropospheric scattering on the measured TEC values. To obtain the vertical TEC at Surat, we are restricted to a longitude grid of ±2° and latitude grid of ±2° from the observing station, in addition to the 50° elevation cut-off.

3. Results and discussions

The TEC obtained were examined for local time, monthly and seasonal variations. The results are discussed below.

3.1 *Diurnal variation of TEC*

To illustrate the feature of diurnal variation, mean TEC on a particular day is shown in figure 1. It can be seen that the TEC decreases slowly from pre-dawn to sunrise period, reaches its minimum at 05:00 IST (IST = Local Time = UT + 05:30 hrs) and increases steadily till noon, reaches its peak (~50 TECU) at 16:00 IST and decreases sharply post-sunset. TEC exhibits the usual diurnal variation of a minimum in the pre-sunrise hours (05:00 IST) and a maximum between 13:00 and 16:00 IST. To illustrate the diurnal variation mass plots of diurnal variations at Surat for different months over a period from August 2008–December 2009 (with an exception of October 2008 and January 2009 when observations were disrupted due to technical problems) is shown in figure 2.

3.2 *Seasonal variation of TEC*

Figure 3 represents monthly mean TEC from February to December 2009 for the region. The morning rise and afternoon decay in TEC is sharp in the equinoxes (March, April, September, and October) 2009. The forenoon rate of production and afternoon decay of ionization is faster in winter (November, December, January, February) 2009 compared to that in summer (May, June, July, August) 2009. The amplitude of the diurnal maximum is higher (~40 TECU) in the equinoxes and lower in the winter and summer thus exhibiting the semi-annual variation. In order to clearly analyze the trend of seasonal variations of TEC, the average monthly value of TEC and average peak value of TEC monthly were computed. Figure 4

represents the average of monthly TEC value (upper panel) and average of peak TEC value (middle panel) in light of monthly solar flux 10.7 cm (bottom panel) for a period February 2009 to December 2009. It is observed that annual variation in solar flux 10.7 cm ranges from 68 to 76 s.f.u (solar flux units). Semi-annual trend is observed in both the average value in the top and middle panels of figure 4. To analyze the trend further, similar graphs were plotted by considering average TEC of five internationally disturbed days (D-days) for all the months from February to December 2009 and are presented in figure 5(a) and of five internationally quiet days in figure 5(b). It is observed that for the current low sunspot activity, the D-days and Q-days have followed the trend of seasonal variations.

Further, TEC is higher (~30 TECU) in the winter than in the summer (~25TECU), i.e., the 'winter anomaly' in seasonal variation is also observed. The time of occurrence of the diurnal maximum varies with season. In the equinoxes, the morning rise and afternoon decay of TEC is sharp compared to that in summer and winter. TEC reaches its daytime peak earlier (~13:00 IST) in equinoxes and later (~15:00 IST) in summer and winter. In summer, the morning pre-dawn value is high and the peak value is low compared to that in equinoxes. In October, the time of occurrence of maximum TEC is earlier and afternoon decay of TEC is very sharp.

The seasonal variations of the ionosphere have been explained in terms of changes in solar zenith angle and thermospheric composition (Rishbeth and Setty 1961) and from global circulations (Millward *et al* 1996). According to the generally accepted theory, the ionospheric TEC depends on
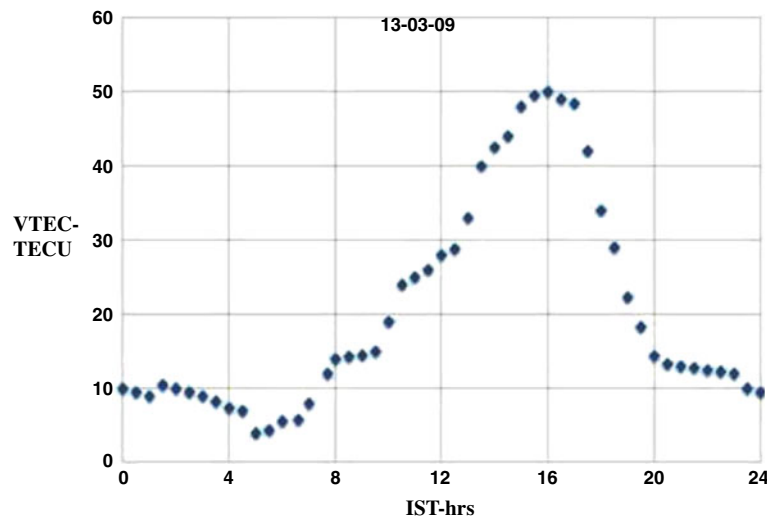

