

# A Quantitative Study of Ionospheric Density Gradients at Mid-Latitudes

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## ABSTRACT

The sub-auroral ionosphere, at the magnetic latitudes which characterize the northeastern United States, is subject to severe *F*-region ionospheric density structuring due to the space weather effects of magnetospheric disturbance electric fields. Communications and navigation systems relying on trans-ionospheric propagation must be able to compensate for the effects of the sharp changes ( $>10\times$ ) in total electron content (TEC) associated with the ionospheric trough and storm-time disturbance effects at mid latitudes. The Millstone Hill incoherent scatter radar database has been used to investigate the spatial extent and temporal evolution of TEC and density altitude/latitude structure at mid and sub-auroral latitudes as a function of solar cycle, local time, and level of geomagnetic activity. More than 11,000 radar elevation scans covering  $>20$  degrees of latitude and altitudes between 150 km and 750 km have been used to identify the characteristics of the density gradient near the equatorward edge of the ionospheric trough in a variety of circumstances spanning 20 years and two solar cycles. Pronounced density gradients can be identified in  $\sim 35\%$  of the Millstone Hill scans and for these we present a statistical characterization of average magnitude and location of these steepest TEC gradients. In some cases (especially near noon), the equatorward edge of the trough lies poleward of our observational field of view and gradients associated with phenomena other than the trough contribute to our statistics. On most days the trough appears in the radar scans between 16 MLT and 20 MLT. Larger TEC gradients occur at solar maximum, when the background TEC is higher. The steepest gradients occur in an environment of high TEC (solar max and adjacent to regions of storm-enhanced density, SED), when the processes which generate the trough are strongest (high  $K_p$ ). High gradient values occur in the sunlit sector with maximum values of TEC gradient ( $\sim 10$  TEC/deg latitude; 1 TEC unit =  $10^{16}$  electrons  $m^{-2}$ ) found in the post-noon ionosphere. Mean solar-maximum TEC gradient at 16 MLT is 3-4 TEC/deg for  $K_p < 2$ , increases linearly with  $K_p$  for  $K_p$  2-4, and is nearly constant at a value of 7-8 TEC/deg for  $K_p$  4-6. Storm enhanced density (SED), the bulk redistribution of *F*-region plasma by disturbance electric fields, can result in TEC  $> 100$  over New England and TEC gradients of  $\sim 50$  TEC / deg.

## Introduction

The sub-auroral ionosphere, at the magnetic latitudes which characterize the northeastern United States, is subject to severe  $F$ -region ionospheric density structuring due to the space weather effects of magnetospheric disturbance electric fields [Foster, 1995]. The sub-auroral ionosphere is not subjected to the precipitation-induced localized ionization enhancements which characterize the auroral oval. Instead,  $\mathbf{ExB}$  plasma motions advect ionospheric plasma with significantly different characteristics through this region [Foster, 1993], and chemical recombination of ions in the presence of large electric fields [Schunk *et al.*, 1976] reduces plasma density producing the deep nighttime ionization trough. These disturbance effects are superimposed on the regular diurnal cycle of solar production and nighttime decay of the  $F$  region which has both a latitude and a solar-cycle variation. This paper presents an overview of the ionospheric effects of such mid-latitude phenomena, as observed by MIT's Millstone Hill incoherent scatter radar, and focuses on the spatial gradients of  $F$ -region total electron content (TEC) which are associated with their occurrence.

### *Ionospheric Trough Associated with Enhanced Electric Field*

During geomagnetic disturbances, the electric fields and particle populations which characterize the auroral region expand equatorward and their effects are felt at previously sub-auroral latitudes. Intense convection electric fields appear in the expanded auroral oval (e.g. Yeh *et al.*, [1991]) and are responsible for density depletion and ionospheric trough formation due to the effects of enhanced recombination [Schunk *et al.* 1976]. Collis and Haggstrom [1988] have derived an empirical relationship between the trough location and magnetic Kp index based on observations with the EISCAT radars, and an overview of the role of ion drift in the formation of the mid and high latitude trough was presented by Rodger *et al.* [1992]. The polarization jet [Galperin *et al.*, 1974] or SAID (sub-auroral ion drifts) event is defined as westward convection with magnitude in excess of  $500 \text{ m s}^{-1}$ , equatorward of the auroral precipitation, and often associated with an ionospheric trough [Spiro *et al.*, 1979]. SAID are associated with disturbed conditions, and specifically with substorm recovery [Anderson *et al.*, 1993]. The high velocities due to intermittent or repetitive SAID events lead to mid-latitude trough formation, leaving a longitudinally extended, conjugate fossil trough [Evans *et al.*, 1983] which persists through the night, corotating with the earth. The fringing northward electric field on the equatorward edge of the SAID overlaps the high-density mid-latitude ionosphere and advects solar-produced plasma toward noon, forming a region

of storm-enhanced density (see below) at the equatorward edge of the evening-sector trough and further steepening the TEC gradient in that region.

#### *Storm Enhanced Density (SED)*

Global electric field models indicate a dominant two-cell pattern of plasma convection whose equatorward portion transports ionospheric plasma sunward toward the noon meridian from both the dawn and dusk auroral and subauroral regions. The effects of plasma transport, and the linkage of the driving electric field to the overlying magnetosphere, dominate ionospheric characteristics at auroral and sub-auroral latitudes. With increasing activity level, and particularly during geomagnetic storms, the equatorward extent of such effects expands to lower latitudes [e.g., *Foster et al.*, 1986]. Associated with the large-scale enhancement of the ionospheric convection electric field during disturbed geomagnetic conditions, solar-produced *F*-region plasma is transported sunward and poleward from a source region at middle and low latitudes in the afternoon sector, producing a latitudinally narrow region of storm-enhanced plasma density (SED) and increased total electron content which is advected toward higher latitudes in the noon sector [*Foster*, 1993]. The Millstone Hill incoherent scatter radar regularly observes SED as a spatially continuous, large-scale feature spanning local times between noon and midnight and at latitudes between the polar cap and its mid- or low-latitude source region. This feature accounts for the pronounced enhancement of ionospheric density near dusk at middle latitudes observed during the early stages of magnetic storms (called the dusk effect) and constitutes a source for the enhanced *F*-region plasma observed in the polar cap during disturbed conditions. Within the region of SED, TEC is greatly enhanced and steep latitude gradients of TEC occur where the SED abuts the trough.

#### Millstone Hill Incoherent Scatter Radar

The Massachusetts Institute of Technology maintains an extensive radar research facility at Millstone Hill, located 35 miles northwest of metropolitan Boston at 42.6° N latitude, 288.5° E longitude. Multi-megawatt UHF transmitters and a fully-steerable 46-m antenna provide wide-ranging spatial coverage, spanning >30° of latitude and 4+ hours of local time at *F* region heights with ~30-min temporal resolution. The facility is situated at 54° invariant geomagnetic latitude ( $\Lambda$ ) such that its extensive field-of-view for ionospheric observations encompasses the full extent of mid-latitude, sub-auroral, and auroral features and processes.

