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Ionospheric Storm Effects at Subauroral Latitudes: A Case Study

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An attempt is made to classify ionospheric storm effects at subauroral latitudes according to their presumed origin. The storm of December 7/8, 1982, serves as an example. It is investigated using ionosonde, electron content, and DE 2 satellite data. The following effects are distinguished: (1) positive storm effects caused by traveling atmospheric disturbances, (2) positive storm effects caused by changes in the large-scale thermospheric wind circulation, (3) positive storm effects caused by the expansion of the polar ionization enhancement, (4) negative storm effects caused by perturbations of the neutral gas composition, and (5) negative storm effects caused by the equatorward displacement of the trough region.

1. INTRODUCTION

Perturbations of the terrestrial ionosphere in association with geomagnetic activity were first discussed more than 60 years ago [e.g., *Anderson*, 1928; *Hafstad and Tuve*, 1929]. Since then more than 200 papers on this subject have been published in English alone, testifying to the complexity, significance, and fascination of this phenomenon [e.g., *Matuura*, 1972; *Prölss*, 1980; *Essex et al.*, 1981; *Goel and Rao*, 1981; *Alamelu et al.*, 1982; *Sojka and Schunk*, 1983; *Volland*, 1983; *Miller et al.*, 1984; *Taieb and Poinsard*, 1984; *Rishbeth et al.*, 1985; *Danilov and Morozova*, 1985; *Huang Tian-xi*, 1985; *Wu Lei and Song Xiao-Ting*, 1985; *Tanaka*, 1986; *Wrenn et al.*, 1987; *Mendillo et al.*, 1987; *Rishbeth et al.*, 1987; *Titheridge and Buonsanto*, 1988; *Forbes et al.*, 1988; *Kilifarska*, 1988; *Oliver et al.*, 1988; *Ezquer and de Adler*, 1989; *Fesen et al.*, 1989; *Rodger et al.*, 1989; *Richards et al.*, 1989; *Jakowski et al.*, 1990; *Balan and Rao*, 1990; *Hajkowicz*, 1990; *Mazaudier and Venkateswaran*, 1990; and references therein]. In spite of this immense effort, no comprehensive concept of the morphology and the origin of such perturbations has emerged. This is partly due to the variability of this phenomenon and also to the many different processes at work. In this study an attempt is made to classify and interpret some of the observed disturbance effects. Only perturbations of the ionization density in the *F* region at higher but (quiet time) subauroral latitudes are considered. The main emphasis will be on changes seen in the northern winter hemisphere. The analysis is based on ionosonde and electron content measurements and also on electron and neutral gas density data obtained by the Dynamics Explorer 2 (DE 2) satellite [e.g., *Hoffman*, 1988; *Brace et al.*, 1982; *Carignan et al.*, 1982].

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2. GENERAL DISTURBANCE MORPHOLOGY

The *am*, *AE*, and *Dst* indices are used as diagnostic tools in Figure 1 to describe the level of magnetic activity during three days in December 1982. Apart from residual perturbations of the *Dst* index, December 6 is a very quiet day ($Kp \leq 1+$). Around noontime on December 7 a moderately strong magnetic storm commences. The maximum deviations recorded during this period are $Kp = 6+$, $AE = 820$ nT, and $Dst = -78$ nT. Conspicuous are the two disturbance peaks of the auroral electrojet activity at about 1430 and 1930 UT. During the night of December 7/8 a partial recovery takes place. Subsequently, activity increases again and reaches maximum disturbance levels of $Kp = 5-$, $AE = 1058$ nT, and

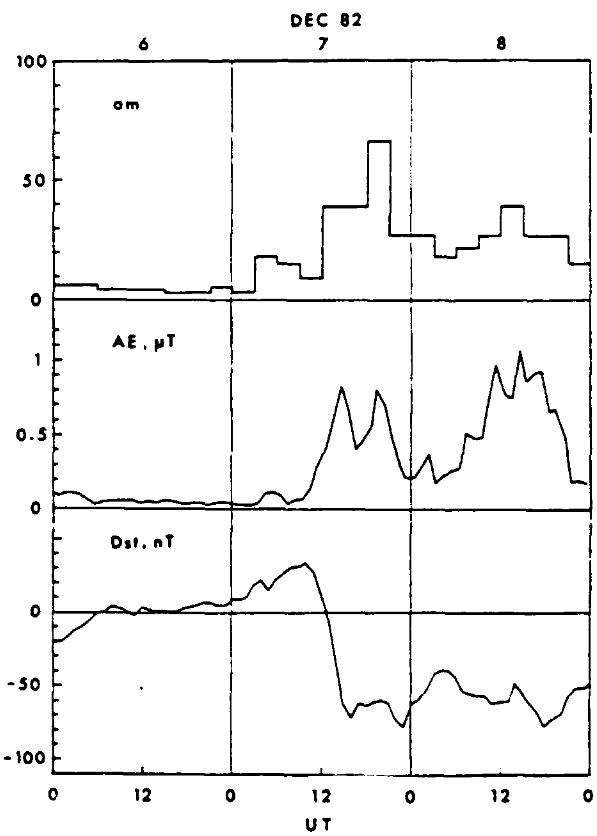

Fig. 1. Geomagnetic activity during a 3-day interval in December 1982 as indicated by the *am*, *AE* (hourly averaged values), and *Dst* indices.

