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The Daytime F Layer Trough and Its Relation to Ionospheric-Magnetospheric Convection

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The daytime F layer trough is studied by means of an extensive network of ground-based ionospheric sounders in the northern hemisphere under conditions of solar maximum near winter solstice. The trough is observed to be a continuous band having an instantaneous extent of thousands of kilometers consisting of depletions in the daytime electron density, often by an order of magnitude. It lies in regions of sunward ionospheric-magnetospheric convection, an afternoon sector corresponding to the dusk cell, a morning sector corresponding to the dawn cell, and morphology and activity dependence consistent with convection. As detected in the diurnal distributions of f_oF_2, the trough is a persistent feature at high latitudes, appearing on each day of a 31-day period of continuous observation, and, although highly variable from day to day, is apparent in the monthly medians. The afternoon trough, which is detected independently by at least five and as many 17 stations on each day, is generally continuous and stationary for a duration of many hours in magnetic latitude/magnetic local time coordinates. The trough contracts during quiet conditions so as to lie above 70° magnetic latitude but expands during disturbed conditions so as to extend from 75° to 52° magnetic latitude. The trough has a pronounced dependence on longitude, appearing principally in the afternoon in eastern magnetic longitudes but in the morning in western magnetic longitudes, an effect so prevalent that it produces large east-west local time asymmetries in the diurnal distributions of median daytime F layer electron densities throughout a wide range of latitudes. The longitudinal dependence is found to result from the relation between the two principal coordinate systems of the ionosphere-magnetosphere interaction: solar geomagnetic coordinates in which the convection pattern and the resultant daytime trough reside, and solar terrestrial coordinates in which solar ion production and the undisturbed daytime F layer in general reside; as a consequence of the fact that these coordinate systems vary with respect to one another with longitude, the trough varies within the daytime F layer with longitude.

1. INTRODUCTION

Depleted regions of ionospheric plasma in the daytime F layer have been known to exist for many years, having been observed by *Muldrew* [1965], *Bowman* [1969], *Hanson and Carlson* [1977], *Spiro* [1978], *Leitinger et al.* [1978], *Leitinger and Putz* [1986], *Ahmed et al.* [1979], *Ben'kova et al.* [1980], *Grebowsky et al.* [1983], *Evans et al.* [1983], *Holt et al.* [1984], *Foster et al.* [1985], *Besprozvannaya et al.* [1986], and *Collis and Haggstrom* [1988]. These workers have termed the regions main trough, mid-latitude trough, or high-latitude trough, and although the three terms may describe the same phenomenon in the daytime [*Grebowsky et al.*, 1983], there is little agreement as to its properties. In general, the daytime trough has been thought to exist only sporadically and to be associated with high magnetic activity [e.g., *Ben'kova et al.*, 1980].

Whalen [1987], using a global network of ionospheric observatories, showed a trough to exist in the daytime F layer on a macroscopic scale as an integral, spatially continuous entity, the instantaneous extent of which was thousands of kilometers. This daytime trough was present during winter conditions under a large range of activities from disturbed to quiet, often appearing as an order of magnitude reduction in electron density at the daytime F layer maximum. The trough, the equatorward boundary of which was stable in solar geomagnetic coordinates for many hours, was seen to recede to high latitudes during quiet conditions but to expand so as to extend continuously from polar cap to mid-latitudes during disturbed conditions. These observations of the daytime trough found it to be similar to the ionospheric-magnetospheric convection pattern in morphology and activity dependence and so consistent with its resulting from sunward convection as indicated by simultaneous measurement of electron density and ion velocity by incoherent scatter radar [e.g., *Holt et al.*, 1984; *Foster et al.*, 1985; *Collis and Haggstrom*, 1988].

In addition, striking differences were observed in the local time occurrence of the trough at stations which were at the same magnetic latitude but at different magnetic longitudes. In particular, the trough appeared principally in the afternoon at Narssarssuaq, Greenland, but in the morning at Barrow, Alaska.

This paper reports in detail the results of the study of the daytime F layer trough described in the earlier brief report [*Whalen*, 1987], and of a study of trough longitude dependence and of the origin of this dependence. It employs the most comprehensive set of observations of the high-latitude ionosphere ever made, those during the International Geophysical Year (IGY) when the largest number of ionospheric sounders ever assembled were in operation. The period studied is December 1958, hence solar maximum and winter solstice, using the array of northern hemisphere ionospheric sounders shown in Figure 1. Ionospheric soundings are made simultaneously at hourly intervals throughout the array, continuously throughout the 31-day period.

The geomagnetic coordinate system used here is the corrected geomagnetic (CG) system of *Hultqvist* [1958] and Hakura [1965] as described further by *Whalen* [1970]. This coordinate system is well established and known to be appropriate for this period since it is the system in which *Feldstein and Starkov* [1967] defined the auroral oval from IGY observations. In the following discussion, corrected

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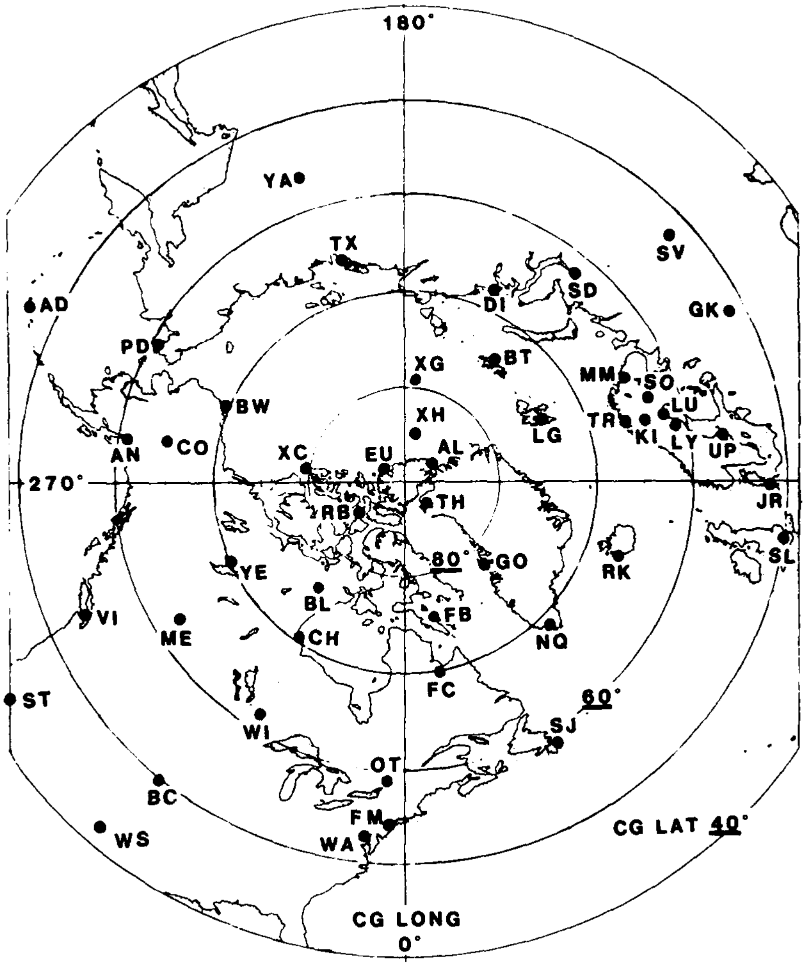

Fig. 1. The IGY network of ionospheric sounders operating during December 1958 which provides the data for this study.

geomagnetic local time (CGLT) and local (solar) time (LT) will denote mean times in the two time coordinate systems.

This paper will show that the daytime trough is a fundamental feature of the daytime ionosphere during this period. The approach will be to show that the trough is visible as a function of LT as well as of latitude; that it has a characteristic LT signature which is detectable by the global array of ground-based sounders under all conditions from quiet to disturbed; that its equatorward boundary is frequently stationary for many hours in corrected geomagnetic latitude (CGlat)/CGLT; and that it is present on every day of the continuous 31-day period. It will show further that the properties of the daytime trough observed here are consistent with its being a product of ionospheric-magnetospheric convection and that this is the cause of its longitudinal dependence. That is, the convection pattern resides in solar geomagnetic coordinates so that the appearance of the trough in the daytime *F* layer, as observed in solar terrestrial coordinates, is subject to the systematic longitudinal variation of the two coordinate systems with respect to one another.

2. Afternoon Trough

2.1. *Detectability as a Function Either of Latitude or of Local Time*

This section will address the seeming paradox that the trough, which was originally defined as a latitudinal feature, is readily observed in the daytime in the diurnal variation of f_oF_2 at constant latitude. It will show the daytime trough in the afternoon sector to move equatorward with time and therefore to yield a characteristic LT signature of its intersection with a ground-based ionospheric sounder.

