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Westward Electric Fields as the Cause of Nighttime Enhancements in Electron Concentrations in Midlatitude *F* Region

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Large enhancements in electron concentrations are frequently observed in the midlatitude nighttime *F* region. These enhancements are explained in terms of enhanced downward diffusion flux from the protonosphere induced by substorm-associated electric fields in the ionosphere. A mechanism is proposed by which a westward electric field enhances downward flux from the protonosphere while lowering the *F* layer. (An eastward electric field has opposite effects.) This mechanism plus height variations of recombination loss can explain the observed behavior of the nighttime *F* layer during substorms. Crude estimates of electric fields and protonospheric fluxes are made from ionospheric parameters observed during a substorm. Under favorable conditions ground-based ionosonde records may be used to infer spatial and temporal variations of electric fields in the ionosphere during substorms. The results of this study suggest that in middle latitudes the nighttime ionosphere is controlled by vertical drifts and fluxes from the protonosphere.

Recent whistler observations under quiet conditions showed that in middle latitudes the protonosphere acts as a significant reservoir of ionization for the nighttime ionosphere [*Park*, 1970*a*]. This paper reports on some evidence that coupling between the ionosphere and the protonosphere is enhanced during geomagnetic disturbances and that enhanced downward flux from the protonosphere is responsible for enhancements in electron concentrations frequently observed in the midlatitude nighttime ionosphere.

In middle latitudes anomalous nighttime enhancements in *F* layer critical frequencies have been observed since the earliest days of ionospheric research. The first report was made by *Gilliland* [1935], who sounded the ionosphere over Beltsville, Maryland, and found that on some nights the peak electron concentration more than doubled during the post-midnight hours. More recently *Evans* [1965] reported the incoherent backscatter results at Millstone Hill (43°N, 72°W, geographic), which showed density increases near 0200–0400 LT at all observable heights up to 600 km. The columnar electron content determined from differential Doppler measurements [*Arendt and Soicher*, 1964] and polarization angle measurements [*daRosa and Smith*, 1967; *Titheridge*, 1968*a*; *Klobuchar et al.*, 1968] of satellite beacon signals also show occasional increases at night.

Similar nighttime enhancements have also been observed at low and equatorial latitudes [*Bajpai and Pant*, 1938; *Rüster*, 1965; *Sato*, 1966; *Rao*, 1968; *Young et al.*, 1970] and in the auroral zone [*Rai and Hook*, 1967]. It is not clear, however, how these enhancements are related to the enhancements observed in middle latitudes. In this paper our discussions will be limited to the midlatitude phenomenon. Although some of the remarks made here may apply to wide latitude ranges, the conclusions of this study should be extrapolated to other latitudes with caution. More discussion on this point will follow.

OBSERVATIONS

Figure 1 shows the behavior of h_mF_2 (top) and N_mF_2 (bottom) deduced from ionosonde records at Wallops Island (37°N, 75°W, geographic; 49°N, geomagnetic). The dots and the solid lines represent the behavior on December 24–25, 1968. On this night there was a polar substorm starting at ~0300 UT (~2200 EST), and the approximate time of onset is shown by arrows. The maximum 3-hour *Kp* index during the period shown in the figure was 5. For comparison with quiettime behavior, hourly values of h_mF_2 and N_mF_2 for the following night, December 25-26, 1968, are shown by open circles. The maximum 3-hour *Kp* index for the control night is 1+. About the time of the substorm onset on December 24, N_mF_2 drops by ~40% and h_mF_2 starts to increase. Following the substorm onset h_mF_2 continues to increase slowly and N_mF_2 remains nearly constant. At 0130 EST h_mF_2 reverses its rising trend and starts to move downward, while at the same time N_mF_2 starts to increase rapidly. As h_mF_2 continues to fall, N_mF_2 increases to 4.7×10^5 electrons/cm^3, roughly twice the presubstorm value, and then decreases very rapidly. When h_mF_2 recovers from a low value of 225 km at 0430 EST to the quiettime level, the rapid decrease in N_mF_2 stops and the ionosphere appears to return to a normal state of slow decay.

