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Electrojet control of ambient ionization near the crest of the equatorial anomaly in the Indian zone

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Abstract. A long-term (1978–1990) database of total electron content (TEC) from a location (Calcutta: 22.58° N, 88.38° E geographic, dip: 32° N) near the northern crest of the equatorial ionization anomaly has extensively been studied to characterize the contribution of fountain effect in the maintenance of ambient ionization. The equatorial electrojet (EEJ) data obtained from ground magnetometer recording are used to assess the contribution of equatorial fountain. Analysis made with instantaneous values, day's maximum values and time-integrated values of EEJ strength exhibit more or less similar features. When instantaneous values of EEJ are considered TEC variations exhibit two maxima in correlation, one around 10:00–12:00 IST and the other around 18:00–20:00 IST. The later maximum in correlation coefficient is conspicuously absent when integrated values of EEJ are considered. An impulse-like feature is reflected in the diurnal TEC variation during the time intervals (09:00–10:00 IST) and (18:00–19:00 IST). The statistical analysis reveals greater correspondence with high level of significance between diurnal TEC and EEJ in the descending epoch of solar cycle than in the ascending one. On the seasonal basis, TEC in the summer solstitial months are observed to be more sensitive to the changes in EEJ strength than in the equinoctial and winter solstitial months. Combining the effects of solar flux, season, local time and EEJ an empirical formula for monthly mean diurnal TEC has been developed and validated using observed TEC data. An estimation of the relative contributions of the several terms appearing in the formula reveals much more solar flux contribution (∼50–70%) in the maintenance of ambient ionization around the present location than the EEJ effects (maximum∼20%).

Keywords. Geomagnetism and paleomagnetism (Time variations, diurnal to secular) – Ionosphere (Equatorial ionosphere; Modeling and forecasting)

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1 Introduction

The equatorial electrodynamics plays a vital role in the distribution of ionization at the low latitude ionosphere. Two most important effects of equatorial electrodynamics are the equatorial electrojet (EEJ) and the equatorial ionization anomaly (EIA). A belt of intense E-region current within a narrow latitude band (∼±2°) about the dip equator is referred to as EEJ. It is manifested by a relatively large daytime perturbation in the horizontal component (H) of the geomagnetic field at the ground level. The daytime E-region electric field driven by neutral wind dynamo (Rishbeth, 1971) is the triggering force for the EEJ and the strength of EEJ is influenced by the conductivity of that region. The magnetic signature of EEJ observed on the ground reflects the height integrated current system of EEJ. Assuming the day-to-day variation of conductivity to be less prominent than that of electric field, EEJ is reported to be a proxy index for E-region zonal electric field (Stolle et al., 2008). There is a strong variability of the EEJ intensity from one season to the other and also with solar activity level (Mouel et al., 2006).

The EIA refers to double humped structure in the latitudinal distribution of ionization at low latitudes with a trough at the magnetic equator and two crests of enhanced ionization at ±15–20° dip latitudes. The latitudes of the anomaly crest and strength of the anomaly vary with day, month, season and solar activity as well as with longitudes and wind systems (Rastogi, 1966; Golton and Walker, 1971; Rush and Richmond, 1973; Huang et al., 1989; Walker et al., 1994; Balan and Bailey, 1995). The vertical $\boldsymbol{E}\times\boldsymbol{B}$ drift of plasma over the magnetic equator at the F-layer altitude and subsequent diffusion along the magnetic field lines, known as equatorial fountain, generate the EIA. The driver of this fountain is the same E-region dynamo related eastward electric field $\boldsymbol{E}$, as in the case of EEJ, communicated to the F-region via highly conducting geomagnetic field lines. There is a good correspondence between the strength of EEJ and vertical drift at the equator (Balseley and Woodman, 1969; Anderson et al.,

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2002). As the strength of EEJ waxes and wanes from one day to the next, the crest latitude expands poleward or contract equatorward accordingly. A remarkable association between the strengths of EEJ and EIA was reported by several workers (Deshpande et al., 1977; Huang et al., 1989; Stolle et al., 2008). The EEJ strength may thus be considered to be a diagnostic for the EIA and hence for equatorial fountain under quiet geomagnetic condition. Ionospheric total electron content (TEC) at any location is the integrated effect of production, loss and transport mechanisms. Production of ionization is mainly controlled by solar radiation while transport is dominated by equatorial fountain and neutral wind systems (Hanson and Moffett, 1966; Balan and Bailey, 1995). The movement of the crest stimulated by variability of the equatorial fountain may result in day-to-day variability of the TEC in the anomaly region (DasGupta and Basu, 1973; Huang et al., 1989; Yeh et al., 2001). To investigate the effect of equatorial fountain in the distribution of ambient ionization locations near the anomaly crest seem to be most suitable.

TEC variability due to EEJ was studied by several groups (Walker and Ma, 1972; Sethia et al., 1980; Balan and Iyer, 1983; Rastogi and Klobuchar, 1990; Walker et al., 1994; Rama Rao et al., 2006). From low latitude region TEC is reported to exhibit a positive correlation with EEJ strength while a negative correlation is reflected from the equatorial stations. On the seasonal basis, observations reported maximum correlation in the equinoctial month with minimum at summer solstice. Some studies exhibited better correspondence between TEC variability and integrated EEJ from low latitude region (Rama Rao et al., 2006). All these studies are actually based on short-term databases and most of the studies considered daily maximum value as a measure of EEJ strength. No systematic study on the variability of diurnal TEC in relation to time evolution of EEJ is reported till date. In the present investigation a long-term (1978–1990) database of TEC from a station (Calcutta, 22.58° N, 88.38° E geographic, dip: 32° N), situated virtually below the northern crest of the equatorial anomaly, has been analyzed in conjunction with the EEJ data to make qualitative and quantitative estimates of relative contributions of fountain effect, considering EEJ as proxy index, in the distribution of ambient ionization near the anomaly crest. The extensive database provides also an opportunity to study solar epoch as well as solar activity and seasonal dependent features of TEC variability associated with the changes in EEJ.

When a radio wave traverses the dispersive ionosphere most of the effects produced in it are proportional, at least to the first order, to TEC (Ezquer et al., 2004). The correction of this effect requires an adequate modeling of the ionospheric TEC. Different models such as IRI, PIM, SLIM and SUPIM are available for evaluation of TEC. But studies (Ezquer et al., 2004; Paul et al., 2005) reveal that no model in general is sufficient to represent TEC variation around the anomaly crest region. Development of a model requires several steps to be followed. Under the present investigation efforts have been made to develop an empirical formula to represent diurnal variation of monthly mean TEC by combining the contributions of solar flux, season, local time and EEJ. The formula has also been validated using observed TEC data.

2 Data

TEC data recorded at Ionosphere Field station, Haringhata (geographic: latitude 22°58′ N, longitude 88°30′ E; dip: 32° N), University of Calcutta, using Faraday rotation technique of a plane polarized VHF signal (136.11 MHz) from a geostationary satellite ETS-2 (130° E) have been used for the present investigation. The 400 km sub-ionospheric point (21° N, 92.7° E, dip: 27° N) was located virtually below the northern crest of the equatorial anomaly. The peculiarity of the location is that during high solar activity period, as the crest moves toward higher latitudes, the station seems to be situated within the anomaly belt but for equatorward movement of the same during low solar activity years the crest may be located just overhead of the observing station. The expansion and contraction of the EIA should be reflected in the measured values of TEC form this location. In the present analysis TEC data for the quiet days with $D_{st} > -50$ nT and normal EEJ days are considered only.

