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Vertical profiles of atmospheric electric parameters close to ground

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Abstract. The ion-aerosol balance equations have been solved for different mixing strengths and two types of ionization profile to get vertical profiles of atmospheric electric parameters close to the Earth's surface. The inclusion of surface radioactivity in the model causes the decrease in electric field to be more intense at lower levels than at higher levels, an increase in the asymptotic value of the field, and an increase in the space charge density gradient. When the mixing of atmosphere is very weak, a reverse electrode effect is observed under the condition of enhanced ionization due to trapped radon, with the decrease in ion densities above 1 m. However, with an increase in eddy diffusivity, the positive ion concentration decreases, and the negative ion concentration increases with increasing height above the diffusion layer. Further increase in eddy diffusivity causes the profiles to become almost similar to those for which the ionization is constant with height. Even with the inclusion of radon radioactivity, relatively higher diffusivity keeps the nature of the profile of the negative ions similar to that for the constant ionization case. On the contrary, there is a drastic change in the profile of positive ions because of the strong downward gradient of positive ions in the diffusion sublayer. The profile of positive ions is more sensitive to the radon radioactivity and that of negative ions to the strength of turbulence. Further, the asymptotic value of aerosol concentration is reached before that of small ions when mixing is very low. Our results are in reasonable agreement with the earlier theoretical and experimental studies.

1. Introduction

The distribution of atmospheric electric variables close to ground is governed by the phenomenon of the electrode effect. In the simplest case of a calm, aerosol-free atmosphere of uniform ionization, the fair weather field is responsible for the separation of ions; that is, it sweeps negative ions away from the surface. Consequently, a sheath of positive space charge is formed near the surface of the Earth. In this sheath the atmospheric electric field magnitude increases, but the electrical conductivity decreases by a factor of about 2 toward the ground. This simple phenomenon is known as the classical electrode effect. However, in the atmosphere, the phenomenon is generally more complicated because of the presence of the aerosol particles, nonuniform ionization, and turbulence. For example, the increased ionization rate at the surface causes changes in the net space charge distribution [*Hoppel*, 1967]. Further, the convective mixing of space charge in the normal turbulent atmosphere is very effective in dispersing the space charge layer, because mixing tries to smooth out gradients and maintain the homogeneous situation. An increase in the strength of turbulence normally increases the thickness of the electrode layer and decreases its intensity to the extent that the phenomenon becomes almost undetectable.

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Adkins [1959] has studied the effect in fields exceeding 500 V m^{-1} but not too high for corona to occur. His observations show that the classical electrode effect occurs under the conditions of strong field even when the complexities due to aerosols, nonuniform ionization, etc., exist. *Law* [1963] has found that the small-ion concentration profiles computed numerically by assuming the ion mobility, lifetime of ions, and electric field to be independent of altitude are consistent with the observed values of ion concentration. His experiments show that in fields weaker than 100 V m^{-1} both the positive and negative small-ion densities decrease with increasing height in the lowest 1 m over short grass. This decrease is more pronounced in nighttime than in daytime and can probably be explained in terms of the surface and trapped radioactivity under weak mixing conditions. *Law* [1963] has also observed that the space charge density at a height of about 50 cm changes from positive by day to negative at night. In a nonturbulent atmosphere he considers (1) a constant conduction current density with height, (2) normal downward electric field, and (3) downward gradient of conductivity and concludes that there are convection currents which are stronger in daytime and weaker in nighttime. On calm nights, *Crozier* [1965] has also observed the reverse electrode effect at his New Mexico site, which is destroyed by a wind as weak as 1 m s^{-1}.

Hoppel [1967] has solved the first-order steady state ion balance differential equations for cases which do not include turbulent diffusion of ions but include a difference in the mobilities of the negative and positive ions, a change in ionization with height, and an arbitrary number of condensation nuclei. His calculations show that under the conditions of enhanced ionization rate due to trapped radon, which decreases with height, the reverse electrode effect can occur. In his case, the asymptotic value of electric field becomes greater than the surface electric field. Further, in the presence of aerosols the thickness of the electrode layer decreases, and the effect of surface α emission becomes pronounced.

In the turbulent electrode layer, *Hoppel* [1969] has considered the profile of variable ionization but not the presence of aerosols. His results show that a weak mixing is responsible for trapping of radon products. When the mixing is strong, the space charge is mixed vertically, and the effect due to the increased ionization is reduced appreciably. From his model he finds that *Crozier*'s [1965] observations could be explained by reduction in radon trapping due to the increased turbulent mixing and that Crozier's and *Law*'s [1963] measurements are consistent and support each other.