Figure 1. Diurnal variation of vertical TEC with time at Surat for a typical day of 13 March 2009. It can be seen that the TEC decreases slowly from pre-dawn to sunrise period reaches its minimum at 05:00 IST and increases steadily till noon, reaches its peak (~50 TECU) at16:00 IST and decreases sharply post-sunset.
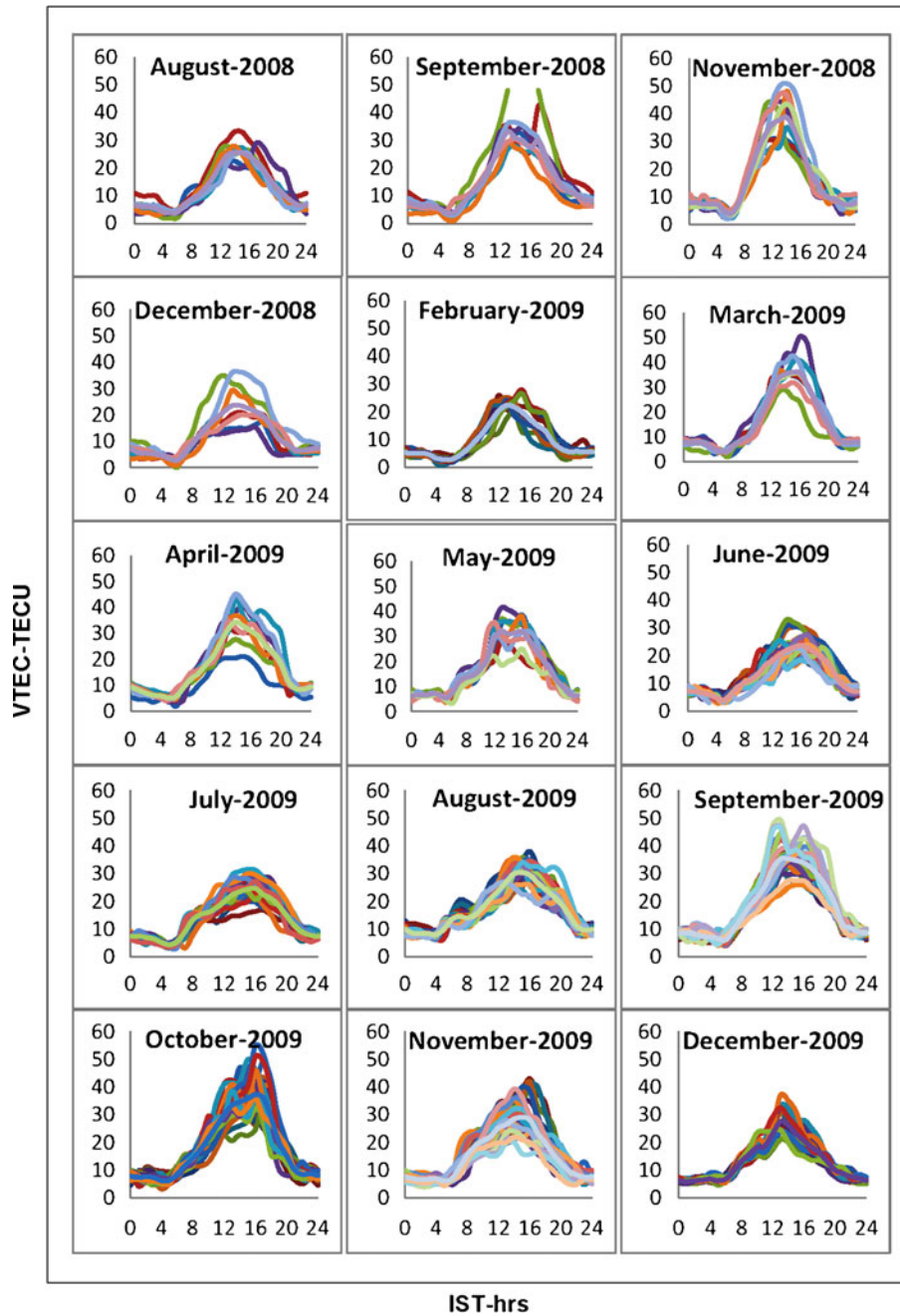
Figure 2. Mass plots of diurnal variations at Surat for different months over a period from August 2008–December 2009 (with an exception of October 2008 and January 2009 when observations were disrupted due to technical problems).