An idea of EEJ related electric field may be obtained from the ground magnetic data which gives, as stated earlier, a measure of overhead current system. Ionospheric electric field at the EEJ station is the superposition of worldwide S_q field and the field attributed to the EEJ currents. The field at a station outside the EEJ region is solely related to normal S_q field prevailing throughout the equatorial region. In the present analysis, the scheme suggested by Chandra and Rastogi (1974) and later used by several workers (Rastogi and Klobuchar, 1990; Rama Rao et al., 2006; Stolle et al., 2008) for the measurement of EEJ strength has been used. According to this scheme EEJ strength is determined by the term ΔH (equator) – ΔH (away from equator). The ΔH values represent the daytime H values after subtracting the night-time baseline H values. Under present investigation magnetometer horizontal intensity data of Trivandrum, an electrojet station (geographic: latitude 8.29° N, longitude 76.57° E; dip: 1.2° S) and Alibag, outside the EEJ belt (geographic: latitude 18.63° N, longitude 72.87° E; dip: 23° N) are considered.

3 Results and discussions

3.1 Diurnal variation of TEC and EEJ strength

To characterize the contribution of equatorial fountain as revealed through EEJ in the diurnal development of TEC near the anomaly crest, instantaneous values of EEJ have been considered. An approximate time delay of 2 h (Rush and

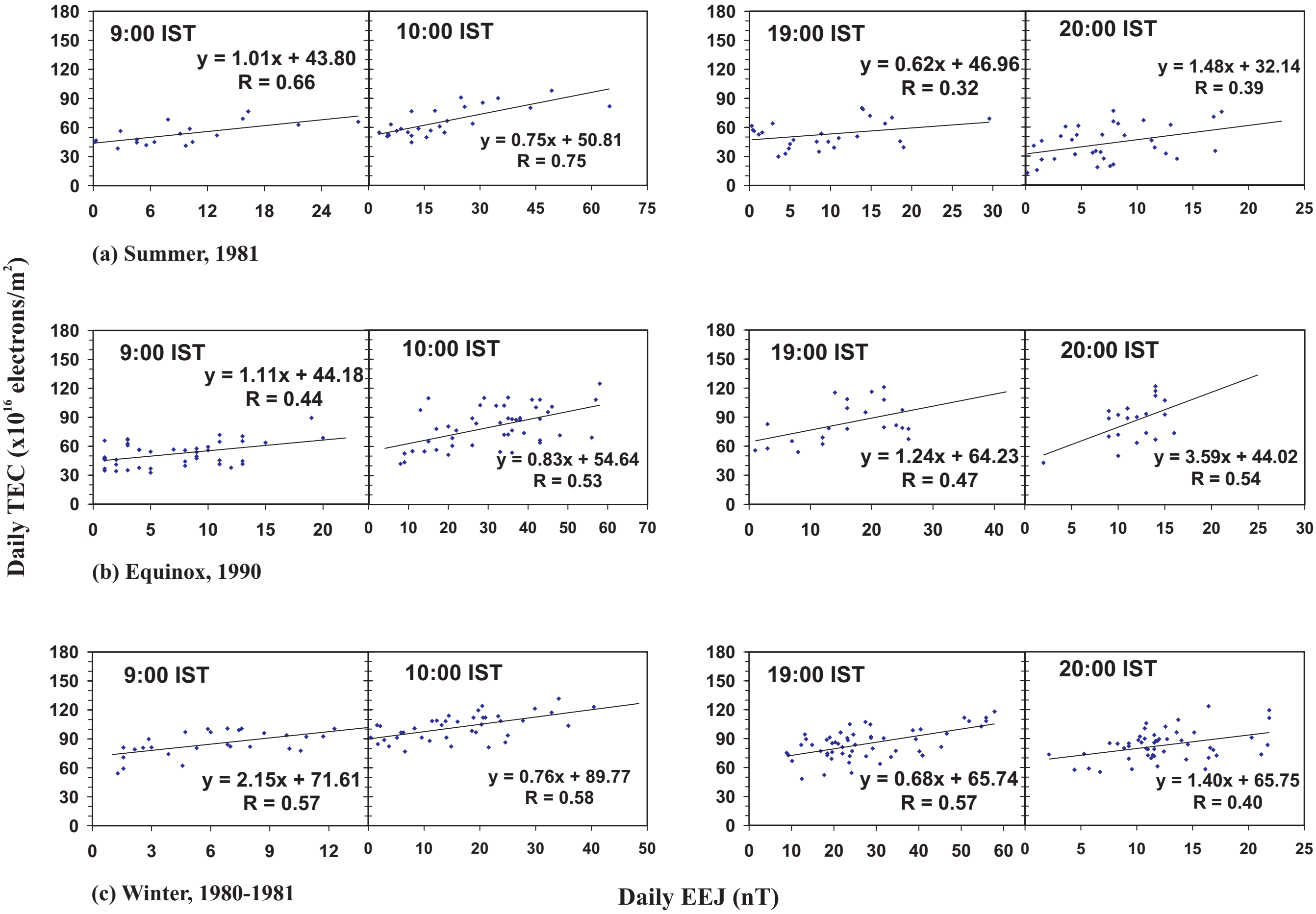

Fig. 1. Daily values of TEC at the specified time (t h) vs. EEJ strength (nT) at time ($t-2$ h) for **(a)** summer solstitial months (May, June, July), **(b)** equinoctial months (August, September, October) and **(c)** winter solstitial months (November, December, January) of the indicated years. A linear regression line with equation and correlation coefficient (R) is shown in each case. 1 TEC unit=10^{16} electrons/m^2. Time is given in h IST (IST=UT+5.30 h).

Richmond, 1973; Iyer et al., 1976; Sethia et al., 1980) between the cause (triggering equatorial fountain) and the effect (changes in ambient level near the anomaly crest) is incorporated in the selection of instantaneous EEJ values. TEC data at a particular local time (t) are plotted against EEJ strength at time ($t-2$) for different seasons (Fig. 1). It is observed that starting from 09:00 IST correlation between TEC and EEJ increases and a maximum value with high level of significance is detected around 10:00–12:00 IST. Association between the two, thereafter, deteriorates (Fig. 2). The initial feature seems to revive after about 17:00 IST. The EEJ contribution throughout the observing period exhibits a secondary maximum around 18:00–20:00 IST. A higher value of correlation coefficient with high level of significance may be the indication of the same. Association between the two, as dictated by correlation coefficient, again decreases at the midnight and post-midnight periods and is mostly rejected at 5% significance level. This may be due to weakening of fountain effect or absence of EEJ as conducting E-layer disappears around this time. Using CHAMP data Mouel et al. (2006) was also unable to detect any EEJ signal at 00:00 LT in the global map of geomagnetic field. The feature is the same in both the solar epochs as well as at different levels of solar activity. Moreover, in response to the variation of EEJ an impulse-like feature is detected in TEC variation around the present location during the intervals of 09:00–10:00 IST and 18:00–20:00 IST. The comparatively higher values of "m" in the linear fit (Fig. 1) around the stated time periods dictate the corresponding sharp changes.