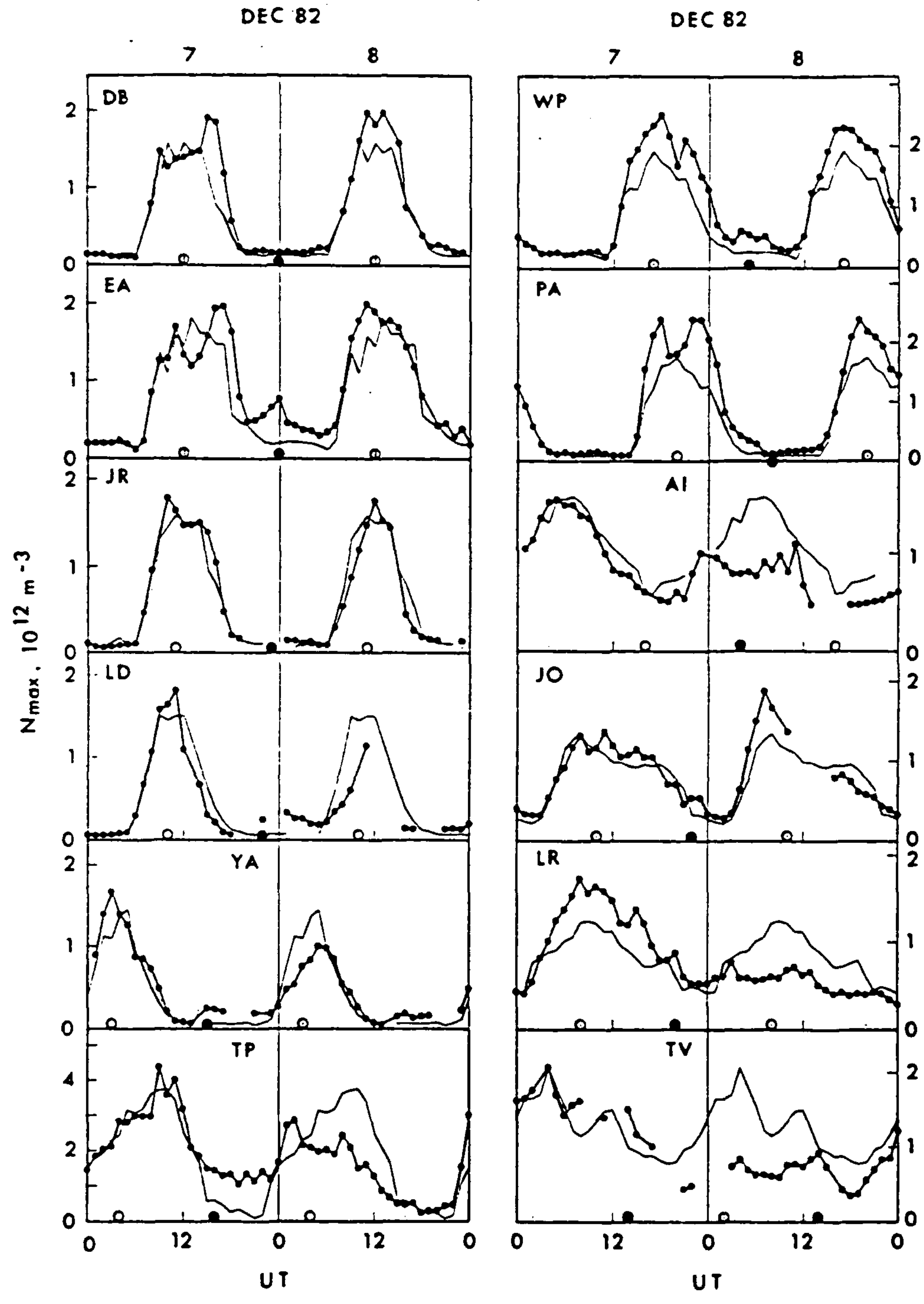

Fig. 2. Ionospheric storm effects observed during the December 7/8, 1982, disturbance event at the following stations: Dourbes (DB), El Arenosillo (EA), Juliusruh (JR), Leningrad (LD), Yakutsk (YA), Chung-Li (TP), Wallops Island (WP), Point Arguello (PA), Argentine Island (AI), Johannesburg (JO), La Réunion (LR), and Townsville (TV). The maximum electron density of the F_2 layer, N_{max}, is used to identify the perturbations. Data obtained on December 6, 1982 (local date), serve as the quiet time reference (thin line without data points). An open circle indicates local noon, and a solid circle local midnight. For station location, see Figure 3 and Table 1.

Dst = −78 nT. The declining activity in the evening of this day marks the end of the storm period considered in this study.

The enhanced dissipation of solar wind energy indicated by the rise in magnetic activity causes a global perturbation of the ionosphere. The morphology of this perturbation is by no means uniform, and this is illustrated in Figure 2. As is evident, anomalous increases of the ionization density or decreases or both are observed at different locations on Earth, during different phases of the magnetic storm, and in different local time sectors. In fact, none of the stations shows exactly the same behavior. In what follows, an anomalous increase of the ionization density will be denoted as a positive ionospheric storm, and a density decrease as a

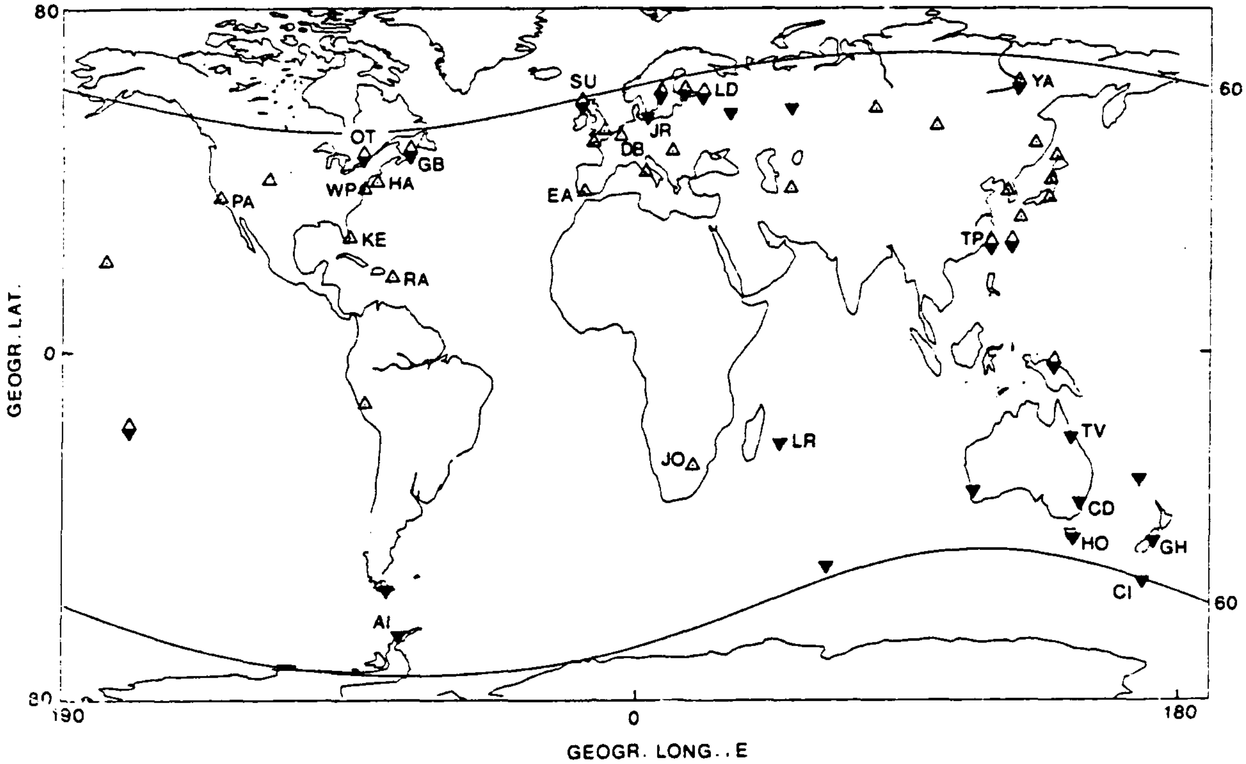

Fig. 3. Global distribution of ionospheric storm effects on December 7/8, 1982. Open (solid) triangles indicate that positive (negative) storm effects are observed at these locations. Stations explicitly mentioned in the text are identified by a code (see Table 1). Two lines mark the position of ±60° magnetic (eccentric dipole) latitude.

negative ionospheric storm, even though the magnitude of the observed effects may not always justify these terms. Figure 3 illustrates the global distribution of these storm effects. Conspicuous are the seasonal differences. Thus in the summer hemisphere, negative perturbations prevail and extend to much lower latitudes [e.g., *Prölss*, 1977, and references therein]. Also, strong latitudinal and longitudinal gradients are observed and may be partly attributed to similar gradients in the neutral atmospheric perturbations [e.g., *Prölss*, 1980]. In what follows, only ionospheric storm effects observed at subauroral latitudes will be considered. Here "subauroral" specifies a location at higher latitudes which is relatively close to but equatorward of the auroral oval during undisturbed conditions. Data obtained on December 6, i.e., 1 day before storm onset, serve as a quiet time reference. DE 2 reference data are also available for this day. In addition, the upper and lower quartiles for December 1982 and other quiet days of this month were used to confirm the identification of ionospheric storm effects.

3. CLASSIFICATION AND INTERPRETATION OF THE OBSERVED STORM EFFECTS

Figure 4 shows storm-associated changes in the maximum electron density as observed at the three subauroral stations South Uist, Ottawa, and Hobart (see Table 1 for station coordinates and Figure 3 for their general location). All three stations exhibit significant positive and/or negative storm effects. According to their presumed origin, they are divided into the following five classes:

3.1. *Positive Storm Effects Caused by Traveling Atmospheric Disturbances*

In response to the first substorm period a fairly rapid increase in the ionization density is observed at South Uist. An even more pronounced positive storm effect is observed at Ottawa in response to the second substorm period. The immediate cause of these density perturbations is a sudden uplifting of the *F* layer. This is documented in Figure 5, which shows the temporal variation of the height of the maximum electron density. Evidently, the density increase is preceded by a nearly 100-km increase in the height of the layer peak. This, of course, leads to a significant reduction of the effective ionospheric loss rate and to a corresponding increase of the ionization density. The interplay between layer height and density becomes even more evident if one considers the associated density height profiles. Figure 6 shows that initially the upward motion of the *F* layer is associated with a decrease of the ionization density. It is only after reaching the maximum height that an increase in the density is observed. The subsequent decrease of the layer height is primarily due to the increase of the ionization density in the region between the original layer and the uplifted layer. This is in good agreement with expectations [e.g., *Rishbeth and Garriot*, 1969, pp. 151ff].

