Global Ionosphere Perturbations Monitored by the Worldwide GPS Network

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Abstract. For the first time, measurements from the Global Positioning System (GPS) worldwide network are employed to study the global ionospheric total electron content (TEC) changes during a magnetic storm (November 26, 1994). These measurements are obtained from more than 60 world-wide GPS stations which continuously receive dual-frequency signals. Based on the delays of the signals, we have generated high resolution global ionospheric maps (GIM) of TEC at 15 minute intervals. Using a differential method comparing storm time maps with quiet time maps, we find that significant TEC increases (the positive effect) are the major feature in the winter hemisphere during this storm (the maximum percent change relative to quiet times is about 150%). During this particular storm, there is almost no negative phase, A traveling ionospheric disturbance (TID) event is identified that propagates from the northern subauroral region to lower latitudes (down to about 30°N) at a speed of -460 m/s. This TID is coincident with significant increases in the TEC. We also find that another strong TEC enhancement occurs in the pre-dawn sector in the northern hemispheric subauroral latitudes, in the beginning of the storm main phase. This enhancement then spreads into almost the entire nightside. The nighttime TEC increase in the subauroral region is also noted in the southern hemisphere, but is less significant. The global TEC increases last for about 2 days, and then a weak decrease followed, These preliminary results indicate that the differential mapping method, which is based on GPS network measurements, appears to be a powerful tool for studying the global pattern and evolution process of the entire ionospheric perturbation,

Introduction

Dual Frequency Global Positioning System (GPS) measurements have been used by several investigators to study the ionosphere [e.g., Lanyi and Roth, 1988; Wilson et al., 1995; Coker et al., 1995; Kelley et al., 1996]. Data from a worldwide network of GPS sites makes it possible, for the first time, to map global ionospheric TEC variations in near real-tilne. Currently more than 60 global GPS stations receive dual -frequency signals from GPS satellites continuously. Based on the dispersion of the received signals, high resolution interpolated TEC fits or Global ionospheric Maps (GIM) can be produced every 15 min (or more frequently) [Mannucci et al., 1996]. These maps can be used for studying global ionospheric disturbances during geomagnetic storms, among many other applications.

Various observation techniques have been used to study ionospheric variations. Trans-ionospheric radio beacons have been used to measure TEC and to study ionospheric storms on several stations [e.g., Mendillo, 1971; Lanzerotti et al., 1975; Titheridge and Buonsanto, 1988]. The ionospheric local struct urcs arc measured by incoherent scatter radar [Buonsanto et al., 1992]. Tremendous effort has been made to classify and interpret the observed ionospheric disturbance effects [e.g., Fuller-Rowell et al., 1990; Prölss et al., 1991; Pi et al., 1993]. Based on long term studies, some empirical and semi-empirical models have been proposed, such as the Bent [1976] model, the International Reference Ionosphere (IRI-90) model, etc. Some theoretic models have also been developed to explain temporal and spatial structures of the ionosphere [e.g., Anderson, 1973; Schunk, 1988; Bailey et al., 1993].

However, ionospheric day-to-day variability (particularly during storm times) is still not well undcrst ood on global-scales. Yet, the coupling processes bet wccn the magnetosphere and the ionosphere/thermosphere become more compl i cated during magnetic storms. Understanding these processes requires a continuously operating global monitoring s ystem. Previous ionospheric studies have been based primarily on measurements from single or local station chains. Researchers in the past were forced to organize their findings from these stations to obtain a global picture, Single orbiting satellites carrying ionospheric sensors also cannot monitor the response of the global ionosphere to magnetic storms because of the lack of instantaneous global coverage.

