Parameterized Study of the Ionospheric Modification Associated With Sun-Aligned Polar Cap Arcs

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Sun-aligned (SA) arcs are a prevalent feature of the polar cap ionosphere during northward interplanetary magnetic field conditions. These arcs are, like the auroral arc, a complex electrodynamic system coupling the ionosphere and magnetosphere. The electron precipitation and convection electric field associated with this system modify the polar cap ionospheric plasma distribution. In the past decade, a wealth of observational information has indicated the complexity of these ionospheric modifications, but only a limited number of model studies have been carried out to elucidate the changes associated with SA arcs. In this investigation, an extensive parametric study has been conducted to identify and order these ionospheric modifications. Specifically, we are interested in modeling the local evolution and decay of ionospheric modification due to a source consisting of an idealized, though representative, SA arc structure. The Utah State University time-dependent ionospheric model (TDIM) has been used to define the ionospheric physics and its dependencies on both solar cycle and season. An SA arc model has been developed. This model enables one to systematically vary the key arc parameters; electric field strength, width, electron precipitation energy flux, and electron precipitation characteristic energy. Our findings indicate that the changes associated with the *E* and *F* regions are quite different. *F* region structures have relatively long lifetimes and are significantly affected by transport. This leads to a significant role for cross-arc convection. The *E* region is much less affected by transport due to short chemical recombination times and thus, *E* region modifications are confined to the arc structure itself where precipitation and enhanced electric fields are present. Furthermore, the response of the *F* region to changes in the arc parameters is not linear, and the largest ionospheric modifications occur for intermediate arc widths and electric field strengths. An important indicator of *F* region modification is the total electron content (TEC) for flux tubes convecting through SA arc structures. The magnitude and variation of the TEC enhancement with various arc parameters can be an important indicator of real processes which are occurring in the arc structure. In addition to TEC we examine the variation of T_e , T_i , N_e , Σp , and ΣH for various arc parameters.

1. INTRODUCTION

The winter polar cap during northward interplanetary magnetic field (IMF) conditions is often characterized by highly structured electric field and plasma distributions [Berkey *et al.*, 1976; Ismail *et al.*, 1977] often present are Sun-aligned (SA) polar cap arcs which may contribute to this electric field and plasma structuring in an as of yet, unspecified way. Reasons for modeling SA arcs are (1) identifying sources of high-latitude plasma structuring during northward IMF; (2) determining whether a simple SA arc model can reproduce basic features of observed arcs as well as predict possible effects which may be observed by future observations; and (3) correlating specific features of plasma structure (N_e distribution, TEC enhancement, etc.) to possible causal arc parameters (arc width, cross flow, precipitation, electron flux and characteristic energy, arc electric field, etc.).

Past studies have extensively described the morphology, distribution, and frequency of SA polar cap arcs [Ismail *et al.*, 1977; Gussenhoven, 1982]. These studies have included ground-based optical imagery [Weber and Buchau, 1981; Lassen and Danielson, 1978] and satellite-based optical and particle observations [Hardy *et al.*, 1982; Petersen and Shelly, 1984; Hoffman *et al.*, 1985; Frank *et al.*, 1982, 1986; Akasofu and Tsurutani, 1984; Gorney *et al.*, 1986; Carlson *et al.*, 1984]. It was found that SA arcs were observed most frequently

during geomagnetic quiet times characterized by northward IMF [Akasofu, 1972; Berkey *et al.*, 1976; Berkey and Kamide, 1976; Gussenhoven, 1982].

The characteristics of SA polar cap arcs span a wide range of spatial sizes and optical brightness. The most prominent of these arcs may extend several thousand kilometers across the polar cap and have a width of several hundred kilometers. The brightest of these transpolar arcs are sometimes known as "theta" aurora [Frank *et al.*, 1982, 1986]. Often, a theta aurora may be composed of several discrete arcs parallel to each other in the noon-midnight direction [Akasofu and Tsurutani, 1984]. There is also evidence that many polar cap auroras may be a conjugate phenomena appearing in both hemispheres [Obara *et al.*, 1988; Mizera *et al.*, 1987] and that they may be more common than previously thought, as at times they may be subvisual [Weber and Buchau, 1981]. Other SA polar cap arcs may extend poleward from the midnight sector of the auroral oval or exist discretely within the polar cap with no obvious connection to the auroral oval [Akasofu and Roederer, 1983; Hoffman *et al.*, 1985].

There remains much debate as to the mechanism of SA arc formation, especially as to the specific magnetospheric topology and plasma population which produces the observed arcs. There does, however, seem to be some consensus on the general features of SA polar cap arcs. They are usually characterized by a region of large-scale shear flow in the plasma convection consistent with a region of $\nabla \cdot \mathbf{E} < 0$, where $\mathbf{E}$ is the horizontal convection electric field [Weber *et al.*, 1989]. There is also a weak upward current associated with precipitation of particles of energy less than a few keV near the

region of $\nabla \cdot \mathbf{E} < 0$. Horizontal electric fields within such arcs may be as high as 100 mV/m, but are usually much lower.