the atomic/molecular ratio ($[O]/[N_2]$) (Titheridge 1974) as well as the solar zenith angle. Both observations and model simulations illustrate a clear seasonal change in thermospheric composition, specifically with higher $[O]/[N2]$ in winter than in summer. Rishbeth and Setty (1961) suggested that the seasonal anomaly may be associated with atmospheric composition changes. The topside ionosphere is not in photochemical equilibrium and transport becomes one of the principal processes. Thus, besides neutral compositions, neutral winds should play an important role in the seasonal

variations of TEC. Thermospheric winds push plasma up and down geomagnetic field lines and transport plasma from one hemisphere to the other by modulating the field-aligned flows, which influences the latitude structure of plasma (Watanabe *et al* 1995) and the observed hemispheric asymmetries. Neutral winds in the magnetic meridian include contributions from both the geographic zonal and meridional winds, which depend on the magnetic declination angle. Therefore, the field-aligned flows due to neutral winds may be a primary cause of the latitudinal and longitudinal
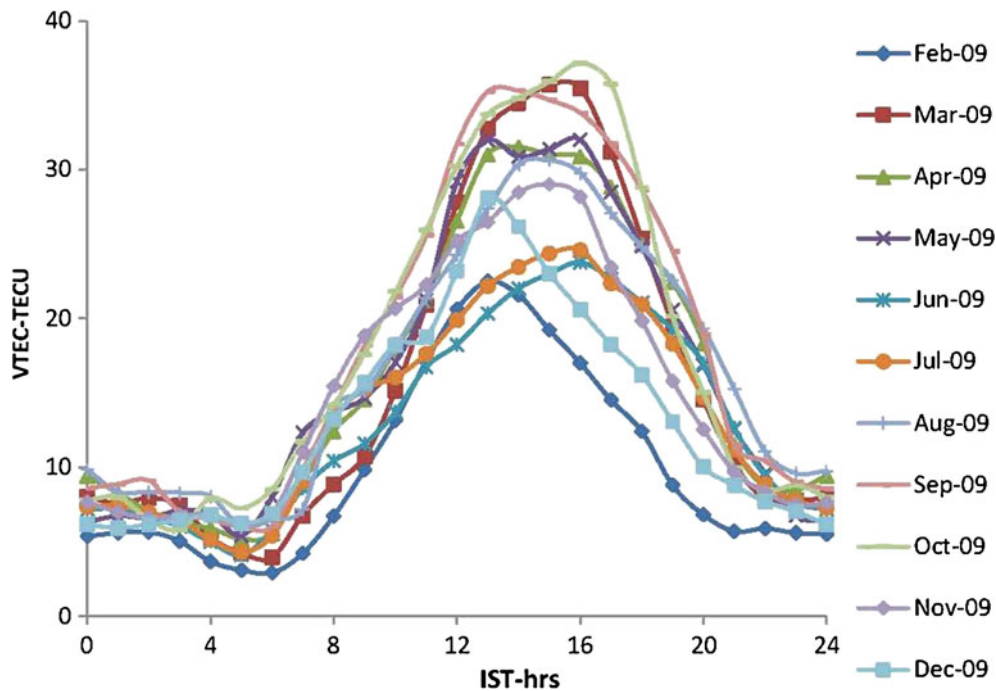
Figure 3. Monthly mean VTEC from February to December 2009.

dependences and the seasonal variations of the top-side plasma densities (e.g., Bailey *et al* 2000; Balan *et al* 1997, 2000; Su *et al* 1998). The seasonal variations of meridional winds may contribute to influence the seasonal variations of TEC, especially at which the thermospheric wind effects are particularly strong.