Hoppel and Gathman [1971] have discussed the solutions for the turbulent electrode effect over the oceanic surface for various values of mixing parameter χ (for definition see equation (10)), assuming a constant rate of ionization with height. However, they have solved the equations for a single value of χ (χ = 12 m^2 s^{-1}) after the inclusion of aerosol concentration of 5 × 10^8 m^{-3}. In their solutions for turbulence with uniform ionization, both ion densities decrease toward the surface because of the turbulent and molecular diffusion there, and this decrease extends to greater heights with an increase in turbulence. In their model the continuity of current in the diffusion sublayer is maintained by downward diffusion current at the surface. Above this layer the space charge due to electrode effect is transported upward by convection current. An increase in turbulence increases the layer thickness, but the final asymptotic value of field reached is the same. Further, the presence of aerosols reduces the thickness of the electrode layer in the nonturbulent case but increases it in the turbulent case by increasing the electrical relaxation time.

Aspinall [1972] has concluded from his surface measurements that the current density at the ground is made up of the conduction and convection components with small difference in their magnitudes. He finds that the convection current varies in nearly perfect correlation with the diurnal variation of the space charge density measured at 80 cm. He observes the space charge to be positive with a maximum at night and a minimum in the afternoon. These results support the calculations of *Hoppel* [1969] and *Willett* [1978] that the space charge is transported down its gradient to the surface by turbulent diffusion.

Willett [1978] has shown that the conductivity profile in the electrode layer becomes independent of the conduction process under strong turbulent conditions. From a relationship between the surface wind stress and the thickness of the electrode layer, he suggests that for the strong turbulence conditions over land, the positive and negative ion density profiles become similar, and ion densities decrease toward zero at the surface. It follows that since the total conductivity must vanish at the surface, the total current there must be carried by the turbulent and molecular diffusion of space charge down its density gradient. A conductivity profile experiment conducted by *Willett* [1981] shows that both polar conductivities decrease toward the ground at least over the lowest meter. A surface current experiment conducted by *Willett* shows that the ratio of negative to positive conductivity near the surface increases toward unity with increasing wind speed. Moreover, it emphasizes the fact that part of the current at the surface is carried by the turbulent diffusion. A combined effect of the nonturbulent electrode effect and trapped radon radioactivity is the downward gradient of positive conductivity and the upward gradient of negative conductivity. *Hoppel* [1967] has shown that this layer is quite shallow.

Observations of *Kamra* [1982] show that the nighttime negative space charge density decreases and the daytime positive space charge density increases with height. The results are consistent with the view that a convection current comparable to the conduction current may flow at the lower levels.

Tuomi [1982] has solved the ion balance equations analytically for conditions, which are appropriate for the snow surface and compared his results of charge density and conductivity with the results of *Willett* [1978]. From his observations, he also obtains a relation between wind velocity and eddy diffusivity. The difference of positive and negative conductivity, which is proportional to the space charge density in his measurements, shows good agreement with his model results for the turbulent and nonturbulent cases provided that the air is stable near the ground and the positive conductivity is less than about 6 f S m^{-1} during fair weather.

Willett [1983] has developed a model for the land surface including the enhanced radioactivity in plant canopy and an appropriate number concentration of aerosols and assuming that any nonuniformity of ionization is neglected under the turbulent conditions. He concludes that if the small-ion concentration is assumed to be zero at the ground, the model results may give significant overestimates. *Willett* [1985] has shown that there is a significant enhancement of surface radioactivity under typical continental conditions and that these enhancement factors vary from about 2 to 30 for different land conditions.

Knudsen et al. [1989] have measured the space charge and conductivity over 10-30 cm thick snow-covered ground having a 5-10 mm thick layer of ice. They consider the aerosol concentration typical of Arctic or oceanic region and conclude that it is possible to get profiles experimentally that are in good agreement with the classical electrode effect. They find good agreement between *Tuomi*'s [1982] model and their observations.

Israelsson et al. [1993] have measured the conductivity in fair weather with no clouds, no snow on the ground, wind of about 3.5 m s^{-1}, and low radioactive emanation from the ground and compared their results with those of *Willett* [1978]. The experimental results are in good agreement with the hypothesis of a turbulent electrode effect in the limit of strong turbulent mixing. The agreement confirms the relation between surface wind, electrical conductivity, and thickness of the electrode layer. In these conductivity profiles over the bare ground, the conductivity increases with height while only the negative conductivity shows a strong height dependence over the ice [*Ruhnke,* 1962].