Coordinated rocket, satellite, and radar campaigns have attempted to comprehensively describe the ionospheric signatures of such arcs [Niciejewski *et al.*, 1989; Weber *et al.*, 1989]. Basu *et al.* [1988, 1990] have examined the plasma structuring in the polar cap associated with SA arcs through use of GPS and polar beacon satellites which measure TEC and scintillation signatures of the plasma density gradient and shear flow associated with SA arcs. They observed a solar cycle dependence upon the TEC enhancement associated with SA arcs. A generalized SA arc based on a compilation of these campaigns and other radar and satellite observations has been recently developed by Valladares and Carlson [1991]. While the optical, electrodynamic, and particle precipitation characteristics of polar cap arcs have been extensively described, no systematic study of the effect of typical SA polar cap arcs upon the high-latitude ionosphere has been done. In a few specific SA arc observations the ionospheric modifications have been noted. Theoretically, the extent of these modifications will depend upon the specific convection electric fields and particle precipitation in a complex manner. Sojka and Schunk [1987], modeled the polar ionosphere for different northward IMF convection patterns, and later Sojka and Schunk [1988] modeled the polar ionosphere's response to small-scale (SA arc scale) convection electric field structures. These studies focused on the effects associated with the convection and did not include those effects associated with the particle precipitation. The effects due to particle precipitation were studied by Schunk and Sojka [1987], but this study did not include SA arc electric field structures. These plasma enhancements were associated with southward IMF polar cap patches. In addition, both of these studies were essentially global in that they examined the modification of the entire polar ionosphere due to various global convection patterns associated with northward IMF.

In this paper we will be primarily concerned with the local ionospheric modification that is due to a generalized steady state arc structure. The SA arc structure is constructed to be locally consistent with observed arcs. We do not attempt to address questions of magnetospheric topology which produce the shear flow and particle precipitation associated with SA polar cap arcs. (Nor do we address the large-scale Birkeland current system associated with positive B_z .) These local modifications are nevertheless important as they contribute to the overall plasma structuring of the entire polar cap, especially during northward IMF conditions. An ability to better understand these local processes may lead to a better capability in modeling the highly structured polar cap [Basu *et al.*, 1990].

For a representative set of SA arc parameters which includes both convection and precipitation, we will concentrate on the modification by SA polar cap arcs upon the F region electron density and the height integrated conductivity. Our findings will be summarized in a way that parameterizes the effect of specific arc parameters upon a particular ionospheric parameter.

2. ARC MODEL

The ionosphere model used in this study is the Utah State University time-dependent ionospheric model (TDIM). This is a first principle ionospheric model which self-consistently solves the continuity, momentum, and energy equations for a

multi-ion plasma (NO^+ , O^+ , N_2^+ , O^+ , N^+ , and He^+) along an ionospheric flux tube. The TDIM was developed over a 2 decade period by Schunk and coworkers. Its theoretical development is described by Schunk [1988], while its comparison with observations by Sojka [1989]. In addition to the ionosphere model [Sojka and Schunk, 1988], a SA arc model was developed. This SA arc model defines a structure in the convection and precipitation inputs that is representative of a SA arc.

The arc model itself was constructed to be simple and yet be representative of a wide range of SA polar cap arcs. The location and orientation of the arc structure is easily varied and may be situated anywhere in the polar cap. For this study, we orientate the model arc on the noon-midnight median passing through the magnetic pole. The relevant variable parameters of the arc are: the width in the dawn-dusk direction; the distribution of the electric potential; the characteristic energy (keV); and energy flux ($\text{ergs cm}^{-2} \text{s}^{-1}$) of the particle precipitation. A background convection pattern is required. This large-scale convection transports plasma into the local SA arc environment. In general, no unique northward IMF convection pattern is available. For the purposes of this study where relative plasma effects in the SA arc region are sought, we only require that the large-scale convection brings representative plasma into the SA arc region. Given this minimal requirement we have adopted a plasma flux tube trajectory from a $B_z \sim 0$ and strong B_y pattern to convect plasma into the SA arc region. The results of this study are not sensitive to this choice.