One noticeable important TEC feature is the day-to-day variability, particularly during the midday to pre-dawn hours. The day-to-day variability is of great importance to the development of empirical models. Day-to-day variability of equatorial and low latitude F region ionosphere in the Indian zone has been studied by Dabas *et al* (2006). As discussed by Forbes *et al* (2000) and Fuller-Rowell *et al* (2000), the day-to-day variability, which is greater in the region of the equatorial ionization anomaly (EIA) area and at high latitudes, is attributed to solar, geomagnetic, and other causes which seem to be originated from lower part of the atmosphere, were termed 'meteorological' by (Rishbeth and Mendillo 2001). The meteorological processes such as planetary waves, gravity waves, and tides can have direct or indirect effects on the ionosphere (Laštovička 2006; Rishbeth 2006).

3.3 *TEC and space weather parameters*

The term 'space weather' refers to the conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that affect the performance and the reliability of technological systems on Earth and in space. Space weather

processes can include changes in the interplanetary magnetic field, solar flares, coronal mass ejection from the Sun, and disturbances in the Earth's magnetic field. These processes could be studied
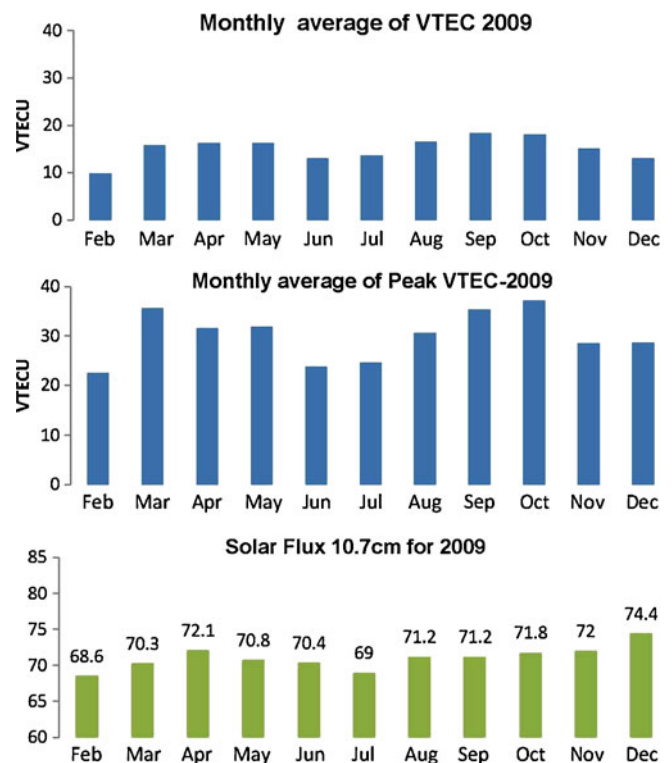

Figure 4. The average of monthly VTEC value (upper panel) and average of peak TEC value (middle panel) in light of monthly solar flux 10.7 cm (bottom panel) for a period February 2009 to December 2009.
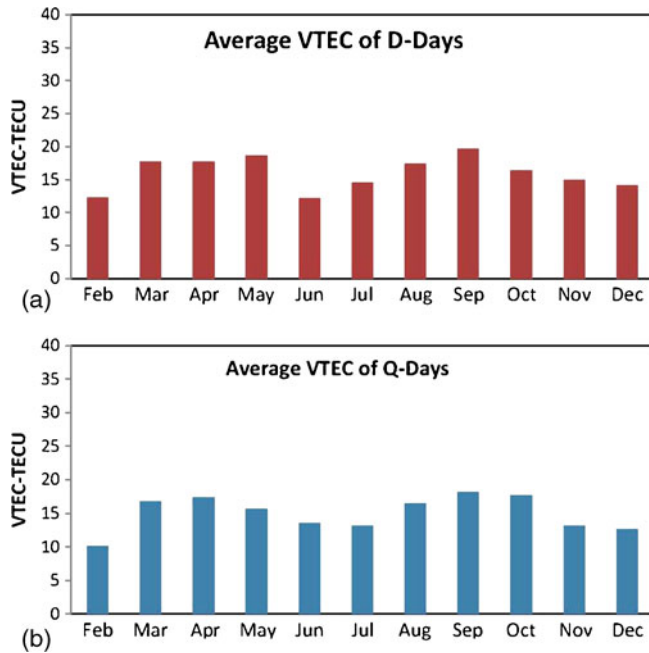
Figure 5. (**a**) The graph plotted by considering the average VTEC of five internationally disturbed days (D-days) for all the months from February 2009 to December 2009. (**b**) The graph plotted by considering the average VTEC of five internationally quiet days (Q-days) for all the months from February 2009 to December 2009.