It is evident from the above that while previous studies have presented rigorous numerical solutions to the steady state ion balance equations, including the effects of turbulence, charged aerosols, and ground radioactivity, none has systematically included the effects of all three. In this paper, we solve the ion-aerosol balance equations in this more general case. We consider a gradual transition of the electrode effect and explain the behavior of atmospheric electric parameters close to ground when the ionization is constant or varying with height. The results of this paper are important to understand the case over land, where the ground radioactivity plays an important role.

2. Model

Most of the equations in this section are from *Hoppel and Gathman* [1971]. The model is based on the usual steady state ion balance equations, which describe the dependence of atmospheric electric quantities on height z, assuming horizontal homogeneity. The variables represent their mean values averaged over the time periods which are long compared to the largest-scale eddies found in atmosphere and during the periods when steady state turbulence applies.

$$\frac{dJ_1}{dz} = q - \alpha n_1 n_2 - \beta_0 n_1 N_0 - \beta_1 n_1 N_2, \quad (1)$$

$$\frac{dJ_2}{dz} = q - \alpha n_1 n_2 - \beta_0 n_2 N_0 - \beta_1 n_2 N_1, \quad (2)$$

$$\nabla \cdot E = \frac{e(n_1 - n_2 + N_1 - N_2)}{\varepsilon_0}, \quad (3)$$

$$\frac{dF_1}{dz} = \beta_0 n_1 N_0 - \beta_1 n_2 N_1, \quad (4)$$

$$\frac{dF_2}{dz} = \beta_0 n_2 N_0 - \beta_1 n_1 N_2, \quad (5)$$

where J_1 and J_2 are the ion fluxes due to positive and negative ions, respectively; F_1 and F_2 are the aerosol fluxes due to positive and negative aerosols, respectively; n_1 and n_2 are the number concentrations of positive and negative ions, N_0, N_1 and N_2 are the number concentrations of the uncharged, positively charged, and negatively charged aerosols; E is the electric field; and e is the elementary charge. Coefficient α is the recombination coefficient between small ions, β_0 is the attachment coefficient between small ions and uncharged aerosols, and β_1 is the attachment coefficient between small ions and oppositely charged aerosols.

The fluxes of positive and negative ions and of aerosols are given by

$$J_1 = kEn_1 - K\frac{dn_1}{dz}, \quad (6)$$

$$J_2 = -kEn_2 - K\frac{dn_2}{dz}, \quad (7)$$

$$F_1 = -\tau\frac{dN_1}{dz}, \quad (8)$$

$$F_2 = -\tau\frac{dN_2}{dz}, \quad (9)$$

where K is the eddy diffusivity for small ions and τ is the eddy diffusivity for aerosols. The profiles of eddy diffusivities K and τ are given by *Hoppel and Gathman* [1971] as

$$K(z) = \frac{(\chi z + \gamma)}{z + 100}, \quad (10)$$

$$\tau(z) = \frac{\chi z}{z + 100}, \quad (11)$$

where χ is called the mixing parameter, i.e., the asymptotic value of the eddy diffusivity for z tending to infinity. Constant γ is the measure of ionic diffusion, which is important in the microlayer very near the surface, and k is the mobility of small ions, which is assumed to be the same for both the ion species. Mobility of large ions is neglected. Following *Hoppel and Gathman* [1971], we take
γ = 5 × 10^{-4} $m^2 s^{-1}$, k = 1.2 × 10^{-4} $m^2 V^{-1} s^{-1}$, e = 1.6 × 10^{-19} C, α = 1.4 × 10^{-12} $m^3 s^{-1}$, β_0 = 1.4 × 10^{-12} $m^3 s^{-1}$ and β_1 = 4 × 10^{-12} $m^3 s^{-1}$.

Following *Hoppel* [1967], the ionization profile is assumed as

$$q(z) = \left[7\times10^6 + Q_1 e^{-2.362 z}\times10^6\right] \mathrm{m^{-3}s^{-1}}, \quad (12)$$

where the first term in the brackets represents the ionization due to γ radiation and cosmic radiation. The second term represents the ionization due to trapped radon gas when Q_1 = 80 and only due to β radiation when Q_1 = 4.8. We do not consider here the dispersion of radon as a function of turbulence because the value of Q_1 used here for the radon case is the average value between those for convective conditions and stable conditions [*Hoppel et al.*, 1986]. The inclusion of the effect of such turbulence-induced dispersion of radon in the ionization profile would certainly give more realistic.