Once in the SA arc region, the plasma flux tube motion is determined by a superposition of the SA arc and background electric fields. This raises yet another unresolved magnetospheric issue; namely, SA arcs occur at/or near convection shears, but is there a cross arc drift that carries plasma through the arc? Our results will show that observations of the plasma on and near arcs can put strong limits on this motion. (In this study we vary the cross arc drift by changing the background convection.) Since the plasma remains in the arc for time intervals of less than about 1 hour, we have chosen to make the background convection and SA arc model time independent. Temporal variations would be the topic of future work. In this study, the length of the SA arc and its exact orientation relative to the Sun-aligned direction are not studied since we are following only one flux tube as it crosses the SA arc region. If plasma flux tubes do not drift across the SA arc (or the arc moves relative to the plasma) the flux tube would remain in the arc for long periods of time since SA arcs are observed to be stable for tens of minutes to hours [Valladares and Carlson, 1991; C. E. Valladares *et al.*, The IMF dependence of stable Sun-aligned polar cap arcs, submitted to *Journal of Geophysical Research*, 1993]. In this case, the plasma would drift but stay inside the arc and densities would increase. Our results predict that for such "stagnant" conditions well-defined plasma signatures should be observed. (By varying the background electric field we can simulate this extreme condition.)

The dawn-dusk distribution of these parameters are summarized in Figure 1 for an arc width of 200 km traversing the SA arc in the midnight sector of the polar cap. Figure 1a shows the arc potential distribution which has a 2.2-kV potential well; Figure 1b shows the corresponding electric fields, and Figure 1c shows the electron precipitation distribution. In order to keep the arc simple, the potential well

Fig. 1. Dawn-dusk distribution of the prototype SA polar cap arc parameters. The horizontal axis represents spatial size in kilometers: (a) Potential structure within the arc; (b) arc electric field across arc structure dusk-dawn direction is positive; (c) energy flux of the precipitating electrons; and (d) general convection trajectory of a flux tube convecting through arc structure.

was chosen to be a ramped vee for which discrete electric field values within the arc could be determined. The potential well was ramped so that for a particular arc width, the maximum electric field values and precipitation were centered within the center portion of the arc potential structure. For the arc in Figure 1, the width of the potential well was 200 km wide. Within this well was a 100 km wide precipitation region and a 100 km wide region where the electric field was maximized. The effect of the electric field upon the convection trajectory of a particular flux tube is shown schematically in Figure 1d. The dashed line indicates the background convection without the arc structure. The solid line indicates the convection trajectory for the superposition of the background and arc electric field. The tick marks along the solid line indicate elapsed time along the trajectory.

This model of a SA polar cap arc is intended to be reasonably consistent with the gross nature of observed SA polar cap arcs. Namely, the arc occurs in a region of $\nabla \cdot \mathbf{E} < 0$, the arc is aligned in a noon-midnight direction, the length of the arc is much greater than its width and the precipitation structure is centered near a shear in flow (or electric field).

In addition to the model arc parameters being varied, the effect of both season and solar cycle level was considered. These latter two geophysical conditions were defined as inputs to the TDIM. The TDIM was otherwise configured as described by *Sojka and Schunk* [1988].

3. RESULTS

For simplicity and to aid in the interpretation of the effect of particular arc parameters upon the ionosphere we introduce a prototype arc. This arc structure has a width of 200 km and a maximum arc electric field of 40 mV/m. The precipitation is a Maxwellian electron beam of 0.5-keV characteristic energy and total energy flux of $1 \text{ erg cm}^{-2} \text{ s}^{-1}$. The relevant ionospheric conditions are for winter solar minimum ($F_{10.7} = 70$). The location of the arc traversal is in the midnight sector (MLT) of the polar cap. This prototype arc will be used in the following parameter study. In each of the following cases, one parameter of the prototype arc or ionospheric condition is varied with all other parameters remaining the same.

An ionospheric pseudo cross section of this arc simulation is shown in Figure 2. The horizontal axis represents elapsed time in hours for a flux tube convecting upon a particular polar cap trajectory. Since the flow across the arc is relatively constant, the horizontal axis also represents horizontal distance across the arc. The arc location is identified in Figure 2c by the two vertical dashed lines. Figure 2a shows the variation of total electron content (TEC) across the arc structure. The solid line represents the time (spatial) variation of TEC for a flux tube convecting across the arc structure which has a precipitation structure imbedded in it as described previously (see Figure 1).

Figure 2b represents the variation of ΣH and ΣP across the arc. The heavy line represents the variation of ΣP across the arc and the thin line represents ΣH . Figure 2c is a contour plot of the electron density between 100 and 800 km across the arc. The maximum contour corresponds to a density of 10^5 cm^{-3} , and the minimum contour is $10^{1.5} \text{ cm}^{-3}$.

From Figure 2 we can readily see some of the gross effects of a SA polar cap arc on the ionosphere. The enhanced ΣH and ΣP occurs within the precipitation region of the arc structure and corresponds to the enhanced E region densities due to the electron precipitation. The TEC increases across the arc and remains elevated outside the arc corresponding to the enhanced plasma densities at F region altitudes observed after the flux tube crosses the arc (see Figure 2c). For this study we will use TEC as an indicator of the relative F region enhancement and ΣH and ΣP as indicators of the relative E region enhancement in addition to density contour plots.

