Storm Effects of Ionospheric Total Electron Content (TEC) at Low Latitudes

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The changes in the ionospheric Total Electron Content (TEC) obtained by the Faraday rotation method at a chain of low latitude stations all in India (longitude about 75°E) are studied during a few selected geomagnetic storms mostly in winter of 1975–76. For the location Octacamund very near the dip equator in India, TEC data were available by the Group delay method also, and these correlated very well with the TEC data obtained by the Faraday rotation method.

Large changes of TEC, both positive and negative, were observed at all locations, but these did not bear any clear relationships either with the specific phases (Main Phase Onset, Recovery) or with the magnitude of the geomagnetic storms. Often, large changes were observed even before the Main Onset. The fountain effect, in which a strong equatorial electrojet is associated with a large noon-time bite-out in equatorial foF2 and a large equatorial anomaly (excess ionization at the crests at about ±30° dip angles) or, its reverse effect (a weak electrojet associated with a lack of foF2 bite-out and a decreased equatorial anomaly), were seen very clearly in some instances during or even before a geomagnetic storm. However, in many other cases, the fountain effect was largely distorted.

It is surmised that apart from electric field effects, neutral winds not only of polar origin but probably of low latitude origin are creating large dynamic upheavals in the low-latitude ionospheric regions, often in a random fashion, not only during geomagnetic storms but even before or long time after the storm onsets. If true, the origin of such winds needs investigation.

1. Introduction

Ionospheric storm effects have been reported by several workers in the past, using foF2 data as well as TEC data (see reviews by RISHBETH, 1975 and EVANS, 1977 and the references therein). It is reported that in association with geomagnetic storms, especially during the main phase, large increases and/or decreases in TEC are observed, which are generally reflected in Nmax also though not invariably so. Most of these observations refer to middle and high latitudes and are interpreted in terms of electric fields and/or neutral winds of polar and auroral origin. However, as shown by KANE (1973a, 1975a, 1978) there are considerable changes from storm to storm, so much so that the average pattern
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claimed viz. decreases at mid-latitudes and increases at low-latitudes is violated more often than not and one wonders whether there is any systematic behaviour at all.

The data for low and equatorial latitudes have been rather meagre. With the ATS-6 geostationary satellite positioned at 34°E, it was possible, during 1975–76, to make TEC measurements by recording the Faraday rotation of signals of 140 MHz in India, at Patiala (subionospheric geomagnetic latitude 18.5°), Udaipur (13.6°), Ahmedabad (12.2°), Bombay (8.5°), and Ootacamund (1.0°), all in the 72–77°E longitude zone. Some results of the storm-time behaviour of TEC at the first four locations have been already reported by Jain et al. (1978a, b). Patiala is located to the north of the well-known equatorial anomaly crest, while Udaipur and Ahmedabad are near the crest of the anomaly and Bombay is to its south. Jain et al. (1978a, b) report that all the locations show TEC increases (positive phase) mostly in the forenoon of the 1st day and almost throughout the 2nd day, or decreases (negative phase) in the afternoon of the 1st day and on the 3rd day and they are in general agreement with the changes in the fountain effect which are depicted by the changes in equatorial fF2 and equatorial electrojet with a diffusion time of about 2 hours from equator to low latitudes. Recently, similar processed data for Faraday rotation for the near equatorial location Ootacamund became available. In addition, recordings of TEC at Ootacamund by the sophisticated Group delay method were also available. There is a general belief that whereas for middle and high latitudes the method of deducing TEC from Faraday rotation is very reliable, the method is unreliable near the equator where the ray path is almost perpendicular to geomagnetic field lines. The Group delay method has no such a disadvantage and is expected to give a true estimate of TEC even at the equator. Sethia et al. (1978) have compared the TEC data obtained by these two methods at Ootacamund and report that, except for the diurnal ratio, which is low for the TEC from Group delay method due to increased plasmasphere electron content during night, the two methods give similar results. In this communication, we first compare the storm-time effects observed at Ootacamund (near the equator) by the Faraday rotation and Group delay method simultaneously, and also study critically the storm-time behaviour of TEC from equator to about 20° geomagnetic latitude for a few selected storms for which we had adequate simultaneous data.