In general, ionospheric storms have been observed to include both a positive (TEC or electron density increases) and a negative (TEC decreases) phase. The occurrence of these phases depends largely on season, location, storm intensity, and local starting time. The positive phase usually takes place in the early stages of a storm. In the polar region, Joule heating duc to the electric currents and/or by particle precipitation will cause an increase in the atmospheric pressure at high latitudes. A meridinal wind is usually generated in the polar region and carried by fast-moving traveling atnlosJ>heric/ionospheric disturbances (TAD/TID) to lower latitudes. The enhanced equatorward winds will lift the plasma to higher altitudes in the F-region ionosphere. This upward drift may also be caused by dayside magnetospheric convection electric fields [Earle and Kelley, 1987; Pi et al., 1993]. in contrast, the negative storm phase often takes a longer period to develop. Neutral compositional changes are responsible for this relative decrease in TEC [e.g., Burns et al., 1991; Prölss et al., 1991]. Changes in thermospheric circulation and composition can cause O/N_2 ratio decreases in the middle ionosphere, leading to a decrease in the F region plasma density.

Using simultaneous global observations to monitor the ionosphere, such as is done with extensive ground-based GPS networks, we can identify the global variations of ionospheric TEC during a magnetic storm, inducting the motion, expansion, and intensity of those disturbed regions. This can aid in classifying and interpreting these global changes. In this paper wc will report a global ionospheric perturbation event occurring during the geomagnetic storm on November 26, 1994, monitored by the GPS global network.

Data and Method

The GIM, an interpolated map of ionospheric TEC measurements, is a relatively ncw i onospheric ret rieval technique based on data from a global GPS network of 60^+ stations [Mannucci et al., 1996; Wilson et al., 1995]. The GPS constellation consists of 24 satellites at 20,200 km altitude, These satellites continuously broadcast dual-frequency (1 .57542 GHz and 1.2276 GHz) signals for navigation purposes. Each station may receive signals from up to 10 GPS satellites simultaneously (typically 6-7 satellites are tracked at any onc moment). Thus, from the inter-frequency delay of the signals, the TEC along the lines of sight between 400^+ receiver and satellite pairs arc measured simultaneously. These signals are recorded every 30 seconds and arc transferred to data centers generally within 24 hours (or faster). Roth carrier phase delays and group delays arc used to derive the TEC integrated along the line of sight. Using a Kalman filter-based fitting procedure, these TEC measurements arc interpolated at 642 spherical grid points to produce global ionospheric TEC maps [Mannucci et al., 1996], The TEC error is within 2.0± 4.0 TECU in most global regions [Ho et al., 1996]. Based on these TEC maps, ionospheric variations with small scales can be studied, particularly, in regions where a high density of GPS stations are available. However, in this study, wc will focus on large global scale perturbations.

In order to clearly identify the ionospheric variations during magnetic storms, a differential mapping method is used to compute the percent change of storm-time TEC relative to TEC maps generated for quiet conditions. To obtain the quiet time database, wc averaged 5 days (Nov. 21- 25) of TEC measurements obtained via GIM, for days associated with low magnetic activity (daily sum $\Sigma Kp < 15$). At any particular time and location, the storm time TEC is compared with the quiet time map, taking the quiet time variation (standard deviation of the 5 day averages) as a threshold. These global percent change maps arc in this case plotted every 15 minutes,

in this study, wc also used the direct ionospheric TEC measurements made by the Topex satellite as a reference to examine the accuracy of G] Ms. The Topex satellite has an onboard dual-frequency radar altimeter which precisely measures the sea-surface height after removing an ionospheric correction. Topex's orbit is relativel y fixed in local time (changes only by about 10 min per day). The Topex alt i meter yiel ds a measurement of ionospheric vertical TEC every second over a wide latitude range. The altimeter data has been smoothed into 12 second averages. We have direct] y compared it against the interpolated, mapped to vertical TEC measurements obtained with the GIM method.