An examination of the contour plot of N_e in Figure 2c allows us to make some qualitative observations of the effect of arc structures upon the ambient ionosphere. The most dramatic effect is seen on the edge of the arc as the flux tube convects into it. The rapid rise in T_e due to the topside heat flux of the precipitating electrons and, to a lesser extent, upon Joule heating due to $\mathbf{E} \times \mathbf{B}$ convection produce an immediate increase in plasma scale height within the arc structure. This is seen as an increase in N_e at very high altitudes. As the flux tube moves out of the enhanced T_e and T_i regions, the scale heights decrease resulting in a sharp decrease in N_e at high altitudes. Near the F peak, the combination of enhanced production due to electron precipitation, vertical transport, and thermal diffusion combine to produce an increasing electron concentration across the arc. This produces an enhanced F region as the flux tube moves outside of the arc structure that may be maintained for many hours. This enhancement and maintenance of the F region density serves to enhance the TEC of the flux tube.

In the E region, the primary effect of the arc structure is to produce enhanced ionization due to the electron precipitation.

Fig. 2. Ionospheric cross section of the prototype SA polar cap arc. (a) The variation of TEC of a flux tube traversing the arc structure from the left (1 TEC unit = 1×10^6 electrons/m²), (b) the variation of Σ_P and Σ_H across the arc structure; and (c) contours of the computed N_e distribution across the arc structure. The relevant arc conditions are winter solar minimum ($F_{10.7} = 70$), arc electric field = 40 mV/m, arc width = 200 km, characteristic energy of precipitating electrons is 0.5 keV and the energy flux of the precipitation is $1 \text{ erg cm}^{-2} \text{ s}^{-1}$. A distance from the arc (dawn-dusk direction) is shown below the flux tube transit time axis.

This enhancement is localized within the arc structure and quickly disappears as the flux tube moves out of the arc region. This is also reflected in the variation of Σ_H and Σ_P across the arc. The integrated conductivities are most enhanced within the precipitation region. If the F region is significantly enhanced, there may also be a significant contribution to the total integrated conductivity from altitudes above 150 km. The general features of the prototype arc correlate with the composite arc constructed by Valladares and Carlson [1991] and displayed in Figure 14 of that paper.

3.1. Temperature and Transport Effects

Within the modeled SA polar cap arcs there are two sources of temperature enhancement. The first source is the T_e enhancement due to the topside heat flux of the precipitating electrons. In this work we assume that the heat flux is proportional to the energy flux of the electrons following the work of Schunk *et al.* [1986]. This electron heating couples to

the ions self-consistently at all altitudes and to the neutral gas at the lowest altitudes. The most prominent effect of the elevated T_e within the arc is to increase the topside scale height of the plasma. In all cases, this serves to increase the O^+ density on the topside of the F region. Figure 3 shows vertical profiles of T_e for the prototype arc for three different precipitation fluxes (0.1, 1, and 5 ergs cm⁻² s⁻¹). The other parameters are the same as those used in Figure 2. These profiles are located at the center of the arc.

The second source of temperature enhancement is by Joule heating due to the component of the electric field perpendicular to the geomagnetic field line. The enhancement in the ion temperature maximizes at low altitudes and increases rapidly for electric fields greater than 40 mV/m [Sojka and Schunk, 1983]. Most of the effects of T_i enhancements upon the evolution of the daytime and nighttime plasma distribution (due to electric fields) have been described in previous work [Schunk *et al.*, 1975, 1976, 1980].

Fig. 3. Plot of the vertical T_e profiles within the prototype arc for energy fluxes of 0.1 (solid line), 1.0 (dashed line), and 5.0 (dotted line) $\text{ergs cm}^{-2} \text{s}^{-1}$.

These heated ions couple to the electrons and serve to generally enhance the molecular ion concentrations at all altitudes due to the following reaction rates being strongly temperature dependent [Schunk *et al.*, 1975]:

Figure 4 shows the T_i profile within the prototype arc for 10, 40, 60, 80, and 100-mV/m electric fields. The other parameters are the same as those used in Figure 2. These profiles show how the bottomside ion temperature becomes enhanced for electric fields greater than 60 mV/m.

For the stronger zonal electric field cases, there is also a significant transport effect associated with the vertical component of the $\mathbf{E} \times \mathbf{B}$ convection. Therefore, within the arc there may exist not only a shear flow in the horizontal direction (sunward/antisunward) but in the vertical direction as well. The sign of the vertical drift depends upon dip angle and is minimized at higher magnetic latitudes. In the E region the plasma is inhibited from moving in the $\mathbf{E} \times \mathbf{B}$ direction as the ion neutral collision frequency (γ_{in}) increases with decreasing altitude. Hence this effect is only an F region mechanism which raises or lowers the layer.