The location of Millstone Hill is such that significant ionospheric structure falls well within the radar's field of view. The ionospheric total density trough is observed nearly overhead at Mill-

stone Hill almost every night and the equatorward offset of the north geomagnetic pole nearly along the Millstone Hill meridian brings high-latitude and auroral phenomena into the observatory's near field of view during geomagnetic storms (e.g. *Buonsanto et al.* [1992]). During disturbed conditions, intense convection electric fields occur at previously sub-auroral latitudes resulting in the formation of a deep, narrow *F*-region ionization trough. Equatorward of this, sunward advection of plasma from later local times and lower latitudes leads to a region of Storm-Enhanced Density (SED) [*Foster*, 1993] in which TEC can exceed average values by a significant amount. These processes contribute to the formation of steep, localized plasma density gradients whose position and characteristics depend strongly on the magnetosphere-ionosphere coupling in that longitude sector. In the noon sector, the dayside trough which has been documented by satellite data (e.g. *Grebowky et al.* [1983]) and ground based ionosonde [*Whalen*, 1989], lies poleward of the radar field of view during normal conditions and trough-related density gradients are seen within the field of view only for the most disturbed conditions.

The Millstone Hill incoherent scatter radar has been in operation through three solar cycles (since 1979 using the fully steerable 150-foot diameter antenna) and its data characterize ionospheric features and response over the altitude range 100 km to 1000 km. Long-term operations as a part of the international Incoherent Scatter World Day program have built up a database of radar elevation scans which sample a span of 15° - 25° latitude with better than 1° latitude resolution and ~35 km altitude resolution. We have developed a semi-automatic technique to review and analyze every N-S elevation scan in the Millstone Hill radar database. Data from each radar elevation scan is sorted to produce vertical TEC in the altitude range 150 km - 650 km with 1° latitude resolution. Each scan is searched for occurrence of a steep latitude gradient in TEC ( $> 2$  TEC/deg) within the radar's field of view. The principal characteristics of each scan (magnitude of the gradient, location of the feature, geomagnetic activity conditions) are determined and cataloged and this reduced data set is analyzed to determine the best characterization of ionospheric gradients (magnitude, location, variability) as functions of solar cycle, local time, and level of disturbance.

Figure 1 presents iso-density contours of electron concentration observed during a Millstone Hill elevation scan along the N-S meridian during disturbed conditions in the pre-midnight sector (02 UT = 21 MLT). Latitude coverage at *F*-region heights spans 25° latitude and altitudes 200 km - 800 km. A pronounced ionospheric trough was observed centered at 52° geomagnetic latitude, nearly overhead the radar facility. The trough is typically 2° - 6° in latitude width and many previ-

ous investigations have shown its great extent in the E-W direction. *Foster et al.* [1994] describe an event similar to that shown in Figure 1 and show that this type of ionospheric trough is often associated with the region of intense sunward plasma convection driven by the polarization jet electric field [*Galperin*, 1974] near the ionospheric projection of the disturbed ring current and the inner edge of the plasmasheet. *F*-region total electron content (TEC), determined by integrating the electron concentration between altitudes 200 km to 800 km at each degree of latitude, is plotted below the elevation scan data. TEC is  $\sim 35$  TEC units (1 TEC unit =  $10^{16}$  electrons  $m^{-2}$ ) immediately equatorward of the trough and drops to  $< 5$  TEC units within the trough. The maximum TEC gradient on the equatorward wall of the trough is defined here as the greatest difference in *F*-region TEC determined over a 1 degree distance and is expressed as TEC per degree latitude. In this case, the TEC gradient is  $-12$  TEC/deg and occurs at  $50^\circ$  magnetic latitude ( $\sim 39^\circ$  geodetic latitude). For the Millstone Hill meridian ( $285^\circ$  E longitude), invariant magnetic latitude is approximately geodetic latitude plus  $11^\circ$ .

#### Method

We have examined over 11,000 N-S Millstone Hill elevations scans of the type shown in Figure 1 and have determined *F*-region TEC for each of them. These scans were taken over a span on nearly 20 years (1982-2000) during World Day and special purpose experiments run to build up a synoptic database to address mid-latitude ionospheric phenomena as well as to address specific events and activity conditions. Scans were taken throughout the 24-hr day and approximately equally distributed in solar maximum ( $F_{10.7} > 120$ ) and solar minimum ( $F_{10.7} < 120$ ) conditions. Individual elevation scans cover a 10-25 deg span of latitude at *F*-region heights in 10 minutes, with successive scans separated by  $\sim 30$  minute intervals. Figure 2a presents the distribution of all 11,000 scans in local time and as a function of the 3-hour Kp index, taken here as a proxy for the level of geomagnetic disturbance. Our experiments provide a normal distribution with Kp and uniform local time coverage. All parameters presented in this study have been sorted into 24 1-hr bins of local time and 21 Kp-index bins ranging from 0 to 9. Averages are determined separately for each bin and are presented without smoothing. As seen in Figure 2a, each Kp bin between 4 and 5 at each local time has been sampled by 20-40 separate scans. For Kp between 2 and 3, there are  $\sim 100$  scans in each sampling bin. Insufficient statistics are available in our data set to present significant results for  $Kp > 6$ .

As will be seen in the statistical analysis to follow, the occurrence a significant density gradi-

ent associated with the ionospheric trough or another plasma feature within the Millstone Hill field of view is a function both of local time and magnetic activity. We were able to identify the steep gradients at the equatorward edge of such features in ~4,000 of the 11,000 scans, and the statistical analyses which follow present average characteristics of the density gradients based on this subset - those scans in which a sharp density gradient could be identified clearly. Figure 2b presents percent-occurrence for the identification of such sharp density features in the Millstone Hill database. A pronounced density gradient is least likely (< 20%) to be seen in the post-midnight/early morning sector where the overall density is low, but it is quite commonly seen in the midnight sector. Significant gradients in TEC are most likely (> 50%) to occur in the post-noon and dusk sectors for high magnetic activity ( $K_p > 3$ ). The probability of observing any density gradient feature in the daytime sector is quite low (10-20 % for the 5-15 MLT region) as the field of view of the radar is well equatorward of the high latitude trough. Plasma density gradients observed in the daytime sector are mainly due to latitudinal structure in the solar produced plasma during the diurnal decay and enhancement of the mid-latitude F layer. In more-disturbed conditions, gradients at the edge of SED and associated with the equatorward incursion of the high-latitude trough are observed in the radar data. For each of the 4,000 identifications of the equatorward edge of trough or other steep gradient, we recorded  $K_p$  and F10.7, the latitude of the steepest gradient, the value of TEC at that point, and the maximum gradient value.

#### Statistical Results

Mid-latitude *F*-region peak density, and TEC, can be a factor of 3-10 higher during solar maximum due to the increased production of ionization by the enhanced solar EUV flux. Accordingly, larger TEC gradients occur at solar maximum, when the background TEC is higher. The steepest gradients occur in an environment of high TEC (solar max and adjacent to regions of storm-enhanced density, SED), when the processes which generate the trough are strongest (high  $K_p$ ).