The initial high values of "m" and the good correlation may be attributed to the signature of dominance of transport mechanism as dictated by fountain effect. At the initial phase rapid increase in EEJ strength may signify faster rise of plasma at the magnetic equator. This, along with faster diffusion due to larger latitudinal/altitudinal gradient in plasma, may accentuate the fountain effect to supply ionization at the

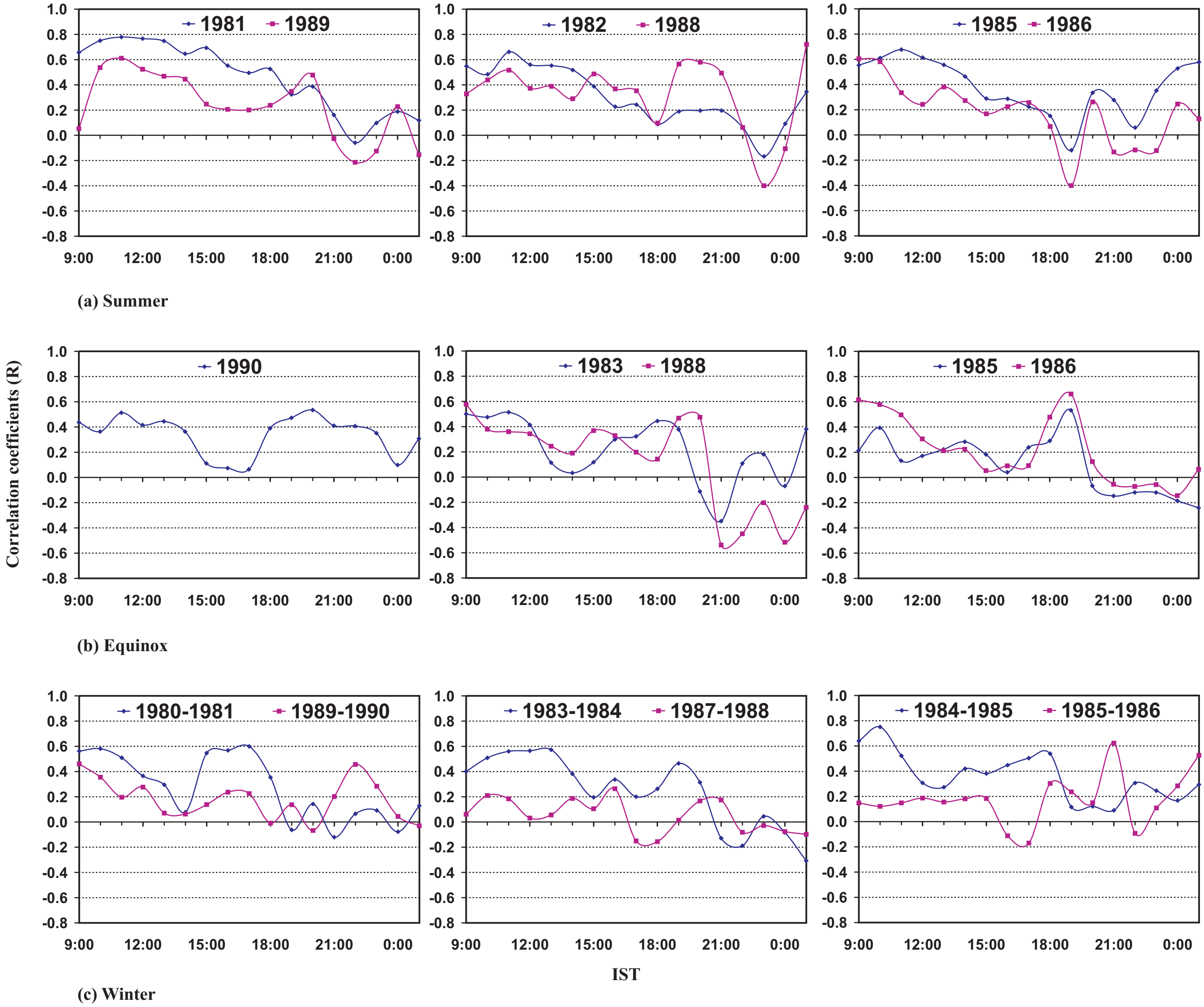

Fig. 2. Diurnal variation of correlation coefficients (R) between TEC (t h) and EEJ strength ($t-2$ h) calculated on the basis of Fig. 1 for high (1980/1981, 1989/1990), moderate (1982/1983, 1988) and low solar activity years (1985, 1986) of the different solar epochs. Panel **(a)** refers to summer solstitial months, **(b)** refers to equinoctial months and **(c)** corresponds to winter solstitial months. TEC data for the equinoctial months of high solar activity period of descending phase (1980–1985) are incomplete due to irregular satellite (ETS-2) transmission.

off-equatorial location. It may exert an impulse to the solar flux dominated steady rate of TEC variation leading to faster rate of growth in response to changes in EEJ. Further, the anomaly generally starts to develop around 09:00 LT and the crest of the anomaly subsequently move poleward with a speed of about 1° per hour (Yeh et al., 2001). The movement of the crest of the equatorial anomaly may contribute to steep and steady rise of the content (Golton and Walker, 1971). The meridional winds may also cause the F-region ionosphere at low latitude to respond at a faster rate (Abdu, 1997).

The higher "m" values and larger correlation coefficients at high level of significance are also recorded around 19:00–20:00 IST, though the overall EEJ strength around the period (17:00–18:00 IST – before sunset) is observed to be low. The anomaly is fully developed around 13:00–16:00 LT depending on season and solar activity level (Walker et al., 1994). After the development, a decaying trend as well as equatorward movement of the crest follows. At times when the anomaly is well developed (12:00–20:00 LT) the wind exerts little influence on its structure (Rush, 1972). It was pointed that low fountain strength leads to faster decrease of crest latitudes (Yeh et al., 2001). Clearly, the period (19:00–20:00 IST) of greater association and higher "m" values corresponds to (1) insignificant influence of wind on the anomaly structure, (2) decay and equatorward movement of