3.2. Solar Cycle Dependence

The first parameter which will be varied is the $F_{10.7}$ solar flux. Figure 5 shows a contour plot of N_e (bottom panel), ΣH and ΣP (middle panel), and TEC for winter solar maximum ($F_{10.7} = 210$) ionospheric conditions. The other parameters are the same as those used for Figure 2. Please note the case without the precipitation is not shown in the top panel of Figure 2.

For solar maximum, the relative enhancement is much less at high altitudes (F region) but the absolute enhancement is larger at all altitudes compared to solar minimum (compare Figures 2 and 5). The F region enhancement occurs at higher altitudes due to the larger-scale height of the neutral atmosphere which has raised $h_m F_2$ from below 300 km (solar minimum) to about 350 km (solar maximum). This also moves upward the region of enhanced ionization due to the soft (0.5 keV) precipitation. This raising of the aurorally produced ionization leads to a slight enhancement of Σp and hence a small $\sim 10\%$ change in the $\Sigma p / \Sigma H$ ratio. In the topside ionosphere, the enhanced topside scale height is readily evident, i.e., few contour lines during solar maximum. The solar maximum background densities for this trajectory are almost an order of magnitude higher than at solar minimum. These higher densities are now on the same order as the density enhancement associated with the $1 \text{ erg cm}^{-2} \text{s}^{-1}$ arc. Basu *et al.* [1990] have observed that the relative TEC enhancement associated with SA polar cap arcs varies with solar cycle. They observed typical ΔTECs of $\sim 5 \times 10^{16}$ electrons/ m^2 for solar maximum conditions and $\sim 2 \times 10^{16}$ electrons/ m^2 for solar minimum conditions. We have examined the ΔTEC associated with the modeled prototype arc for solar minimum and maximum conditions. Figure 6 shows the ΔTEC enhancements versus characteristic energy of the precipitating electrons for solar minimum and maximum. The TEC enhancement is heavily dependent on characteristic energy of the precipitation but does show the general trend observed by Basu *et al.* [1990].

3.3. Electric Field Strength Comparison

Next, we examine the effect of the arc electric field strength on the ionosphere. Again, the arc structure described previously for Figure 2 is used. The arc electric field is varied in 10 mV/m increments from 10 to 100 mV/m. Figures 7a and 7b show the N_e contours for the 10 and 100 mV/m cases, respectively, while Figure 2 is for 40 mV/m.

Fig. 4. Vertical profiles of T_i within the prototype arc for arc electric fields of 10, 40, 60, 80, and 100 mV/m.

Fig. 5. Same as Figure 2 except for winter solar maximum conditions ($F_{10.7} = 210$).

In general, the plasma enhancement due to the SA arc increases for increasing arc electric field between 10 and 40 mV/m. As the arc electric field increases above 40 mV/m, the plasma enhancement becomes smaller, especially in the F region. For this particular arc structure, the plasma enhancement of the ionosphere maximizes for an arc electric field near 40 mV/m. The competing processes, enhanced production, transport, and thermal diffusion produce a maximum enhancement. As the electric field increases above 40 mV/m, more of the enhanced ionization is converted to molecular ions due to the temperature dependent reactions in equations (1) and (2). Therefore the overall density is lower and decays more rapidly when the flux tube leaves the arc due to the faster recombination times for the molecular ions. Figure 8 quantifies the magnitude of the electric field dependence by showing the $N_m F_2$ (solid line) inside the arc and the $N_m F_2$ (dotted line) ~ 20 min after leaving the arc. The $N_m F_2$ versus electric field strength trend is readily seen, as is the peak around 40 mV/m.

In the E region, the variation of Σ_H and Σ_P across the arc is about the same for all electric field strengths. For very large fields, there may be important sources of enhancement which are beyond the capability of this work to examine.

Specifically, there may be significant effects due to realistic E region transport, wave particle heating, and electrodynamics which we do not address here.

3.4. Characteristic Energy Comparison

Previously, we examined the effect of characteristic energy versus ΔTEC in Figure 6. TECs increased significantly for low characteristic energy corresponding to enhanced F region production. This is also evident if we examine the ratio of Σ_P/Σ_H versus characteristic energy. Figure 9 shows the variation of the Σ_P/Σ_H ratio versus characteristic energy for solar minimum and solar maximum conditions. These results are comparable to values previously calculated by Vickery *et al.* [1981] and Rasmussen and Schunk [1988]. The effect of increasing the characteristic energy is to lower the altitude of maximum production. This serves to decrease the TEC as seen in Figure 6 and to increase the conductances. The Σ_P shows a small increase with increasing characteristic energy, while Σ_H is dramatically increased (a factor of 12 from the 0.5 to 5 keV cases). The net result upon the Σ_P/Σ_H ratio is that it decreases from a value of ~ 3.0 to ~ 0.5 . This may lead to important

Fig. 6. Same as Figure 2 except for summer solar minimum conditions.

differences in the electrodynamics and current flow associated with the arc for differing precipitating particle characteristic energies. The F region enhancements decrease with increasing characteristic energy as indicated by the TEC. Specifically, the $N_m F_2$ enhancement in the arc decreases from a factor of 10 at 0.5 keV to a factor of 4 at 5 keV. These factors, since they are relative, will depend upon ionospheric conditions and the other arc parameters.