through the solar wind parameters such as proton velocity (Vp), proton density (Np) as well as inter planetary magnetic field component (Bz). Many organizations around the world are now actively engaged in monitoring, modelling and predicting the space weather. Violent eruption in the Sun's outer atmosphere on November 8, 2000, spewed billions of tons of charged particles towards the earth and caused severe turbulence in the space around the Earth (Burch 2001). One of the consequences of severe space weather is often the disruption to satellite communications and even disruption of power grid on the Earth. GPS navigation accuracy is greatly affected by the space weather, as it is particularly sensitive to changes in the electron density in the ionosphere. Ionospheric storm phenomena are shown to be closely related to space weather characterizing quantities such as solar radio emission, solar wind speed and geomagnetic activity indices (Jakowski *et al* 2001). As the present period is falling under solar minimum conditions, the probability of encountering the disturbed ionosphere is very low (Basu and Basu 1981; Aarons 1982). To see the variation in TEC with respect to the space weather parameters, a geomagnetically disturbed day, 4 September 2009 (Dst = −50 nT), has been selected from the period of study. The level of geomagnetic activity during the examined period is indicated by the Kp index issued by World Data Center for Geomagnetism,

Kyoto. The Kp index describes geomagnetic conditions at mid-latitudes, and the Dst index describes geomagnetic conditions at low latitudes. Solar wind interplanetary magnetic field (IMF) Bz component in the GSM coordinate has been obtained from the ACE satellite. Figure 6 shows the co-relation of TEC with the various parameters like Kp, Dst, interplanetary magnetic field Bz, solar wind parameters proton velocity, Vp and proton density, Np
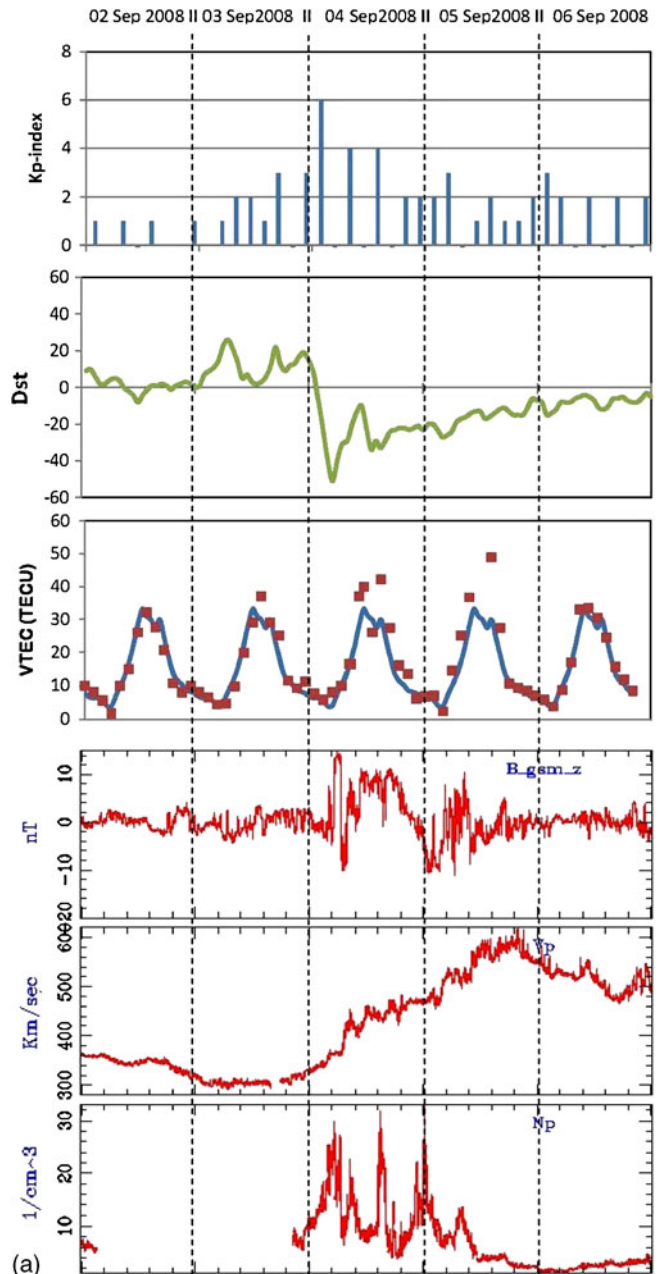