Equations (1) to (5) are solved numerically by the fourth-order Runge Kutta method for obtaining the profiles of electric field, ion concentrations, and aerosol concentrations with proper boundary conditions such that the asymptotic value for each variable is attained. The asymptotic values of ion concentrations $n(\infty)$ and of charged aerosols $N(\infty)$ of both polarities can be found from (1), (2), (4), and (5) as given below:

$$n_1(\infty) = n_2(\infty) = n(\infty) = \frac{-bZ + \sqrt{(bZ)^2 + 4\alpha q(\infty)}}{2\alpha}, \quad (13)$$

$$N_1(\infty) = N_2(\infty) = N(\infty) = \frac{\beta_0 Z}{2\beta_0 + \beta_1}, \quad (14)$$

where b = 2 $\beta_0 \beta_1$ / (2 β_0+ β_1) and $Z = N_0 + N_1 + N_2$ is the total number of aerosols.

The total current density j is constant with height and is given as

$$\frac{j}{e} = kE(n_1 + n_2) - K(z)\left\{\frac{dn_1}{dz} - \frac{dn_2}{dz}\right\} - \tau(z)\left\{\frac{dN_1}{dz} - \frac{dN_2}{dz}\right\}. \quad (15)$$

The first term on the right-hand side of (15) is due to the conduction of small ions, the second term is due to the convection of small ions, and the third term is due to the convection of charged aerosols.

Now, as discussed by *Hoppel and Gathman* [1971], ions are annihilated at the surface. So, $n_1(0) = 0$ and $n_2(0) = 0$. Further, since $\tau(0) = 0$, there is no need to consider the source term for aerosols. On the other hand, at $z = 0$, $K(0)$ is not 0, and the continuity of current at the surface is maintained through the diffusion of space charge due to small ions. Also, from (4) and (8),

$$\frac{dF_1}{dz} = -\tau(z)\frac{d^2N_1}{dz^2} - \frac{d\tau}{dz}\frac{dN_1}{dz} = \beta_0 N_0 n_1 - \beta_1 N_1 n_2 . \quad (16)$$

Similarly, from (5) and (9),

$$\frac{dF_2}{dz} = -\tau(z)\frac{d^2N_2}{dz^2} - \frac{d\tau}{dz}\frac{dN_2}{dz} = \beta_0 N_0 n_2 - \beta_1 N_2 n_1 . \quad (17)$$

At $z = 0$ it yields

$$\left(\frac{dN_1}{dz}\right)_{z=0} = 0 . \quad (18)$$

Similarly,

$$\left(\frac{dN_2}{dz}\right)_{z=0} = 0 . \quad (19)$$

Now, at the surface,

$$\frac{j}{e} = -K(0)\left\{\frac{dn_1}{dz} - \frac{dn_2}{dz}\right\}_0 . \quad (20)$$

The same current density at infinity is given as

$$\frac{j}{e} = kE(\infty)[n_1(\infty) + n_2(\infty)] . \quad (21)$$

Equating (20) to (21), and assuming $n_1(\infty) = n_2(\infty) = n(\infty)$, we get

$$E(\infty) = \frac{-K(0)}{2kn(\infty)}\left\{\frac{dn_1}{dz} - \frac{dn_2}{dz}\right\}_0 . \quad (22)$$

There are now four unknown boundary conditions at $z = 0$, namely, $N_1(0)$, $N_2(0)$, $(dn_1/dz)_0$, and $(dn_2/dz)_0$, which are to be chosen to satisfy the asymptotic boundary conditions given by (13), (14), and (22).

In our calculations we study the variability of profiles when $Z = 5 \times 10^8$ m^{-3} and 5×10^9 m^{-3}, $Q_1 = 4.8$ and 80, and $E(0) =$ 50, 100, and 200 V m^{-1} and consider the cases of nearly stable and unstable atmosphere for different values of χ.

3. Results and Discussion

The experiments of *Crozier and Biles* [1966] and calculations of *Hoppel* [1967] show that in nonturbulent stable conditions, radon is trapped at lower levels when wind speeds are less than 1 m s^{-1} and it causes anomalous ionization and the reverse electrode effect. In our calculations we start with nearly nonturbulent conditions characterized by an eddy diffusivity $K(z)$ at 1 m of approximately 0.01 m^2 s^{-1} (χ = 1 m^2 s^{-1}), which corresponds to an air velocity of approximately 0.5 m s^{-1} [*Tuomi*, 1982]. Under such conditions, radon trapping is effective, and we can study the transition of the electrode effect from nearly nonturbulent to turbulent conditions. Figures 1a, 1b, and 1c show the vertical profiles of the electric field, small ion concentration, and charged aerosol concentrations, respectively.