3.5. Arc Width Comparison

The effect of arc width upon the plasma density is represented in Figure 10. Figure 10a shows a contour plot of N_e for a 100-km-wide prototype arc. Comparing Figure 10a to Figure 2c we can see that the 100-km-wide arc produces less of an F region enhancement than the 200-km-wide arc. The enhancement below 200 km is roughly equal for both cases,

differing only by the spatial size of the precipitating region. In Figure 10b we show the N_e contour for a 400-km-wide arc. When compared to Figure 2c, there is only a very moderate enhancement in the F region density for the larger arc. Again, the enhancement below 200 km is about the same except for the width of the precipitation region.

For the simulations performed in this study the degree of F region enhancement is approximately linear for increasing arc width below 200 km. As the width of the arc exceeds 200 km, the degree of F region enhancement saturates and there is little further enhancement with increasing width.

The arc width may also be viewed as the time spent in the arc ionization region. Hence the wider arcs correspond to longer times in the ionization region which gives the flux tube F region time to reach "steady state" for the given auroral ionization. For the Figure 2 and 10 arc scenarios this is approximately reached for the 200-km-wide arc. This arc width/time in our discussion also depends on the background electric field strength. For a flux tube that moves quickly (large electric field) across a wide arc the degree of enhancement may be less than for a flux tube which moves slowly across a much narrower arc. In addition, this does not address the issue of the arc structure itself producing a significant cross arc flow component due to self-consistent magnetospheric-ionosphere electrodynamic coupling [Zhu *et al.*, 1992]. The extreme case of very little cross arc drift is discussed below.

3.6. Stagnation

In the limiting case where the plasma flow across the arc is zero, the flux tube can be thought of as "stagnating" within the precipitation of the SA arc structure. If this occurs, the flux tube may spend a much longer amount of time within the region of enhanced precipitation and sunward/antisunward convection. To examine this in a simple way, we have again used the prototype arc structure. After the flux tube convects into the arc structure the cross drift is set to zero and the flux tube only

Fig. 7a. N_e contour plot for the prototype arc with an arc electric field of 10 mV/m. The relevant arc conditions are arc width equal to 200 km, characteristic energy of precipitating electrons is 0.5 keV, and the energy flux of the precipitation is $1 \text{ erg cm}^{-2} \text{ s}^{-1}$.

Fig. 7b. N_e contour plot for the prototype arc with an arc electric field of 100 mV/m. The relevant arc conditions are arc width equal to 200 km, characteristic energy of precipitating electrons is 0.5 keV, and the energy flux of the precipitation is $1 \text{ erg cm}^{-2} \text{ s}^{-1}$.

moves in the sunward or antisunward direction. Figure 11 shows the TEC enhancement associated with such a "stagnated" flux tube. The top curve is for solar maximum and the bottom curve is for solar minimum. If the flux tube stays within the precipitation region for a significant amount of time (~ 1 hour), the TEC enhancement can be very significant, of the order of $\sim 6 \times 10^{16}$ electrons/m² which is much larger than observed values [Basu *et al.*, 1990]. In order to produce a more reasonable TEC enhancement in a flux tube which has stagnated within the SA arc we must then either decrease the flux or increase the characteristic energy of the precipitation.

Figure 12 shows the TEC enhancement as in Figure 11 associated with the prototype arc but with a flux of $0.1 \text{ ergs/cm}^2 \text{ s}$. The TEC enhancement after approximately 1 hour is now less than $\sim 2 \times 10^{16}$ electrons/m². These monotonically increasing TEC trends are distinctly different from the $N_m F_2$ trends found in section 3.6. $N_m F_2$

asymptotically approaches a limit. This limit takes longer than say the E region chemistry time constant of seconds; however, it is much less than an hour. This contrasting $N_m F_2$ TEC behavior is potentially a useful tool to establish how long plasma flux tubes have been within an arc. However, as Figures 2, 10, 11, and 12 indicate, arc parameters such as characteristic energy would be needed in addition to $N_m F_2$ and TEC observations.

3.7. Flux Comparison

Finally, we will examine the effect of varying the precipitating electron flux in the arc. Figure 13a shows the TEC, variation across the prototype arc for energy fluxes of 0.1 and $5 \text{ erg cm}^{-2} \text{ s}^{-1}$. Figure 13b shows the variation of Σ_H and Σ_P across the arc for energy fluxes of 0.1 and $5 \text{ erg cm}^{-2} \text{ s}^{-1}$.