Observations

The magnetic storm studied occurs on November 26, 1994. observations from the WINI) spacecraft indicate that the interplanetary magnetic field B_z component at 0600 UT had a large variation associated with a high speed solar wind stream and a magnetic compressed region. The ground magnetic field measurements show that a sudden commencement occurs at -0700 UT, while the main phase of the storm starts at 0900 UT. At 1300 UT the Dst index reaches its maximum value of 122 nT. The maximum Kp value is 6^+ in the 0900-1200 UT interval. The storm slowly recovers and the Dst index reaches its quiet time val uc on December 2. Figure 1 shows the magnetic field (H component) measured around the northern auroral region, the Dst index and the Kp index during this storm.

An analysis of the differential ionospheric maps shows that no large (> 20% increase relative to the quiet time map) TEC changes are found before the storm onset. At 0830 UT, two peaks (range from +80 to + 100%) appear within 15 minutes, in the pre-dawn and morning sectors (north American and north European areas) around subauroral regions. At 0945 UT the two peaks become stronger. They are later identified as one (nightside) being a subauroral enhancement, while the other (dayside) evolves to a TID. Then the peaks become stronger and the enhanced regions become larger. At 1100 UT, the two peaks nearly connect and then cover all regions from post-midnight to noon at subauroral high latitudes. The daytime peak shows a clear equatorward expansion during next few hours. Based on the differential TEC maps, wc find that at 1245 UT the dayside enhancement reaches its maximum value (~+1 50%), coincident with the maximum deviation in Dst. In Figure 2 we give the percent TEC change maps at three time intervals (0945, 1245 and 1545 UT) from the top to bottom panels, respectively. Note that the gray dots in the figure give the locations of the GPS stations. From these maps, wc can see that significant TEC changes occur in the northern hemisphere. Three maps clearly show the evolution of the ionospheric storm and a process of the TID starting, expanding, propagating, damping, and disappearing. This dayside peak has extended equatorward from subauroral region to ~30°N across a large latitude range, We have marked the three intervals (by A, B, and C) in Figure 1 to see the correlation with geomagnetic activity.

After 1545 UT, only the northern subauroral enhancement remains in the map. At its conjugated latitudes in the southern hemisphere, there are also some TEC increases, but the magnitude is weaker. The phenomena of the conj ugated enhanced TEC has been noted by previous studies (e.g., Tanaka, 1979). When these arc displayed in a geomagnetic coordinate system, the increased TEC in the subauroral region is observed to persist at nearly constant latitudes (-60°) in both hemispheres. This feature lasts until 0700 UT on November 27.

In order to assess the accuracy of the GIM measurements, wc have compared TEC values derived from GIMs with satellite. The ionospheric absolute TEC values obtained from GIM, Topex, and Parametrized ionospheric Model (PIM) during both storm (top) and quiet (bottom) times are plotted in Figure 3. Because of the limit of Topex operations, this comparison can only be made above the ocean where GPS stations are largely absent, On Nov. 25 and 26, Topex had trajectories along the Eastern Pacific Ocean from the Aleutian islands at post-midnight, through east Hawaii to the east of Easter Island at pre-noon.

From the top figure, we see that the interpolated TEC values from GIMs follow the measurements from Topex reasonably well. During the storm, two TEC peaks are visible from both measurements of GIMs and Topex at around 40°S and 30°N, that have increases of +80% and +100% relative to the quiet time profile shown in the bottom panel of the figure, respectively. We have also plotted TEC predictions from PIM along the Topex track. This PIM model in this case does not follow well the storm-time TEC enhancement. During the quiet period, the two measurements and the model's predictions show similar profiles in this latitude and local time range.

With GIM and the differential mapping techniques, continuous TEC perturbations in a particular longitude sector can be studied. in Figure 4, we have plotted the percent TEC changes at Green with meridian in the northern hemisphere averaged over a 10° latitude band. A vertical line in the figure shows the start time of the main phase of the storm. As we stated before, the enhancements at high latitudes of the northern hemisphere starts immediately after storm onset. The positive phase is very strong (about +150% in the 50 °-60° band), while there is apparently no negative phase during the entire storm period. The peaks between the 60° and 30° latitudes have a delay of about two hours. This shift may be caused by a TID that is propagating from high to low latitudes at a speed of 460 m/s, which is within the range of typical TID speeds [e.g., Prölss et al., 1991].