We have separated our database of ~4000 observations of the trough or other steep density-gradient feature by  $K_p$  index, solar max/min ( $F_{10.7} >$  or  $< 120$ ), and into one-hour increments of local time. In Figure 3a we present the average value of the most equatorward TEC gradient as functions of  $K_p$  and local time for solar maximum conditions. It is apparent that the large gradients are an afternoon/disturbed- $K_p$  phenomenon. Figure 3b presents the average TEC gradients for solar minimum conditions. For both solar min and solar max, the largest gradients are observed in the post-noon sector and for disturbed conditions with  $K_p > 3$ . The density gradients in the post-

noon sector are appreciably stronger for solar maximum conditions with the value of density gradient at 15 LT  $\sim 8$  TEC/deg for solar maximum and  $\sim 3$  TEC/deg for the solar minimum. Only weak gradients are seen in the post-midnight / pre-noon sectors for both cases. The data of Figure 2 indicate that steep density gradients we discuss in this study are rarely seen in the noontime sector for moderate levels of geomagnetic activity.

Figure 4 presents the local time variation of the maximum observed TEC gradient for solar maximum conditions for  $K_p = 2$  and  $K_p = 4$ . Average values are shown by the continuous lines and the variability is shown by the standard deviation of our observations at 16 MLT. Gradients are approximately the same at midnight and morning hours, but are significantly higher in the early post-noon hours for the higher value of  $K_p$ . We argue that this is an effect of the increase in background TEC in the sub-auroral post-noon ionosphere caused by advection from lower latitudes (SED) [cf. *Foster*, 1993]. TEC is enhanced in the post-noon sector with increasing level of geomagnetic disturbance during magnetic storms. High variability in TEC gradient is found in this post-noon region for both solar max and min, while a much smaller statistical variability is associated with the nighttime region. TEC gradients are  $\sim 8$  TEC/deg in the dusk sector for  $K_p = 4$  and  $\sim 4$  TEC/deg for  $K_p = 2$ . The post-midnight gradient is  $\sim 2$  TEC/deg independent of  $K_p$  and solar cycle. It is most likely that the gradients seen in the dusk and night sector are associated with the equatorward wall of the ionospheric trough, while those near noon, when the trough lies poleward of our field of view, are associated with spatial variations in the solar-produced mid-latitude  $F$  region plasma.

In Figure 4 we see that the maximum gradient is found in the post-noon ionosphere, and in Figure 5 we present the magnetic-activity dependence of the trough TEC gradient for 16 MLT, in the local time sector of the largest gradients. The variation of the average TEC gradient with  $K_p$  index for solar maximum conditions is shown by the solid line, with the dashed contours indicating one standard deviation centered on the mean value. Solar minimum values of the mean are shown by Xs. Mean solar maximum TEC gradient at 16 MLT is 3-4 TEC/deg for  $K_p < 2$ , increases linearly with  $K_p$  for  $K_p$  2-4, and is nearly constant at a value of 7-8 TEC/deg for  $K_p$  4-6.

The latitude of the region of steep density /TEC gradient is significant for assessing the space weather impact of ionospheric structure. The magnitude of the density gradient and the average geomagnetic latitude of its occurrence during solar maximum are plotted against local time for four levels of the  $K_p$  index in Figure 6. (The latitude variation for solar minimum conditions is shown by the dashed line.) Gradients are steepest in the dusk sector with the highest values appearing at

high latitudes somewhat after noon. Near noon, the average characteristics of the gradient region are dominated by structure in the solar-produced plasma. Consistent with satellite observations of the location of the high-latitude trough [Grebowsky et al., 1983], the equatorward edge of the trough gradient region appears in the radar field of view at highest latitudes near 16 MLT. For Kp 3, 4, or 5, this average trough gradient region moves equatorward steadily at a rate of  $\sim 1^\circ \text{ hr}^{-1}$  between 16 LT - 24 LT. In the post-midnight region, the latitude of the equatorward edge of the trough is near  $44^\circ$  geodetic ( $55^\circ$  magnetic) independent of Kp, indicative of the association of the trough with the stagnation/recombination boundary at those local times. In the post-noon sector, poleward and noonward advection of solar-enhanced density from later local times (SED) sharpens and accentuates the equatorward edge of the trough during solar-maximum conditions, resulting in a higher latitude for the trough boundary in this sector at solar maximum.

We quantify our statistical results in tabular form in Tables 1 and 2 which present average TEC gradients and the geodetic latitude of the steepest gradient associated with the equatorward edge of the trough (dusk and night sectors) or other plasma feature for solar maximum and solar minimum conditions as functions of magnetic activity and local time. These tables and the graphical results shown in the figures are specific to the eastern North American sector where high magnetic latitudes occurs at relatively low geodetic latitude due to the offset of the north geomagnetic pole toward this longitude sector.

#### Discussion

Whereas the main ionospheric trough is a nighttime feature characterized by a widespread reduction in plasma density, our study indicates that severe mid-latitude density and TEC gradients are more often a post-noon feature whose percentage occurrence peaks in the dusk sector for high magnetic activity. The occurrence of storm enhanced density in this local time sector elevates TEC and steepens the trough-induced gradient on its poleward edge.

Figure 7 presents a typical example of steep dusk-sector trough gradients observed near solar maximum on October 19, 1982 at 18 MLT when Kp was 4<sup>-</sup>. Mid-latitude ( $\Lambda < 56^\circ$ ) plasma density exceeded  $10^{12} \text{ m}^{-3}$  with *F*-region TEC  $\sim 30$  TEC units. The steep equatorward wall of the trough (maximum gradient  $-12 \text{ TEC/deg}$ ) was seen at  $59^\circ \Lambda$  ( $48^\circ$  geodetic latitude) some  $6^\circ$  poleward of the Millstone Hill site. TEC dropped to  $\sim 5$  TEC units within the trough.

Many previous studies of the ionospheric trough have been based on in situ measurements with satellite probes [e.g. *Grebowsky et al.*, 1983] which provide a detailed picture at a specific

height, or on ground-based ionosonde profiles [e.g. *Whalen*, 1989] which probe the bottom side of the  $F$  layer. The incoherent scatter radar technique has been used to study the characteristics of the  $F$  region and the trough from 200-800 km altitude (e.g. *Holt et al.* [1983], *Evans et al.* [1983]). A quantitative statistical study of the equatorward edge of the trough and its associated density gradient using the extensive incoherent scatter radar database has not been done until now.

The density-gradient characteristics presented in this study are average values, characteristic of conditions which can be expected to occur over the northeastern US. Space Weather effects and systems design often depend on a knowledge of the maximal conditions which can be expected - for density gradients, these occur during the sudden-onset phase of major geomagnetic storms. An example of the severity of TEC perturbations and gradients which can be observed at normally mid latitudes is provided in the Millstone Hill radar observations of the great magnetic storm of February 8, 1986 ( $K_p = 9$ ). Millstone Hill observations spanned the interval of mid-latitude disturbance with wide-ranging elevation scans and sweeping azimuth scans which detailed the evolution of intense mid-latitude electric fields [*Yeh et al.*, 1991] and their ionospheric consequences [*Yeh et al.*, 1990]. Storm enhanced density in the North American sector was tracked at latitudes from Canada ( $L > 6$ ) to the Caribbean ( $L < 2$ ) [*Foster*, 1993] and associated TEC exceeded  $100 \cdot 10^{16} \text{ m}^{-2}$  in the region of post-noon SED. Figure 8 presents iso-density contours observed by the Millstone Hill radar scanning N-S across the region of SED near local noon on February 6, 1986. Our determination of  $F$ -region TEC and TEC gradient in this region derived from the radar elevation scan, as done in this study, is shown in the bottom panels. TEC near  $48^\circ$  N geodetic latitude, within the region of SED, is nearly 100 TEC units. The latitude gradient in TEC, observed associated with the region of SED near  $45^\circ$  latitude, was  $\sim 50$  TEC/deg. The February 8, 1986 event represents a severe example of the ionospheric density perturbation that can occur over the continental US during large geomagnetic storms. The study by *Foster* [1993] presents the related conditions and occurrence frequency associated with storm enhanced density over the northeastern US. SED is regularly seen throughout the afternoon sector at Millstone's longitude and can be identified at all disturbance levels down to  $K_p = 2$ .