Fig. 8. $N_m F_2$ versus arc electric field inside the precipitation region (solid line) and ~ 20 min after leaving the precipitation region.

Fig. 9. Ratio of Σ_P/Σ_H versus characteristic energy of a $1 \text{ erg/cm}^2 \text{ s}$ electron flux for winter solar maximum and solar minimum conditions.

Fig. 10. N_e contour cross section of prototype arc with an arc width equal to (a) 100 km and (b) 400 km. The relevant arc conditions are winter solar minimum, arc electric field equal to 40 mV/m, characteristic energy of precipitating electrons is 0.5 keV, and the energy flux of the precipitation is $1 \text{ erg cm}^{-2} \text{ s}^{-1}$.

These can be compared with Figures 2a and 2b which is for an energy flux of $1 \text{ erg cm}^{-2} \text{ s}^{-1}$.

The most dramatic effect of increasing the flux is seen in the F region. TEC increases by a relative factor of 10 and 50,

Fig. 11. Delta TEC enhancement due to a 0.5 keV electron flux of $1 \text{ erg/cm}^2 \text{ s}$ versus elapsed time in the precipitation region for winter solar maximum ($F_{10.7} = 215$) and solar minimum conditions ($F_{10.7} = 75$). Precipitation begins at ~ 0.5 hours.

respectively, as the flux increases from 0.1 to $1 \text{ erg cm}^{-2} \text{ s}^{-1}$ and then from 0.1 to $5 \text{ erg cm}^{-2} \text{ s}^{-1}$. This nearly linear increase is associated with the almost linear dependence of F region O^+ chemistry. In contrast, the E region chemistry yields a square root dependence of the electron density upon the ionization flux. This differential E and F region density dependence upon the flux leads to the Σ_H and Σ_P having different flux dependences. Figures 2 and 13 show these Σ_H/Σ_P differences. For the $0.1 \text{ erg cm}^{-2} \text{ s}^{-1}$ case, the Σ_H/Σ_P ratio is ~ 0.5 which decreases to ~ 0.3 at $1 \text{ erg cm}^{-2} \text{ s}^{-1}$ and to ~ 0.25 at $5 \text{ erg cm}^{-2} \text{ s}^{-1}$. This specific dependence is also very dependent upon the characteristic energy. In the example shown a 0.5-keV characteristic energy was used. As this increases, less of the ionization occurs in the F region (see preceding section). Consequently, the effect becomes less significant since the F region contribution to Σ_P is smaller.

4. DISCUSSION

In this study we have examined the time dependent modification of the flux tube plasma distribution convecting through an idealized SA arc structure in the midnight (MLT)

Fig. 12. Same as Figure 11 but for a $0.1 \text{ erg/cm}^2 \text{ s}$ electron flux.

sector. It is apparent that SA polar cap arcs produced by low characteristic energy precipitation can be a significant source of F region plasma enhancement in nonsunlit portions of the polar cap. Such enhancements and associated density gradients may explain some of the high-latitude scintillation data [Weber and Buchau, 1981; Klobuchar *et al.*, 1985] which are often observed in the winter polar cap in the absence of visible arcs. Additionally, the relative TEC enhancements associated within the SA arcs are consistent with the observations of Basu *et al.* [1990]. Larger TEC enhancements are seen at solar maximum for the same arc inputs. The reason for this is that the solar maximum F region slab thickness is larger and the peak density

occurs at a higher altitude, both of these effects are due primarily to the MSIS neutral profiles assumed for solar maximum and solar minimum. The overall trend is that SA arcs in the solar minimum polar cap produce larger relative TEC enhancements but SA arcs in the solar maximum polar cap produce larger absolute TEC enhancements. This, in turn, implies that the high-altitude electron density gradients should have a solar cycle dependence, being largest during solar minimum.

The parametric study has covered both ionospheric conditions of solar cycle as well as arc parameters (width, energy flux, characteristic energy, and electric field). Although general trends for each have been identified, these trends are heavily coupled to the other parameters. For commonly found arc conditions, widths less than or equal to few hundred kilometers, energy fluxes $\leq 1 \text{ erg cm}^{-2} \text{ s}^{-1}$, characteristic energies $\leq 2 \text{ keV}$, and electric field strengths $\leq 40 \text{ mV/m}$ the ionosphere has the same order of magnitude dependence for each of these parameters. The largest F region enhancements are observed in the model for the lowest characteristic energies and moderate (40 mV/m) electric fields within the arc for winter solar minimum conditions. If the SA arc is sunlit either in a summer hemisphere or in the sunlit noon sector of a winter hemisphere, there is very little F region enhancement. Solar maximum winter conditions lie between these two extreme types of conditions. The polar cap E region enhancements are