For the case of very low turbulence the conduction of ions under the fair weather electric field drives negative ions upward out of the region of high ionization, leading to an excess of negative ions in the region above about 1 m. The downward conductive flow of positive ions leads to a region of excess positive ions below about 1 m. Since the ion concentrations at the surface are zero, this leads to an extremely high gradient in the positive ion concentration very close to the ground. Turbulent diffusion acts to destroy gradients, so that as the turbulence is increased, the regions with the greatest gradients are affected most and all gradients are spread out over a greater height, causing the electrode effect to extend to higher altitudes. It is clear from Figure 1b that as the turbulence increases, the gradients are reduced with the greatest effect on the positive ions, which had the largest initial gradient. As the strength of turbulence increases, the upward mixing of the positive space charge slowly destroys the region of negative charge. Since positive charge decreases the strength of negative electric field, the asymptotic value of the electric field decreases and is attained at higher altitudes. In support of *Hoppel* [1969] and *Hoppel and Gathman* [1971], Figure 1 shows that just like surface radioactivity, the increase in stability also contributes in reducing the thickness of the electrode layer.

In Table 1 we compare our case, where the ionization decreases with height, with that of *Hoppel and Gathman* [1971], where the ionization is assumed as constant with height. In our case the field at 10 m is smaller than the field attained in their solutions at 10 m. The decrease in field is more intense at lower levels than at higher levels. When the ionization is constant with height, the asymptotic value of field is the same in the presence or absence of aerosols, and the surface value of the small-ion space charge density gradient decreases in the presence of aerosols. However, after the inclusion of surface radioactivity the decrease in field

Table 1. Values of Electric Field at Different Altitudes in the Absence and Presence of Radioactivity ($Q_1 = 80$) When $\chi = 12$ m^2 s^{-1}

Altitude, m	Electric Field, V m^{-1}	
	Without Ra $q = 1.2 \times 10^6$ m^{-3} s^{-1}	With Ra $Q_1 = 80$
10	83	77
15	79	73
20	72	72
60	53	68