### Conclusions

Steep ionospheric density and TEC gradients are observed at sub-auroral and mid latitudes associated with the ionospheric trough and with advecting density enhancements during geomagnetically disturbed conditions. Latitude gradients in TEC associated with the equatorward wall of

the trough in the dusk sector are  $\sim 10$  TEC units/degree of latitude for solar max condition, while gradients associated with regions of greatly-enhanced TEC (storm enhanced density, SED) are observed as great as  $\sim 50$  TEC units/deg. Communications and navigation systems relying on trans-ionospheric propagation must be able to compensate for the effects of such sharp gradients in total electron content in the Northeastern American sector.

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**Table 1: Average TEC Gradients and Latitude at Solar Maximum**

Kp/MLT	0	3	6	9	12	15	18	21
1	1.65	1.27	1.42	2.52	3.92	2.94	4.28	2.33
	48.07	46.00	45.62	43.31	45.31	43.51	49.94	49.98
2	2.26	2.07	2.25	3.50	4.46	3.75	4.04	2.92
	47.95	46.23	45.10	42.75	43.57	45.78	49.04	49.48
3	2.63	2.55	1.89	3.07	4.44	4.31	5.26	3.60
	44.55	41.81	44.83	40.92	46.02	49.40	51.50	47.11
4	2.39	2.25	1.64	2.94	4.09	9.59	8.58	4.37
	43.22	39.58	40.95	45.23	43.40	49.45	48.70	46.29
5	3.82	0.97	1.14	3.19	4.33	5.37	7.79	3.79
	40.20	38.16	37.33	42.78	42.99	48.31	47.87	41.60

**Table 2: Average TEC Gradients and Latitude at Solar Minimum**

Kp/MLT	0	3	6	9	12	15	18	21
1	0.90	0.71	1.22	2.02	1.96	2.01	1.35	1.55
	43.34	39.05	40.92	41.99	42.59	42.82	43.92	49.12
2	0.72	0.90	1.16	1.30	1.84	1.40	1.83	1.77
	42.44	42.31	40.40	40.45	41.42	42.05	45.88	46.98
3	0.97	0.55	0.87	1.78	2.40	1.71	2.84	2.32
	43.33	42.84	40.21	42.91	42.97	43.02	48.91	46.24
4	1.07	0.78	1.39	2.49	3.30	2.10	2.53	1.83
	42.64	40.35	42.98	45.50	43.20	45.26	46.84	45.20
5	1.04	0.48	0.45	1.23	1.91	1.59	3.76	3.51
	42.29	40.15	41.24	39.91	46.27	44.89	46.30	45.22

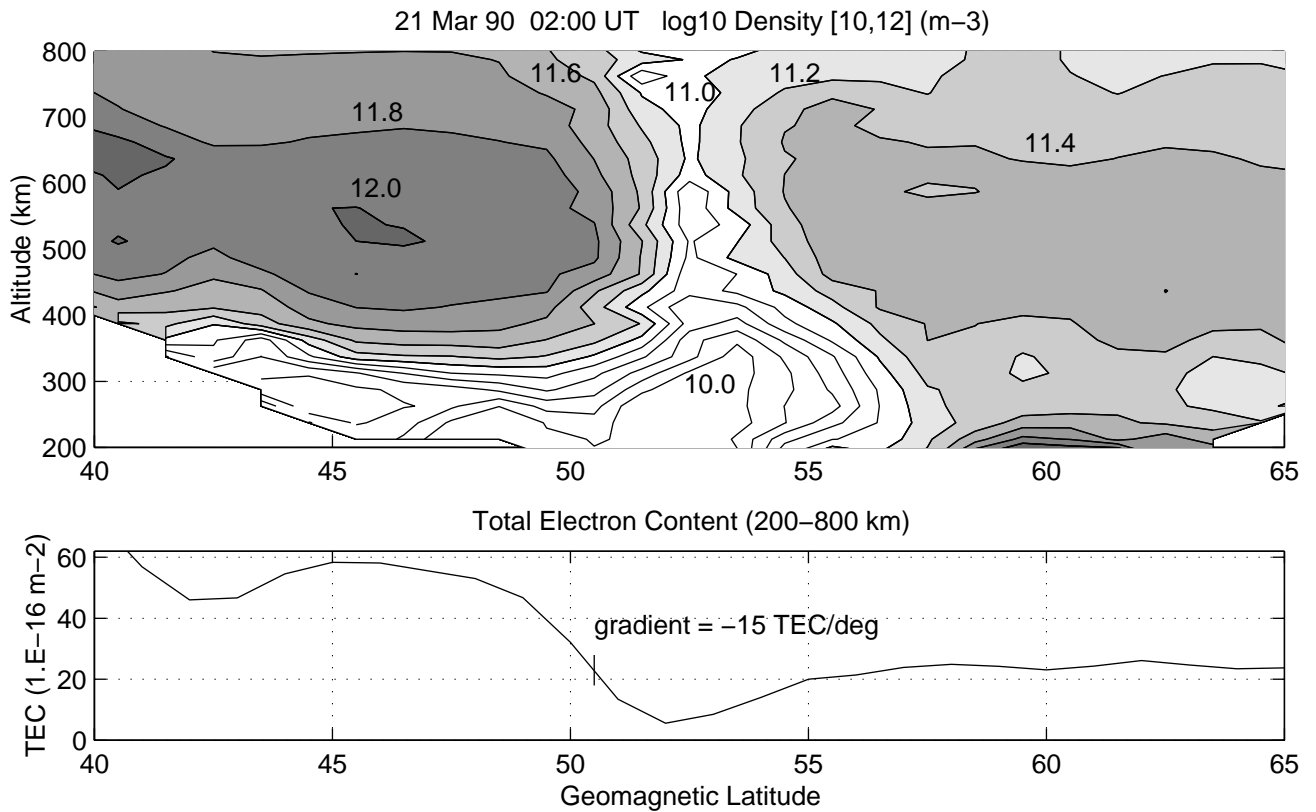


Figure 1. Iso-density contours of electron concentration (logarithmic over the range  $[10,12] \text{ m}^{-3}$  with  $0.2 \text{ m}^{-3}$  spacing) are shown for a Millstone Hill elevation scan along the N-S meridian during disturbed conditions (02 UT = 21 MLT). A pronounced ionospheric trough is centered at  $52^\circ$  geomagnetic latitude, nearly overhead the radar facility. TEC determined by integrating the electron concentration between altitudes 200 km to 800 km is plotted below the elevation scan data. Maximum TEC gradient on the equatorward wall of the trough is  $-12 \text{ TEC/deg}$ .