Figure 6. (**a**) The variations of Dst, Kp (first and second panels from top) and VTEC (red dotted line) during 2–6 September 2008 are shown. The mean VTEC of the month is shown by the solid blue line in the third panel. The variations of interplanetary magnetic field Bz, solar wind velocity Vp, and proton density Np during the period of 2–6 September are shown in the fourth, fifth and sixth panel from top. (**b**) O/N_2 variation for 3–4 September 2009.
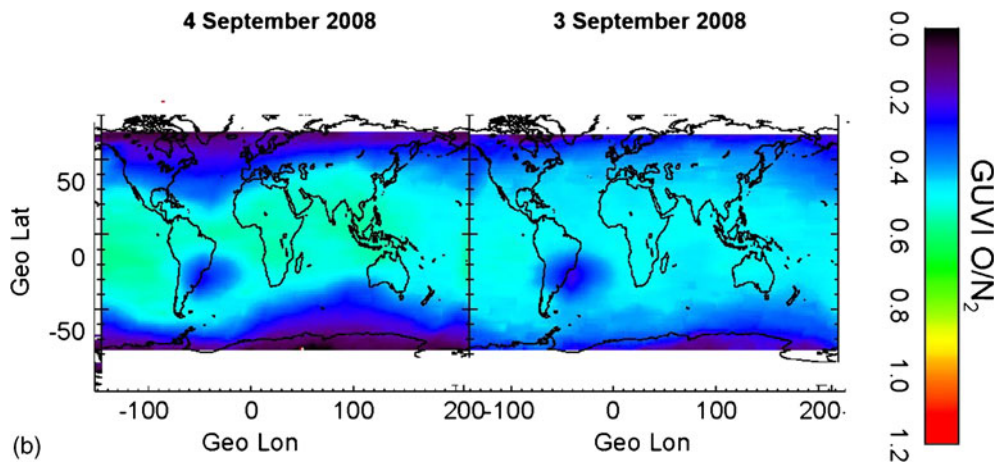
Figure 6. (*Continued*).

for the period 2–6 September 2008. Figure 6(b) shows TIMED/GUVI image for O/N_2 distribution on 3 September 2008 and 4 September 2008. It can be observed that the O/N_2 decreased at high latitudes and enhanced at lower latitudes on 4 September compared to that on 3 September. Thus, the event from 2–6 September may be considered as a positive storm effect with the enhancement of O/N_2 at low and mid-latitude (Field *et al* 1998). It has been shown that TEC is a quite useful parameter to design perturbations in the magnetosphere/ionosphere/thermosphere systems. The GPS technique provides a unique opportunity to monitor the perturbations in space weather parameters, continuously on global scale in near real time.

4. Conclusions

The diurnal, monthly and seasonal variations of TEC derived from Surat (21.16°N, 72.78°E) located at the northern crest of equatorial anomaly region are studied for the low sunspot activity period from August 2008 to December 2009. The measured TEC exhibits features like the equatorial ionization anomaly, seasonal, monthly and day-to-day variability. The diurnal variation at the region reaches its maximum value between 13:00 and 16:00 IST. Similarly, the day minimum in TEC occurs between 05:00 and 06:00 IST. The monthly average diurnal variations show that the TEC maximizes during the equinox months followed by the winter months, and are lowest during the summer months. The lower values of TEC during the summer months may be attributed to the low ionization densities, due to the reduced production rates (indicated by O/N_2 ratio). Further, seasonal variations of meridional winds may contribute to influence the seasonal variations of TEC,

especially at which the thermospheric wind effects are particularly strong.

The ionospheric range delay to TEC for the primary GPS signal is 0.162 m per TECU. The diurnal variation in TEC shows a minimum to maximum variation of about 5 to 50 TECU (in current low sunspot activity periods). These TEC values correspond to range delay variations of about 1–9 m at Surat. These variations in the range delay will certainly increase in high sunspot activity periods. The observed variation in TEC has shown strong relation with the space weather parameters for the selected event (2–6 September 2008).

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