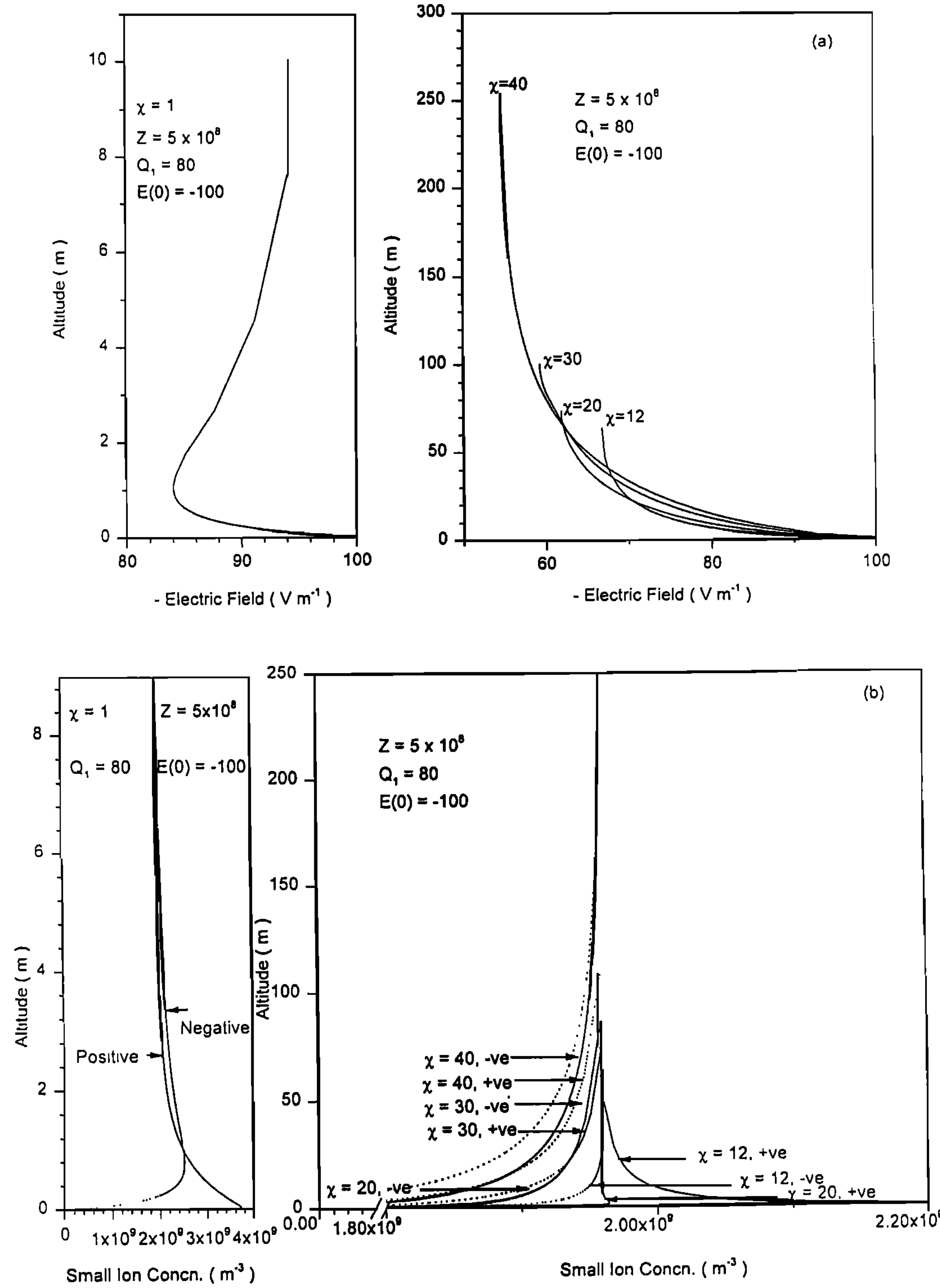


Figure 1. Vertical profiles of (a) electric field, (b) small-ion concentration, and (c) charged aerosol concentration when $\chi = 1$, 12, 20, 30, and 40 $m^2\ s^{-1}$, $Q_1 = 80$, $Z = 5 \times 10^8\ m^{-1}$, and $E(0) = -100\ V\ m^{-1}$.

with height is smaller in the presence of aerosols, the space charge density gradient at ground increases in the presence of aerosols, and we get higher values of the asymptotic electric field and total current. The ion concentration near ground increases, and the gradient of space charge density becomes a function of the ion concentrations. Unlike the nonturbulent case of *Hoppel* [1967], where $E(\infty)$ exceeds $E(0)$, $E(\infty)$ remains smaller than $E(0)$ in our case. However, the intensity of electrode effect is much higher when χ is low. The situation differs substantially from that of *Hoppel* [1967] when diffusivity is included in our case. Here the diffusivity acts to remove the positive ions. Even a low diffusivity is sufficient for lifting up the positive and negative space charge regions.

Table 2 displays the asymptotic values of electric field for the nonturbulent and turbulent cases and further clarifies the