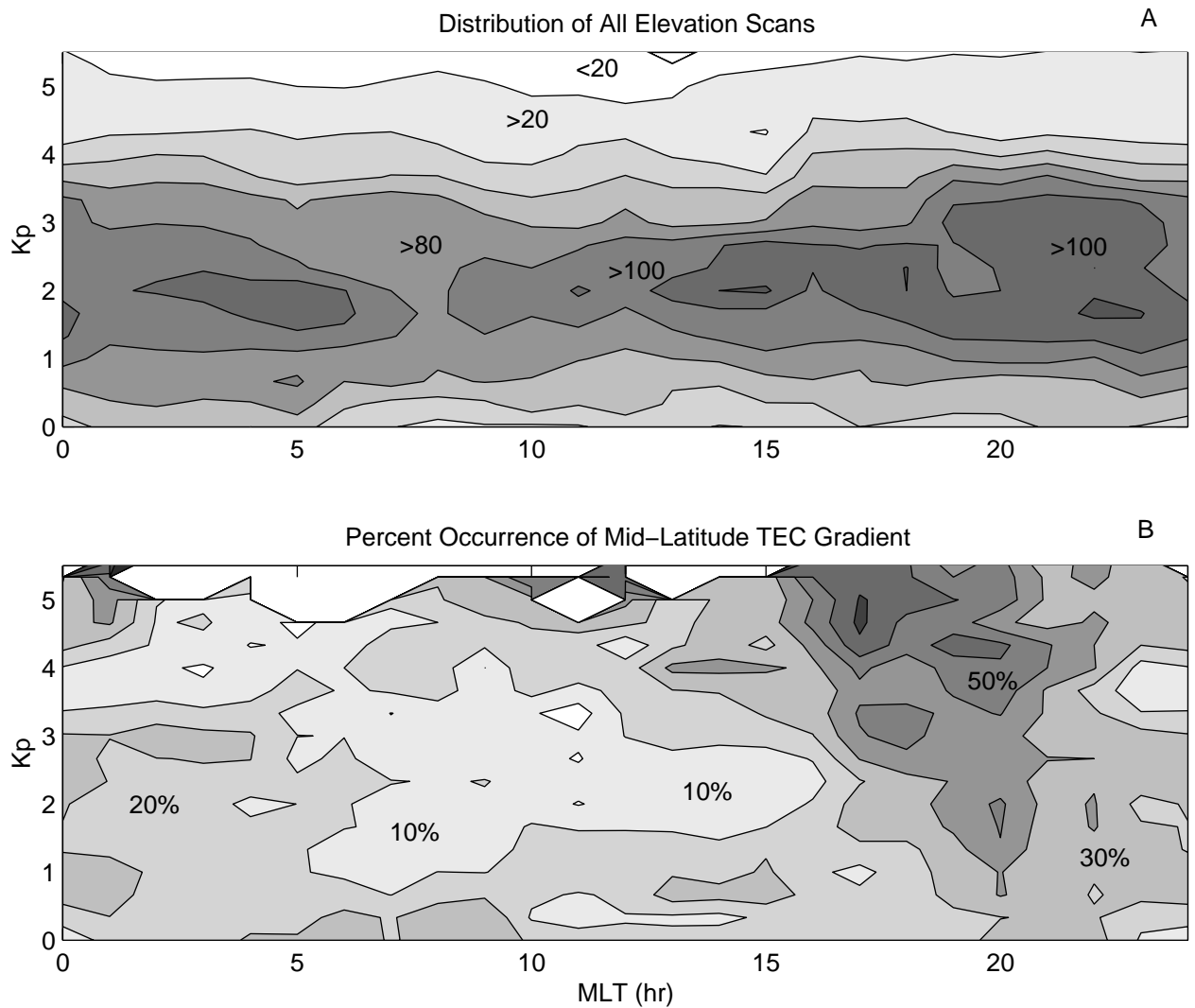


Figure 2. (a) Distribution of 11,000 Millstone Hill radar elevation scans in local time and as a function of the 3-hour Kp index. Our experiments provide a normal distribution with Kp and uniform local time coverage.

(b) Percent-occurrence of scans in which a pronounced latitude gradient in TEC can be identified in the Millstone Hill database. A steep gradient is most likely (> 50%) to occur in the post-noon and dusk sectors for high magnetic activity ( $K_p > 3$ ).

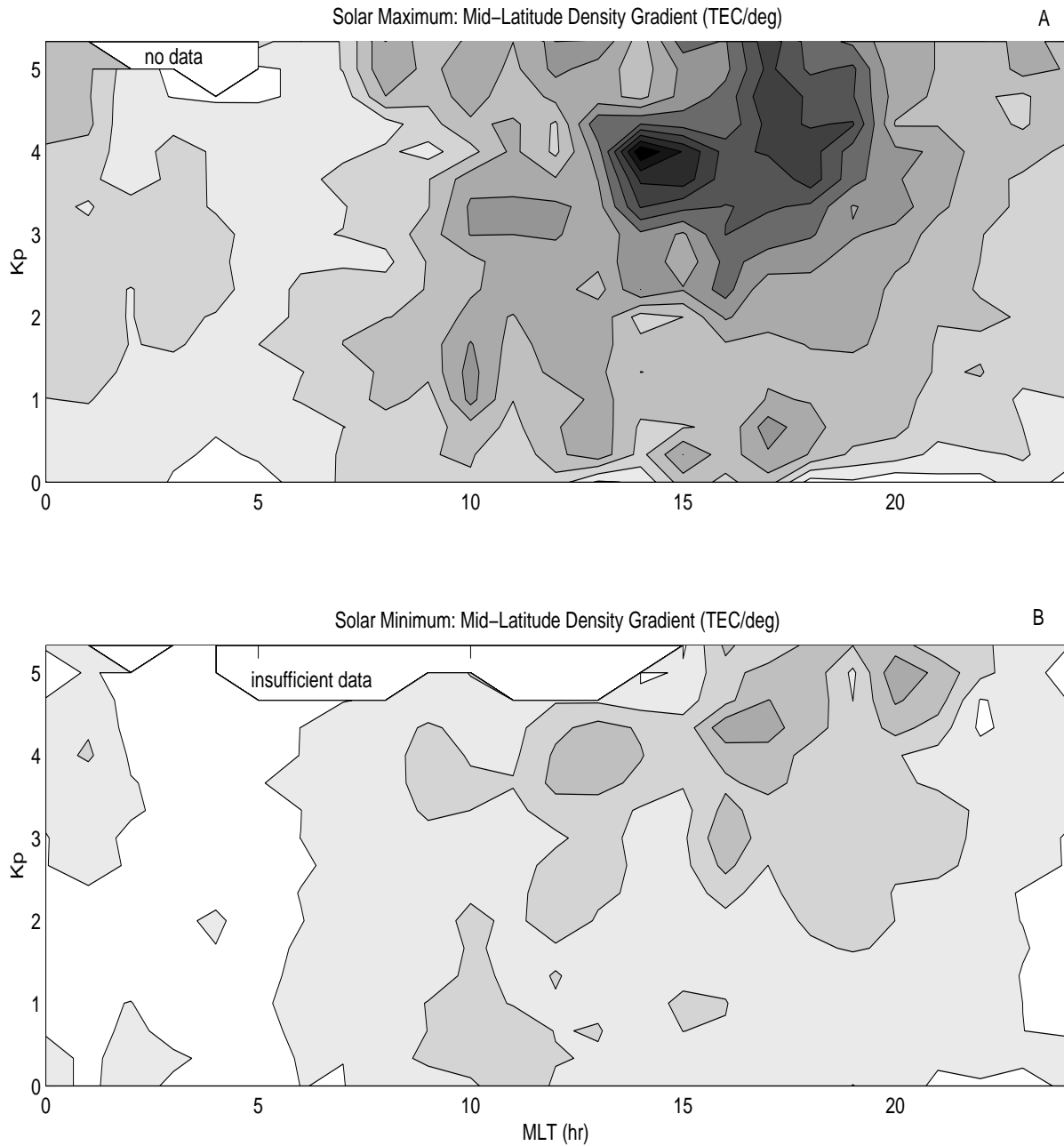


Figure 3. (a) Average value of the steepest TEC gradient (in units of TEC/deg) on the equatorward edge of the trough or other plasma feature is shown as a function of Kp and local time for solar maximum conditions. Large gradients are a daytime/disturbed-Kp phenomenon. Contour spacing is 1 TEC/deg.