An example of the afternoon trough as a latitudinal feature is available in measurements from the longitude sector of western Europe, principally the Scandinavian peninsula. This sector is unique in having a latitudinal chain of nine sounders which can measure *F* layer latitude profiles with good resolution over a large range in latitude (Figure 1). The plasma frequency at the *F* layer maximum, f_oF_2, measured by nine sounders in this chain, is plotted versus CGlat at hourly intervals starting at 1200 LT for 2 days: the first is a quiet day (December 10, 1958, average Kp ~ 1o) when no

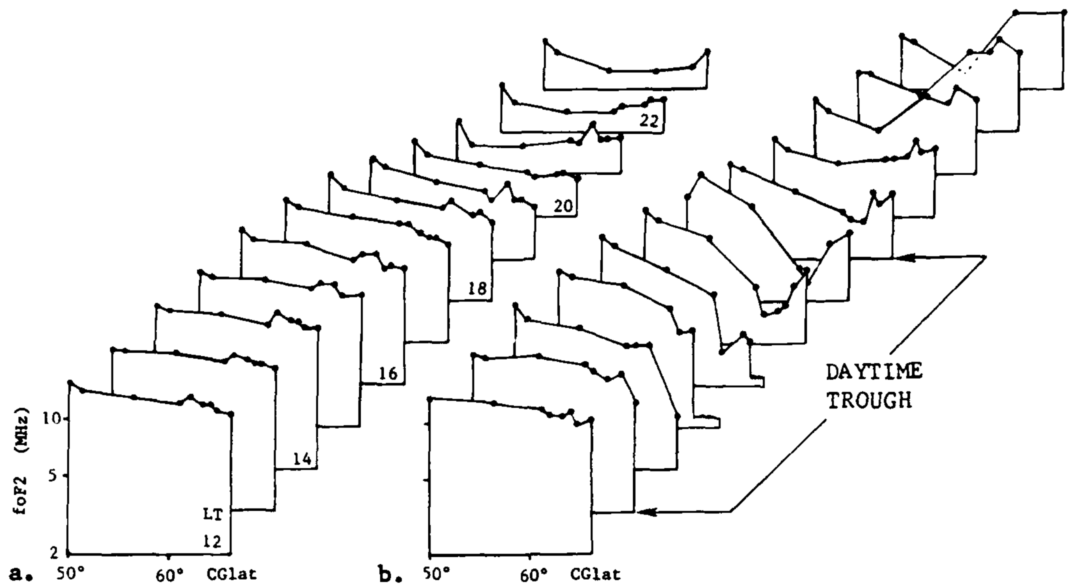

Fig. 2. The daytime trough in latitude. Latitudinal profiles of F layer ionization at hourly intervals of local time from a chain of nine ionospheric sounders in and near Scandinavia. Two days are shown: (*a*) a quiet day when no daytime trough is observed, and (*b*) a moderate day when the daytime trough is observed to exist between 1300 and 1900 LT and to move equatorward during that interval.

daytime trough is detected by the chain (Figure 2*a*); the second is a moderate day (December 21, 1958, average Kp = 2o) when a trough appears at 1300 LT as a decrease in f_oF_2 at the highest-latitude station (Figure 2*b*) and moves equatorward with time so that the minimum is clearly resolved in latitude between 1600 and 1900 LT.

Because the trough moves equatorward, its passage is recorded as a decrease in f_oF_2 as a function of LT at individual stations. This is shown in the diurnal distributions of f_oF_2 for these same two days at Tromso, the chain station at highest latitude, the smooth curve in Figure 3 being that of the quiet day and the curve plus points that of the moderate day. The depletion on the moderate day as compared to the quiet day (shaded) is thus the LT profile of the daytime afternoon trough with onset corresponding to the passage of the equatorward boundary over Tromso. Although conditions are moderate, electron density is reduced by a factor of nearly 8 within 2 hours following trough onset. Such a catastrophic disappearance of the daytime F layer is not unusual for this period, and in general the trough signature is easily recognizable, as will be seen below.

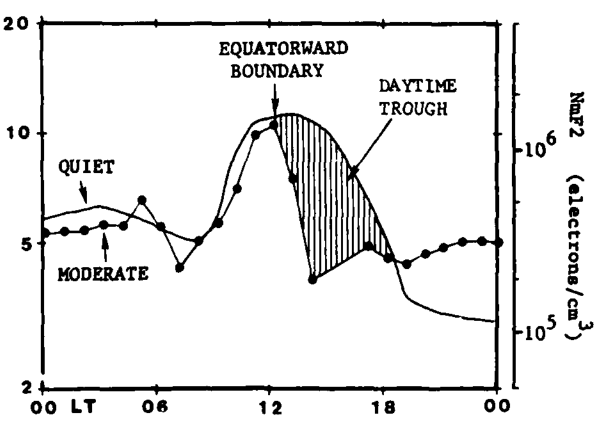

Fig. 3. The daytime trough in local time. Diurnal distributions of F layer ionization for the two days of Figure 2 recorded at Tromso, the station at highest latitude in the Scandinavian chain. Because the daytime trough moves equatorward, the station intersects it as a function of LT so that it appears as the depletion in ionization (shaded) which occurs on the moderate day, the onset of the depletion recording the trough equatorward boundary.

2.2. *Detectability at Differing Longitudes and Activities*

The detection of the trough is limited neither to the locale nor to the conditions of Figure 2, as will be illustrated for three days of varying conditions of activity by means of partial latitudinal chains in two different longitudinal sectors. However, a different format will be used because that of Figure 2 is not suitable if, as often occurs, stations are far apart or there is loss of data due to spread F or other disturbances.

Latitude signatures. The first of these days is a disturbed day (December 4, 1958, average Kp = 5o) observed by a European chain consisting of JR, UP, LY, KI, MM, and TR (Figure 1). Latitudinal profiles of f_oF_2 from 1100 through 1600 LT are plotted together in Figure 4*a*. At 1100 LT the profile is relatively flat, but at 1200 LT a decrease appears at the highest-latitude station. At 1300 LT the decreasing profile has moved equatorward, so as to be seen by the three highest-latitude stations. At 1400 LT this profile has moved further equatorward, but the two highest-latitude stations no longer can measure f_oF_2 because of disturbed conditions. This equatorward progress of the decreasing profile continues through 1600 LT. Although the minimum is not resolved, the equatorward boundary and the decrease poleward of it reveal a latitudinal trough in f_oF_2 which moves equatorward with time.

For a moderately active day (December 23, average Kp = 3−) the same chain of stations first detects the trough at 1400 LT though having a somewhat irregularly decreasing latitu-

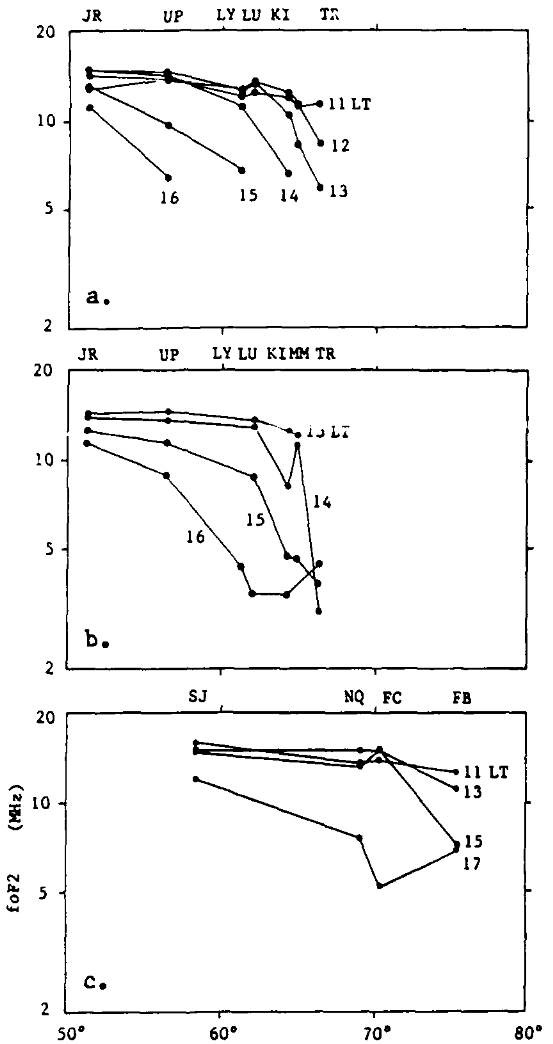

Fig. 4. Daytime trough profiles for a range of activities recorded at two different locations. Latitudinal profiles of f_oF_2 detected on three days by latitudinal chains of ground-based ionospheric sounders. Stations are identified above each graph, and the LT of each profile is labeled. In each case there is a latitudinal trough which progresses equatorward with time. (*a*) Disturbed conditions (December 4, 1958) observed by a Scandinavian chain. (*b*) Moderately active conditions (December 23, 1958) observed by a Scandinavian chain. (*c*) Moderately quiet conditions (December 11, 1958) observed by an eastern North American chain.

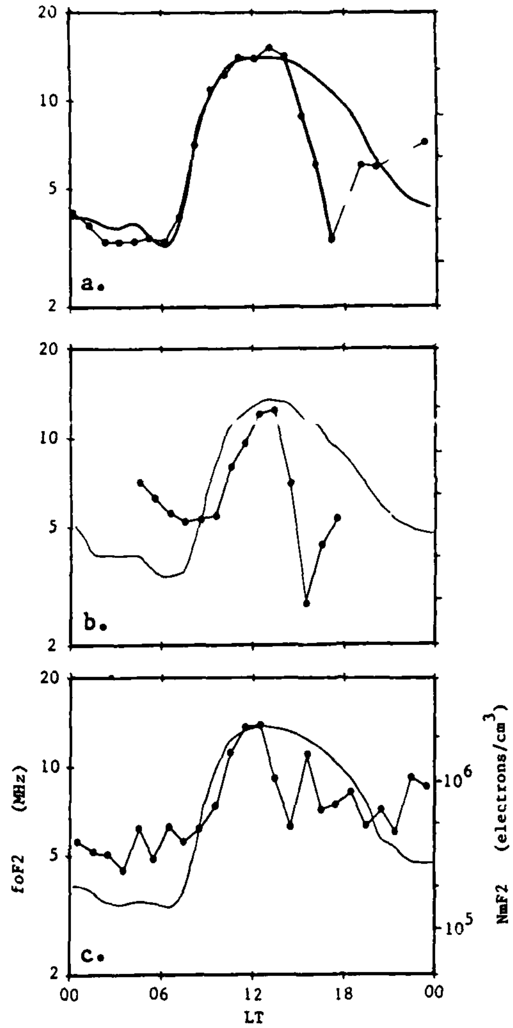

Fig. 5. LT signatures of the daytime trough. Examples of diurnal distributions of the trough recorded over a large range of latitudes on the three days of Figure 4 (points) compared to the distributions for a quiet day (smooth curve). (*a*) Disturbed conditions observed at UP (56.5° CGlat). (*b*) Moderately active conditions observed at KI (64.3° CGlat). (*c*) Moderately quiet conditions observed at FB (75.4° CGlat). Quiet day curve is inferred as described in the text.

dinal profile between MM and KI (Figure 4*b*). The profile moves progressively equatorward with time, the trough minimum being detected in the final profile at 1600 LT.