In Figure 2 the data for December 24-25 of Figure 1 are compared with magnetic records and columnar electron content data. The magnetic records shown are the *D* component at Fredericksburg, Virginia (38°N, 77°W, geographic; 50°N, geomagnetic), and the *X* component at Fort Churchill, Canada (59°N, 94°W, geographic; 69°N, geomagnetic). The directions of increasing westward field for Fredericksburg and northward for Fort Churchill are indicated by arrows. The onset of the magnetic disturbance roughly coincides with a decrease in N_mF_2 and the beginning of increasing h_mF_2, but at later times there is no one-to-one relationship between the magnetic variations and the variations in the ionospheric parameters. (See next section.)

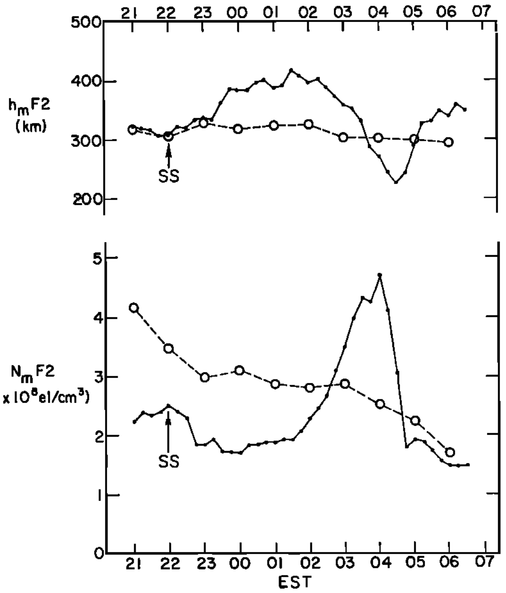

Fig. 1. Plots of h_mF_2 (top) and F_mF_2 (bottom) over Wallops Island illustrating a nighttime enhancement in N_mF_2. The dots and the solid lines are for the night of December 24-25, 1968. The arrows mark the approximate time of onset of a substorm that occurred that night. The open circles and the broken lines represent the behavior of h_mF_2 and N_mF_2 on the following night, December 25-26, 1968, which was magnetically quiet.

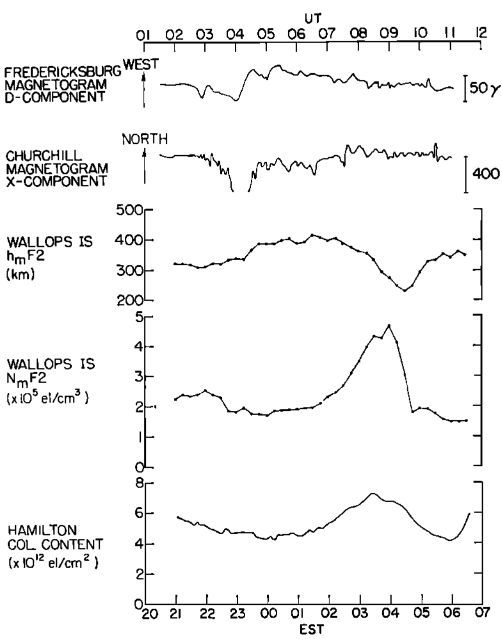

Fig. 2. The same data for December 24-25, 1968, of Figure 1 with the addition of simultaneous magnetic records and electron columnar content data. Electron columnar content is deduced from polarization angle measurements of VHF signals from the ATS 3 satellite received at Hamilton, Massachusetts. The subionospheric point for 350-km altitude (on the path from the satellite) is approximately 500 km from Wallops Island.

At the bottom of Figure 2 is a plot of the integrated electron columnar content deduced from the polarization angle measurements of VHF signals from the ATS 3 satellite received at Hamilton, Massachusetts. The subionospheric point for 350 km (on the path from the satellite) is 39°N, and 70°W, approximately 500 km from Wallops Island. The columnar content

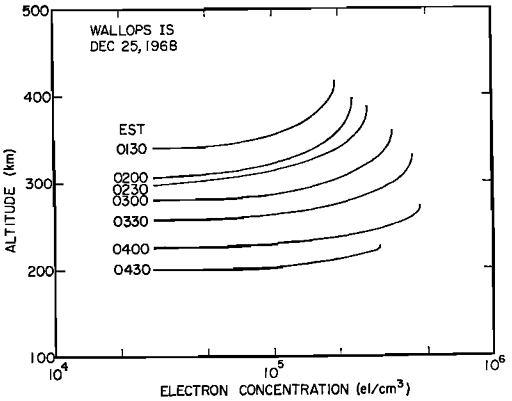

Fig. 3. $N(h)$ profiles deduced from ionosonde records at Wallops Island.