(b) Average TEC gradients for solar minimum conditions are significantly less than those observed during solar maximum.

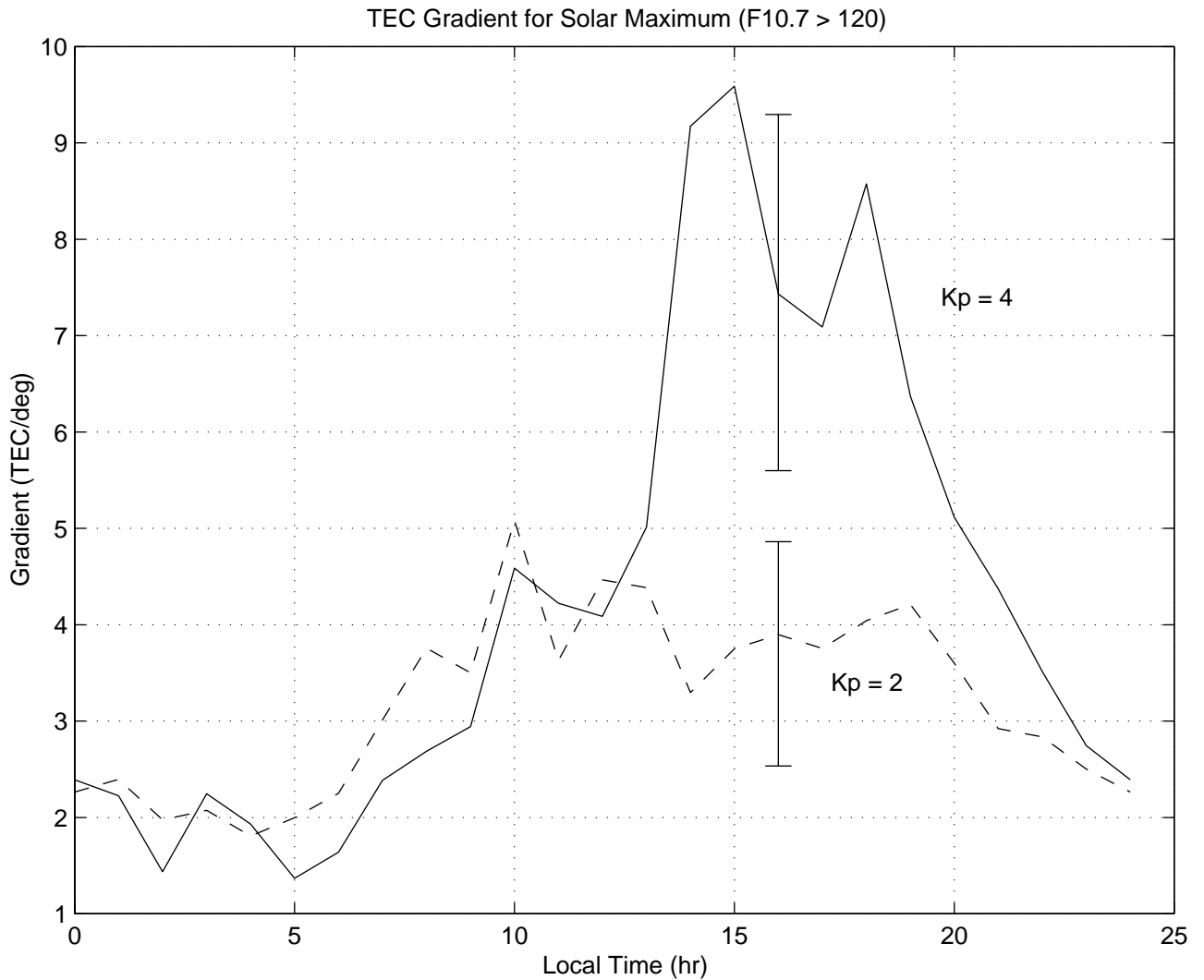


Figure 4. Local time variation of the maximum observed TEC gradient for solar maximum conditions for  $K_p = 2$  and  $K_p = 4$ . Average values are shown by the continuous and dashed lines and the  $1-\sigma$  variability is indicated. Gradients are approximately the same at midnight and morning hours, but are significantly higher in the early post-noon hours for the higher value of  $K_p$ .