For a moderately quiet day (December 11, Kp = 2o), stations in eastern North America are employed, consisting of SJ, NQ, FC, and FB. Figure 4*c* shows a pattern similar to the previous two in that the latitudinal depression of f_oF_2 appears first at the highest latitudes and moves progressively equatorward with time. Although the latitudinal resolution is poor, the trough minimum is detected in the last profile at 1700 LT.

As in Figure 2 the trough in each of the three cases is a latitudinal depletion in f_oF_2 which moves equatorward with time. With decreasing activity the pattern as a whole is displaced poleward and to later times and moves equatorward more slowly. This will be shown below to be a consequence of the morphology of the trough in CGlat/CGLT and of its stability in these coordinates.

LT signatures. Examples of the LT signature of the afternoon trough as observed by individual stations in the above three cases are shown in Figure 5, in which the diurnal distribution for each day is compared to that for the most quiet day (December 1, average Kp = 1−): UP at 56.5° CGlat for the disturbed day in Figure 5*a*; KI at 64.3° CGlat for the moderately active day in Figure 5*b*; and FB at 75.4° CGlat for the moderately quiet day in Figure 5*c*.

At FB the comparison quiet day distribution is not from FB because the afternoon trough occurs at this station on even the most quiet day. Instead, the undisturbed quiet day distribution is inferred near midday from LY, a station which has nearly the same geographic latitude as FB (64.6° compared to FB at 63.8°) and hence has nearly the same solar ion production but has a much lower CGlat (61.2° as compared to FB at 75.4°). Since the trough does not occur in the daytime F layer at LY on this quiet day, it is adequate to show that there is a trough at FB which departs considerably from an expected regular distribution. The trough signature is so evident that its detection does not require the comparison of a specific quiet day curve, not only here but also in Figures 4, 5*a*, and 5*b*. However, other phenomena which might affect such comparisons are discussed in the appendix.

The depletions identified as the afternoon trough in Figure 5 have very similar signatures in the nearly exponential decrease between the equatorward edge and trough minimum, although they span nearly 20° of CGlat and a large range of activity. These three cases illustrate the general case that the trough onset is a characteristic signature of the afternoon trough equatorward boundary which is detectable throughout a large range of activities, latitudes, longitudes, and local times. As a result the detection of the equatorward boundary is not limited to latitudinal chains of stations in the same longitudinal sectors but is possible virtually worldwide by the members of the IGY array of sounders for each of the 31 days of December 1958. The high visibility and frequency of occurrence of this LT signature as observed at a single station during the entire month will be seen in Figure 7. The following section will show this feature to be remarkably stable when observed over much of the Earth in CGlat/CGLT.

CGlat/CGLT. By use of all available measurements by the array of sounders shown in Figure 1, the observed time of onset of the afternoon trough expressed in CGLT is plotted versus CGlat for each station for each of the above three days.

The measurements on the disturbed day by 16 stations between DI and YE during 14.5 hours UT are shown in Figure 6*a*. *Whalen* [1987] has given a detailed description of the individual measurements on this day. The measurements on the moderately active day by 13 stations between DI and BW during 18 hours UT are shown in Figure 6*b*. The measurements on the moderately quiet day by 13 stations between BT and YE during 17.25 hours UT appear in Figure 6*c*.

In each of the three cases the trough equatorward boundary is continuous, single valued, and stationary in CGlat/CGLT for many hours. It is because the trough boundary remains fixed for such an extended period in this solar geomagnetic frame of reference that ground stations detect it as a consistent feature irrespective of longitude as they are carried beneath it with the rotation of the Earth. Because the trough decreases in CGlat with increasing CGLT, ground stations at the same longitude intersect it earliest at the highest latitude, and progressively later at progressively lower latitudes. In the reference frame of the latitudinal chain the trough therefore appears as a depression in f_oF_2 that moves equatorward with time, as seen in Figures 2*a* and 4. Figure 8 will display the equatorward boundary for each of the 31 days studied, and Figure 10 will show the similarity of this boundary to that of the convection pattern.

2.3. *Daily Occurrence*

LT. An example of how frequently the afternoon trough is observable via its LT profile in this data set is shown in the diurnal distributions of f_oF_2 from Narssarssauq, Greenland (NQ), for each of the 31 days of December 1958 in Figure 7.

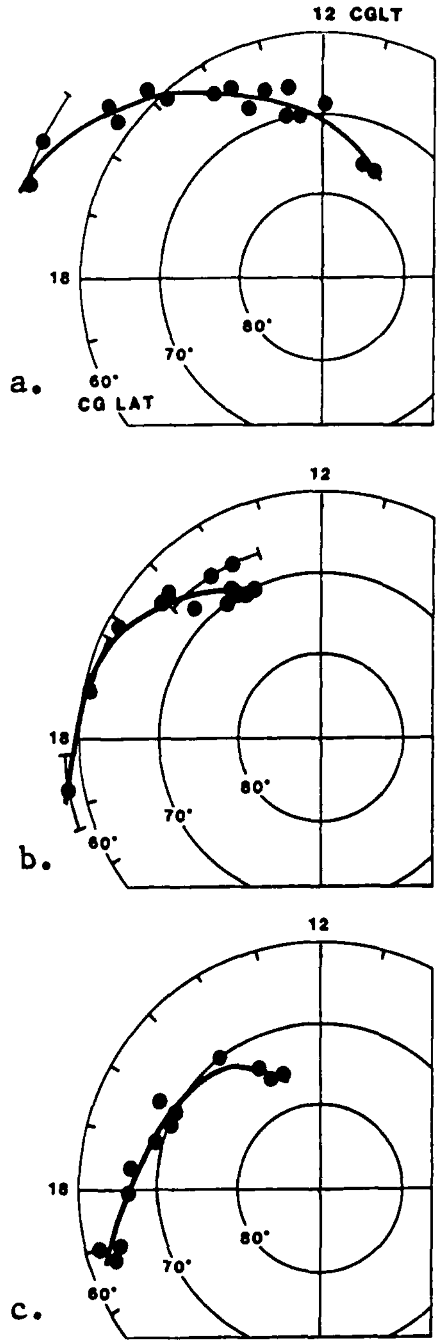

Fig. 6. Equatorward boundaries of the afternoon trough. Trough onsets detected by the sounder array in Figure 1 for the three days of Figure 4 plotted in CGlat/CGLT. (*a*) Disturbed. (*b*) Moderately active. (*c*) Moderately quiet.

As compared to the smooth curve, which is derived from the most quiet days of the month, there is a trough principally in the afternoon which occurs on most days, the onset/equatorward edge of which is indicated by the arrow in each case. This depletion is often very large, reducing f_oF_2 near midday when solar ionization rates are greatest to values near or below the quiet nighttime levels (e.g., December 2). On other days, no afternoon trough is evident at this station (e.g., December 1 and 10). The day-to-day variability is very large, a fact which will be emphasized in the overplot of these distributions in Figure 12.

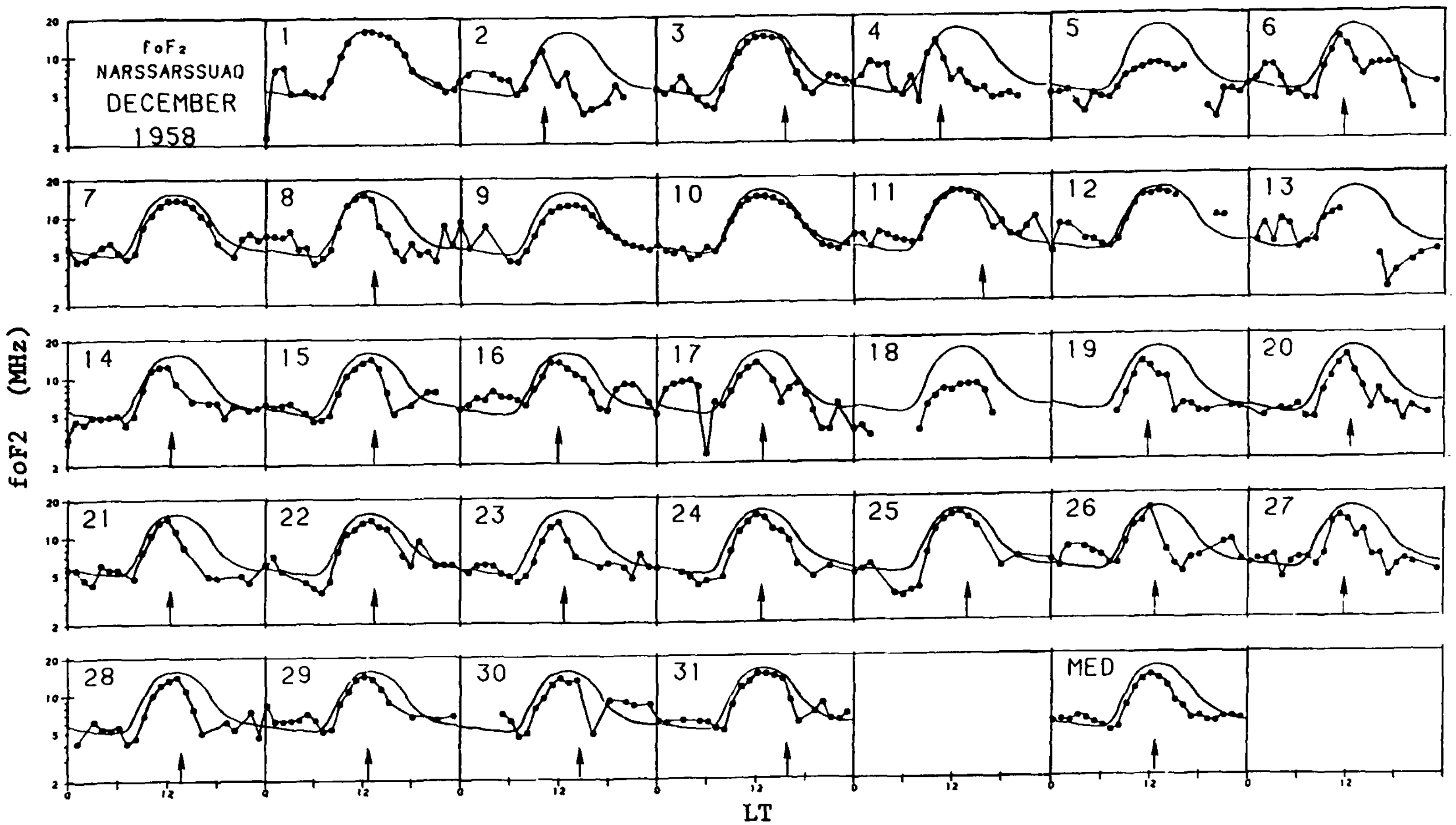

Fig. 7. Daily occurrence of the trough observed in LT. Diurnal distributions of f_oF_2 recorded by the ionospheric sounder at Narssarssuaq, Greenland, on each day of December 1958 (points) compared to the quiet day distribution (smooth curve). The afternoon trough is observed on most days, the onset/equatorward boundary of which is indicated by the arrow.