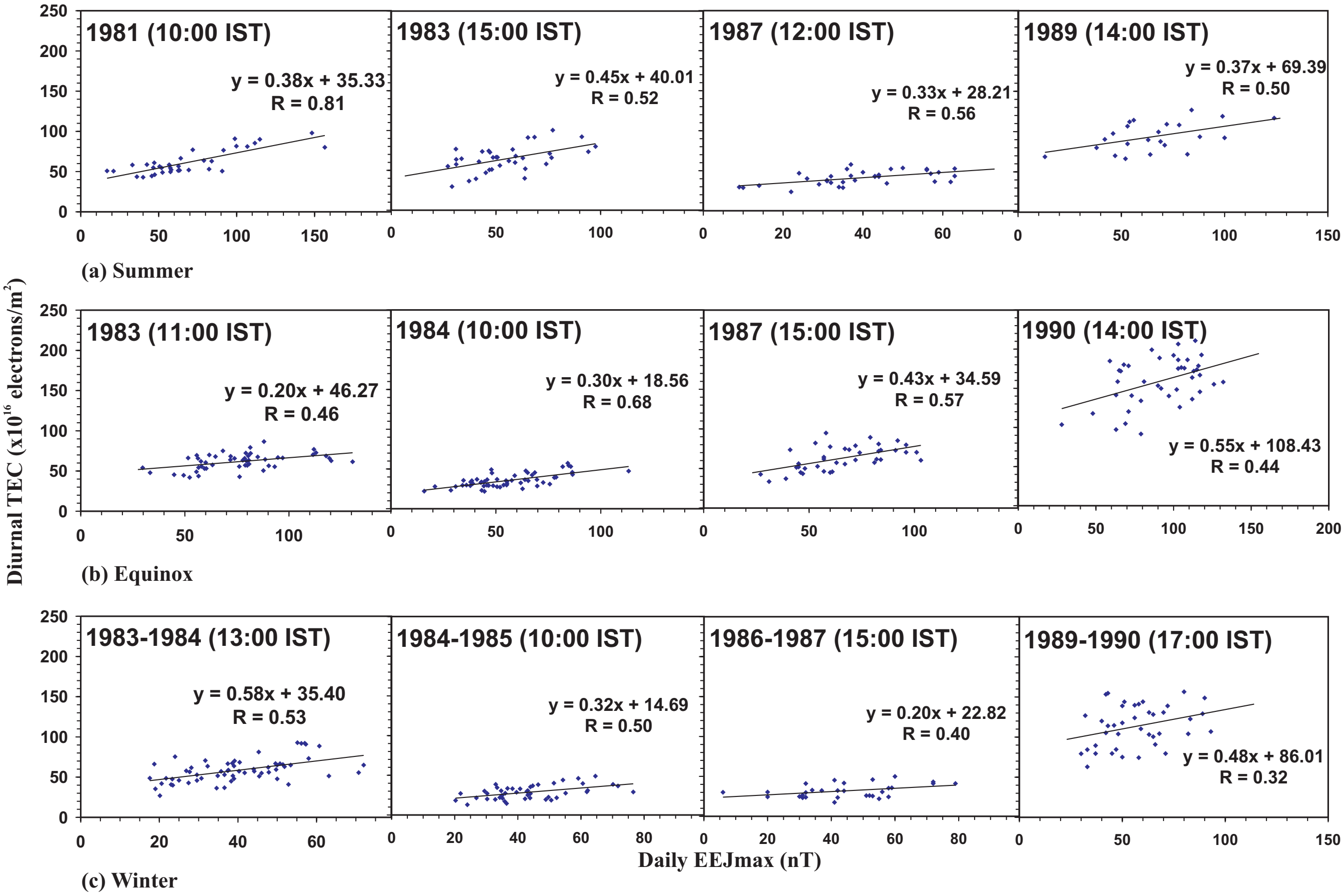

Fig. 3. Daily TEC at the indicated time and year vs. day's maximum values of EEJ strength (nT). Plots are shown for the time of maximum correlation. Panel **(a)** corresponds to summer solstitial months, **(b)** pertains to equinoctial period and **(c)** refers to winter season.

the anomaly crest as reflected in lower TEC value around the present location, and (3) weaker EEJ strength during 17:00–18:00 IST. An inspection of the available *fo*F2 data from an equatorial station Kodaikanal (geographic latitude 10.25° N, longitude 77.5° E, dip 4° N) reveals a trend of enhanced values rather than exhibiting a dip during the interval 16:00–18:00 IST. This may indicate a reverse fountain effect – leading to equatorward movement of the crest rather than resurgence of the anomaly. The simultaneous in-phase occurrence of the later two conditions may result in better correspondence between TEC and EEJ. The first one may be considered as a favorable condition leading to higher "*m*" values.

On the seasonal basis, the overall maximum correlation coefficients in the summer solstitial months are observed to be somewhat larger (0.6 to 0.8) and highly significant compared to the other seasons (Fig. 2). Further, during the solstitial months of two solar epochs a notable difference in the correspondence between TEC and EEJ, with descending phase exhibiting better correspondence, is prominent.

The seasonal changes in the correlation are suggested (Rush and Richmond, 1973) to have two components: (1) annual component minimizing around June solstice and (2) solar zenith angle component maximizing when sun is between the geographic and magnetic equator. Although equinoctial maxima in correlation with high level of significance (except for the years 1988, 1989) obtained in the present analysis may corroborate the explanation (2), results accrued from the summer solstitial data seem to exhibit a reverse picture. The location of the observing station with respect to position of the anomaly crest seems to play a dominant role in reflecting the seasonal behavior. Earlier occurrence of peak in meridional wind (Igi et al., 1999) at all levels of solar activity in summer may accentuate the fountain effect to reflect better correspondence with TEC.

3.2 Variation of TEC with day's EEJ strength

Instead of correlation studies on the temporal evolution of EEJ and TEC most of the workers reported TEC variability with respect to day's EEJ strength. The maximum value of ΔH (TRD)–ΔH (ABG), i.e., EEJmax is taken as the measure of day's EEJ strength. When this strength is considered in conjunction with TEC at different local times (Fig. 3), maximum correlations around 10:00–11:00 IST and subsequent smooth decay in correlation characterize the fountain contribution in the equinoctial months of various solar activity levels. In the May–July months of low solar activity years maximum correlation is observed around 10:00–11:00 IST while for the same season correlation maximizes around 12:00–15:00 IST during moderate-to-high solar activity periods. One maximum around 10:00–11:00 IST and another around 13:00–15:00 IST characterize the December solstitial months. In the summer solstitial months a better association, compared to the other season, is reflected through the statistical analysis. The descending phase of solar cycle (1980–1985) seems to be more sensitive in this respect.

The EEJ strength maximizes around 11:00–13:00 IST and peak EEJ strength corresponds to largest vertical $\boldsymbol{E}\times\boldsymbol{B}$ drift (Anderson et al., 2002) leading to maximum height rise of plasma at the magnetic equator. This may produce larger latitudinal gradient in TEC favoring diffusion process. The correlation maxima obtained in the later period may be related to the day's EEJ strength while the former cases may be attributed to the initial surge developed by the fountain effect in the steady rate of solar flux dominated TEC variability. Further, the earlier occurrence of electrodynamical effects in the equinoxes than in other seasons was suggested (Sethia et al., 1980) to be related to the earlier occurrence of equinoctial maxima in daytime westward ionospheric drift (Chandra and Rastogi, 1969). The pronounced influence of the EEJ on TEC, with maxima at equinoxes, at stations within and near the crest of the equatorial anomaly in the Indian zone was reported by several workers (Sethia et al., 1980; Balan and Iyer, 1983; Rastogi and Klobuchar, 1990). Present observations, using long-term database of TEC and EEJ, more or less follow the trend reported earlier but the response in the summer solstitial months reveals a reverse picture.

3.3 Variation of diurnal TEC with integrated EEJ strength

Due to various geophysical considerations as well as relatively slower rate of diffusion, one may not expect a good correlation between TEC and instantaneous EEJ – rather TEC variation at a particular local time may be a cumulative effect of EEJ variation at earlier times. The time-integrated values of EEJ may be considered as an approximate index to affect the ambient levels (Raghavarao et al., 1978) at the off-equatorial locations. With this assumption diurnal TEC variations are investigated in relation to the time-integrated EEJ strength. The EEJ values are integrated from 07:00 IST up to 2 h earlier of the time at which TEC values are selected.

A statistical analysis made on the database reveals that in the equinoctial months the estimated correlation coefficients lie in the range of 0.4–0.7 with high level of significance at the time interval of 10:00–12:00 IST. Thereafter a decaying trend in correlation is detected (Fig. 4). A comparatively low value of correlation coefficient marked the high solar activity period (1990). The secondary maximum is occasionally observed in the time interval of 16:00–17:00 IST. Even a negative correlation during afternoon-to-evening hours (16:00–20:00 IST) of both the solar phases is noted for the moderate/high solar activity periods (1988/1989). It may be mentioned that TEC data for the equinoctial months of descending phase (1980–1985) are incomplete due to irregular satellite (ETS-2) transmission.

In the summer solstitial months of the ascending phase (1986–1990), prominent pre-noon maximum in correlation coefficient is observed around 10:00–11:00 IST. In the descending phase (1980–1985) and throughout the day slightly higher (>0.5) values of correlation coefficients are observed compared to the ascending solar epoch. The test of significance reveals high level of significance throughout the day for summer solstitial months of descending phase. In the December solstitial month somewhat higher values of correlation coefficient in the daytime period distinguishes the descending phase from the ascending one. An overall smooth variation in correlation coefficients is observed with integrated EEJ compared to the erratic variation of the same obtained with instantaneous values of EEJ.