Summary

The GIM and the differential mapping based on worldwide GPS network data allow for near instantaneous monitoring of global scale ionospheric TEC changes. These global observations may provide important input for space weather monitoring and early warning of large ionospheric disturbance, especially during severe storm periods. We have used TEC measurements from this new technique to confirm some storm-time characteristic features of the ionosphere, such as subauroral enhancements, dayside mid-latitude expansions associated with TIDs, and conjugated latitude enhancements.

TEC values derived from the GIM techniques show a good agreement with independent Topex altimeter measurements, Compared with other techniques, however, the GPS network currently has a much larger global coverage and higher time resolution. The differential mapping method (based on GIM differences) has a potential use in global storm monitoring and warning systems. Since the measured TEC changes more directly affect the radio signal's propagation, this technique has potential for instantaneous feedback of space weather changes. Currently, there are more than 60 GPS stations all over the world. The numbers of stations have increased by a factor of 2 between 1993 and 1995. Real-time global ionosphere measurements and maps derived from GPS network data with high temporal and spatial resolutions should be available soon.

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Figure Captions

Figure 1. Geomagnetic Indices for the magnetic storm on November 26, 1994. The top panel shows H component variations from 6 ground magnetic stations around the northern aurora] region. The middle panel is the three hour Kp index, while the lower panel gives the Dst index during this storm. The three vertical lines give time intervals of the ionospheric maps shown in figure 2.

Figure 2. Global percent ionospheric TEC change map at 0945 (top), 1245 (middle) and 1545 UT (bottom), Nov. 26, 1994. The maps give 15 min averages of TEC changes relative to the quiet time. In the northern hemisphere, TEC shows significant changes. Two large enhanced regions are seen at post-midnight and noon respectively. The latter is identified as a TID propagating from high to low latitudes.

Figure 3. A comparison of TEC measurements from GIMs, Topex and the PIM model along a Topex trajectory. We see that during the quiet time (lower pane]), three measurements have consistent profiles. However, during the storm time, TEC data deduced from GIMs fits the direct measurements from Topex, but has a large difference from PIM.

Figure 4. A latitude dependence of percent TEC changes relative to the quiet times along the Greenwich meridian. Only northern hemispheric variations arc shown in 10° latitude bins, After the storm main phase onset (solid line), the TEC peaks progressivel y shift from high to lower latitudes, which suggests a TID propagation equatorward. The dashed lines indicate local noon.