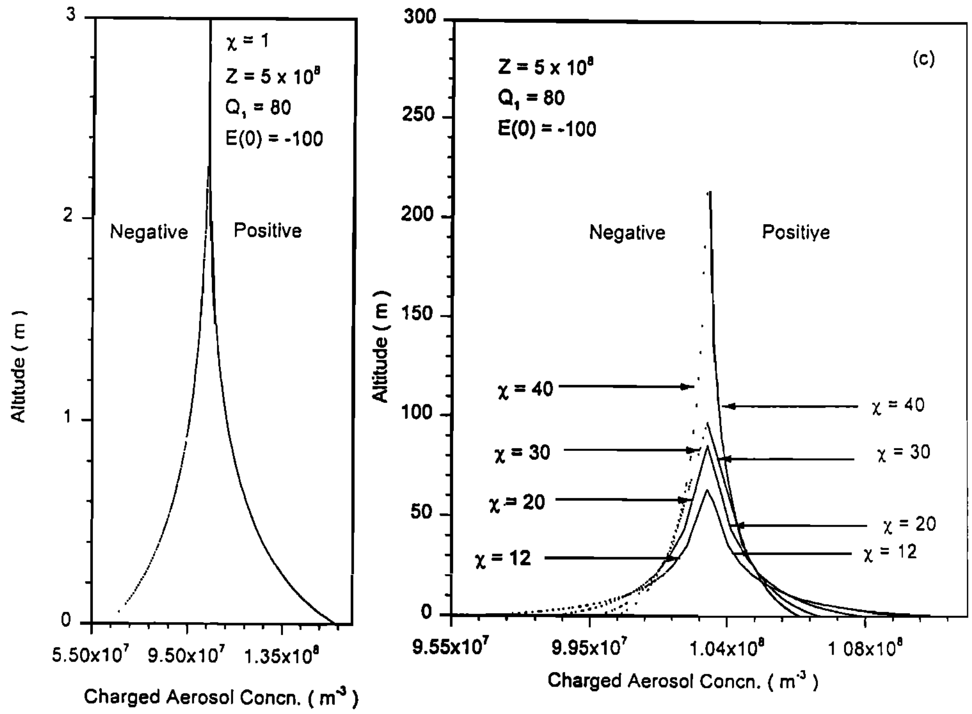


Figure 1. (continued)

role of χ. In the nonturbulent case of *Hoppel* [1967] the concentrations of small ions of opposite polarity become equal quite rapidly, and the asymptotic field is attained at about 5 m. This height is lower in the presence of aerosol particles [*Hoppel et al.*, 1986]. However, when χ = 1 m² s⁻¹ in our case, the small-ion concentrations become equal relatively slowly, and the asymptotic conditions are attained at a height of about 10 m. Further increase in χ makes this rate still slower, and the asymptotic conditions are attained at still higher altitudes.

In the turbulent cases of *Hoppel* [1969] and *Hoppel and Gathman* [1971] the surface radioactivity lowers the electrode effect, and the presence of aerosols extends the electrode effect to greater heights. However, when the effects of both surface radioactivity and aerosols are considered together in our case, the vertical extension of the electrode effect decreases in the turbulent atmosphere. Moreover, the thickness of the electrode layer increases with increasing χ irrespective of whether an ionization is constant or variable with height. It appears from Table 2 that for χ > 12 m² s⁻¹ the electric field profile for an ionization variable with height may approach the profile for an ionization constant with height. Thus an increasing turbulence nullifies the effect due to the surface radioactivity.

Following the scale analysis procedure of *Willett* [1978], the thickness scale of the turbulent electrode layer is

$$L_T = (2\varepsilon_0 \chi / \lambda)^{1/2} . \qquad (23)$$

Here the conductivity λ is

$$\lambda = \lambda_\infty = 2en_\infty k , \qquad (24)$$

Table 2. Asymptotic Values of Electric Field and Total Current Density for the Nonturbulent and Turbulent Cases

Cases	χ, $m^2\,s^{-1}$	Z, m^{-3}	E, $V\,m^{-1}$	J, $pA\,m^{-2}$
Nonturbulent (variable ionization with height, Q_1 = 80)	-	-	-102	-10.18
Turbulent	1	5×10^8	-95	-7.15
(variable ionization with height, Q_1 = 80)	12	5×10^8	-65	-4.89
Turbulent (constant ionization with height, $q = 1.2 \times 10^6\,m^{-3}s^{-1}$)	12	5×10^8	-48	-3.61

where λ_∞ is the asymptotic conductivity. The thickness values of the electrode layer calculated from (23) agree well with those shown in Figure 1.

For the positive ion profiles in Figure 1b the effect of trapped radon activity is appreciable up to about χ = 20 m^2 s^{-1} (i.e., $K(z) \approx 0.2$ m^2 s^{-1} at 1 m). For higher values of χ the profiles become similar to those for constant ionization [*Hoppel and Gathman,* 1971]. However, this effect due to radioactivity is not apparent in the case of negative ions except for χ = 1 m^2 s^{-1}.

In Figure 1c the ground level concentrations of positive aerosols decrease, and those of negative aerosols increase with the increase in turbulence. This may be because of (1) the higher concentration of the positive ions and, consequently, the higher probability of the formation of positively charged aerosols than negatively charged aerosols close to the ground and (2) the downward turbulent diffusion of negative small ions, which increases the capture of negative ions by aerosols with increasing turbulence.

The region of positive space charge in Figure 1b, where the negative small-ion concentration increases and the positive small-ion concentration decreases with height, is confined to relatively lower levels when χ = 1 m^2 s^{-1} and spreads to higher levels when χ = 12 m^2 s^{-1} or higher. Assuming that only small ions contribute to the conductivity in this region, we can write

$$\lambda^- = \lambda^+ - \rho k, \tag{25}$$

where $\lambda^- = e\, n_2\, k$ and $\lambda^+ = e\, n_1\, k$ are the negative and positive polar conductivity, respectively, and ρ is the space charge density. Since λ^- increases with height, the rate of decrease in small-ion space charge density, $d\rho/dz$, must be greater than the rate of decrease in positive ion density, dn_1/dz, throughout this regime. Also, since the total conductivity decreases with height in this region, the rate of decrease of λ^+ (or dn_1/dz) must be higher than the rate of increase of λ^- (or dn_2/dz). Therefore, when we include radon radioactivity, $d\rho/dz > edn_1/dz > edn_2/dz$; that is, the variation of space charge density with height is larger than that of the individual ion densities. Such a general inference cannot be drawn when the ionization is assumed constant with height since both polar conductivities keep increasing with height. Therefore we conclude that the variation in small ion positive space charge density depends upon the surface radioactivity and, as previously shown, the region in which this variation occurs is determined by χ.