The observed upward motion of the layer and the associated upward drift of ionization may be caused either by electric fields [e.g., *Martyn*, 1951; *Tanaka and Hirao*, 1973; *Lanzerotti et al.*, 1975; *Mendillo et al.*, 1987; and references therein] or by meridional winds. In the first case the distur-

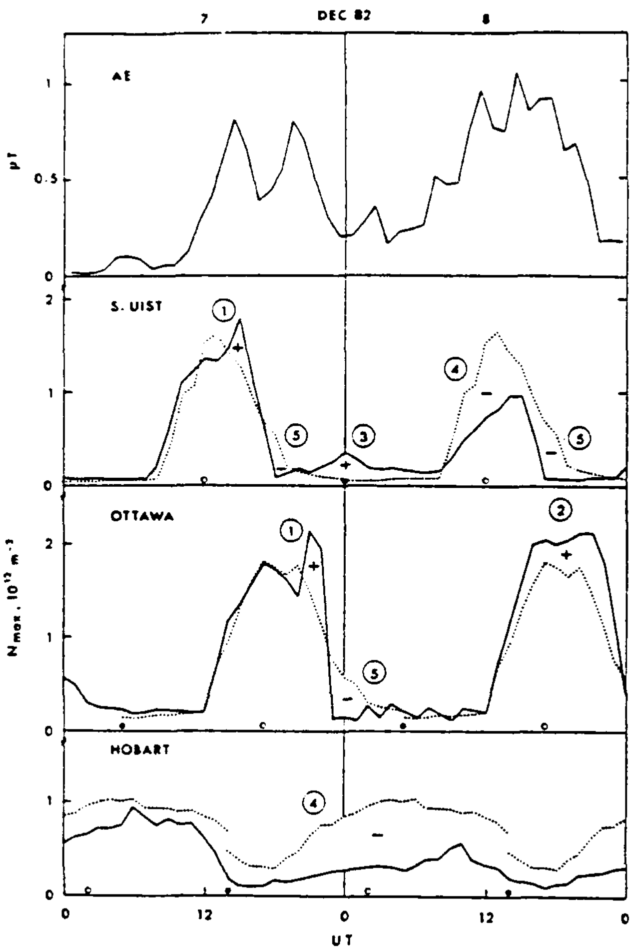

Fig. 4. Ionospheric storm effects observed at three subauroral stations during the December 7/8, 1982, event. The maximum electron density of the F_2 layer, N_{max}, is used to identify the perturbations. Data obtained on December 6 (local date) serve as the quiet time reference (dotted lines). An open circle indicates local noon, and a solid circle local midnight. Anomalous increases of the ionization density are marked by pluses (positive storm effects), and anomalous decreases by minuses (negative storm effects). According to their presumed origin, five different classes of storm effects are distinguished. Numbers indicate the order in which they are discussed in section 3. For comparison, the uppermost panel shows the associated perturbations of the *AE* index.

bance should be seen nearly simultaneously at high and low latitudes; in the second case it is expected to propagate from high to low latitudes. Thus it appears improbable that an electric field source moves from high to low *L* shells at velocities typical for traveling atmospheric perturbations. Figure 7 shows electron content data from a chain of stations along the east coast of North America (see Table 1 and Figure 3). In agreement with ionosonde data from Ottawa, all stations show a significant increase in the electron content at about 21 UT. The onset of this perturbation, however, is increasingly delayed with decreasing latitude. This progression of the positive storm phase to lower latitudes has been noted previously by *Mendillo and Klobuchar* [1975]. If the time of the steepest disturbance increase is selected as a reference point, a north-south propagation velocity of about 500 m/s is obtained. (A similar velocity is obtained if the time delay between the density increases at Ottawa and Wallops Island is considered.) This velocity, however, is typical for traveling atmospheric-ionospheric disturbances (TAIDs [e.g., *Bowman*, 1965; *Davis and Da Rosa*, 1969; *Testud et al.*, 1975; *Francis*, 1975; *Richmond*, 1978; *Roble et al.*, 1978; *Prölss and Jung*, 1978; *Hunsucker*, 1982; and references therein]). Therefore it is suggested that the observed uplifting of the *F* layer is caused by meridional winds of moderate intensity which are carried equatorward by fast-moving traveling atmospheric perturbations. The intensity of these meridional winds (u_y^N) may be roughly estimated from the observed upward drift of ionization (u_z^I) using the relationship $u_y^N \geq u_z^I / \sin I \cos I$, where I is the inclination of the magnetic field. The wind velocities deduced in this way (Ottawa: ≥140 m/s; Wallops Island: ≳70 m/s) are consistent with corresponding model predictions [e.g., *Testud et al.*, 1975; *Richmond and Matsushita*, 1975]. Note that while TAIDs are normally associated with gravity waves, they may also arise from "sudden" changes in the global wind circulation which are initiated in the polar region and propagate with high velocity (at approximately the speed of sound) toward lower latitudes [e.g., *Mayr et al.*, 1978; *Miller et al.*, 1979].

An unexpected feature of the Ottawa ionization density data is that significant positive storm effects are observed only in response to the second substorm period. This is all the more surprising since the layer height also increases (less abruptly) during the first substorm period. Moreover stations located to the south of Ottawa, such as Wallops Island and Point Arguello (see Figure 2), and all electron content subionospheric points also respond to the first substorm period. A speculative and nonverifiable explanation of this behavior would be that during the first substorm period, Ottawa is affected by changes in the neutral gas composition which prevent a significant buildup of ionization (see section 3.4).

Another feature of interest is that the first substorm period

TABLE 1. Observation Sites

Name	Code	Geographic Latitude, deg	Invariant Latitude, deg	Geographic Longitude, °E
Argentine Island	AI	65 S	50	296
Baker Lake		64 N	75	264
Camden	CD	34 S	46	151
Campbell Island	CI	53 S	60	169
Christchurch	GH	44 S	50	173
Chung-Li	TP	25 N	10	121
Churchill		59 N	70	266
Dourbes	DB	50 N	48	5
El Arenosillo	EA	37 N	34	353
Goose Bay	GB	47 N	58	298
Great Whale River		55 N	68	282
Hamilton	HA	39 N	52	289
Hobart	HO	43 S	54	147
Johannesburg	JO	26 S	37	28
Juliusruh	JR	55 N	52	13
Kennedy	KE	26 N	41	280
La Réunion	LR	21 S	35	56
Leningrad	LD	60 N	56	31
Ottawa	OT	45 N	58	284
Point Arguello	PA	36 N	41	239
Ramey	RA	17 N	35	293
South Uist	SU	57 N	57	353
Townsville	TV	19 S	26	147
Wallops Island	WP	38 N	51	285
Yakutsk	YA	62 N	55	130

is associated with a weak decrease of the local magnetic field strength but the second period is associated with a very significant increase (a factor of 3 difference; see Figure 8). This coincidence of "positive" perturbations of the locally measured magnetic field strength and positive ionospheric storm effects was first noted by *Mendillo et al.* [1970] and *Evans* [1970] and led to a number of speculations on the origin of both phenomena [*Papagiannis et al.*, 1971; *Evans*, 1973] (see also *Rishbeth and Hanson* [1974]). Here the observed asymmetry of the magnetic field perturbation is attributed to the local time dependent position of the auroral electrojet. According to *Rostoker and Phan* [1986], the westward directed electrojet of the forenoon sector flows at higher latitudes than the eastward directed electrojet of the afternoon/evening sector. Therefore electrojet-associated perturbations at subauroral latitudes should be more pronounced in the afternoon/evening sector. To support this interpretation, the position of the electrojet was roughly determined using a method described by *Kisabeth and Rostoker* [1971]. By analyzing magnetic field measurements obtained at Baker Lake, Churchill, Great Whale River, and Ottawa, it was found that during the first substorm period the