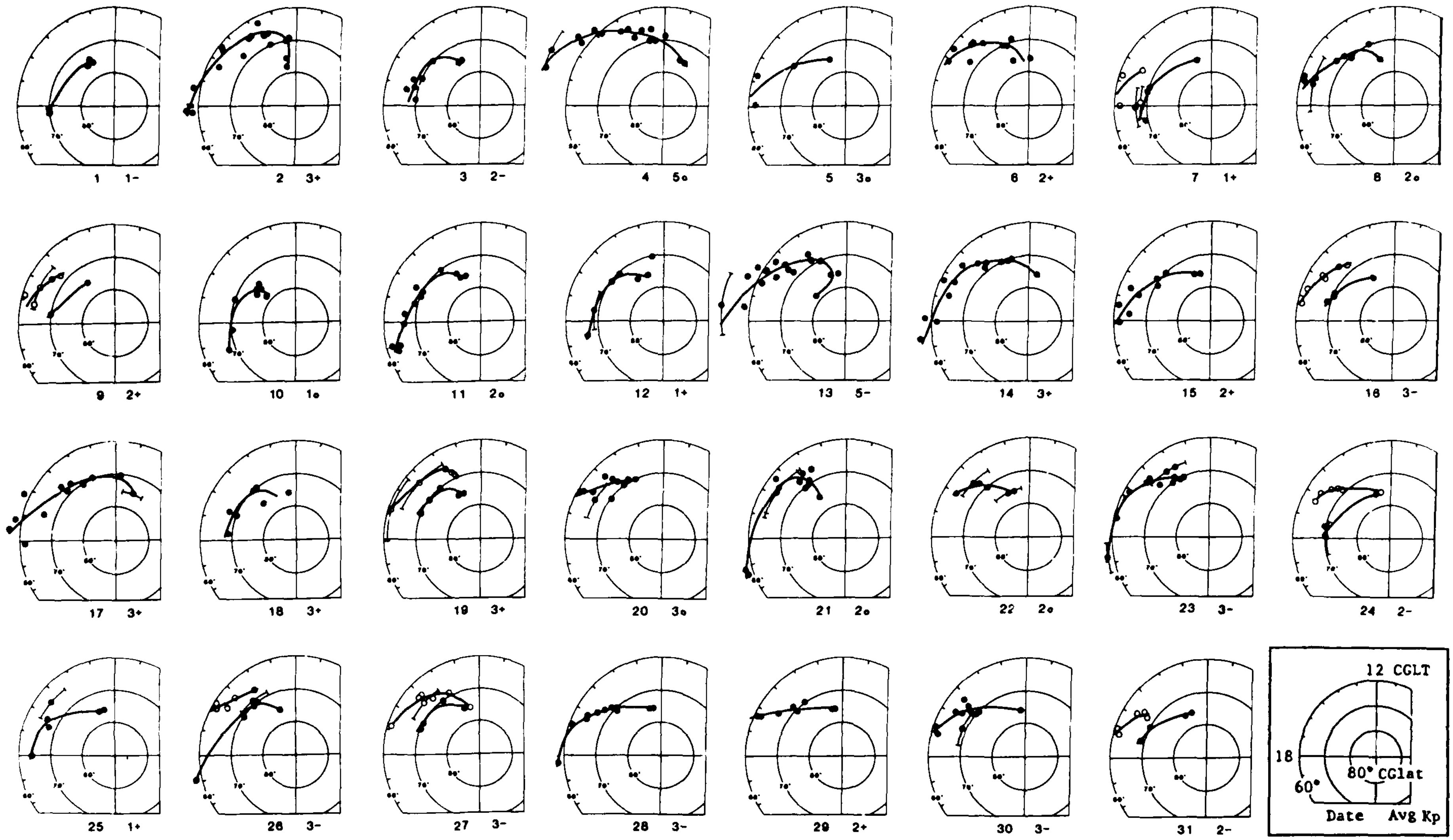

Fig. 8. Daily occurrence of the daytime trough in CGlat/CGLT. Ensemble of all determinations of trough equatorward boundaries recorded in the afternoon sector by the global array of sounders for each day of December 1958. Date and average Kp for the UT day are shown below each plot.

The depressed daytime values of f_oF_2 seen clearly on three days, December 5, 13, and 18, are negative storm effects associated with the magnetic storms of December 4–5, 13, and 17–18. Although this infrequent storm effect tends to obscure the trough signature at NQ, it is seen at other stations on these three days.

The afternoon trough is such a common occurrence that it is evident in the median for the month (MED in Figure 7). Section 3 will show the trough to be such a fundamental feature that it appears in the monthly medians throughout a large range of latitudes and longitudes.

Equatorward boundary in CGlat/CGLT. By use of the entire ensemble of stations, the afternoon trough equatorward boundary is observed on each day of December 1958. The results are displayed in Figure 8 plotted in CGlat/CGLT, the date and average Kp appearing below each graph. The boundary is continuous, extensive, and often stationary in these coordinates for many hours on individual days but can be extremely variable from day to day. The scatter which appears in the measurements particularly on active days implies variations in position over the course of the observations. On eight days, systematic changes in position occur which permit detection of two relatively stable distributions which are separated by longitude and UT. The position of the boundary observed principally in Europe is shown by open circles, and the position observed principally over North America is shown by solid circles for each of these days (December 7, 9, 16, 19, 24, 26, 27, and 31).

There are 313 observations of the trough boundary shown in Figure 8. On the individual days the number of independent observations of the trough varies from a minimum of five to a maximum of 17, the average being 10 per day.

Note that the trough boundary often spans continuously an extensive range of latitudes, particularly during active conditions. Accordingly, the terms high-latitude trough and mid-latitude trough do not adequately describe the phenomena.

UT dependence. Each of the observations of the equatorward boundary is shown as a function of UT for each day in Figure 9. A line connects those measurements which are interpreted as a single boundary in Figure 8. As in Figure 8 when two distributions are resolved, that from the European sector, observed at the earlier UT, is shown by open circles; that from the North American sector, observed at the later UT, by solid circles.

Continuity in space and time. The continuity shown in CGlat/CGLT in Figure 8 is the cumulative result of measurements which are generally separated in UT. However, there are many simultaneous observations of the equatorward boundary in Figure 9. Because these simultaneous observations are at different locations, the equatorward boundary is observed to be spatially continuous instantaneously between the two locations in each case.

Because a station remains beneath the trough for several hours after the passage of the equatorward boundary, a given station is usually still observing the trough at the time the next station encounters it, so that both observe the trough simultaneously at different locations. Accordingly, the trough itself is seen to be a spatially continuous entity instantaneously for each such pair of consecutive observations. This instantaneous spatial continuity of the trough was shown in a "snapshot" of the daytime trough on December 4 by *Whalen* [1987] which mapped the instantaneous extent as a spatially continuous feature of approximately 6000 km in length from Baffin Island (FB) to the Ural Mountains (SV). Although observed in segments in Figure 9, instantaneous spatial continuity of the trough is observed on every day of December 1958.

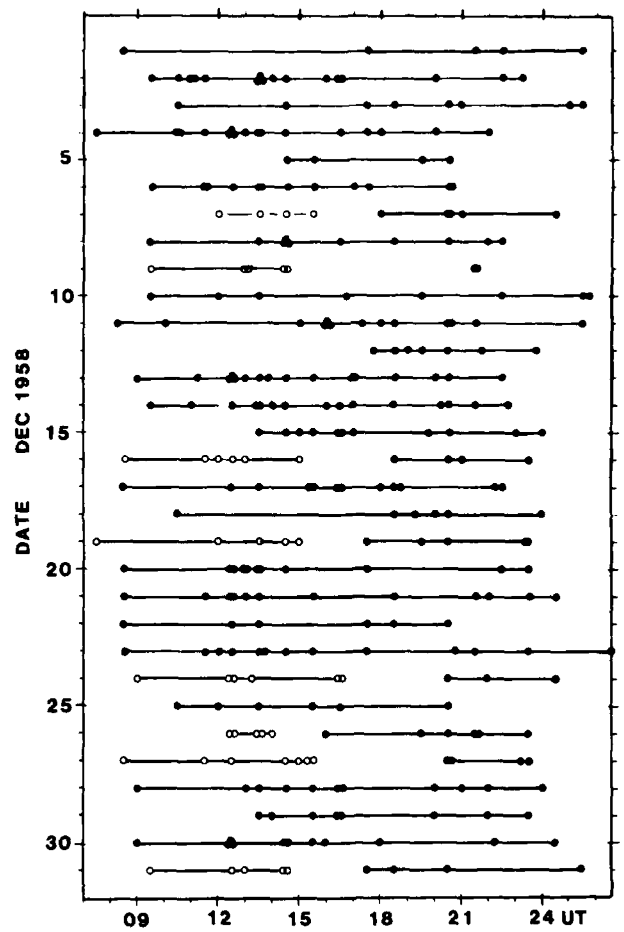

Fig. 9. Duration and continuity of the afternoon trough. UT of all the measurements of the equatorward boundaries of the afternoon trough shown in Figure 8 for each day of December 1958. Points which form a single distribution in Figure 8 are connected by a line. Open circles are the earlier of the two distributions in Figure 8. Since stations are within the trough for several hours following the passage of the equatorward boundary, the trough is observed to be continuously present for durations which in most cases correspond to the lengths of these lines.