information was provided by J. A. Klobuchar and M. Mendillo. As N_mF_2 over Wallops Island increases, there is a similar increase in columnar content measured at Hamilton. Hence the increase in N_mF_2 cannot be simply due to a redistribution of ionization in the ionosphere. The rapid increase in columnar content near 1100 UT is the sunrise effect, which occurs earlier at the subionospheric point than at Wallops Island because of the local time difference. Simultaneous ionospheric data from other midlatitude stations from coast to coast in the North American continent show concentration enhancements similar to that of Figure 2. Details of latitude and local time effects are under study and will be reported later, but preliminary results show that these enhancements cannot be interpreted in terms of dense plasma clouds passing over the observing stations.

Figure 3 shows $N(h)$ profiles over Wallops Island for the period 0130 to 0430 EST on December 25 when h_mF_2 decreased from 415 to 225 km (see Figure 1). Between 0130 and 0330 EST the shape of the profile remains nearly unchanged, but the peak density increases exponentially as the ionosphere drops in altitude. Between 0330 and 0400 EST the profile becomes flattened, and N_mF_2 increases only slightly as h_mF_2 drops below 300 km. As the ionosphere drops to a still lower altitude, N_mF_2 decreases rapidly, whereas the profile remains fairly flat. Figures 4*a* and 4*b* show some selected $N(h)$ profiles at other times during the same night when the ionosphere is generally rising. The rising ionosphere maintains a relatively constant shape, with only slight changes in peak density. These features are also apparent in Figure 5, which shows a plot of the locus of N_mF_2 versus h_mF_2 from 2200 to 0600 EST.

The ionosphere over Wallops Island was studied during several substorms in December, 1968, when the station was near midnight. Although there are differences in matters of detail, the behavior during substorms is generally repeatable and similar to the case described here. When the ionosphere drops from a high altitude, the peak density at first increases but then decreases rapidly as the height of the peak drops below a certain level. When the ionosphere rises in altitude, the peak density remains nearly constant or decreases slightly.

INTERPRETATION

In this section a mechanism is proposed to explain the behavior of the ionosphere described in the previous section. The mechanism involves (*a*) electric fields that cause vertical movements of the ionosphere, (*b*) changes in downward diffusion flux from the protonosphere caused by vertical movements of the ionosphere, and (*c*) height variations of recombination rate. The behavior of the ionosphere between ~2200 and 0130 EST (see Figure 1) is interpreted in terms of an eastward electric field, and between 0130 and 0430 EST, a westward electric field. Interpretation of the behavior after 0430 EST is not straightforward, as will be discussed later. Only a qualitative description will be given here, since the quantitative analysis is exceedingly complex.

To illustrate the mechanism, we first consider the effects of a westward electric field. The following sequence of events starting from the imposition of a westward electric field is suggested to explain increasing N_mF_2 when the ionosphere is lowered (see Figure 3). Figure 6 shows a sketch of O^+ and H^+ concentration profiles in a model ionosphere that is assumed to consist of O^+, H^+, and electrons. We suppose that the ionization is initially in equilibrium as represented by the solid curves 1 for $[O^+]$ and 2 for $[H^+]$. If a westward electric field is now applied, the downward component of electromagnetic drift lowers the $[O^+]$ profile in altitude as shown by dashed curve 3. The effect on the $[H^+]$ profile depends on the altitude. Above the critical level (assumed to be at 700 km for illustration) where $[H^+]$ is under diffusive control, the [H^+] profile is shifted to a lower altitude as for [O^+]. Below the critical level, however, [H^+] is under chemical control and tends toward the chemical equilibrium concentration given by [H^+] = (9/8)([H] [O^+]/[O]). At a given altitude [O^+] has been reduced by downward drift, whereas [O] and [H] remain unaffected. Hence [H^+] decreases in proportion to the reduction in [O^+]. The resulting [H^+] profile is as shown by dashed curve 4, and the nonequilibrium gradient of [H^+] near the critical level causes downward diffusion of H^+. The protons that diffuse down into the chemical equilibrium region go through the charge exchange reaction, $H^+ + O \rightarrow H + O^+$, to increase [$O^+$] toward the predisturbance level. The new equilibrium profile for [O^+] is illustrated by curve 5. A lowering of the F layer has resulted in increased N_mF_2.