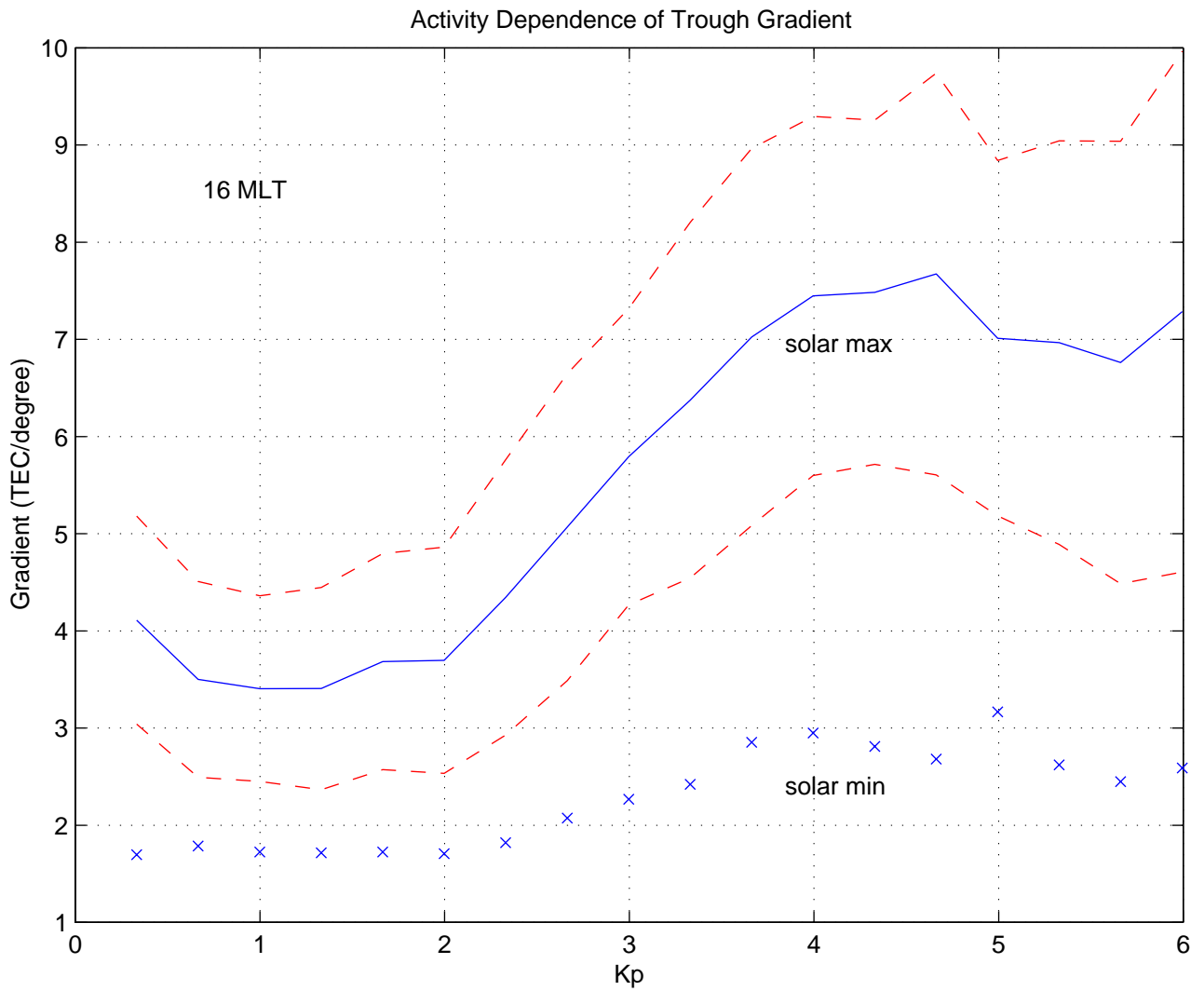


Figure 5. Magnetic-activity dependence of the trough TEC gradient at 16 MLT, in the local time sector of the largest gradients. The dashed contours indicate one standard deviation centered on the mean value. Solar maximum values are presented as the solid curve, with solar minimum values shown as Xs. Gradients are significantly enhanced for  $K_p > 3$ .

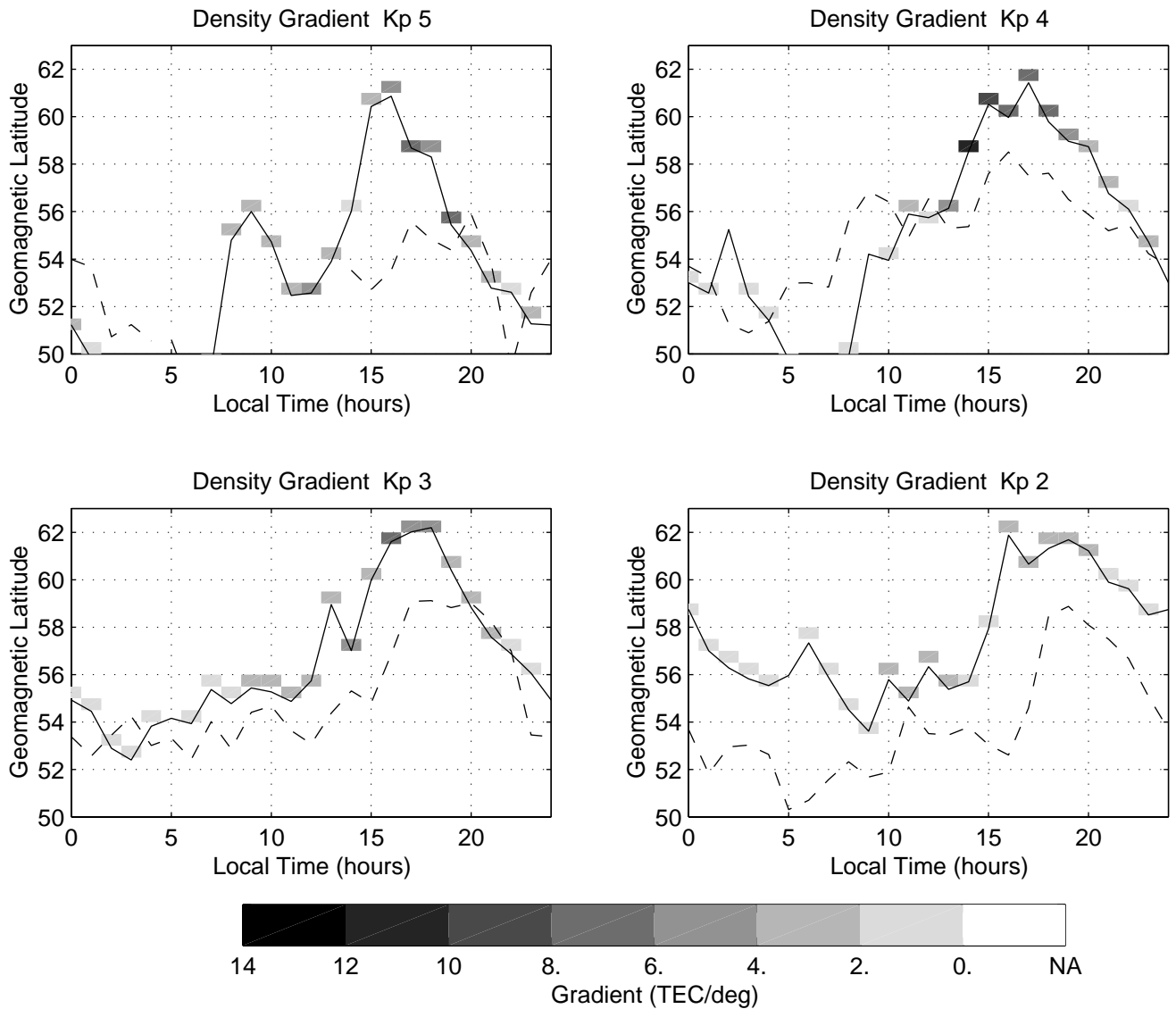


Figure 6. Average magnitude and geomagnetic latitude of the steepest density gradient associated with the equatorward wall of the trough or other plasma feature are plotted against local time for four levels of the Kp index during solar maximum. (The latitude variation for solar minimum conditions is shown by the dashed line.) The magnitude of the gradient is indicated by shading and is in the range [0,8] TEC/deg. Gradients are steepest in the dusk sector when the ionospheric trough comes into the radar field of view, with the highest values appearing at high latitudes shortly after noon.