Because of the overlap of adjacent observations, the trough itself is observed continuously for durations corresponding to the lengths of the lines in Figure 9 in most cases. The most prolonged observation occurs on December 23 when the trough is under continuous observation for more than 18 hours UT.

The absence of data points between about 0230 and 0730 UT in Figure 9 corresponds to an absence of observations in the longitudinal sector between BW in Alaska and DI in Siberia (Figure 1). This is because TI, the only station in this sector at a latitude where the trough appears routinely in other sectors, did not produce usable data during this month.

The afternoon trough is observed on each of the 31 days, under all conditions of activity from quiet to disturbed and at all UTs and longitudes, with the exception of the Asian

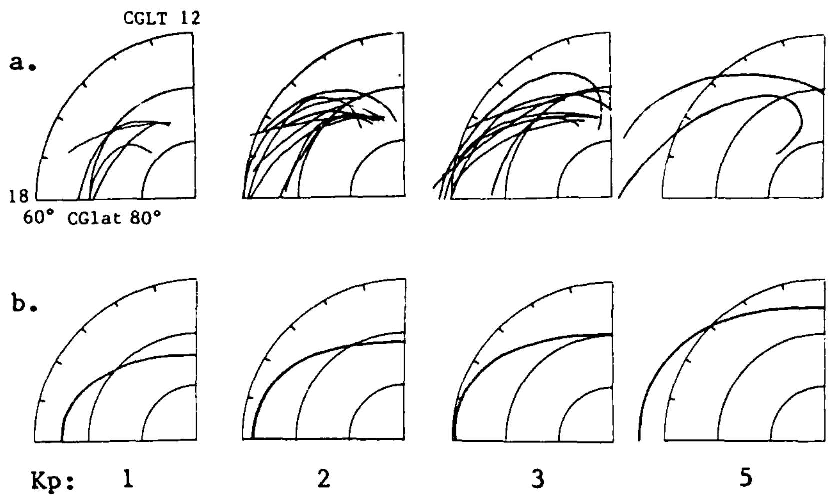

Fig. 10. *Kp* dependence of the daytime trough. (*a*) Equatorward trough boundaries from Figure 4 overplotted for four levels of average *Kp*. (*b*) Comparison of convection boundaries determined from DE 2 electric field measurements.

longitude sector noted above. The fact that the trough expands equatorward with increasing activity means that more stations can observe it during active/expanded conditions than during quiet/contracted conditions. This increased likelihood for detection is apparently the reason that the daytime trough has been thought to be associated exclusively with periods of high activity [e.g., *Ben'kova et al.*, 1980].

An example of how a limited array of measurements can fail to observe the trough occurs on December 10 when the afternoon trough is not detected by the Scandinavian chain (Figure 2) but is seen to exist elsewhere on this day, as is indicated in Figure 8. On this quiet day the trough is contracted poleward, so as not to extend below about 69°, and hence does not intersect the chain, the high-latitude limit of which is 66°.

Kp dependence and relation to the convection boundary. The equatorward boundaries of the afternoon trough for all days when a single boundary is observed in Figure 8 are grouped in terms of *Kp* as averaged over the UT day and overplotted in Figure 10*a* for four values of *Kp*: 1, 2, 3, and 5 (there being no day with average *Kp* of 4). Although there is considerable spread and consequent overlap between the groups, there is a trend to rotate clockwise and expand equatorward as *Kp* increases. This trend is consistent with that of the convection pattern [e.g., *Marklund et al.*, 1985].

As a more direct comparison, the median low-latitude convection boundaries inferred from electric field threshold measurements by Dynamics Explorer 2 [*Heppner and Maynard*, 1987] are shown below each of the overplots at the corresponding values of *Kp* (Figure 10*b*). The two sets of boundaries are similar to one another in *Kp* dependence and, particularly for the more active conditions, in morphology. Apparently, the equatorward boundary of the afternoon trough is the equatorward threshold of the ionospheric effects of convection. Further evidence of the relation of the trough to the convection pattern will be shown in section 3 and in the longitude and latitude dependence of the trough in section 4.

3. Morning and Afternoon Troughs and the Two-Cell Convection Pattern

Baker Lake, Canada (BL), at 75.1° CGlat is an oval station in daytime but a polar cap station at night and so can be expected to spend time in both sunward and antisunward convective flows. This station is therefore well positioned to observe the effects of convection on its *F* layer both in the daytime and in the nighttime. Figure 11*a* shows the December 1958 median f_oF_2 (points) as a function of LT. The smooth curve labeled "PD" is not from BL since the daytime trough is observed there on every day, even the most quiet. Instead, the smooth curve is the median from Providenya (PD), a station which is at nearly the same geographic latitude as BL (64.4° as compared to BL's 64.3°) but at a much lower CGlat (60.3° as compared to BL's 75.1°). As a result, solar ion production is the same for the two stations, but convective effects in the daytime are minimal at PD. Thus the smooth curve is an inference of what the median daytime distribution of f_oF_2 would be at BL in the absence of convective effects. (The possible effects of other phenomena on this comparison are discussed in the appendix.)

In relation to this reference curve, there is a depletion in electron density at BL (shown shaded) in the afternoon which is the signature of the afternoon trough described above. In addition, there is a similar depletion in the morning which is the signature of a morning trough. Conversely, there are enhancements at BL relative to PD from evening through midnight to morning.

To illustrate schematically how these effects are related to convection, a model of a two-cell convection pattern [Heelis et al., 1982] is shown in Figure 11*b* bounded by solid curves, the dashed circle representing the convection reversal boundary. Regions in which sunward convective transport can displace high-density daytime plasma with low-density nighttime plasma are shown shaded. As the rotation of the Earth carries BL along the path shown as the circle near 75° CGlat, its intersection with these regions corresponds to its observation of the daytime trough, the morning trough with the dawn cell and the afternoon trough with the dusk cell. Conversely, when the station crosses the convection reversal boundary passing into the region of antisunward convection, it observes a relative enhancement consistent with displacement of low-density nighttime plasma with higher-density daytime plasma. The maximum near midday corresponds to the passage of the station through the so-called

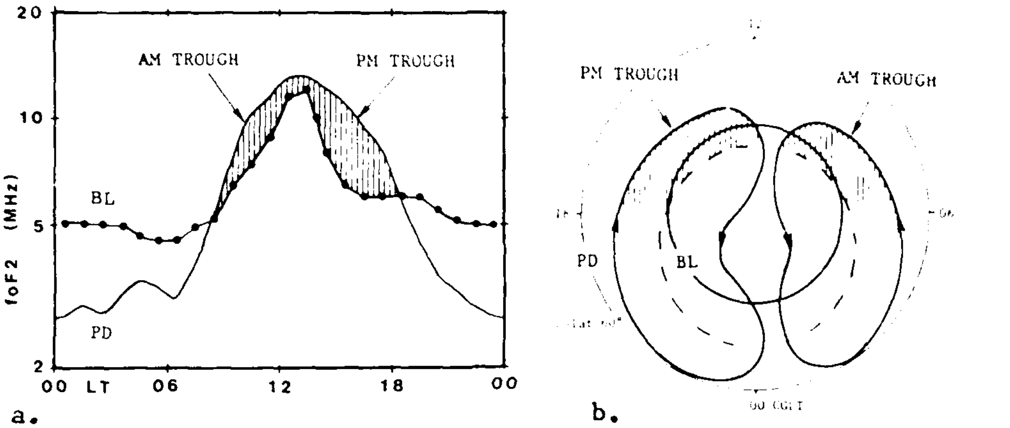

Fig. 11. Relation of morning and afternoon troughs to convection. (a) Median f_oF_2 from Baker Lake (BL) at 75.1 CGlat showing morning and afternoon troughs as compared to an undisturbed distribution inferred from Providenya (PD). (b) Schematic two-cell convection pattern showing the morning and afternoon troughs observed in Figure 11a to occur during the passage of the station through regions of the dawn and dusk cells in which high-density daytime plasma is displaced by low-density nighttime plasma via sunward convection. Conversely, BL observes elevated levels at night which correspond to displacement of nighttime plasma by daytime plasma via antisunward convection.

throat between the two cells. Here the F layer approaches the undisturbed level, which may be due either to local ion production or to the flow of plasma into the throat from elsewhere on the dayside via antisunward convection, as reported by *Kelly and Vickrey* [1984]. The next section will show variations of the morning and afternoon troughs with both longitude and latitude which are also consistent with the interpretation that the troughs result from a two-cell convection pattern.

The existence and location of the morning and afternoon troughs, the midday peak, and the polar cap enhancement are therefore all qualitatively consistent with plasma displacement by convection. However, it is by no means certain that a single mechanism is responsible for these observations, and other mechanisms have been proposed, such as ion chemical effects, which could produce depletions contributing to the formation of daytime F layer trough [e.g., *Moffett and Quegan*, 1983]. In addition, ionization by particle precipitation is a possible source contributing to the elevated electron density in the polar cap. However, a detailed determination of the mechanisms responsible for these observations is clearly beyond the scope of the measurements of f_oF_2 reported here.

Irrespective of the mechanism, it is clear that convection plays a fundamental and persistent role in the daytime F layer at BL. Further evidence of this role will be seen at a variety of latitudes and longitudes in the next section.