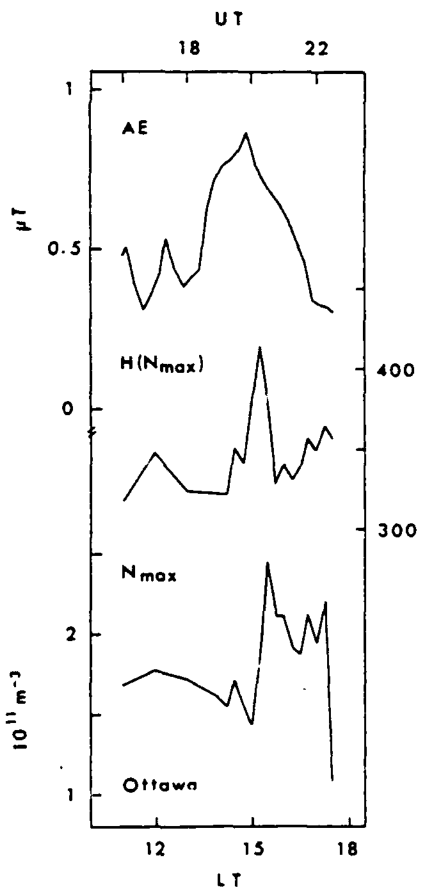

Fig. 5. Causal relationship between the uplifting of the F layer and the subsequent increase of the peak ionization density during short-duration positive storms. The middle and bottom parts of the figure show the temporal variation of the height of the maximum electron density, $H(N_{max})$, and of the maximum electron density itself, N_{max}, during the positive storm event observed at Ottawa in the afternoon of December 7, 1982. For comparison, the uppermost curve shows the associated perturbations of the (quarter-hourly averaged) AE index.

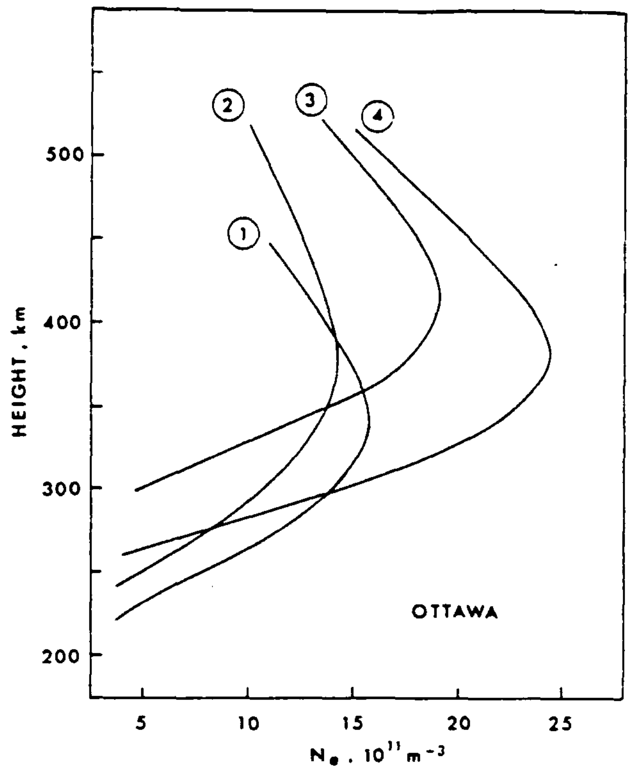

Fig. 6. Changes in the height distribution of the electron density during short-duration positive storms. The height profiles were deduced from ionosonde data obtained at Ottawa on December 7, 1982. They refer to the following local times: (1) 1445, (2) 1500, (3) 1515, and (4) 1530. The topside values are extrapolations of the theoretical model used to reduce the ionograms [*Titheridge*, 1985].

equatorward boundary of the electrojet was located north of Great Whale River but during the second it was south of this station. This nicely explains the difference in disturbance intensities observed at Ottawa.

3.2. *Positive Storm Effects Caused by Changes in the Large-Scale Wind Circulation*

Figure 4 shows that in response to the relatively slowly increasing magnetic activity on December 8 the Ottawa data exhibit lasting and smoothly varying positive storm effects. Similar perturbations are also seen at other stations in North America and Europe (see Figure 2), indicating the large-scale extent of this phenomenon. Again the density increase may be attributed to an increase in the layer height. This is documented in Figure 9, which shows that on the average the height of the maximum electron density has increased by about 20 km. Again, meridional winds are thought to be primarily responsible for the observed upward motion. Thus it appears highly improbable that the magnetosphere can maintain a large-scale electric field extending from high to low latitudes and lasting for many hours. In contrast, it is easily visualized that the polar energy dissipation leads to changes in the global wind circulation system. This is supported by many observations and calculations [e.g., *Mayr et al.*, 1978; *Volland*, 1979; *Mazaudier et al.*, 1985; *Forbes et al.*, 1987; *McCormac et al.*, 1987; *Rees et al.*, 1987; *Salah et al.*, 1987; *Roble et al.*, 1988; *Hernandez and Killeen*, 1988; *Hagan*, 1988; *Forbes*, 1989; and references

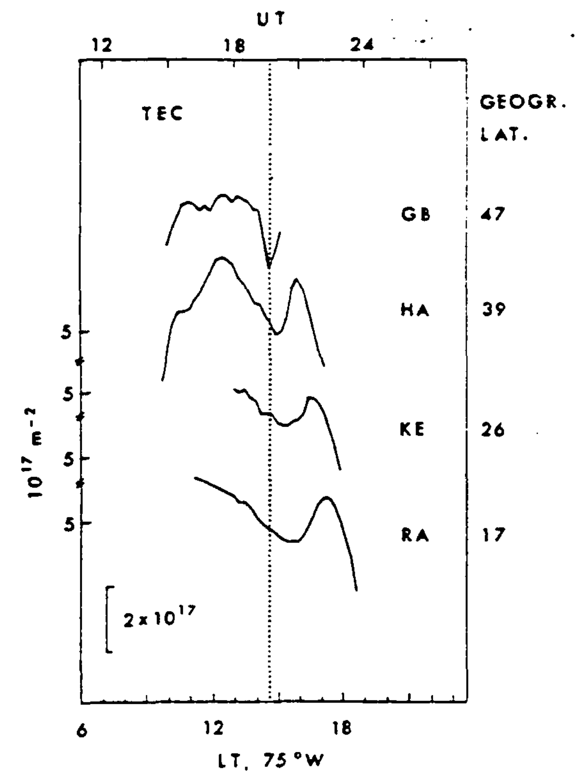

Fig. 7. Propagation of short-duration positive storm effects. The onset times of positive storm effects in the total electron content (TEC) as observed on December 7, 1982, by a chain of stations are compared. The chain is located on the east coast of North America, and the geographic latitudes of the respective subionospheric points are given on the right side of the figure (also see Figure 3 and Table 1). A tick mark on the ordinate gives the 5×10^{17} m^{-2} content level (for each station separately), and a bar in the lower left-hand corner indicates the common scale used for all stations.

therein]. Thereby it is sufficient that the polar high-pressure zone reduces the intensity of the poleward directed winds in the winter daytime sector. The efficiency of this process is supported by model calculations and observations [e.g., *Jones and Rishbeth*, 1971; *Alcayde et al.*, 1972; *Evans*, 1973; *Jones*, 1973; *Yagi and Dyson*, 1985; *Goel and Jain*, 1988; and references therein].