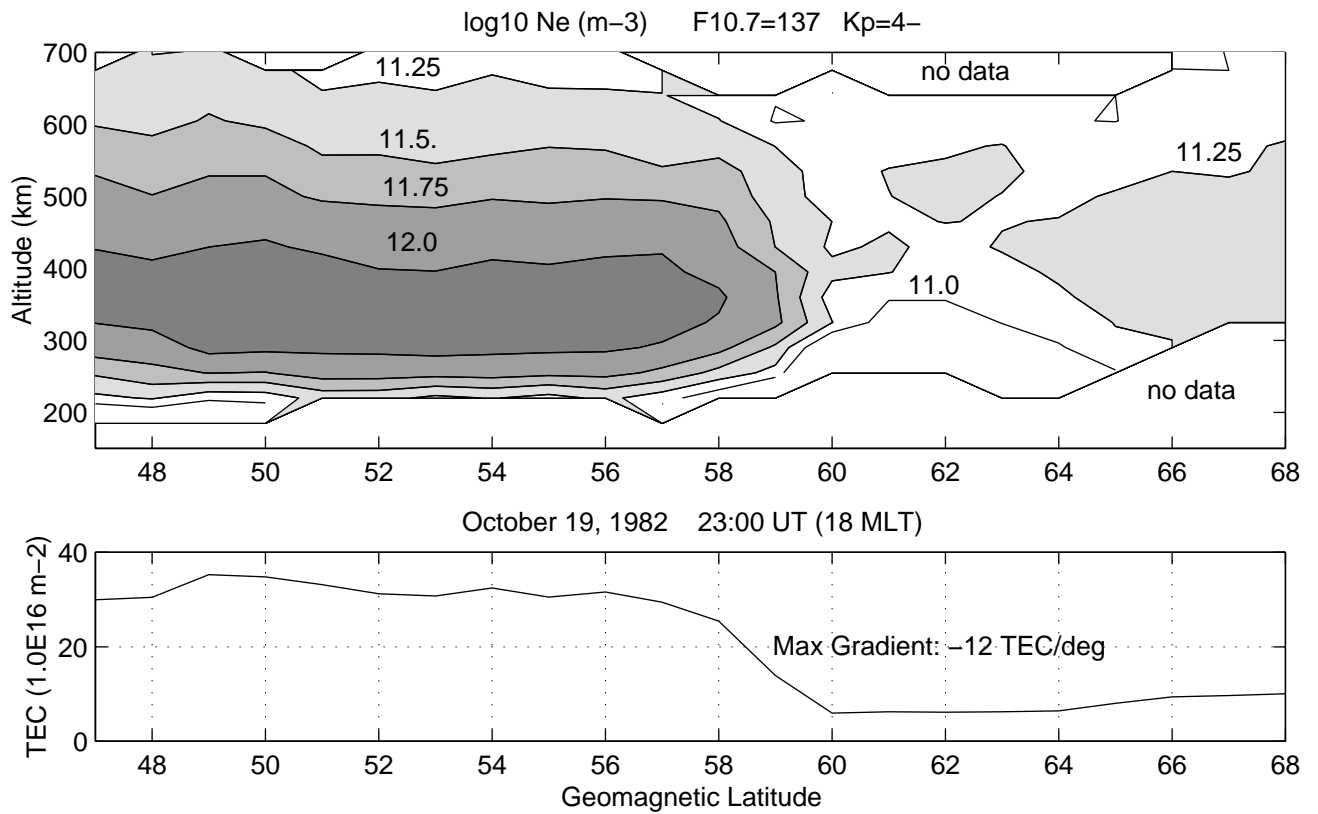


Figure 7. Iso-density contours of electron concentration observed on October 19, 1982 with a N-S elevation scan during typical dusk-sector disturbed conditions at solar maximum reveal a steep density gradient on the equatorward wall of the trough at  $59^\circ \Lambda$  ( $L \sim 4$ ), some  $6^\circ$  poleward of the radar facility. TEC determined by integrating the electron concentration between altitudes 200 km to 700 km is plotted below the elevation scan data.

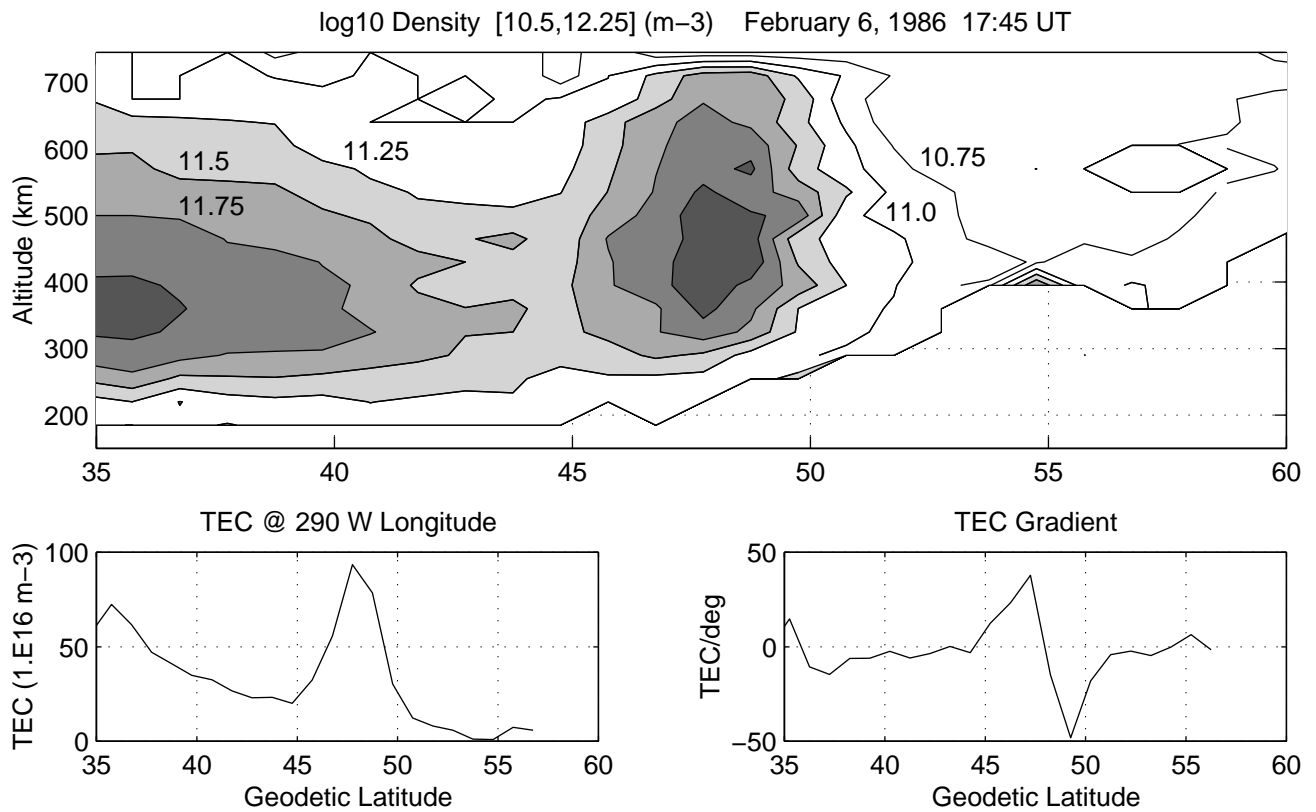


Figure 8. Iso-density contours observed by the Millstone Hill radar scanning N-S across a region of strong SED (storm-enhanced density) near local noon are presented with  $0.25 \text{ m}^{-3}$  spacing as a function of geodetic latitude (invariant latitude = geodetic latitude +  $11^\circ$ ). *F*-region TEC and TEC gradient across the region are derived from the radar elevation scan and are shown in the bottom panels. The February 8, 1986 event represents a severe example of the ionospheric density perturbation that can occur over the continental US during large geomagnetic storms. TEC near  $48^\circ \text{ N}$  geodetic latitude is  $\sim 100$  TEC units and the latitude gradient in TEC associated with the region of SED near  $45^\circ$  latitude was  $\sim 50$  TEC/deg.