Geomagnetic Activity Index of Magnetic Storm on Nov 26, 1994

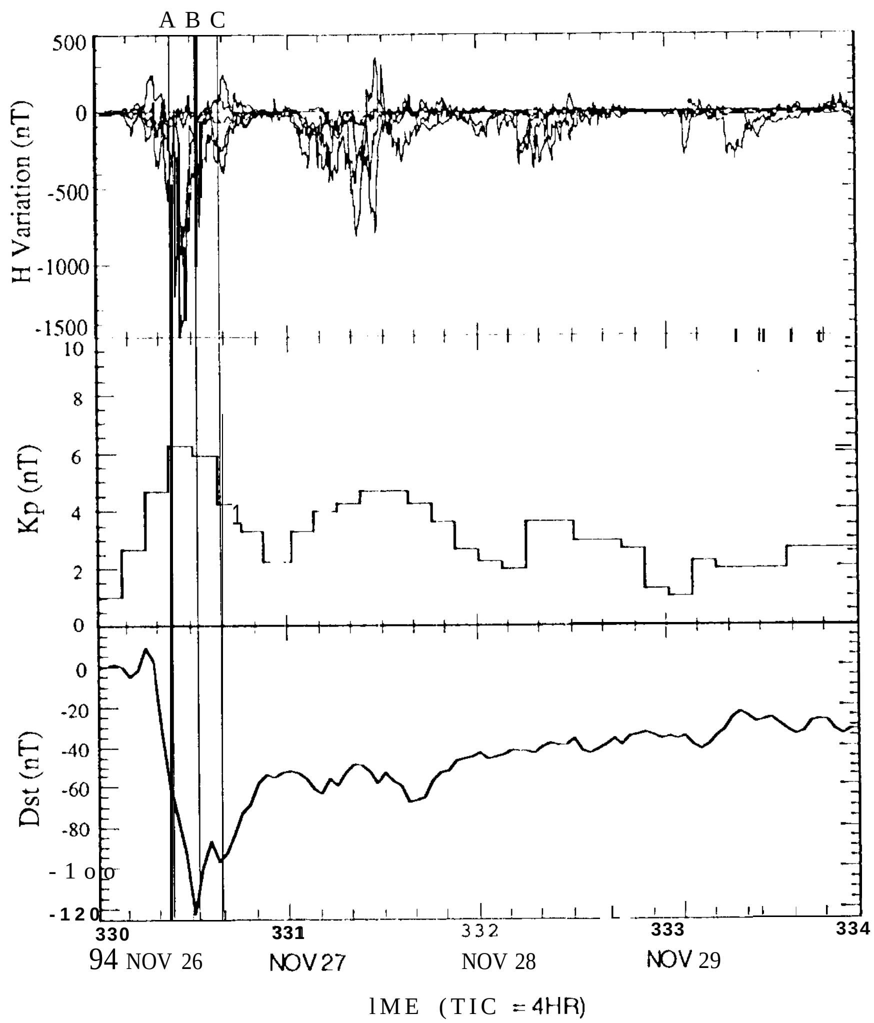
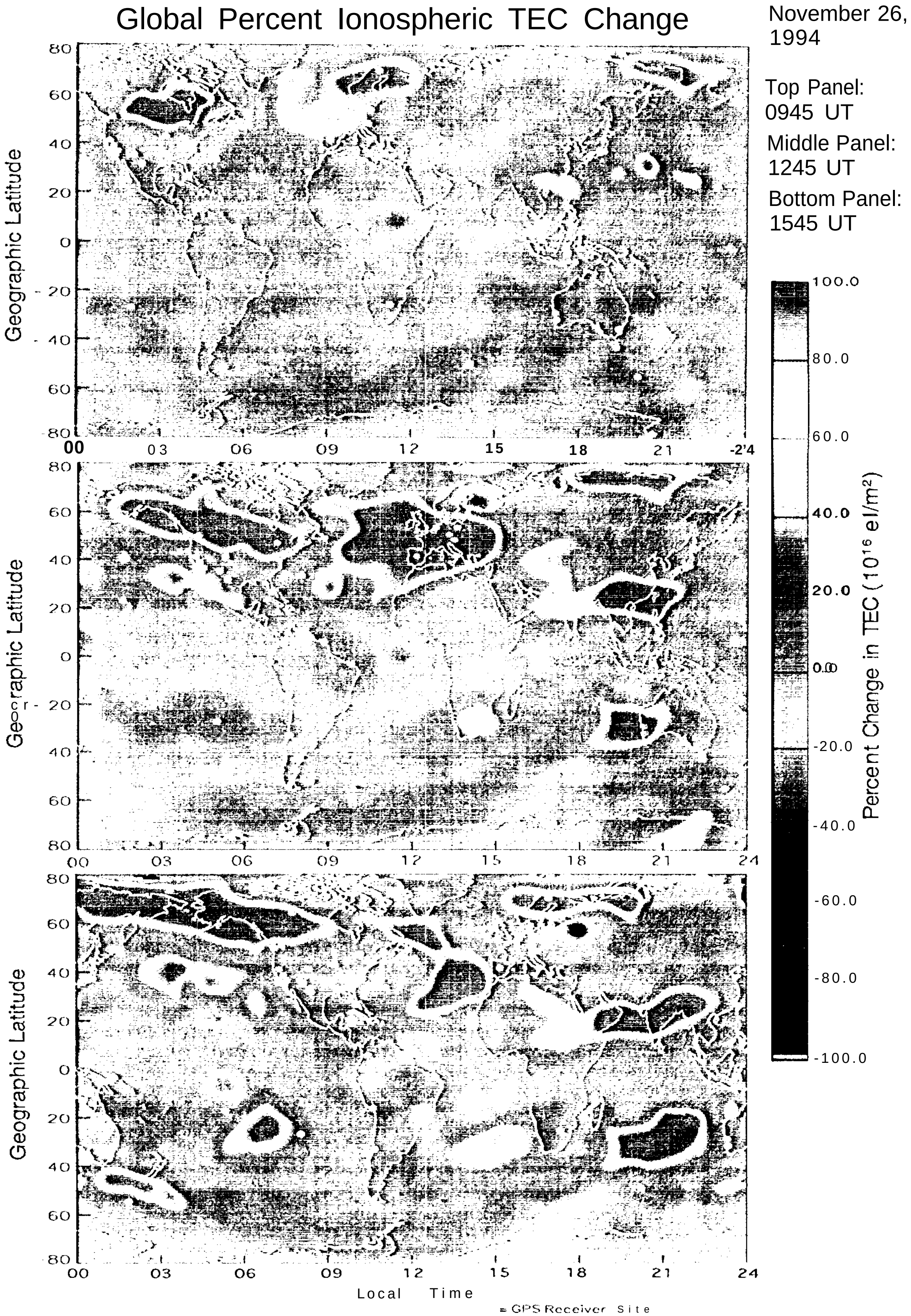