At solar minimum the formation of the anomaly appears to be influenced mainly by daytime drift (Rush and Richmond, 1973) the driver of which is E-region electric field. At solar maximum not only daytime vertical drift but expansion of the ionosphere and concomitant higher altitude of F-layer also lead to the formation of an extended anomaly. There is consistent increase in EEJ intensity from solar minimum to solar maximum for all seasons indicating corresponding increase in the electric field $\boldsymbol{E}$ and enhancement of the EIA (Walker and Ma, 1972) though according to Rastogi (1993) the increase in EEJ is mainly attributable to the E-region electron density rather than electric field changes. Inspite of less dependence of daytime vertical drift on solar activity, presence/absence of other modulating factors may lead to lesser/better correspondence between TEC and EEJ at different levels of solar activity.

Though EEJ strength is an important index for the equatorial electrodynamics, transport of plasma to off-equatorial locations should also be heavily weighted by diffusion and wind system. In winter solstitial month meridional wind generally accentuates the rate of diffusion process more compared to that in the equinoctial period (Patil et al., 1990) while in the summer solstitial month trans-equatorial wind may impede the rate of diffusion. The location of the observing station with respect to the position of the anomaly crest seems to be very critical to exhibit better/lesser correspondence. In the summer solstitial months the competitive effects of trans-equatorial wind and diffusion process may locate the anomaly crest just overhead of the observing station to reflect better correspondence with EEJ.

The development of anomaly in the evening hours was reported to be related to the past history of the EEJ variation in the earlier hours, rather than the instantaneous values of the midday EEJ strength (Raghavarao et al., 1978; Rastogi and

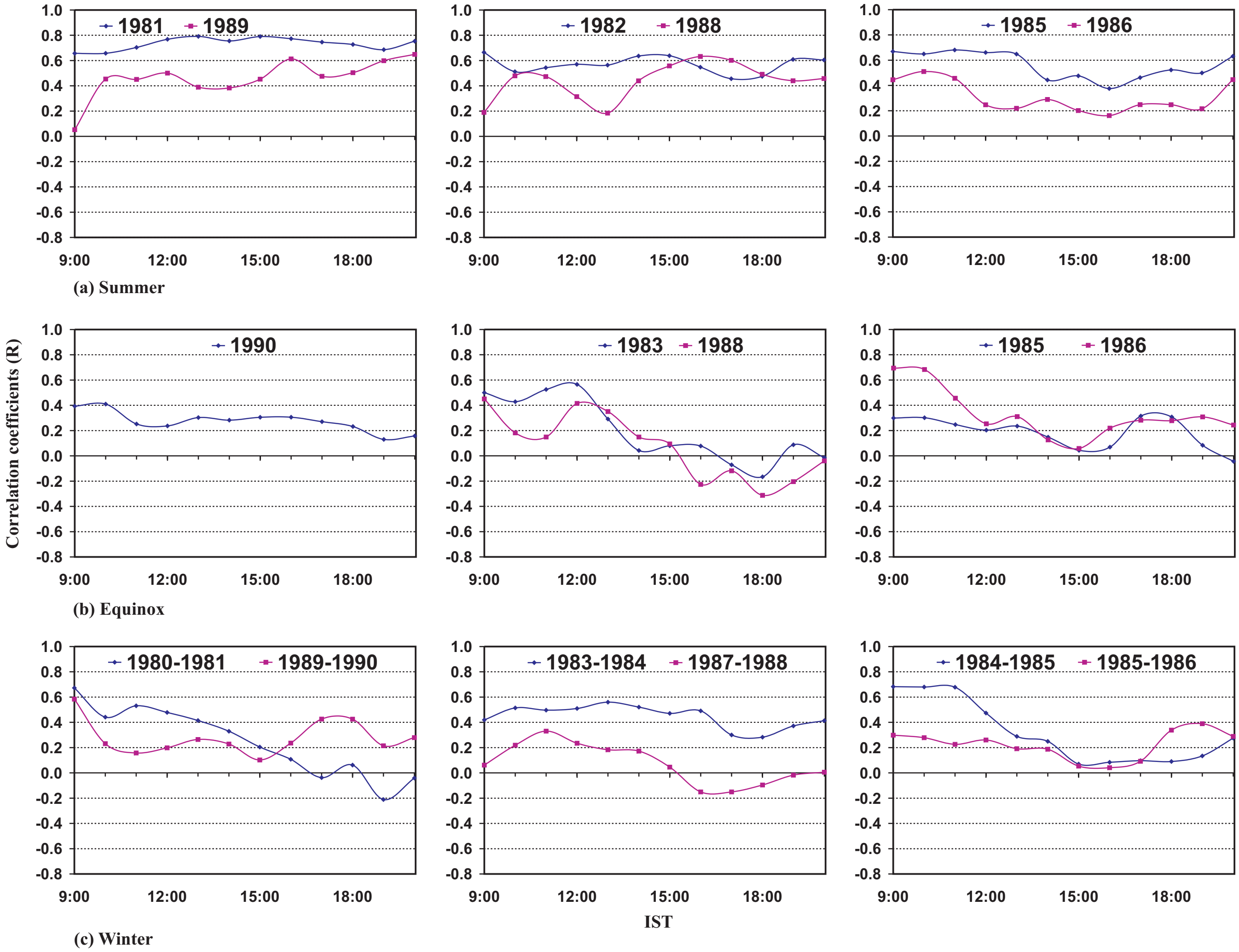

Fig. 4. Diurnal variation of correlation coefficients (R) between TEC and time-integrated EEJ (nT-h) for high, moderate and low solar activity years. Panels **(a)**, **(b)** and **(c)** refer to summer, equinoctial and winter solstitial months respectively. TEC data for the equinoctial months of high solar activity years of descending phase are incomplete due to irregular satellite transmission.

Klobuchar, 1990). Instead of instantaneous EEJ if integrated values of the same are considered, no prominent post-sunset maximum in correlation is detected – sometimes even a negative correspondence is reflected. When instantaneous values of EEJ are considered correlation maximum are recorded to be more or less regular feature in the equinoctial months. In the integrated EEJ values an ever increasing trend may not reflect the finer details of fountain related anomaly variation.

Although a good linear fit is observed when diurnal TEC values are plotted against EEJ (instantaneous as well as integrated), scatterings in the data points may be attributed to several factors. TEC is not a simple function of equatorial dynamics as revealed through changes of EEJ. Solar flux, winds, tides and waves contribute to the TEC variability. Moreover, vertical plasma drift at the magnetic equator is proportional to the electric field while EEJ gives an estimate of current. It should be mentioned that the EEJ current which dictates the magnetometer deflection is proportional, as stated earlier, to the product of conductivity, dictated by the number density and the electric field strength (Rastogi, 1993). Day-to-day variability of TEC is basically due to electric field.

3.4 Empirical formula for diurnal monthly mean TEC variation

Variability of TEC at any location is dictated by several factors among which solar flux and equatorial fountain may be considered as two important contributors in the low latitude ionosphere. Considering solar flux, seasonal and local time dependent features, an empirical formula for monthly mean TEC, applicable in the early morning hours (07:00–09:00 IST), was developed (Chakraborty and Hajra, 2008).