Another possibility is that long-lasting positive storm effects are caused by changes in the neutral gas composition [e.g., *Danilov et al.*, 1987; *Rishbeth et al.*, 1987; *Rodger et al.*, 1989]. Thus equatorward of the main composition disturbance zone a moderate decrease of the N_2/O density ratio at constant pressure height is frequently observed [e.g., *Prölss*, 1987]. The resulting reduction of the ionospheric loss rate will certainly contribute to any increase of the electron density observed in this region. However, the significance of this mechanism for larger positive storm events remains to be established, and so far no observational evidence has been presented in support of this concept for more active conditions. We also note that a decrease of the N_2 density is expected to decrease the layer height. This effect, however, may be compensated by a concurrent increase of the neutral gas temperature [*Rishbeth and Edwards*, 1989].

Another point which needs clarification is the relation between the positive storm effects discussed in the previous and present sections. Consider the following scenario: changes in the global wind circulation are initiated by frontal systems which propagate with high velocity toward lower latitudes. At the same time, gravity waves are launched which also move with high velocity toward the equator. Both phenomena are associated with a sudden increase in the meridional wind velocity, causing traveling ionospheric disturbances and short-duration positive storm effects. How well developed these traveling disturbances are in each case will depend on the specific properties of the excitation mechanism [e.g., *Hunsucker*, 1982; *Mayr et al.*, 1987]. It is only in the wake of these transient perturbations that the large-scale wind system changes, causing long-duration positive storm effects. This scenario appears to be consistent with observations and model calculations [e.g., *Mayr et al.*, 1978; *Miller et al.*, 1979; *Fuller-Rowell and Rees*, 1981; *Roble et al.*, 1987; *Crowley et al.*, 1989; *Buonsanto et al.*, 1989].

Also note that for the resulting perturbations of the ionization density, local time effects are important. First of all, uplifting can produce positive storm effects only when ionization production or addition occurs. This happens primarily (but not exclusively) during daytime conditions.

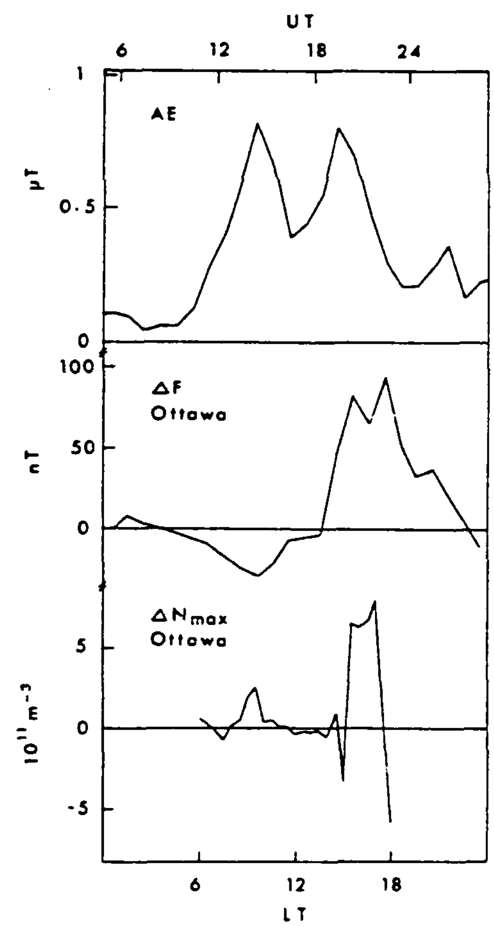

Fig. 8. Coincidence of positive ionospheric storms and enhancements of the locally measured magnetic field strength. The lower part of the figure compares changes in the total magnetic field strength, ΔF, with changes in the maximum electron density of the F layer, ΔN_{max}, as measured at Ottawa during the December 7, 1982, storm event. In both cases, data obtained on December 6 serve as the quiet time reference. For further comparison, the top part shows the associated variations of the AE index. Note the different units for AE and ΔF.

Therefore the largest (absolute) density increases are expected to occur in the local afternoon sector [e.g., *Davies and Rüster*, 1976]. Moreover, changes contrary to the general trend, as observed in the afternoon sector, are especially conspicuous. As for the duration of the circulation-associated positive storm phase, it evidently will depend on the duration of the magnetic activity, but also on competing processes causing negative storm effects.

3.3. *Positive Storm Effects Caused by Expansion of the Polar Ionization Enhancement*

As is shown in Figure 4, a significant increase of the electron density is observed at South Uist during the night of December 7/8 which extends into the early morning hours. Other northern European stations confirm this effect, with some examples being even more pronounced (see Figure 2). Also, the Ottawa data indicate a perturbation of the night sector; a more precise specification of these effects, however, is difficult because of missing data points. Fortunately, the electron content measurements obtained at the neighbor station, Goose Bay, are complete and show very pronounced and strongly structured positive storm effects (Figure 10). In view of the seemingly irregular fluctuations, it has been suggested that auroral particle precipitation is responsible for this phenomenon [e.g., *Matuura*, 1972; *Mikkelsen*, 1975; *Buonsanto et al.*, 1979; *Mendillo et al.*, 1987; *Wagner*, 1988; *Providakes et al.*, 1989; and references therein]. A comparison with the electron density measurements of the DE 2 satellite shows that the ionization density enhancement is in fact due to a displacement of the polar "wall" of the trough toward lower latitudes (Figures 11 and 12). Thus South Uist, Ottawa, and Goose Bay are all located within the range of the polar ionization density enhancement, at least during the early morning hours (≈0530 LT) of December 8.

According to the recent literature [e.g., *Robinson et al.*, 1985; *Rodger et al.*, 1986; *Senior et al.*, 1987; and references therein], there is no simple explanation for this density enhancement. Local ionization production by incident low-energy electrons and medium-energy ions is certainly important. But ionization transport may also play an important role. In the present study, it will be sufficient to attribute the nighttime positive storm effects at subauroral latitudes in the winter hemisphere simply to the expansion/displacement of the polar ionization enhancement.

It is remarkable that also stations at middle and low latitudes in the North American, European, and east Asian sectors exhibit an anomalous high electron density during the night of December 7/8 (see Figure 2). A classification of these effects, however, is beyond the scope of the present analysis.

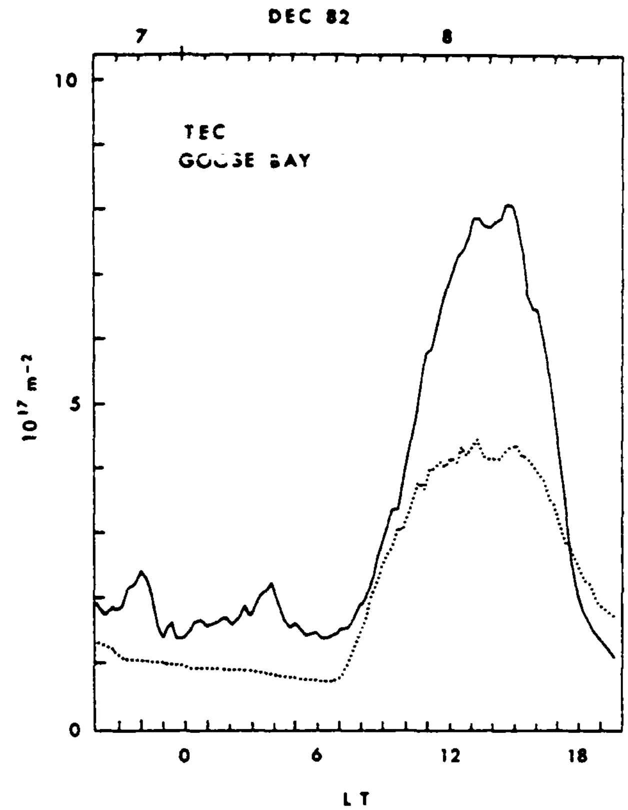

Fig. 10. Nighttime positive ionospheric storm effects at subauroral latitudes. Total electron content (TEC) data obtained at Goose Bay document the anomalous and irregular increase of the ionization density during the night of December 7/8, 1982. Measurements made on December 5/6 serve as the quiet time reference (dotted line). Also note the long-duration positive storm effects observed at this station on December 8.