2. Experimental Results

In November 1975, there were several geomagnetic storms. Figure 1 shows in the upper half the plot of geomagnetic Dst (Sugiura and Poros, 1971 and similar later publications) for the period November 21–24, 1975. The first day November 21, was not completely quiet (Dst had negative values about -30 gamma), but a big storm started on November 22 at about 1200 LT. The next two plots are for TEC observed at Ootacamund by the Faraday rotation method (N_F) and Group delay method (N_T). What is plotted is ΔN_F and ΔN_T, i.e., deviations of TEC from the respective monthly median daily variation patterns. The resemblance between the two is very remarkable indeed, and there are large changes, positive as well as negative indicated by both. The lower half of Fig. 1 shows similar plots for another storm which occurred a few days later (November 28 – December 1, 1975) with a main phase onset on November 29 at about 1200 LT, i.e., same as for the
Fig. 1. Plot of hourly values of geomagnetic $D$ and the deviations from monthly average curves for the Total Electron Content measured at Ootacamund (near the equator) by the Faraday Rotation method ($\Delta N_F$) and by the Group delay method ($\Delta N_T$) for the storms of November 21–24, 1975 (upper half) and of November 28–December 1, 1975 (lower half). Positive deviations are shown black and negative deviations are hatched.

Fig. 2. Plot of hourly values of $\Delta N_T$ versus $\Delta N_F$ for (a) the storm of November 21–24, 1975 and (b) the storm of November 28–December 1, 1975. Open circles represent hours before Main Phase Onset (MPO) and triangles represent hours after MPO. Correlation coefficients as well as slopes of regression lines with standard errors are indicated.
earlier storm. In Fig. 2, the actual deviations of $\Delta$TEC obtained by these two methods, viz. $\Delta N_T$ and $\Delta N_F$, are plotted versus each other for the storms separately, the open circles representing pre-storm periods (i.e., hours before the Main Phase Onset) and the triangles representing periods from MPO onwards. Following points are noteworthy:

1) In Fig. 2, all the points are reasonably near the 45° regression line, indicating that the TEC measured by the two methods is almost the same. This is very gratifying indeed and indicates that in contrast to the popularly held belief, the Faraday rotation method gives fairly reliable results even at the equator. The correlation coefficients are very high, exceeding +0.85 in all cases as indicated in the figure.

2) In Fig. 2, $\Delta$TEC attains large positive as well as large negative values. The two storms have almost the same Main Phase Onset time (1200 LT) and the $D_{st}$ magnitudes are exceeding 50 gamma in both. But the $\Delta$TEC patterns (see Fig. 1) are completely different in the two cases. In the November 22 storm, $\Delta$TEC was highly positive from noon to dusk not only during the main storm but even one day earlier; and, during night hours, $\Delta$TEC was negative on all the nights. The daytime increases are not high all through but seem to be made up of positive oscillations of a few hours duration at a time. In contrast, the November 29 storm shows highly negative $\Delta$TEC on the storm days and even before and a highly positive $\Delta$TEC on the third day. Comparison with variations of TEC at other higher latitudes is undertaken later on (Figs. 3 and 4); but we want to emphasize here that in the same season (northern winter) for two storms within a few days of each other and having a noontime MPO for both, the $\Delta$TEC patterns at equator are radically different, showing a highly positive phase in one storm and a highly negative phase in another. Also the effects occurred even before the storm MPO and hence throw a serious doubt upon whether the geomagnetic storm had any relation at all with the TEC changes. In Kane (1975b) it was shown that there was great day-to-day variability in TEC during quiet as well as disturbed days. The above evidence also shows a similar behaviour. There is also a large difference of behaviour in the post-storm period of these two storms. On the third storm day, the first storm shows very small $\Delta$TEC but the latter storm shows a very large positive phase. Of course in the latter case, the $D_{st}$ has not yet recovered to normal and there might be a second storm in progress; but the $D_{st}$ values were only about −40 gamma, while the positive $\Delta$TEC was enormous, larger than even the positive $\Delta$TEC of the earlier geomagnetic storm which had a $D_{st}$ as large as −100 gamma. Thus the magnitude of the $D_{st}$ or the LT of MPO seems to bear no relation either with the nature of the TEC changes (positive or negative) or with the magnitude of TEC changes.