Since the loss rate in the ionosphere increases exponentially with decreasing altitude, enhanced loss rate competes with enhanced downward flux from the protonosphere as the ionosphere drifts downward. The relative importance of these opposing effects depends on the height of the F layer. Thus at high altitudes where the loss rates are small, flux from the protonosphere has a stronger influence on N_mF_2, but at low altitudes loss rates become the dominant factor. This is apparent in the behavior of the $N(h)$ profiles in Figure 3.

The effects of an eastward electric field are the reverse of those discussed above: (*a*) the ionization drifts upward to higher altitudes where the loss rates are smaller, and (*b*) downward diffusion flux of protons from the protonosphere is reduced. Between ~2200 and 0130 EST an eastward electric field can qualitatively explain increasing h_mF_2 and nearly constant N_mF_2 following an initial decrease. An eastward electric field is not expected to have as large an effect on N_mF_2 as a westward electric field, because even if diffusion flux from the protonosphere is completely cut off the ionosphere can decay only as fast as ionization can be removed by recombination. In addition, recombination rates decrease as the ionosphere drifts upward, thereby increasing the decay time.

In principle neutral air winds as well as electric fields can cause vertical movements of the ionosphere. However, it is unlikely that a neutral wind is responsible for the observed movements, because the wind would be required to reverse its direction suddenly at 0130 LT and blow poleward until 0430 LT.

The increase in h_mF_2 after 0430 EST cannot be interpreted simply in terms of an eastward electric field. At 0430 EST h_mF_2 reaches a minimum altitude much lower than the quiettime level (see Figure 1). If the westward electric field that forced the ionosphere down to this low altitude is now removed, the ionosphere would tend to move upward to the quiettime level because of height variations of recombination rate or the southward component of neutral wind or both. The changes in $N(h)$ profile between 0430 and 0445 EST in Figure 4*b* suggest that the former effect is important at low altitudes.

In Figure 3 the $N(h)$ profile maintains a

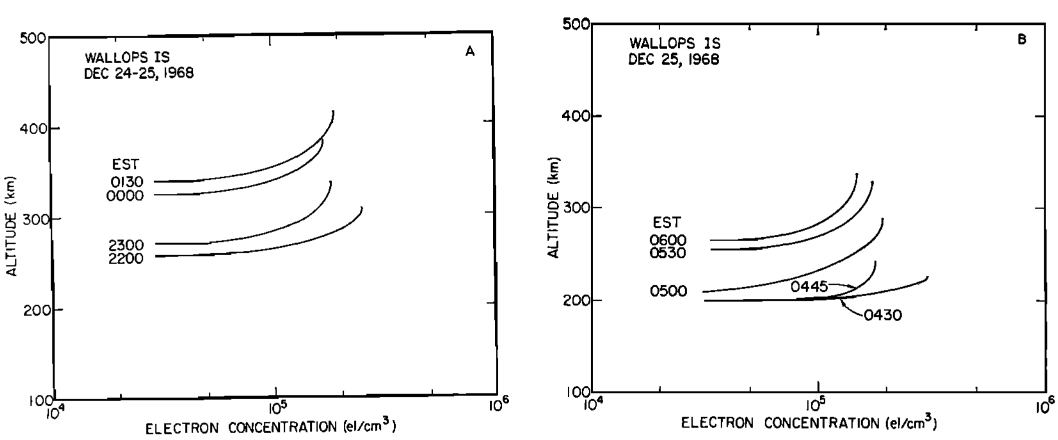

Fig. 4, *a* and *b*. $N(h)$ profiles deduced from ionosonde records at Wallops Island.