Figure 1



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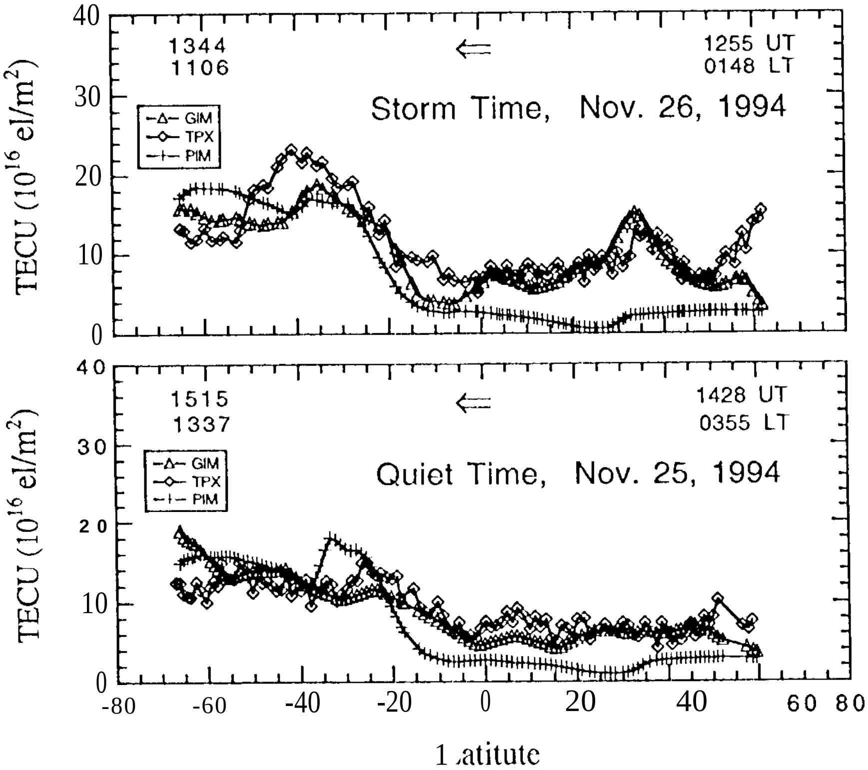
1344
1106
⇐
1255 UT
0148 LT
Storm Time, Nov. 26, 1994
GIM
TPX
PIM
1515
1337
⇐
1428 UT
0355 LT
Quiet Time, Nov. 25, 1994
GIM
TPX
PIM
TECU (10^{16} el/m^2)
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Figure 3