3) In the storm of November 29 (lower half of Fig. 1), there is a dissimilarity of TEC obtained by the two methods in the morning hours. The Group delay method shows a positive $\Delta$TEC while the Faraday rotation does not. A comparison with $\Delta N_{\text{max}}$ as obtained from $f_0F_2$ at the equatorial station of Kodaikanal (geomagnetic latitude 0.6°, geographic longitude 77.5°E) showed that the $N_{\text{max}}$ changes were more similar to the TEC changes obtained by the Faraday rotation method. The Faraday rotation method gives the electron content up to about 2,000 km altitude, while the Group delay method gives the content up to the plasmasphere. The increase shown by the TEC of the Group delay method may be predominantly of plasmaspheric origin. The actual plots of $\Delta N_{\text{max}}$ are
shown in later diagrams (Figs. 3 and 4), where these storms are reconsidered.

Figures 3 and 4 show four day sequences with geomagnetic $D_{st}$ at the top followed by changes of TEC obtained by the Faraday rotation method ($\Delta N_F$) at Patiala, Udaipur, Ahmedabad, Bombay and Ootacamund and by the Group delay method ($\Delta N_T$) at Ootacamund only, $N_{\text{max}}$ deviations for Kodai Kanal and the equatorial electrojet strength $\Delta S_{d}$ at Trivandrum, for the storm period November 21–24, 1975.

2.1 *Storm of November 21–24, 1975 (Fig. 3)*

This has already been depicted in Fig. 1. The pre-storm day November 21 was not very quiet and $D_{st}$ changes of $-30$ gamma did occur. Whether the large positive TEC can be attributed to this small magnetic disturbance or is a quiet day phenomenon is a moot question. The equatorial electrojet was strong and $\Delta N_{\text{max}}$ was negative in the afternoon. So the whole picture is consistent with a strong fountain effect. On November 22, the electrojet was abnormally weak, $N_{\text{max}}$ and TEC changes at equator were positive and TEC changes at the crest were large negative. Thus a strong inhibition of the fountain
effect is indicated. If this is to be related to the geomagnetic storm which had an MPO at about 1200 LT on November 22, then this would be an example of a negative phase without an earlier positive phase at low latitudes. On the next day, the electrojet was still weak and $\Delta N_{\text{max}}$ (and to some extent TEC) at equator were positive. TEC at the crest was positive before noon and slightly negative in the afternoon. November 24 had a strong electrojet, negative $\Delta N_{\text{max}}$, $\Delta N_F$, and $\Delta N_F$ at equator and positive TEC changes at the crest in the afternoon as expected for a good fountain effect. However, the negative values at the crest at noon hours are not easily understood.

2.2 Storm of November 28 – December 1, 1975 (Fig. 4)

This was also depicted in Fig. 1. A conspicuous feature was that TEC changes were large and negative on the afternoon of the pre-storm day November 28, not only at the crest but even at the equator. What caused this large depletion of ionospheric electron content over such a wide latitude range? On November 29, the MPO was at about 1200 LT. TEC changes on November 29 were similar to those on November 28. The equatorial electrojet was large on both the days. So, fountain effect should have been operative giving negative $N_{\text{max}}$ (and probably TEC) changes at the equator, which were seen, and positive TEC changes at the crest, which were not seen. On November 30 also, a similar discrepancy is noticed. On December 1, the $N_{\text{max}}$ and TEC changes at equator were largely positive, indicating an inhibition of the fountain effect and the TEC changes at the crest were highly negative as expected. Thus, December 1 is a very good example of an
inhibition of the fountain effect; but the previous three days are bad examples of a normal fountain effect in the sense that whereas the electrojet was strong and \( N_{\text{max}} \) (and TEC) changes at equator were negative on all the three days, the TEC changes at the crest expected to be positive were found to be highly negative.

On November 30, the TEC at Patiala showed a very large positive change slightly before noon. This feature was not seen at other locations. A check of the data showed no errors.