Fig. 13. Variation of TEC, Σ_H and Σ_P across the prototype arc with a precipitating energy flux of $0.1 \text{ erg cm}^{-2} \text{ s}^{-1}$ and $5 \text{ erg cm}^{-2} \text{ s}^{-1}$. The relevant arc conditions are winter solar minimum, arc electric field equal to 40 mV/m , arc width equal to 200 km , and the characteristic energy of precipitating electrons is 0.5 keV .

relatively independent of the background ionospheric condition. This general E and F region difference can lead to significant ΣP and ΣH differences along an extended SA arc in cases where the solar terminator crosses the arc. Depending on season and UT when the SA arc is partly sunlit or under solstice conditions for SA arc structures which are conjugate in both hemisphere, these variations of ΣP , ΣH and F region density along the arc may have an important impact on the self-consistent arc electrodynamics.

Another parameter of consequence in this E and F region comparison is the cross arc drift. For the E region where chemical equilibrium dominates, convection is unimportant and the densities only depend upon the production and loss characteristics. However, for the F region where transport is significant, the density does depend on cross arc transport. In the extreme case of no cross arc transport, $N_m F_2$ will asymptotically approach a "steady state" value but TEC would increase to very large values. Comparison of these different observations would place strict limits on the degree of stagnation found in SA arcs. Measurements of TEC enhancements associated with SA arcs may be an important tool for diagnosing such arcs. If the flux and characteristic energy of such arcs are known, then the observed TEC enhancement sets a limit upon how much time the flux tube spends within the precipitation region of the arc. This then is useful in determining the degree of plasma cross flow (if any) associated with SA arcs. A parameter which is difficult to measure directly. Cross flow of the plasma can have basically two manifestations. The first which is explicitly modeled here is for the plasma flow to have a convection component across a stationary (with respect to magnetic coordinates) SA arc structure. The second is for the SA structure to move with respect to the background plasma. This is what most SA arcs do at one time or another, move in a dawnward or duskward direction (C. E. Valladares et al., submitted manuscript, 1993). Both methods have similar local effects upon the plasma but each implies a different magnetospheric topology. The first is merely a superposition of an arc electric field structure and a background convection electric field both fixed or varying with UT. The second implies either an arc structure moving relative to the background convection pattern or (if the arc structure is assumed to exist on an adionic line separating two convection cells) the overall convection pattern (and corresponding cell boundaries) are moving with respect to UT. The ability to definitively answer which mechanism produces cross flow is beyond the scope of this work.

What we have done is correlate an observed parameter, i.e., the Δ TEC enhancement with the modeled Δ TEC as a function of cross flow, characteristic energy, etc. In the case of the Δ TEC enhancement we generally reproduce the solar minimum results but are lower than the observed Δ TEC for solar maximum. This implies that for solar maximum, flux tubes must spend more time within the arc region to produce the observed Δ TEC enhancement. Otherwise, the flux must be increased or the characteristic energy decreased if the cross flow is the same for solar minimum and solar maximum.

5. SUMMARY

In general, we can summarize our results of the ionospheric modification associated with SA polar cap arcs as follows:

1. At low fluxes ($< 2 \text{ ergs cm}^{-2} \text{ s}^{-1}$) and low characteristic energies ($< 1 \text{ keV}$), SA polar cap arcs have the most pronounced

relative effect at F region altitudes in darkness for winter solar minimum conditions. The absolute enhancement in summer solar minimum and winter solar maximum is equivalent to that of winter solar minimum, but the higher ambient densities make the relative enhancement less.

2. The modeled TEC enhancements are comparable to observed enhancements and show a similar solar cycle dependence to the results of Basu et al. [1990].

3. The TEC enhancement associated with a SA arc may be used to indicate the degree of plasma cross flow across the arc.

4. For the prototype arc modeled here: (1) The largest F region enhancements increased with the arc electric field strength up to 40 mV/m. As the arc electric field increases above 40 mV/m, enhanced molecular production due to increased T_i decreases the F region enhancement both inside and then beyond the arc. (2) The lowest characteristic energies for the particle precipitation produce the largest F region enhancements and result in a $\Sigma H/\Sigma P$ value below 0.5. As energy increases, the F region enhancement decreases and the ratio of $\Sigma H/\Sigma P$ rises well above 1. (3) Arc width has little effect upon the variation of ΣH and ΣP across the arc. The F region enhancement for a particular flux and characteristic energy increases as arc width increases and saturates as the width becomes larger than 200 km.

5. As the flux increases for low characteristic energy precipitation, ΣP may increase faster than ΣH due to enhanced F region densities. This reduces the $\Sigma H/\Sigma P$ ratio below 0.5 with increasing flux.

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