4. Trough Longitudinal Dependence

Whalen [1987] found a longitudinal dependence of the LT occurrence of the daytime trough which caused the daytime F layer to be very different at NQ, Greenland, from that at BW, Alaska, although the two stations are at nearly the same CGlat. In particular, the trough appeared principally in the afternoon at NQ but in the morning at BW. This section will show that this is a very general effect which results from the fact that the trough is produced by the convection pattern.

4.1. *Longitudinal Chain*

The longitudinal effect appears in more detail in the measurements by five ionospheric sounding stations which span the North American continent between NQ and BW at nearly the same CG latitude (~70°). Table 1 identifies the stations and their coordinates, the locations of which are shown in Figure 1. These stations thus form a longitudinal chain which can observe the daytime trough as a function of CGlong while holding CGlat constant.

Figure 12 shows f_oF_2 as a function of LT for each of the five stations of the longitudinal chain in an overplot of all 31 days of December 1958. The order of the stations top to bottom corresponds to their order east to west. The two or three distributions which have the lowest daytime values of f_oF_2 in each of these overplots are the negative effects associated with magnetic storms. As noted in relation to

TABLE 1. Ionospheric Sounding Stations Forming the Longitudinal Chain

Station	Symbol	Corrected Geomagnetic Latitude, °N	Corrected Geomagnetic Longitude, °E	Geographic Latitude, °N	Geographic Longitude, °E
Narssarssuaq	NQ	69.0	45.6	61.2	314.6
Ft. Chimo	FC	70.3	10.4	58.1	291.6
Churchill	CH	70.3	325.9	58.8	265.8
Yellowknife	YE	69.8	295.0	62.4	245.6
Barrow	BW	69.7	246.9	71.3	203.2

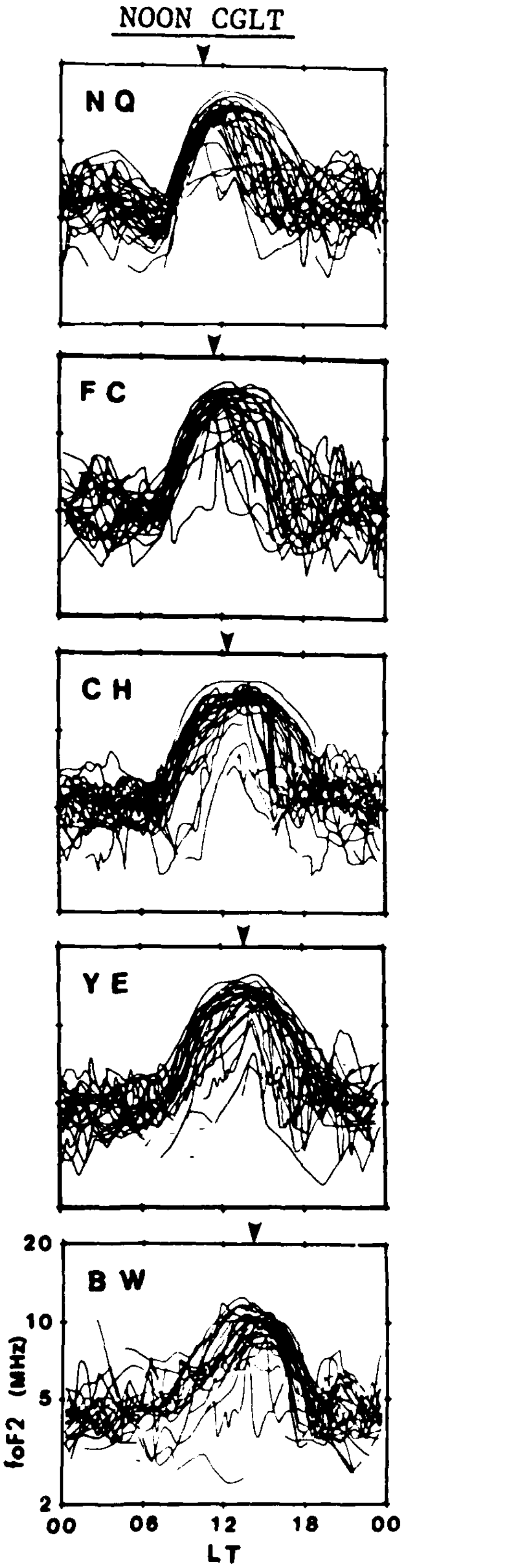

Fig. 12. The longitudinal dependence of the daytime trough. An overplot of diurnal distributions of f_oF_2 for all 31 days of December 1958 for each station of a longitudinal chain at ~70° CGlat. The trough, though variable, occurs principally in the afternoon at NQ but in the morning at BW, a change in LT occurrence which takes place progressively with longitude. Noon CGLT, shown as the arrow at the top of each graph, shifts from prenoon LT to postnoon LT over this same longitude interval, indicating the variation of the coordinate systems responsible for the variation of the trough.

Figure 7, this negative storm effect is both very infrequent and very different from the trough effect.

At NQ the overplot of the distributions (which are all shown individually in Figure 7) finds the increases of f_oF_2 following sunrise to be very similar from day to day. However, as compared to the most quiet days which form the upper envelope of the overplots in the daytime, there is a depletion occurring on nearly every day indicating the afternoon trough. The large variation of LT in the onsets of these depletions results from the large day-to-day variation in the afternoon trough morphology seen in Figure 8.

The pattern at BW is nearly the opposite of that seen at NQ in that the decreases in the afternoon are quite similar to one another, but the increases in the morning are highly variable. Thus the principal trough at BW is the morning trough, and its day-to-day variation is also highly variable. In moving from east to west along the chain, the extent in LT of these variable occurrences of the morning trough increases, and that of the afternoon trough decreases. Therefore the longitudinal effect which was observed by means of two stations, NQ and BW, is seen here to occur continuously as a function of longitude by means of all five stations of the chain.

The reason for this behavior is indicated in the variation of noon CGLT (shown as the arrow at the top of each graph in Figure 12) from prenoon LT in the east to postnoon in the west. Thus because CGLT undergoes a displacement relative to LT with longitude, the convection pattern and its effects, the morning and afternoon troughs, undergo a displacement relative to the undisturbed daytime F layer with longitude, so as to occur earlier in LT in the east than in the west.

At CH, noon CGLT occurs at nearly the same time as noon LT, and the effects of both dawn and dusk convection cells are apparent in the morning and afternoon troughs, a situation similar to that at BL in Figure 11*a*. By contrast at NQ, noon CGLT is displaced to earlier LT, so that the dawn cell tends to occur before the sunrise increase in electron density. Thus the dawn cell does not produce a visible morning trough at NQ, but the dusk cell occurs nearer midday and so produces an enhanced afternoon trough which is in effect the only one apparent there.

At BW the displacement of noon CGLT is to later LT, so that the dusk cell tends to occur after the sunset decrease in electron density, so that the afternoon trough is not visible. However, the dawn cell occurs near midday and so is enhanced to the point of being the only one visible. The next section will show that this longitude effect is not limited to the latitude regime of this chain of stations but occurs over a large range of latitude and longitude and is a very general effect of the relation between the two coordinate systems.

4.2. *Identical Twin Stations*

The large number of stations available during this period presents an extraordinary opportunity to examine the above longitudinal dependence over a large range of latitudes in a controlled manner. This is because there are pairs of stations which have nearly the same CG latitudes as one another as well as nearly the same geographic latitudes as one another. Figure 13 maps the location of these "identical twin" stations shown connected by straight lines, and Table 2 lists their coordinates. The four pairs thus span a latitude interval

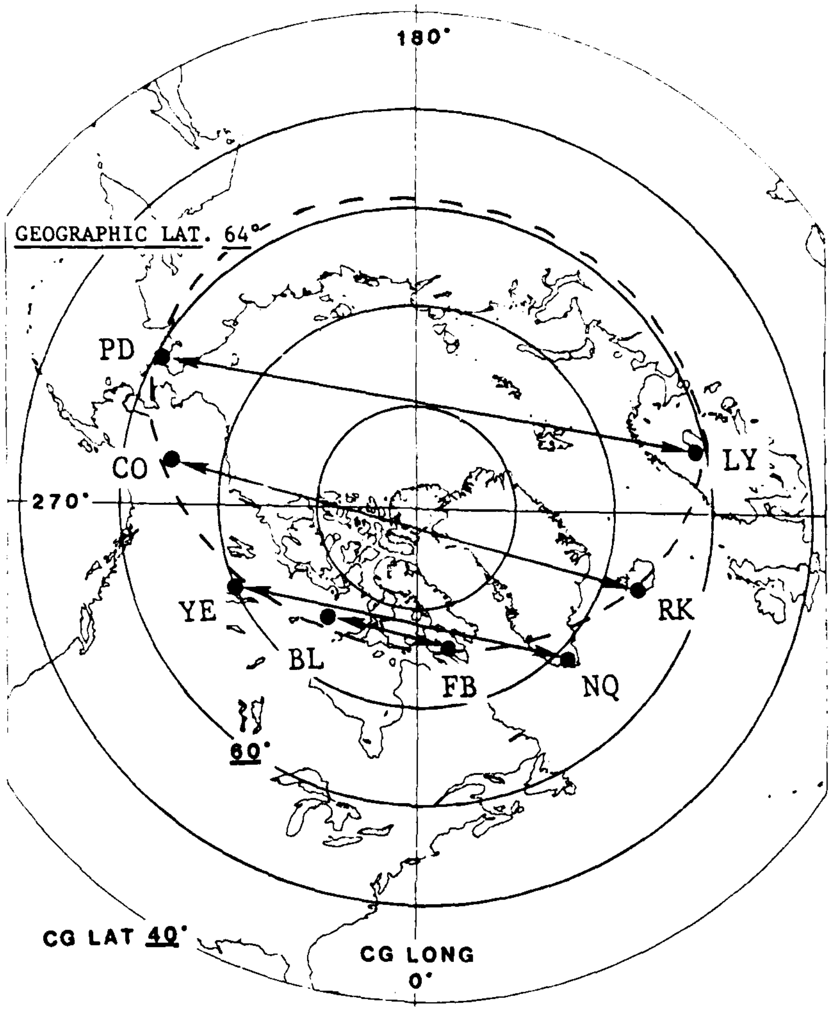

Fig. 13. "Identical twin" stations: pairs of stations which have nearly the same magnetic latitude and nearly the same geographic latitude. These form the basis of a controlled study of trough dependence on longitude.

approximately from 60 to 75° CGlat at 5° intervals. As a reference the parallel of geographic latitude at 64°, which is close to nearly all the stations, appears as the dashed elliptical curve in these coordinates. Thus both stations in a given set have nearly the same solar ion production, neutral wind, and rotational velocity by virtue of their common geographic latitude. What differences exist in their daytime F layers can therefore be reasonably attributed to the differences in longitude of convective effects. (The appendix discusses the possible role of other phenomena in this comparison.)