2.3 Storm of January 9–12, 1976 (Fig. 5)

This was probably the cleanest geomagnetic storm for which TEC data are available to us. The major storm had an MPO at about 1900 LT on January 10. On January 9 (pre-storm day), the electrojet was normal. \( N_{\text{max}} \) data for the equator are missing, but TEC changes at the equator were negligibly small. If the fountain effect was supposed to be normal, TEC changes at the crest should have been negligible, or positive. Instead, these were somewhat negative before noon. On January 10, the electrojet was normal and TEC changes at the equator were negative. The fountain effect was expected to be normal. But TEC at the crest shows small positive and negative fluctuations. Specifically at Bombay, the TEC changes were definitely negative.

On January 11, the equatorial electrojet was weak and had a counter-electrojet in the afternoon. Thus the fountain effect was expected to be inhibited. \( N_{\text{max}} \) data are not available but TEC at the equator did show positive effects. TEC at the crest was expected...
to show negative effects and there was a strong negative phase in the afternoon; but there was a strong positive phase before noon which is obviously not connected with the fountain effect. On January 12, which was in the recovery of the geomagnetic storm, the electrojet was strong and TEC changes at the crest were largely positive, as expected.

Besides these three storms, several others, viz. those of November, 1–4, November, 8–11, November, 16–19, December, 7–10, December, 25–28, 1975, and May, 1–4, 1976 were studied in detail. The diagrams are not shown here.

3. Discussion

It is known (MacDougall, 1969; Kane, 1972; Iyer et al., 1976) that there is a large day-to-day variability in the magnitude and profile of the equatorial electrojet, the $f_0F_2$ (and hence $N_{max}$) at the equator and TEC at low latitudes (anomaly crest). The precise cause of this variability has not yet been ascertained, but there is a fountain effect which connects these three; viz. whenever the equatorial electrojet is strong, the vertical Hall polarization field is large, the equatorial $f_0F_2$ (and $N_{max}$) shows a noon-time bite-out (negative changes from average) in its daily variation pattern, electrons are convected upwards at the equator and later fall back along magnetic field lines to the regions corresponding to the low and middle latitude anomaly crests, giving positive TEC changes there. The TEC changes at the equator may or may not show the $f_0F_2$ bite-out, depending upon how high the fountain rises. If the equatorial electrojet is weak, this fountain effect is inhibited (i.e., reversed), $f_0F_2$ (or $N_{max}$) bite-out disappears, equatorial TEC may or may not show any positive changes, but the TEC at the crest is expected to show a negative change.

In this paper, we investigated this relationship before and during a few selected geomagnetic storms, and observed the following:

1) Results for the Faraday rotation method and Group delay method are similar even at the equator, which is a pleasant surprise.

2) Whereas a relationship between geomagnetic and ionospheric storms is usually claimed, we notice that large changes in ionospheric TEC at low and equatorial latitudes are often observed even in the pre-storm period and can be at least as large as those observed during storms, sometimes even more.

3) These changes can be positive as well as negative at the crests and, when considered in conjunction with the equatorial $N_{max}$ and TEC changes (which can also be positive as well as negative) and the changes in the equatorial electrojet strength, sometimes give a plausible pattern consistent with the fountain effect but not always. In some cases, other effects seem to interfere with the fountain effect or its inhibition (i.e., negative fountain effect) in a big way.

4) Negative effects without seeing first the positive effects are quite common and if interpreted in terms of composition changes (molecular enrichment of air), would imply either a very rapid transit of neutral winds from poles to equator or a local equatorial turbulence.

5) Positive or negative TEC changes either in the pre-storm period or in the late recovery (3rd or 4th storm day) would imply that changes in the geomagnetic field as such
are not directly connected with ionospheric changes. Either local effects or effects brought on from the polar regions by neutral winds are occurring even when there is no perceptible geomagnetic activity. The geomagnetic storm triggering as indicated by SSC or MPO may be only an harbinger of something else which enters the polar region and then spreads towards the equator in its own way, unrelated to the further development of the geomagnetic storm; or there might be entries of plasma directly in low and middle latitudes. It is particularly noteworthy that large geomagnetic $D_n$ changes could look associated with small TEC changes or vice versa.