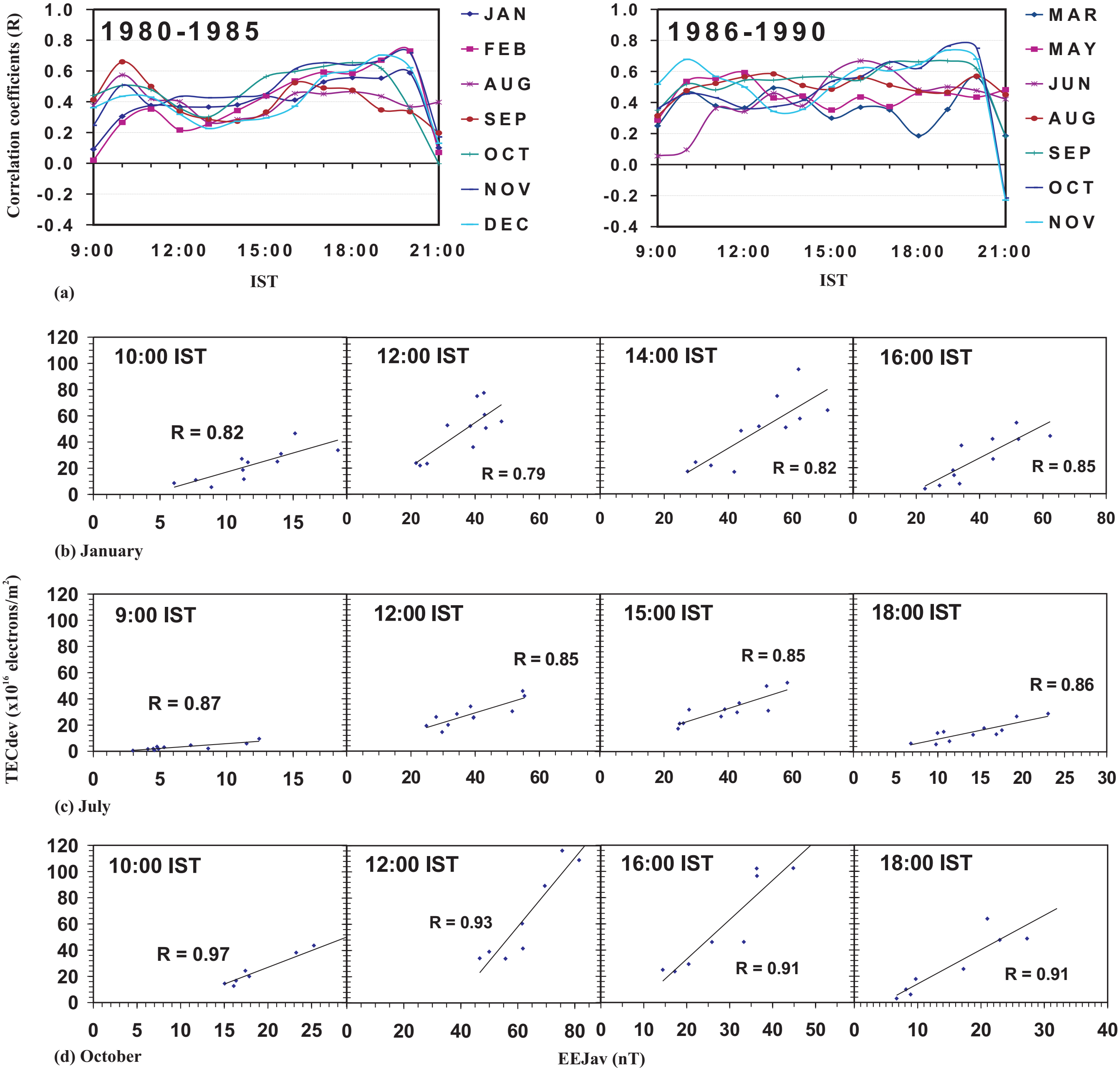

Fig. 5. (a) Plots of diurnal variations in correlation coefficients (R) between TEC deviations and EEJ strength with a time delay of 2 h for two phases of solar cycles and for the months as indicated. The deviations at a particular time are calculated from solar flux normalized TEC values at 08:00–09:00 IST. Panel **(b)** shows the deviations of monthly mean TEC at the specified time vs. monthly mean EEJ strength at 2 hrs earlier time for the month of January. For the months of July and October the same are plotted in panels **(c)** and **(d)**, respectively.

In the present analysis slight modification of the formula has been attempted by incorporating an additional term dependent on EEJ so that it may be applicable in the later periods. The modified form of the empirical formula may be written as:

$$\mathrm{TECcal} = \Phi(m_k, F_{10.7}, F_k)\Big[(a_s \times F_{10.7} + c_s) + \left(\frac{m_k}{12}\right) \times \left(a_m \times \sin\left(\frac{2\pi m}{\lambda_m} - \delta_m\right) + c_m\right) + \left(\frac{t}{24}\right) \times \left(a_t \times \sin\left(\frac{2\pi t}{\lambda_t} - \delta_t\right) + c_t\right)\Big] + (a_e \times \mathrm{EEJ}_{\mathrm{av}} + c_e)$$

where

$\Phi(m_k, F_{10.7}, F_k)$ = a function of m_k and $F_{10.7}$ and F_k;