nearly constant shape between 0130 and 0330 EST, when h_mF_2 is greater than ~300 km. A comparison of the bottomside profile with the total columnar content data from Hamilton indicates that there was little change in the topside profile during the same period. Figure 7 shows bottomside profiles at 0130 and 0330 EST. The area between the two profiles, shaded in the figure, represents an increase in electron content by 3.7×10^{12} electrons/cm^2 due to the changes in the bottomside profile. Since this increase compares well with the increase in total columnar content observed at Hamilton (from 4.8×10^{12} at 0130 to 7.3×10^{12} electrons/cm^2 at 0330 EST), it is inferred that no drastic changes occurred in the topside profile during this period. On the basis of these considerations, it will be assumed that losses are negligible when $h_mF_2 > 300$ km in the following simple calculations.

If losses are neglected, an increase in downward flux by $\sim 3.5 \times 10^8$ electrons/cm^2 sec is required for the observed increase in total content between 0130 and 0330 EST. If the same flux persists until 0430 EST when the downward motion of the ionosphere ceases, the amount of ionization provided by the protonosphere for the duration of the enhancement event in the ionosphere is estimated at $\sim 4 \times 10^{12}$ electrons/cm^2. Whistler observations show that near the latitude of Wallops Island (49°N, geomagnetic) a protonospheric tube of force with 1 cm^2 cross-sectional area at 1000-km altitude that extends to the equator has typically $\lesssim 10^{13}$ electrons. The protonosphere, therefore, has sufficient ionization to produce the observed concentration enhancement in the ionosphere.

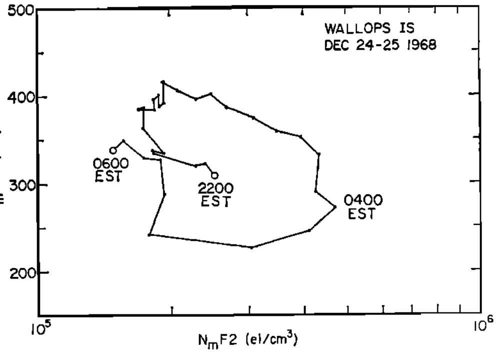

Fig. 5. A plot of the locus of h_mF_2 versus N_mF_2 over Wallops Island for the night of December 24–25, 1968. The beginning and the end at 2200 and 0600 EST, respectively, are marked by open circles. The dots represent intermediate values at 15-min intervals.

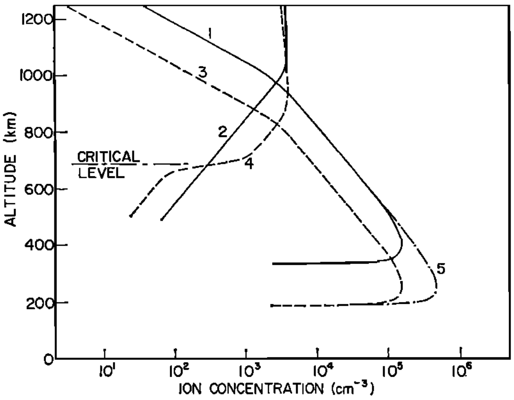

Fig. 6. Ion concentration profiles in a model ionosphere illustrating the mechanism for inducing downward diffusion of protons by lowering the *F* layer. The critical level separates the region of diffusive control (above) and the region of chemical control (below) for protons. The profiles marked 1, 3, and 5 are for O^+ and those marked 2 and 4 are for H^+. See text for details.

The $N(h)$ profile drops in altitude by 85 km between 0130 and 0330 EST. This gives a downward velocity of 12 m/sec, which corresponds to a westward electric field of 1.8 mv/m. Between ~2200 and 0130 EST the velocity is generally upward with an average value of 9 m/sec, corresponding to an eastward electric field of 1.3 mv/m. These electric fields are consistent with electric fields measured by various other techniques. For example, cross-*L* drift measurements of whistler ducts during polar substorms have repeatedly shown the presence of a westward electric field of 0.2–0.5 mv/m in the equatorial plane of the magnetosphere after ~2300 LT [*Carpenter and Stone*, 1967; *Carpenter et al.*, 1969; *Park and Carpenter*, 1970]. In one case reported by *Park and Carpenter* [1970], the electric field associated with substorms prior to ~2300 LT was eastward, but it became westward during a later substorm that started near 0100 LT. The reversal of the electric field direction near midnight, with a westward component during post-midnight hours and an eastward component during premidnight hours, was also observed by the barium cloud technique [*Haerendel and Lüst*, 1970] and by elec-