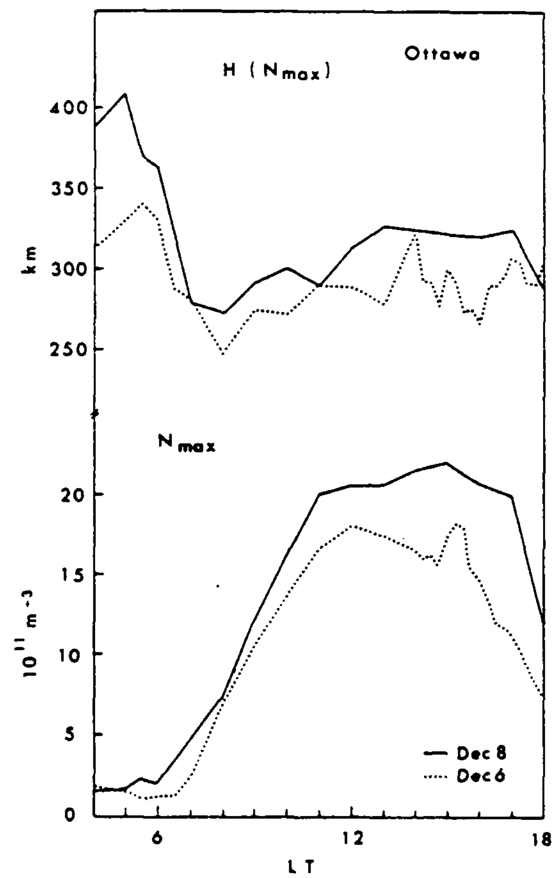

Fig. 9. Increase in layer height during long-duration positive ionospheric storms. Data obtained at Ottawa on December 8, 1982, document the increase in the height of the maximum electron density of the F_2 layer, $H(N_{max})$, and in the associated increase of the maximum electron density, N_{max}. In both cases, data obtained on December 6 serve as the quiet time references (dotted lines).

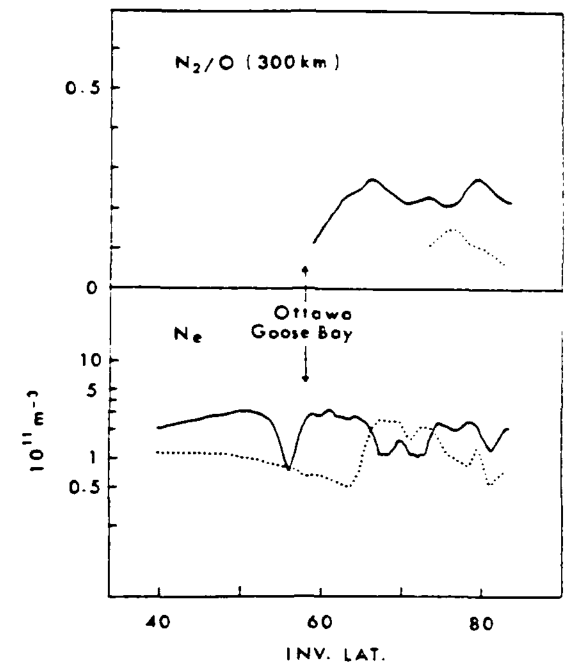

Fig. 11. Latitudinal profiles of composition and electron density perturbations. The data were obtained by the DE 2 satellite on December 8, 1982, in the North American sector. Measurements recorded on December 6 serve as the quiet time reference (dotted lines). The upper panel shows the latitudinal variation of the N_2/O density ratio. The measurements have been adjusted to a common altitude of 300 km. During quiet times and in the winter hemisphere, N_2 densities above about 400 km altitude are below the sensitivity threshold of the gas analyzer instrument. Therefore a significant part of the reference data at lower latitudes is missing. The available high-latitude measurements, however, may be considered as an upper limit to the undisturbed N_2/O density ratio in this lower-latitude region. The lower panel shows the electron densities recorded during the same satellite pass. No attempt was made to adjust these data to a common altitude. Accordingly, these measurements refer to different altitudes between about 450 km at 40° invariant latitude and 370 km at 84° invariant latitude. Local time and longitude of observation are approximately 0530 and 288°E, respectively. Universal time at 60° invariant latitude is 1018. The positions of Ottawa and Goose Bay are indicated by an arrow.

3.4. *Negative Storm Effects Caused by Perturbations of the Neutral Gas Composition*

Besides positive storm effects, very pronounced depletions of the ionization density are observed. Thus Figure 4 shows that at South Uist and Hobart the rate of ionization density increase is significantly reduced during the (local) morning hours of December 8. This reduced ionization density increase is typical for negative storm effects caused by changes in the neutral gas composition. The prominent features of these neutral gas perturbations are an increase of the molecular nitrogen and oxygen densities and a concurrent decrease of the atomic oxygen density [e.g., *Taeusch et al.*, 1971; *Mayr and Volland*, 1972; *Shimazaki*, 1972; *Hays et al.*, 1973; *Jacchia et al.*, 1976; *Hedin*, 1988; *Prölss et al.*, 1988; *Burns et al.*, 1989; and references therein]. Both changes will lead to a decrease of the *F* layer ionization density [e.g., *Seaton*, 1956; *Prölss and von Zahn*, 1974; *Chandra and Spencer*, 1976; *Hedin et al.*, 1977; *Mayr et al.*, 1978; *Prölss*, 1980; *Titheridge and Buonsanto*, 1988; *Forbes*, 1989; and references therein].

Supporting this explanation, Figure 12 shows the changes in the N_2/O density ratio as observed near South Uist before sunrise on December 8. A prominent feature is the steep disturbance rise at 50° invariant latitude where the density ratio increases by a factor of 4 within 7° latitude. (A second steep increase is observed in the Joule heating zone at about 67° invariant latitude.) Consistent with this latitudinal structure, significant negative storm effects are observed 4 hours later at South Uist (57° invariant latitude; see Figure 4) but not at Dourbes (48° invariant latitude; see Figure 2). Measurements in other longitudinal sectors confirm the close spatial correlation between neutral atmospheric and ionospheric perturbations of this kind. Specifically, the lack of negative storm effects at Ottawa on December 8 may be attributed to the limited extent of the composition disturbance zone in this region (see Figure 11). There remains the interesting question of why the extent of the composition perturbation is so asymmetric.

It is worth noting that in response to the magnetic activity, negative ionospheric storm effects are seen almost immediately at Hobart but only after a delay of three quarters of a day at South Uist (Figure 4). This is partly explained by the local time dependence of the expansion of the composition disturbance which is most pronounced in the midnight/early morning sector (Hobart, see Figure 13) but rather limited in the afternoon/evening sector (South Uist [e.g., *Prölss*, 1981, 1984]). An additional time delay is introduced by the polar ionization density enhancement which dominates the ionospheric behavior before sunrise (Figure 12).