In short, SSC, Main phase and Recovery, which are the striking features of a geomagnetic storm, may not be directly related to an ionospheric storm at all and the origin or origins of the latter will have to be searched independently. Complex neutral wind motions and penetration of magnetospheric and polar electric fields to the equatorial ionospheric region seem to be involved and their dynamics may have nothing to do with the ring currents that produce geomagnetic changes. Normally, the polar regions are supposed to be sources of large scale neutral winds blowing towards the equator during storms. We suspect, however, that either these polar neutral winds have a considerable random component which causes complications in the ionospheric dynamics of the equatorial region not only in conjunction with geomagnetic storms but even during geomagnetically quiet periods or, that turbulent neutral winds are produced independently in low latitudes, and the connection with geomagnetic storms is not at all obvious either qualitatively or quantitatively. During geomagnetic storms, TEC is generally believed to show an evening increase for stations lying on $L$ shells within the plasmasphere and several mechanisms are proposed as explanations (MENDILLO et al., 1970, 1974; EVANS, 1970, 1973, 1977; PAPAGIANNIS et al., 1971; SOMAYAJULU et al., 1971; JONES and RISHBETH, 1971; OBAYASHI, 1972; TANAKA and HIRAO, 1973; DAVIES and RUSTER, 1976; SOICHER, 1976; RISHBETH, 1975).

For the equatorial region, several processes are likely to affect the electron density. Firstly, the neutral winds originating from the polar regions would eventually converge on the magnetic equator and would thus oppose the fountain effect and hence reduce the magnitude of the equatorial anomaly (BURG et al., 1973) and equatorial locations would show positive $N_{\text{max}}$ (and probably TEC) changes. The convergence of the winds may also give rise to plasma compression resulting in an increase in equatorial $N_{\text{max}}$. Both these effects would give a positive phase at the equator. On the other hand, changes in air composition, in particular an increased molecular/atomic ratio which may eventually reach equator too, would increase the loss coefficients and thus reduce the equatorial electron density $N_{\text{max}}$ and perhaps TEC also. In addition, if the quiet-time electric field structure at the equator is altered during storms because of some magnetospheric or polar connection, this would affect the fountain effect in a complicated way.

Earlier results on low and equatorial storms are as follows. WALKER (1973) reported for Hong Kong (geomagnetic latitude $10.9^\circ$) that MPOs occurring during the daytime were sometimes preceded by a slight increase but often followed by a sharp decrease in TEC and $N_{\text{max}}$. KAUSHIKA and MADAN (1975) reported for São Paulo, Brazil (geomagnetic latitude $-11.9^\circ$) a considerable negative effect on the storm day. BASU et al. (1975) reported for Honolulu (geomagnetic latitude $21.0^\circ$) an initial positive phase followed by a
long enduring negative phase for TEC as well as $N_{\text{max}}$ during summer and only a marked positive phase during winter. Yeboah-Amankwa (1976) reported for Legon (geomagnetic latitude 9.7°) for equinox and winter storms a general rise (positive phase) sometimes persisting long after the geomagnetic storm. It would be interesting to study the evolution of ionospheric storms at close-by spaced locations right from poles to the equator preferably in the same longitude zone, as this would throw considerable light on the actual movements of neutral winds. It is hoped that such an opportunity will arise in future.

The data used in this analysis are available in the ISRO Scientific Note ISRO-SN-07-78, December 1978, entitled “Total Electron Content data collected during ATS-6 Radio beacon experiments in India” published by ISRO Headquarters, Bangalore, India. Thanks are due to Prof. R. G. Rastogi and his colleagues for running this network of stations very successfully and making the data available. Thanks are due to Prof. K. Davies SEL/NOAA Boulder for collaboration on the ATS-6 RBE project at Ootacamund. Thanks are due to Dr. Nelson de Jesus Parada, Director of INPE for support. This work was partially supported by Fundo Nacional de Desenvolvimento Científico e Tecnológico under contrast FINEP-537-CT.

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