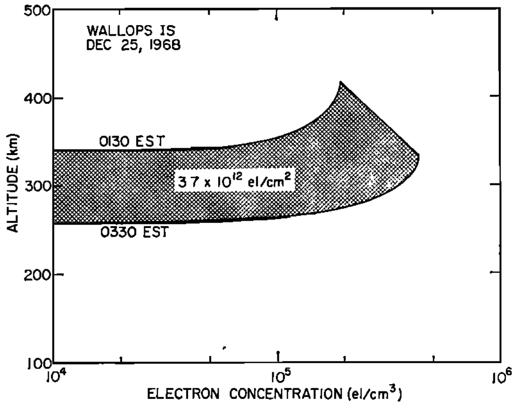

Fig. 7. $N(h)$ profiles over Wallops Island deduced from the ionograms at 0130 and 0330 EST. The shaded area represents a change in electron content owing to the changes in the bottomside profile.

trostatic probes on balloons [*Mozer and Serlin*, 1969]. *Winckler* [1970] reported a similar reversal in the direction of electric fields deduced from the electron fluxes at the geostationary orbit.

An eastward (westward) electric field should drive a southward (northward) Hall current in the ionosphere and cause an eastward (westward) deflection of magnetic field on the earth's surface. As noted earlier, the D component of magnetogram from Fredericksburg shows little resemblance to the apparent east-west electric fields in the ionosphere (see Figure 2). This is a complex problem requiring much more detailed investigations. No attempt will be made here to interpret the magnetic records except to note that electric currents other than ionospheric Hall currents probably contributed to the observed magnetic perturbations. For example, in a model current system proposed by *Meng and Akasofu* [1969] the D component of disturbance vector in middle latitudes during a substorm is interpreted in terms of field-aligned extraionospheric currents flowing into and out of the auroral oval. The lack of close correlation between observed electric fields and magnetic perturbations was also noted by *Haerendel and Lüst* [1970] and *Mozer and Serlin* [1969].

The interpretation given here is also consistent with the nightglow observations. *Brown and Steiger* [1967] and *Gulledge et al.* [1968] reported observations of enhanced 6300-A nightglow intensity at times when the ionosphere is lowered and electron concentrations increase in a manner similar to the event described here.

Discussion

The present study emphasizes the importance of the protonosphere in controlling electron concentrations in the nighttime ionosphere. It is significant that N_mF_2 decreases when the ionosphere starts to move upward near the beginning of the substorm (see Figure 1). This decrease was interpreted in terms of a reduction in downward flux from the protonosphere. If this interpretation is correct, it implies that the downward flux from the protonosphere contributes significantly to electron concentrations in the undisturbed nighttime ionosphere. Consistent with this interpretation are recent whistler observations that show a downward flux of $\sim 1.5 \times 10^8$ electrons/cm^2 sec from the protonosphere into the nighttime ionosphere near $L = 4$ under quiet conditions [*Park*, 1970*a*]. Incoherent backscatter observations at Millstone Hill ($L = 3.2$) also show a downward flux of $\sim 10^8$ electrons/cm^2 sec at night [*Evans*, 1970] (L. A. Carpenter, private communication, 1970).

The maintenance of the nighttime ionosphere has been a matter of controversy for some time (see *Rishbeth* [1968] for a recent review). One explanation that has received much attention is that the ionization is lifted up by an equatorward neutral wind or an eastward electric field to regions of small loss rates [*Hanson and Patterson*, 1964]. *Kohl et al.* [1968, 1969], however, showed that vertical drifts alone cannot fully explain the persistence of the nighttime ionosphere. Some authors, *Yonezawa* [1965] and *Evans* [1965] in particular, stressed the necessity of invoking downward flux from the protonosphere. The present study shows that there is an intimate relationship between vertical drifts and protonospheric fluxes and that they are both important in the nighttime ionosphere. These results emphasize the need for further theoretical studies of the ionosphere including its interactions with the protonosphere.