TABLE 2. Latitude Coordinates of "Identical Twin" Stations

Designation	Station	Symbol	Latitude: Corrected Geomagnetic	Latitude: Geographic
~75°E	Frobisher Bay	FB	75.4°	63.8°
~75°W	Baker Lake	BL	75.1°	64.3°
~70°E	Narssarssuaq	NQ	69.0°	61.2°
~70°W	Yellowknife	YE	69.8°	62.4°
~65°E	Reykjavik	RK	66.6	64.1°
~65°W	College	CO	64.9°	64.9°
~60°E	Lycksele	LY	61.2°	64.6°
~60°W	Providenya	PD	60.3°	64.4°

The median f_oF_2 for each of the pairs is plotted together versus LT, the eastern one shown as a solid curve and the western one as a dashed curve (Figure 14). The arrows at the top of each plot locate noon CGLT on the LT axis for each pair, again solid for east and dashed for west.

At the highest latitude, BL has trough-related depletions in both morning and afternoon (as described in Figure 11*a*), whereas FB has principally an afternoon trough. The net effect is that the maximum of the daytime F layer occurs at FB about 2 hours earlier than the maximum at BL. The arrows at the top of the figure which mark the occurrence of noon CGLT for each station show that the F layer peak occurs near noon CGLT in each case. Figure 11*b* indicates that this peak occurs during the interval in CGLT that the station passes through the throat of the convection pattern. Displacements of the daytime F layer (east to earlier LT, west to later LT) are seen also at the lower latitudes in Figure 14, the east-west asymmetry decreasing with decreasing latitude.

For the two stations at ~75° the displacement of the afternoon trough onsets in LT is the consequence of the

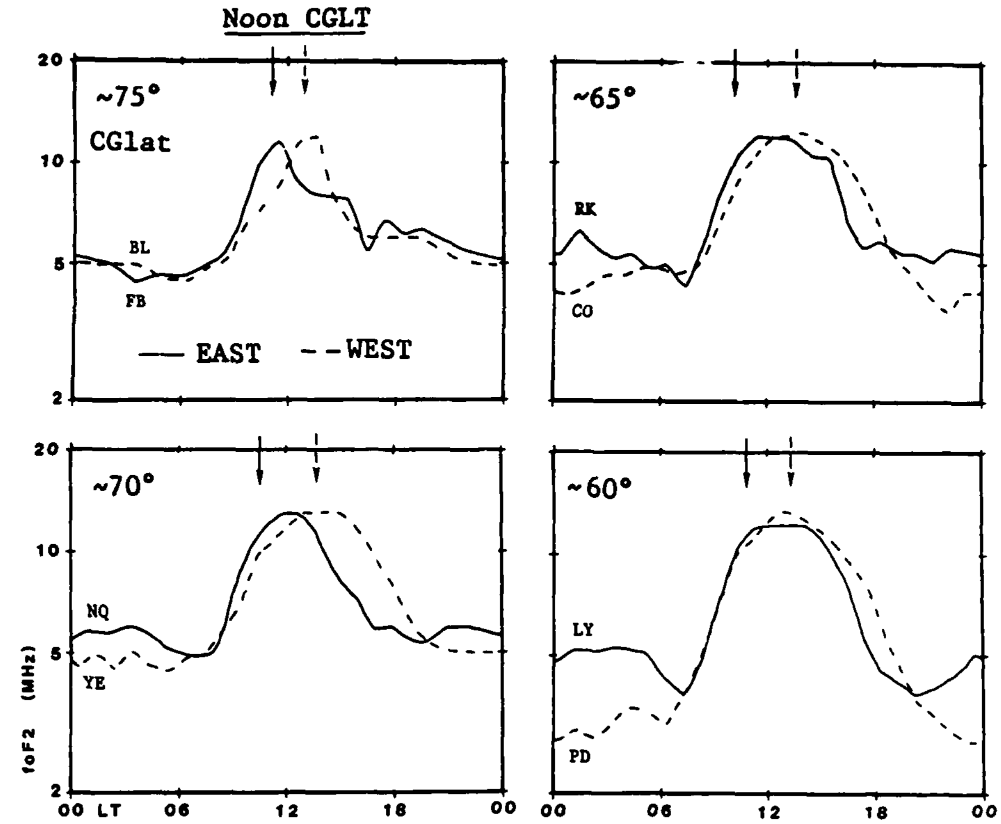

Fig. 14. Trough longitude dependence. For each set of identical twin stations of Figure 13, median f_oF_2 varies with longitude, so that there is a relative displacement of the daytime F layer at the eastern station (solid curve) to the earlier LT and at the western station (dashed curve) to later LT. This displacement is in the same sense as the displacement of noon CGLT for each station shown above each graph.

onsets being coincident in CGLT. That is, the onsets are displaced from one another in the same direction as the values of noon CGLT (FB to earlier LT and BL to later LT) and have nearly the same separation in LT as the values of noon LT. In this regard the medians display the relation seen on the individual days in that this onset occurs at virtually the same CGLT at the two stations on 16 of the 18 days that it was recorded at both (Figure 8).

To show further how the two coordinate systems contribute to this daytime longitudinal effect, noon LT is plotted for each of these eight stations in CGlat/CGLT together with a two-cell convection pattern [Heelis et al., 1982] in Figure 15. With respect to the noon LT meridian through the east stations, the CGlat/CGLT reference frame together with the convection pattern which it contains is rotated clockwise, or to earlier LT. For stations in the west, rotation is counterclockwise, or to later LT.

Because the convection pattern occurs at the earlier LT in the east, the morning trough, the afternoon trough, and the peak in f_oF_2 which occurs between the two are observed at the earlier LT. In the west the convection pattern occurs at the later LT with the result that the *F* layer peak appears at the later LT.

The east-west asymmetry in LT is therefore consistent with the differences in longitude dependence of the two principal coordinate systems of the ionosphere-magnetosphere interaction: solar geomagnetic (CGlat/CGLT) in which the convection pattern resides and solar terrestrial (geographic latitude/LT) in which solar production and the undisturbed daytime F layer in general reside. Since the pairs of stations are at the same latitude in the two coordinate systems, the cause of the longitudinal effect is primarily

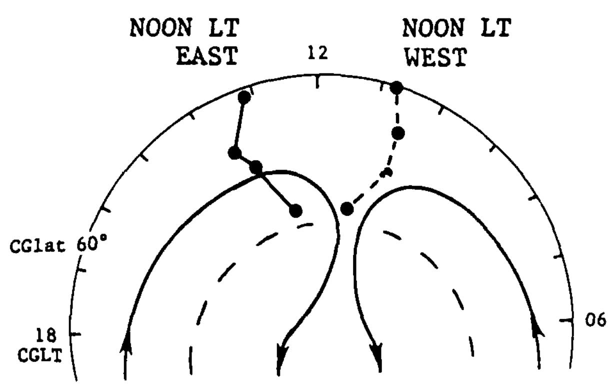

Fig. 15. Coordinate system relations responsible for trough longitude dependence. Convection pattern shown in its reference frame of CGlat/CGLT together with noon LT meridians for the four east and the four west twin stations. With respect to the noon LT meridian, the convection pattern and the resultant morning and afternoon troughs are rotated to earlier LT in the east and to later LT in the west. This is the reason that the diurnal maxima of the daytime *F* layer are seen in Figure 14 to occur at earlier LT in the east and later LT in the west.