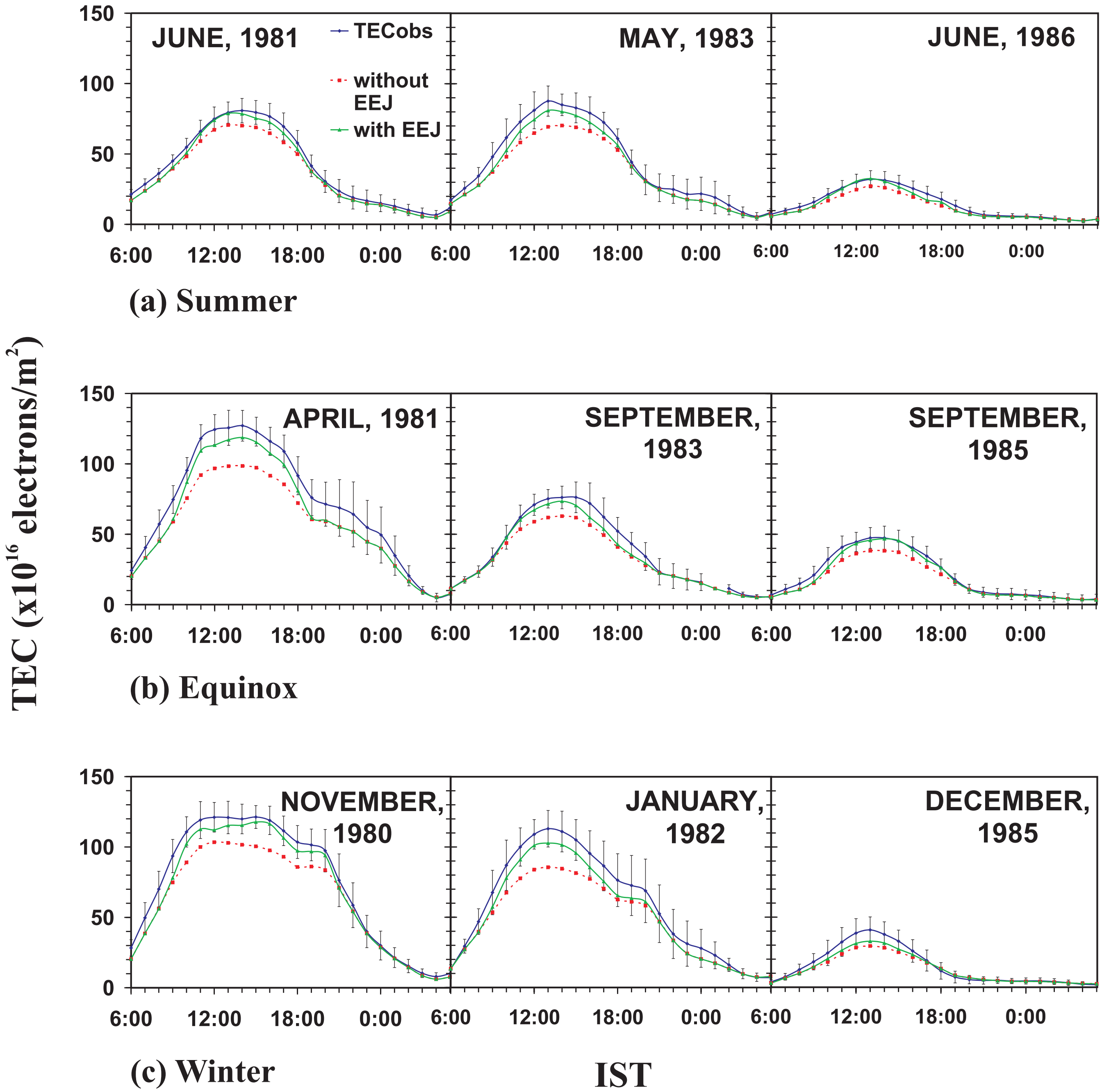

Fig. 6. Plots of observed monthly mean diurnal TEC (solid blue lines with vertical bars), calculated TEC without (red dotted lines) and with (solid green lines) the effect of EEJ for summer solstitial months **(a)**, equinoctial months **(b)** and winter solstitial months **(c)** of the years as mentioned. Vertical bars represent standard deviations of the monthly mean observed TEC.

m_k=8 for winter (November, December, January);

m_k=6 for equinox (February, March, April, August, September, October);

m_k=6 for summer (May, June, July);

$F_{10.7}$=solar flux value;

F_k=80, 100, 125, 150, 175, 200, 225 (matching solar flux values);

m=month;

t=time (IST);

λ_m, λ_t=periodicities of seasonal and temporal variations of TEC.

The first term within the third bracket is assumed to represent the dependence of TEC variability on solar flux. The seasonal and local time contributions are represented

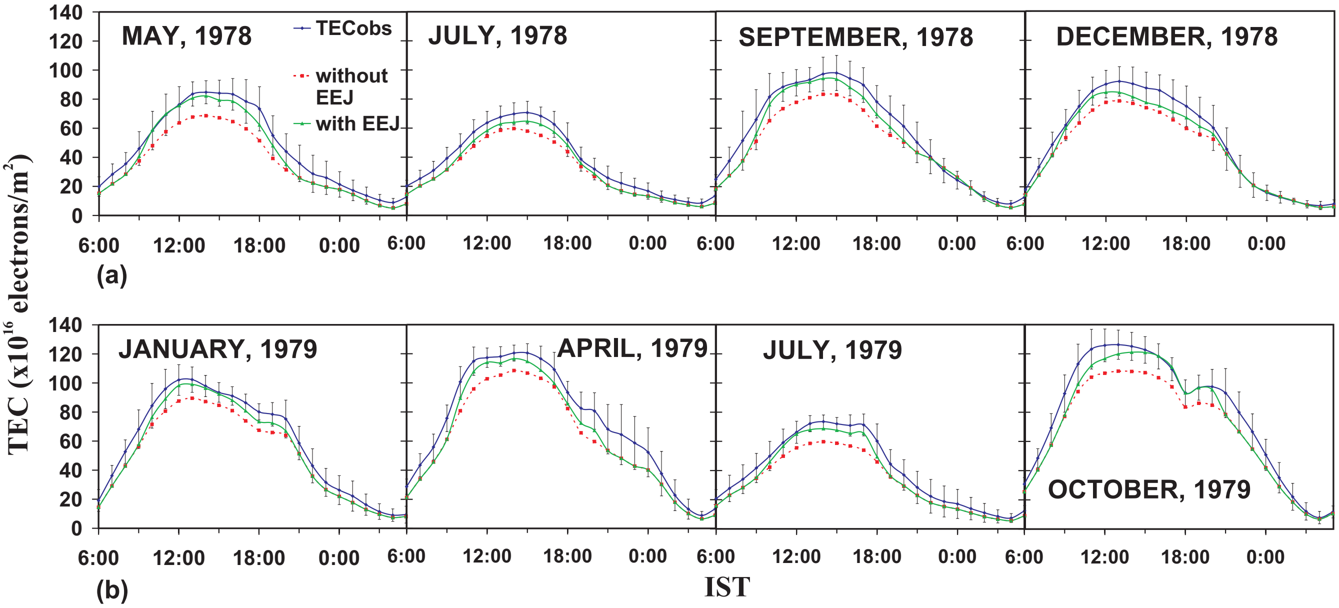

Fig. 7. Plots of diurnal variation of monthly mean observed TEC (solid blue lines with vertical bars), estimated TEC with (solid green lines) and without (red dotted lines) EEJ contribution for various months of the years **(a)** 1978 and **(b)** 1979, respectively. For derivation of the empirical formula TEC data for the period 1980–1990 have been used. Vertical bars represent standard deviations of the monthly mean observed TEC.

by the second and third terms respectively. The solar flux contribution is observed to be maximum around 08:00–09:00 IST (Chakraborty and Hajra, 2008). Thereafter, the rate of production may be assumed to remain constant (Garriott and Smith, 1965). The variability in TEC around the later period may be attributed to the variability of fountain effect, wind systems, etc. As stated earlier, EEJ may be considered as proxy index of equatorial fountain. For the contribution of fountain, deviations of the monthly mean diurnal TEC from the corresponding solar flux normalized values around 08:00–09:00 IST are considered. The deviations in TEC are observed to vary linearly with the EEJ (Fig. 5b, c, d). The diurnal variations of correlation coefficients calculated on the basis of daily values are shown in Fig. 5a. The coefficients are found to be significantly high during the time period from 09:00 to 20:00 IST. From the linear fit between TEC deviation and EEJ, contribution of EEJ (last term) has been extracted.

3.4.1 Validation of the formula

Using the empirical formula diurnal values of monthly mean TEC are calculated for the period (1980–1990). A pictorial representation of the observed diurnal values and the estimated values, with and without contribution of EEJ, is shown in Fig. 6. It is apparent from the figure that when the contribution of EEJ is excluded, large deviations from the observed TEC values result during the time period of 09:00–20:00 IST. Inclusion of EEJ term in the formula successfully enhances the calculated values and all the estimated values fall well within the 1σ range of the observed values. A typical solar activity dependent feature in the estimated TEC is also evident in the plots.

A further validation of the empirical formula has been made using the observed TEC data for the years 1978 and 1979 (Fig. 7). It may be noted that development of empirical formula is based on observed TEC data for the period (1980–1990). Data for the years 1978–1979 are beyond that range and provide a good opportunity for validation of the formula with the experimental values. Calculation, excluding the EEJ contributions, although generates TEC values within 1σ range in the early morning and late night hours, larger deviations in the time interval of 09:00–20:00 IST seems to be minimized by the introduction of term involving EEJ.