A vertical movement of the ionosphere brings about two opposing effects: changes in loss rates and changes in protonospheric fluxes. A lowering of the ionosphere can cause an enhancement or a reduction in N_mF_2 depending on the atmospheric parameters and the initial conditions. In the case reported here a lowering of the ionosphere was accompanied by an increase in N_mF_2 when h_mF_2 was above ~300 km, but a decrease when below ~300 km. The height at which the two opposing tendencies are balanced depends on the atmospheric parameters, and hence on the season and the solar cycle epochs. This may be the reason why nighttime enhancements in f_oF_2 are more frequent and pronounced in the winter and near the solar cycle minimum. Neutral winds probably play a role in producing nighttime enhancements by lifting the ionosphere and setting up favorable initial conditions.

During the initial and main phase of a magnetic storm, the protonosphere is generally depleted both inside and outside the plasmapause. *Carpenter* [1962] distinguished the 'latitude-independent' depletion from a more pronounced latitude effect, an inward displacement of the plasmapause. *Park* [1970*b*] reported observations of a depletion of the protonosphere inside the plasmapause and simultaneous enhancements in f_oF_2 in the underlying ionosphere. It is suggested that westward electric fields of sufficient strength and duration may be responsible for the 'latitude-independent' depletion of the protonosphere during magnetic storms by the same mechanism proposed here to explain nighttime enhancements in N_mF_2 associated with substorms. A mechanism rather similar to the one proposed here was suggested by *Hanson and Ortenburger* [1961] for the stormtime depletion of the protonosphere. In their scheme [H^+] gradient required for downward diffusion is produced by hydromagnetic heating that results in a reduced ratio of [O^+] to [O], and hence a reduced [H^+] in the chemical equilibrium region. They noted, however, that the amount of heating required is much larger than what is observed.

On the dayside, effects of electric fields are more complicated because ion-drag is important in the daytime ionosphere [*Hirono and Kitamura*, 1956; *Dougherty*, 1961; *Rishbeth et al.*, 1965]. When the horizontal neutral wind induced by ion-drag reaches a steady state velocity, it effectively cancels the vertical component of electromagnetic drift. The time required to reach a steady state is inversely proportional to ion concentration and is estimated to be ~20 min for an ion concentration of ~10^6 cm^{-3} [*Dougherty*, 1961]. Therefore, near the F_2 layer peak ion-drag should inhibit vertical electromagnetic drifts. Near the critical level, however, where the ion concentrations are small, vertical drifts and resulting modulations in protonospheric flux should not be impaired seriously by ion-drag. The altitude dependence of ion-drag effects implies the existence of divergence in vertical drift velocity, which tends to accentuate the effects of protonospheric fluxes. Thus a compressional effect of a westward electric field adds to the enhancement in F layer concentrations owing to an enhanced downward flux from the protonosphere.

The mechanism proposed here for nocturnal enhancements in f_oF_2 should operate at all latitudes except near the equator and the poles, but the magnitude of its effect should depend on the latitude, since the amount of ionization in the protonospheric tube of force varies with latitude. At low latitudes tube content in the protonosphere decreases with decreasing latitude [*Angerami and Carpenter*, 1966; *Park and Carpenter*, 1970] and becomes less than 10^{13} electrons/cm^2 tube for geomagnetic latitudes below ~25° [*Titheridge*, 1968*b*]. On the high-latitude side, tube content decreases to ~10^{12} electrons/cm^2 tube in the plasma trough region beyond the plasmapause [*Angerami and Carpenter*, 1966]. In these regions of small protonospheric tube content, other processes such as precipitation of energetic particles in the auroral zone [*Rai and Hook*, 1967] and the equatorial anomaly [*Sato*, 1966] may become important compared with the mechanism proposed here.

CONCLUSIONS

Evidence has been presented that the protonosphere plays an important role in controlling electron concentrations in the nighttime ionosphere. Downward diffusion flux from the protonosphere is modulated by east-west electric fields in the ionosphere, and westward electric fields associated with substorms can explain anomalous concentration enhancements often observed in the midlatitude nighttime ionosphere. Under favorable conditions this phenomenon may permit the use of ground-based ionosonde records to infer spatial and temporal variations of electric fields in the ionosphere during substorms.

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