The high ionization density of the nocturnal summer hemisphere allows a rough determination of the expansion velocity of the composition perturbation. Figure 14 shows

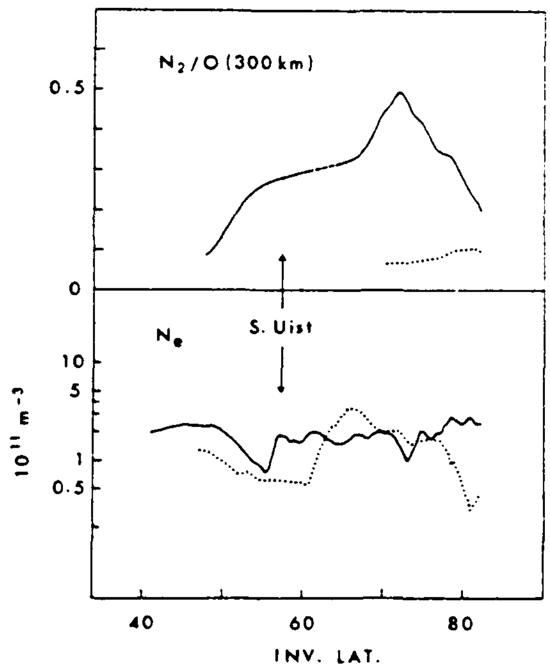

Fig. 12. Latitudinal profiles of composition and electron density perturbations. The data were obtained by the DE 2 satellite on December 8, 1982, in the west European sector. The presentation corresponds to that of Figure 11. Local time and longitude of observation are approximately 0530 and 357°E, respectively. The position of South Uist is indicated by an arrow.

that the onset of negative storm effects at middle latitudes is delayed with respect to subauroral latitudes. The derived expansion velocity of 200–300 m/s is consistent with a convective transport of composition perturbations [e.g., *Rishbeth*, 1974; *Prölss et al.*, 1988].

3.5. *Negative Storm Effects Caused by a Displacement of the Trough Region*

A different kind of negative storm effect is observed at Ottawa on December 7. Following the positive storm phase, the electron density shows a spectacular drop to one fifteenth of its original value in less than an hour. Basically similar but less spectacular density depletions are also observed in the local evening sector at South Uist and at other northern European stations. The common origin of this kind of negative disturbance effect is a storm-associated displacement of the trough region toward lower latitudes [e.g., *Mendillo et al.*, 1974; *Brace et al.*, 1974; *Mendillo et al.*, 1987]. Figure 15 documents this displacement with the help of DE 2 data. A comparison of the electron density measurements taken on December 6 and 7 shows tha in response to the magnetic storm the equatorward boundary of the trough has moved south by more than 10°. In this way the ionospheric behavior at Ottawa becomes fully dominated by this phenomenon and exhibits a corresponding drop of tne ionization density. That the spatial-temporal correlation between the ground-based and satellite measurements is not perfect (the density drop at Ottawa appears to be somewhat delayed) may be explained by the spatial separation of both measurements (≃3° in longitude) and also by the poor quality of the Ottawa data at this time. In particular, the ionosonde measurements at 1715 and 1730 LT are impaired by spread *F* and double reflections which are evidently caused by the motion of the trough wall across the station [e.g., *Bowman*, 1969].

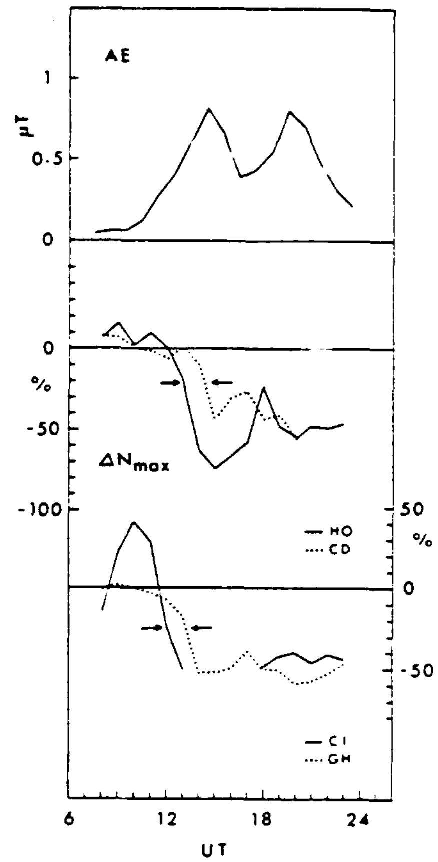

Fig. 14. Expansion of negative ionospheric storm effects toward lower latitudes. The onset times of negative storm effects at subauroral and middle latitudes are compared. Data obtained on December 6 (UT date) serve as the quiet time reference Arrows indicate the estimated time delay between the disturbance onset at Hobart (43°S) and Camden (34°S) and between Campbell Island (53°S) and Christchurch (44°S). For comparison, the top panel shows the onset of magnetic storm activity as indicated by the (hourly averaged) *AE* index. Note that the atmospheric-ionospheric disturbance expansion takes place in the local midnight sector.

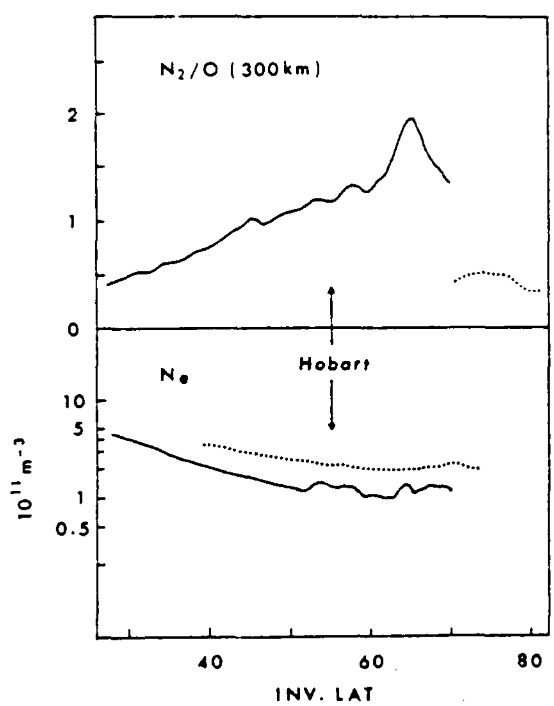

Fig. 13. Latitudinal profiles of composition and electron density perturbations. The data were obtained by the DE 2 satellite on December 8, 1982, in the east Australian sector. The presentation corresponds to that of Figure 11. This time, however, the electron density measurements refer to altitudes between 505 and 512 km (satellite apogee). Local time and longitude of observation are approximately 0540 and 142°E, respectively. Universal time at 55° invariant latitude is 2000. The position of Hobart is indicated by an arrow.

The bottom part of Figure 15 shows the N_2/O density ratio measured during the same satellite pass. The obvious lack of correlation between the latitudinal variation of this parameter and the trough structure confirms the supposition that trough effects are not caused by neutral composition changes during quiet or disturbed conditions [e.g., *Raitt et al.*, 1975; *Schunk et al.*, 1976; *Spiro et al.*, 1978; *Sojka et al.*, 1981; *Quegan et al.*, 1982; *Evans et al.*, 1983; and references therein]. What actually causes this phenomenon is not clear at this time, and different mechanisms have been proposed. More recent discussions of this subject can be found, for example, in the work by *Senior et al.* [1987], *Collis and Häggström* [1988], and *Sojka and Schunk* [1989].