3.4.2 Relative contributions

A comparative study on the relative contribution of separate terms appearing in the formula has been made. The results are shown in the surface plots of Fig. 8 from which the following points may be extracted:

1. The solar flux effect appears to be maximum around 08:00–09:00 IST and the contribution thereafter remains more or less same (50–70%) throughout the day. During high solar activity years percentage contribution of solar flux is remarkably higher than the lower ones though the features are not so prominent in summer solstice months. Nighttime contribution is higher

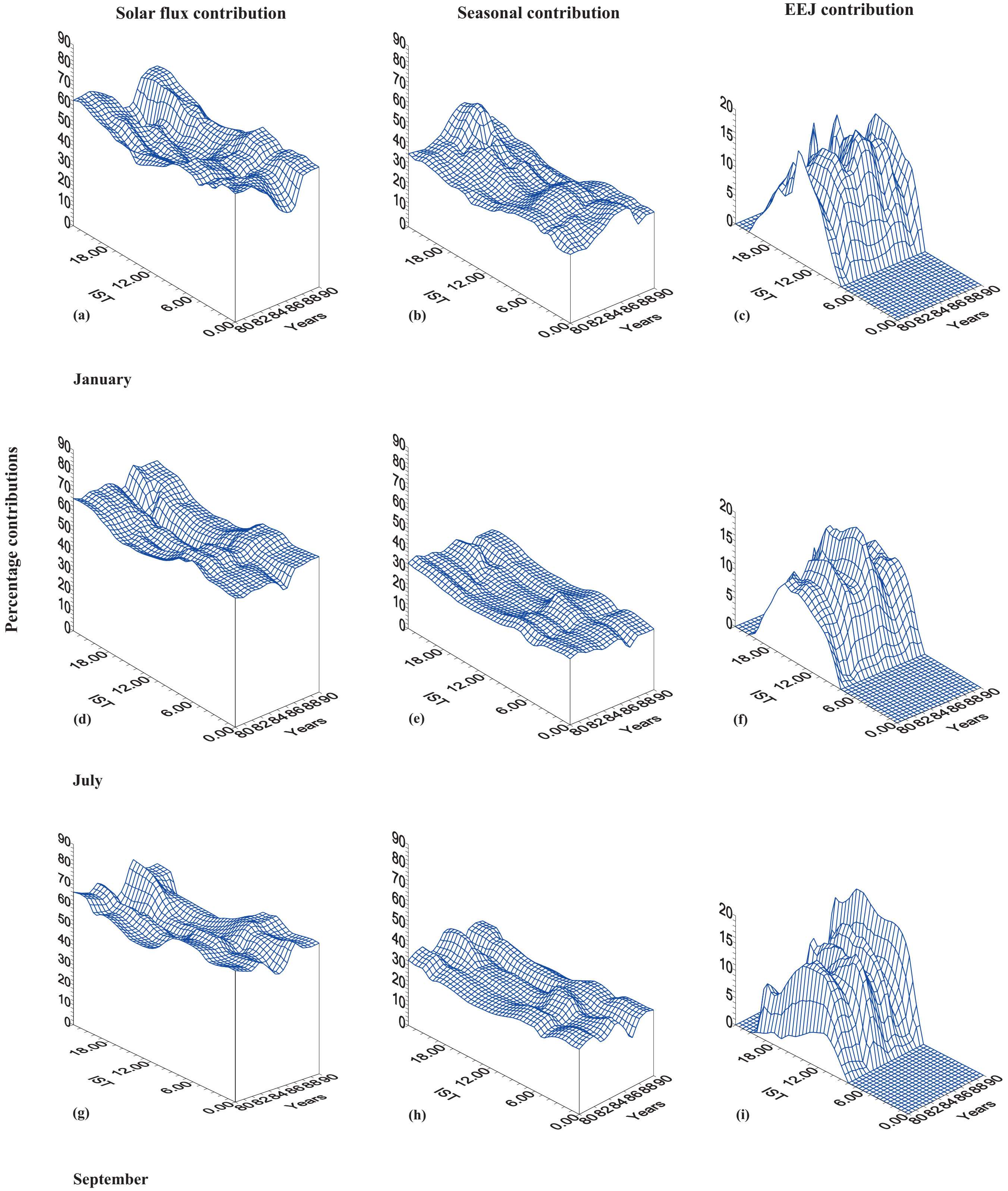

Fig. 8. Surface plots characterizing solar flux (first column), seasonal (second column) and EEJ contributions (third column) respectively in the estimated TEC values for the period 1980–1990 and for the months of January (upper panel), July (middle panel) and September (bottom panel), respectively.

during summer compared to the winter solstitial months and the overall solar flux contribution is highest during equinox.

2. The percentage contribution of EEJ increases gradually after 09:00 IST to attain the maximum level (∼15–20%) around 14:00–15:00 IST. Thereafter a decreasing trend follows and a secondary peak in EEJ contribution is observed around 18:00–19:00 IST. In the low-to-moderate solar activity years comparatively larger dependences on EEJ are recorded in the summer months than the equinoctial ones.

3. After sunrise seasonal contribution increases and becomes maximum (∼30%) around 08:00–09:00 IST. A secondary peak is noted well after sunset. The higher seasonal contribution is reflected in the equinoctial months of high solar activity years. In the other seasons the feature is not so comprehensible. Overall seasonal contribution in winter months appears to be somewhat larger. Trans-equatorial neutral wind, composition changes may lead to the seasonal anomaly.

Though the estimated values more or less reproduce the observed TEC values – some deviations from the experimental values are still evident in the plots (Figs. 6 and 7). It may be noted that the contributions of EEJ are incorporated for the time interval (07:00–18:00 IST), as E-region conduction current which is mainly responsible for EEJ seems to persist during this interval. TEC, being a height integrated parameter, is weighted mostly by topside ionosphere where dynamical processes controlled by meridional component of neutral wind and the perpendicular $\boldsymbol{E}\times\boldsymbol{B}$ drift of plasma dominate. The meridional wind, blowing toward the pole during the day and toward the equator at night (Kohl and King, 1967; Igi et al., 1999) with a prominent seasonal dependence, controls decisively the appearance, strength and duration of the anomaly. Further, tides and waves also contribute to the TEC variability. The nighttime variability of TEC is influenced by cosmic rays, ionization influx from more distant protonosphere and the equatorward neutral wind. TEC observations made at Calcutta situated virtually below the northern crest of the equatorial anomaly are expected to be influenced by these dynamical aspects and deviations in estimated TEC may be attributed to above mentioned factors.

4 Summary

An extensive study on the variability of TEC, using long-term (1978–1990) database obtained from a location near the equatorial anomaly crest (Calcutta) in relation to EEJ clearly exhibits a remarkable solar epoch dependent feature with descending phase resembling better correspondence compared to the ascending epoch. On the seasonal basis, TEC in summer solstitial months correlates better with EEJ than the equinoctial and winter months. Analysis based on instantaneous values of diurnal EEJ reveals two maxima in correlation, one in the time interval 10:00–12:00 IST and the other in the interval 18:00–20:00 IST. An impulse-like feature is also detected around the above mentioned periods. The feature of secondary maximum in correlation is conspicuously absent when integrated values of EEJ are considered. The greater association between the two in the stated time period may be related to movement of the crest (poleward/equatorward) or concomitant dominance of fountain (forward/reverse) effect. The location of the observing station seems to play a crucial role in controlling the EEJ related TEC variability. Combining the contributions of solar flux, EEJ, season and local time in TEC variability an empirical formula of diurnal monthly mean TEC has been developed. Though the formula successfully generates the diurnal TEC pattern, certain deviations from the actual values call for further improvement involving terms related to neutral wind, tides and waves, etc.

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