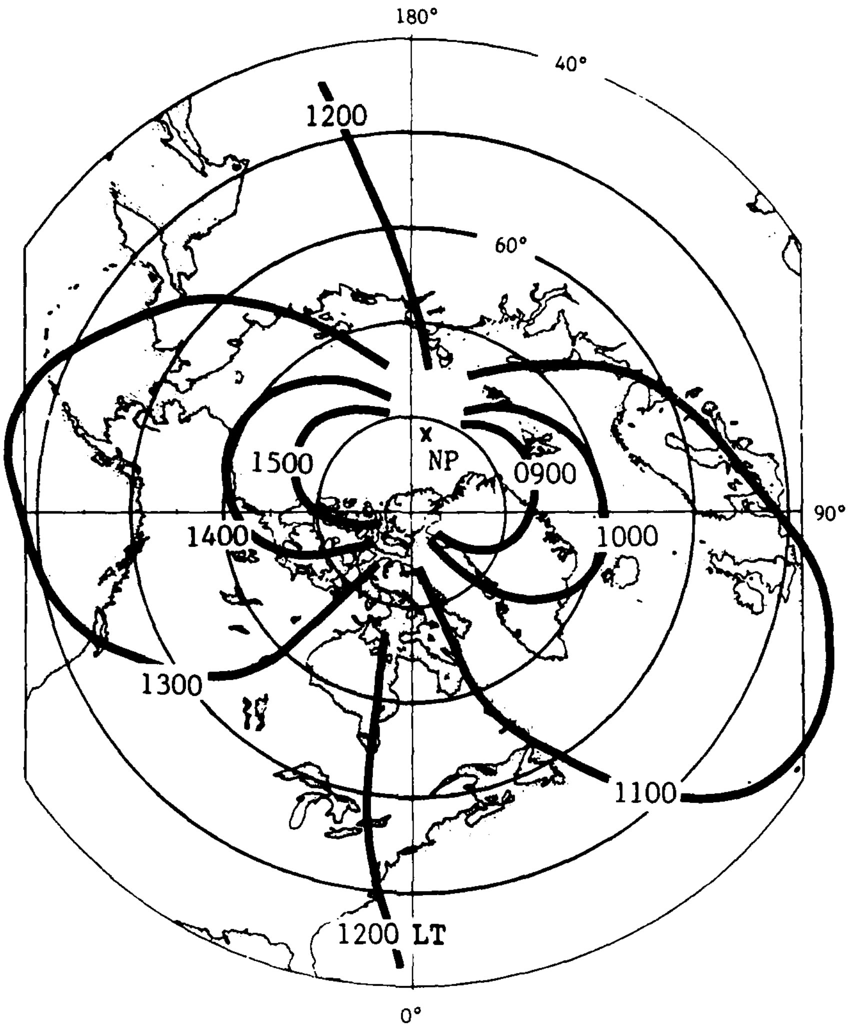

Fig. 16. Spatial relationship between local time and magnetic local time. Northern hemisphere map in CGlat/CGlong of the contours of the LT at which noon CGLT occurs. In general, CGLT leads LT in the east but lags LT in the west, so that convective effects resulting in the trough occur in the daytime *F* layer at earlier LT in the east than in the west.

the longitudinal variation of local time in the two coordinate systems.

The latitude dependence of the LT width of the solar-produced daytime *F* layer is also consistent with this two-cell pattern. That is, at ~75° the daytime *F* layer is most narrow in LT because the time interval that it spends between leaving the dawn and entering the dusk cell is the shortest. At ~70° the daytime *F* layer is wider because this CGLT interval between the cells is greater.

At lower latitudes the trend is less clear, and at PD the morning trough is not visible in the median values. The morning trough thus appears to be smaller than the afternoon trough, which is consistent with the dawn convection cell being smaller than the dusk cell [e.g., *Foster et al.*, 1986; *Holt et al.*, 1987].

4.3. *Local Time Relations*

The general relation of these two local time coordinates as a function of location in the high-latitude northern hemisphere is illustrated in a map of the contours of the LT at which noon CGLT occurs (Figure 16). The two time coordinates are the same near the 0° and 180° CGlong meridians. In eastern CGlong, noon CGLT occurs earlier than noon LT, and in western CGlong, noon CGLT occurs later than noon LT, increasingly so at increasingly higher latitudes. CGLT can be said in general to lead LT in eastern CGlong, to lag LT in western CGlong, and to be in phase with LT near 0° and 180° CGlong.

The pattern of Figure 16 is thus the spatial relation between the times in the two coordinate systems which give rise to the longitudinal dependence of the daytime trough and the resulting east-west asymmetry of the daytime *F* layer seen in Figures 12 and 14.

5. SUMMARY AND CONCLUSIONS

1. The trough is a major and persistent feature of the winter daytime *F* layer at high latitudes during this study.

2. On each of the 31 days of this study the worldwide sounder network detects the afternoon trough by at least five and as many as 17 stations, maps the morphology of its equatorward boundary in CGlat/CGLT, and observes its continuous existence for periods up to 18 hours UT.

3. The trough in the afternoon sector is an integral entity extending continuously in latitude and longitude for thousands of kilometers, as seen by multiple simultaneous observations at widely separated locations.

4. The equatorward boundary of the afternoon trough is observed to remain nearly stationary in CGlat/CGLT coordinates for durations of many hours.

5. Because the afternoon trough decreases in CGlat with increasing CGLT, ground stations are carried by the rotation of the Earth beneath it, so as to detect it as a characteristic depletion in the diurnal distribution of electron density at the F layer maximum.

6. Because of this morphology, ground stations at the same longitude see the afternoon trough as a depletion moving equatorward with time.

7. The daytime trough can extend continuously from high latitude to mid-latitude and hence is not well described in terms of a particular latitude regime.

8. The daytime trough is observed to exist under all conditions from quiet to disturbed, contracting to high latitudes during quiet conditions and expanding to lower latitudes during active conditions. The increased likelihood for detection when expanded is apparently the reason that the daytime trough has been thought to exist only under active conditions.

9. The equatorward boundary of the afternoon trough is very similar to the convection boundary in morphology and in activity dependence.

10. The morning and afternoon troughs are observed by ground stations when they pass through regions of sunward convection in the dawn and dusk cells.

11. The occurrence in LT of the morning and afternoon troughs is observed to vary with longitude in the same manner that the coordinate system of the convection pattern, CGlat/CGLT, varies with longitude with respect to the coordinate system of the undisturbed daytime F layer, geographic latitude/LT.

12. The spatial variation of these two principal coordinate systems of the ionosphere-magnetosphere interaction is such that CGLT leads LT in east CGlong and lags LT in west CGlong. As a result the daytime F layer maxima are displaced in relation to one another to earlier LT in the east and to later LT in the west.

Appendix: On the Possibility That Other Phenomena Are Mistaken for the Daytime Trough

This appendix discusses whether the observations attributed to the daytime trough and its relation to convection can be the result of other phenomena.

One area in which other phenomena might affect the interpretations is in the diurnal distributions of f_oF_2 from different stations compared in Figures 5*c*, 11*a*, and 14. These comparisons, between members of the identical twin stations of Figure 13 and Table 2, take the undisturbed daytime F layer electron density to be the same for each and the differences to demonstrate properties of the daytime trough. These stations have nearly the same geographic latitude not only for the individual pairs but also for the entire set of eight stations, so that all eight have nearly the same solar ion production, pressure-driven neutral winds, and rotational velocities. That these stations have the same undisturbed daytime F layer electron density is based on observations. These observations are possible for the six stations below ~75° CGlat within the interval 1200–1300 LT, where for all six the F layer is least likely to be disturbed by the trough (Figure 14). Within this interval the maximum values of f_oF_2 for the six stations are nearly all the same. Accordingly, whatever differences exist within the group of stations (including magnetic field inclination and thermospheric composition), the effects are not detectable in the daytime F layer.

The two stations at ~75° cannot be compared on the same basis as the others, but the facts that the effects of other phenomena are negligible at the six stations at lower CGlat, and that these stations span a large spatial range and variety of conditions, argue that such effects are also negligible at ~75°. However, these stations are likely to be subject to an additional source of ionization in the soft particle precipitation present in the daytime cusp/cleft. The effect of this precipitation would be larger values of f_oF_2 at ~75° than at lower latitudes. However, the values of f_oF_2 at ~75° are the same as or smaller than those at the lower latitudes in Figures 14, 5*c*, and 11*a* and so indicate no observable effect of particle precipitation. This result is consistent with the absence of a detectable contribution by precipitating particles to the maximum of the daytime F layer in this sector as determined by the Sondrestrom incoherent scatter radar [*Kelly and Vickrey*, 1984].

Thus in the several cases where individual stations are compared, other phenomena do not have observable effects that could interfere with the interpretation of the trough. In a larger sense, when taking the body of observations as a whole, other phenomena cannot be mistaken for the trough. That is, the often catastrophic depletions seen in the diurnal distributions of f_oF_2 (Figures 3, 5, and 7) are shown to be the LT signatures of a latitudinal trough (Figures 2 and 4). In spite of extreme day-to-day variability these depletions appear in the medians for the month (Figure 7, also evident in Figure 12). Furthermore, the depletions are observed on nearly every day to be a part of a spatially continuous band thousands of kilometers in extent (Figure 8) having a continuous duration of many hours (Figure 9) with a morphology and activity dependence consistent with convection (Figure 10). In the course of its existence this depleted region sweeps across a substantial part of the Earth's surface at high northern latitudes where it retains its identity as it encounters large variations in solar illumination, particle precipitation, neutral wind, rotational velocity, magnetic field, and thermospheric composition. Accordingly, the ionospheric effects of these phenomena cannot give rise to the macroscopic, persistent, unitary feature identified as the trough and its relation to convection.

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19. ABSTRACT

The daytime F layer trough is studied by means of an extensive network of ground-based ionospheric sounders in the northern hemisphere under conditions of solar maximum near winter solstice. The trough is observed to be a continuous band having an instantaneous extent of thousands of kilometers consisting of depletions in the daytime electron density, often by an order of magnitude. It lies in regions of sunward ionospheric-magnetospheric convection, an afternoon sector corresponding to the dusk cell, a morning sector corresponding to the dawn cell, and morphology and activity dependence consistent with convection. As detected in the diurnal distributions of f_0F_2, the trough is a persistent feature at high latitudes, appearing on each day of a 31-day period of continuous observation, and, although highly variable from day to day, is apparent in the monthly medians. The afternoon trough, which is detected independently by at least five and as many 17 stations on each day, is generally continuous and stationary for a duration of many hours in magnetic latitude/magnetic local time coordinates. The trough contracts during quiet conditions so as to lie above 70° magnetic latitude but expands during disturbed conditions so as to extend from 75° to 52° magnetic latitude. The trough has a pronounced dependence on longitude, appearing principally in the afternoon in eastern magnetic longitudes but in the morning in western magnetic longitudes, an effect so prevalent that it produces large east-west local time asymmetries in the diurnal distributions of median daytime F layer electron densities throughout a wide range of latitudes. The longitudinal dependence is found to result from the relation between the two principal coordinate systems of the ionosphere-magnetosphere interaction: solar geomagnetic coordinates in which the convection pattern and the resultant daytime trough reside, and solar terrestrial coordinates in which solar ion production and the undisturbed daytime F layer in general reside; as a consequence of the fact that these coordinate systems vary with respect to one another with longitude, the trough varies within the daytime F layer with longitude.

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