The fact that trough-associated negative storm effects are

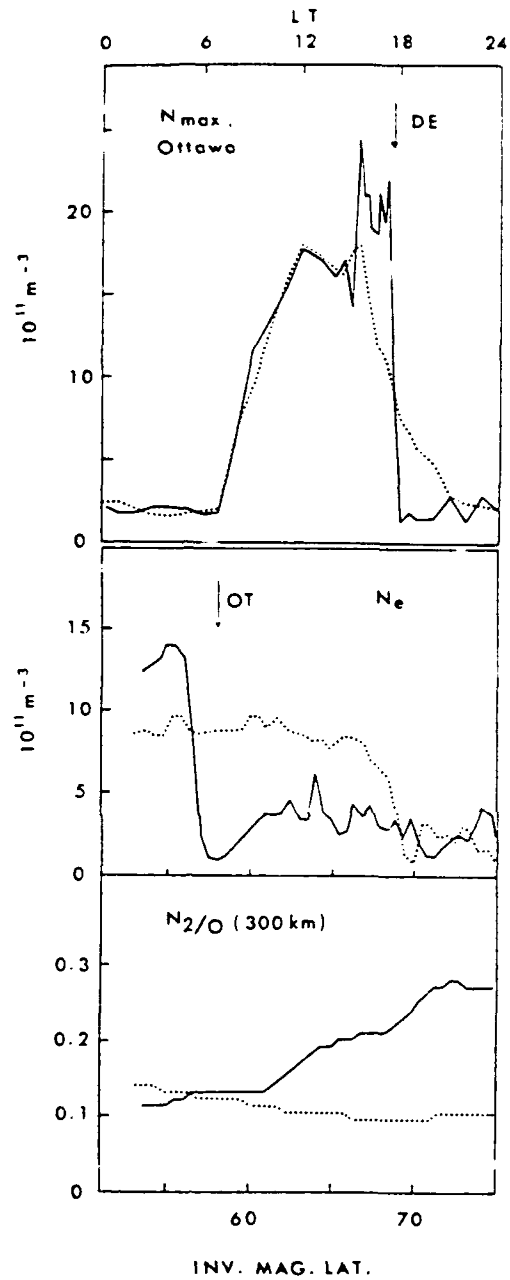

Fig. 15. Trough-associated negative ionospheric storm effects. The top panel shows the (local) time variation of the maximum electron density of the F layer, N_{max}, as observed at Ottawa on December 7, 1982. As before, data obtained on December 6 serve as the quiet time reference (dotted line). The middle panel shows the latitudinal structure of the electron density as recorded by the DE 2 satellite on December 7 at approximately 1740 LT and at a geographic longitude (287°E) close to Ottawa (284°E). The measurements refer to altitudes between about 270 km (53° invariant latitude) and 300 km (75° invariant latitude). The time of the satellite measurement is indicated in the top panel, and the relative position of Ottawa in the middle panel. A comparison of the two data sets demonstrates that the low ionization densities observed at Ottawa after 18 LT are a trough-associated phenomenon. The bottom panel shows the neutral composition changes observed during the same satellite pass. The lack of correlation between the latitudinal variation of the N_2/O density ratio and the trough structure is evident.

mainly observed in the local evening sector is explained by the local time dependent position of this phenomenon: thus during the afternoon the trough steadily "moves" toward lower latitudes. The additional equatorward displacement caused by magnetic activity is superimposed on this local time variation [e.g., *Moffett and Quegan*, 1983; *Collis and Häggström*, 1988; and references therein]. A similar local time variation also applies to the polar ionization enhancement (section 3.3) whose equatorial foot point frequently coincides with the trough minimum. Therefore one expects and observes that positive storm effects associated with the polar ionization enhancement are displaced in local time toward the night sector. It is only during particularly strong storm expansion phases that a trough-associated density decrease and a polar density increase are observed at a station in quick succession [e.g., *Taylor*, 1973].

4. SUMMARY

The aim of the present contribution is to classify ionospheric storm effects at subauroral latitudes according to their presumed origin. Such an attempt is desirable for several reasons. First, it helps to organize a somewhat confusing field of research. Second, it may elucidate some weak points in our present understanding of this phenomenon. And third, it may serve as a reference and starting point for future studies in this field. The following storm effects are distinguished.

4.1. *Positive Storm Effects Caused by Traveling Atmospheric Disturbances*

This kind of positive storm effect is marked by a sudden uplifting of the F layer, an effect which propagates with great velocity (many hundred meters per second) from polar latitudes toward lower latitudes. Accordingly, this discontinuity is associated with large-scale traveling atmospheric-ionospheric perturbations (TAIDs). The duration of the upward drift is of the order of 1 hour, and the associated meridional winds have velocities of up to several hundred meters per second. As a result of this uplifting, a sudden increase in the ionization density is observed which is particularly pronounced in the noon/afternoon local time sector. Although plausible, this interpretation needs further confirmation by observations.

4.2. *Positive Storm Effects Caused by Changes in the Large-Scale Wind Circulation*

This second kind of daytime positive storm effect is marked by its large spatial and temporal extent. Thus it may last a whole day and cover the whole range of middle latitudes. Presumably, these effects are mainly caused by changes in the large-scale wind circulation with poleward directed winds reduced and equatorward directed winds enhanced. This kind of perturbation is frequently observed in the wake of traveling positive storm effects, which initiate or accompany changes in the large-scale wind circulation.

4.3. *Positive Storm Effects Caused by Expansion of the Polar Ionization Enhancement*

The third kind of positive storm effect considered in this study is a typical night phenomenon. It is frequently marked by a strongly fluctuating intensity and is attributed to the expansion of the polar ionization enhancement toward lower

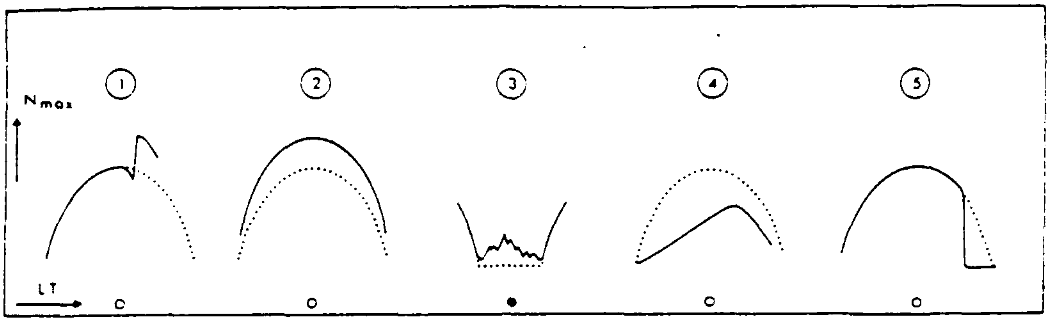

Fig. 16. Classification of ionospheric storm effects observed in the winter hemisphere at subauroral latitudes. In each case the dotted line indicates the "normal" behavior, and the solid line the storm time variation. The disturbance effects are ordered in a local time frame with an open circle marking local noon and a solid circle local midnight. The following five disturbance mechanisms are considered: (1) traveling atmospheric disturbances, (2) changes in the large-scale wind circulation, (3) expansion of the polar ionization enhancement, (4) neutral composition changes, and (5) displacement of the ionospheric trough region.

latitudes during magnetic storms. In the present context it is of secondary importance whether this ionization density enhancement is caused by local particle precipitation or by ionization transport.

4.4. *Negative Storm Effects Caused by Perturbations of the Neutral Gas Composition*

This kind of negative storm effect is most clearly observed in the morning sector. There it is marked by an anomalously low rate of ionization increase after sunrise. Its duration is of the order of many hours and may reach days during continued magnetic activity. This sometimes spectacular phenomenon originates from changes in the neutral gas composition. Its onset is determined by the preferential expansion of the composition disturbance in the midnight/early morning sector and by the effectiveness of competing processes.

4.5. *Negative Storm Effects Caused by a Displacement of the Trough Region*

The onset of this kind of negative storm effect is typically observed in the afternoon/evening sector. There it is marked by a steep density drop, which is particularly impressive if it terminates a positive storm phase. The resulting negative storm effects may extend into the night sector. The origin of this phenomenon is the storm-associated displacement and expansion of the trough region toward lower latitudes.

The storm effects discussed in the present study are summarized once more schematically in Figure 16. It is understood that this list is by no means complete, and other processes are expected to operate, especially at higher and lower latitudes. It is also clear that these effects may be superimposed on one another and that they may partly cancel each other. This in turn suggests that it will be very difficult to extract the physics of ionospheric storms from averaged data, as has been frequently attempted in the past.

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