Storm Time TEC Variations in the Northern Hemisphere along 0° Longitude

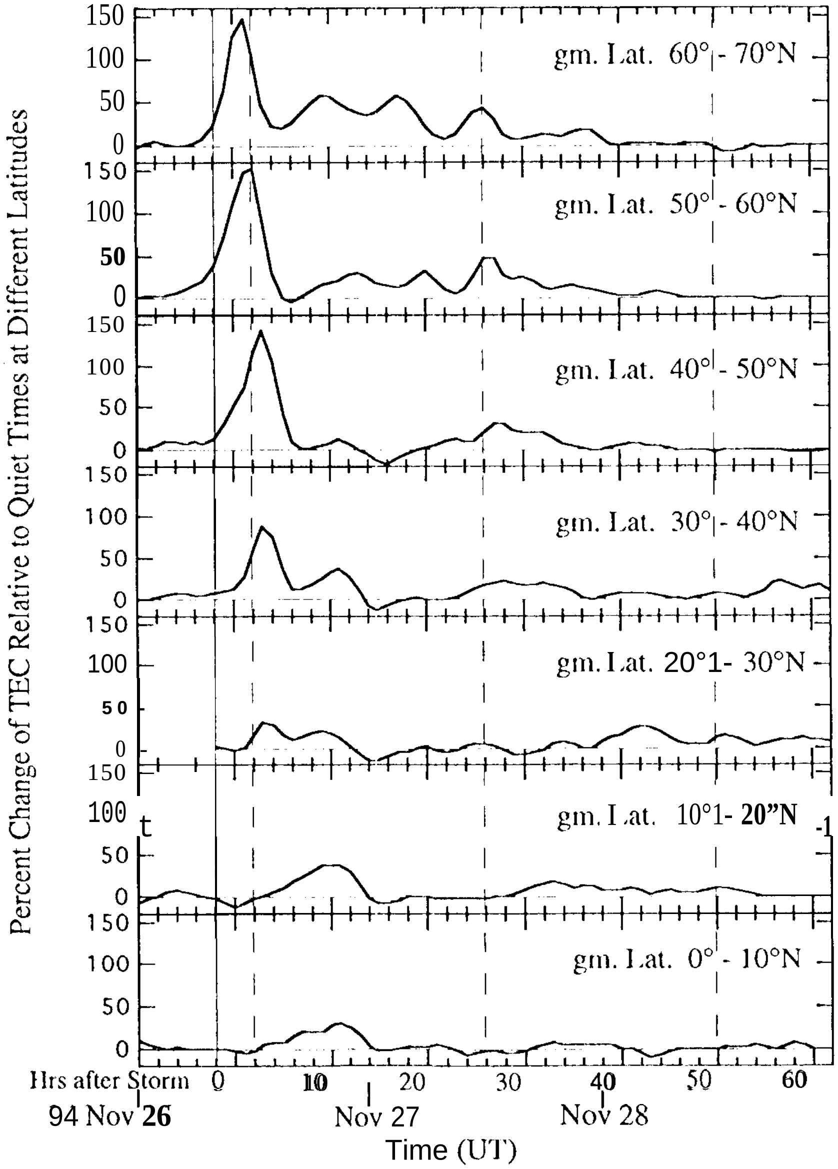

Figure 4