3.1. Variability of the Profiles With Aerosol Concentration, Surface Electric Field, and Surface Radioactivity

Willett [1983] has discussed the propriety of boundary conditions used by *Hoppel and Gathman* [1971] and *Willett* [1978] and also in the present calculations for the turbulent electrode effect over the land surface. However, the purpose of the present calculations is to elucidate the interactions between turbulent mixing, nonuniform ionization, and aerosol attachment in the electrode layer. Therefore the emphasis in the following discussion is only on the intercomparison of the effects of these parameters on the behavior of various profiles.

Figures 2a, 2b, and 2c show the profiles of electric field, small-ion concentration, and charged aerosol concentration, respectively, for $Z = 5 \times 10^8$ and 5×10^9 m^{-3} when χ = 12 and 20 m^2 s^{-1} and $Q_1 = 80$. The figures show that with an increase in aerosol concentration the thickness of the convection current layer increases, and the thickness of the electrode layer decreases since the lifetime of ions decreases in the presence of aerosols [*Willett*, 1983]. The asymptotic value of the electric field attained is much larger when $Z = 5 \times 10^9$ m^{-3} than when $Z = 5 \times 10^8$ m^{-3}. Also, the small-ion concentrations

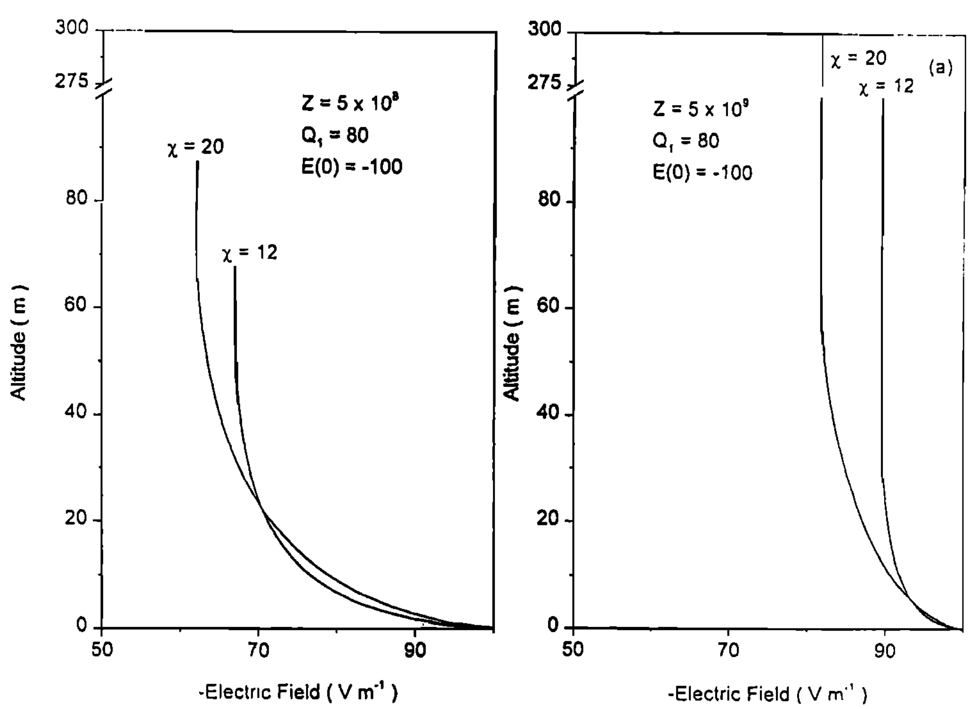


Figure 2. Vertical profiles of (a) electric field, (b) small-ion concentration, and (c) charged aerosol concentration when χ = 12 and 20 m^2 s^{-1}, $Q_1 = 80$, $Z = 5 \times 10^8$ and 5×10^9 m^{-3} and $E(0) = -100$ V m^{-1}.

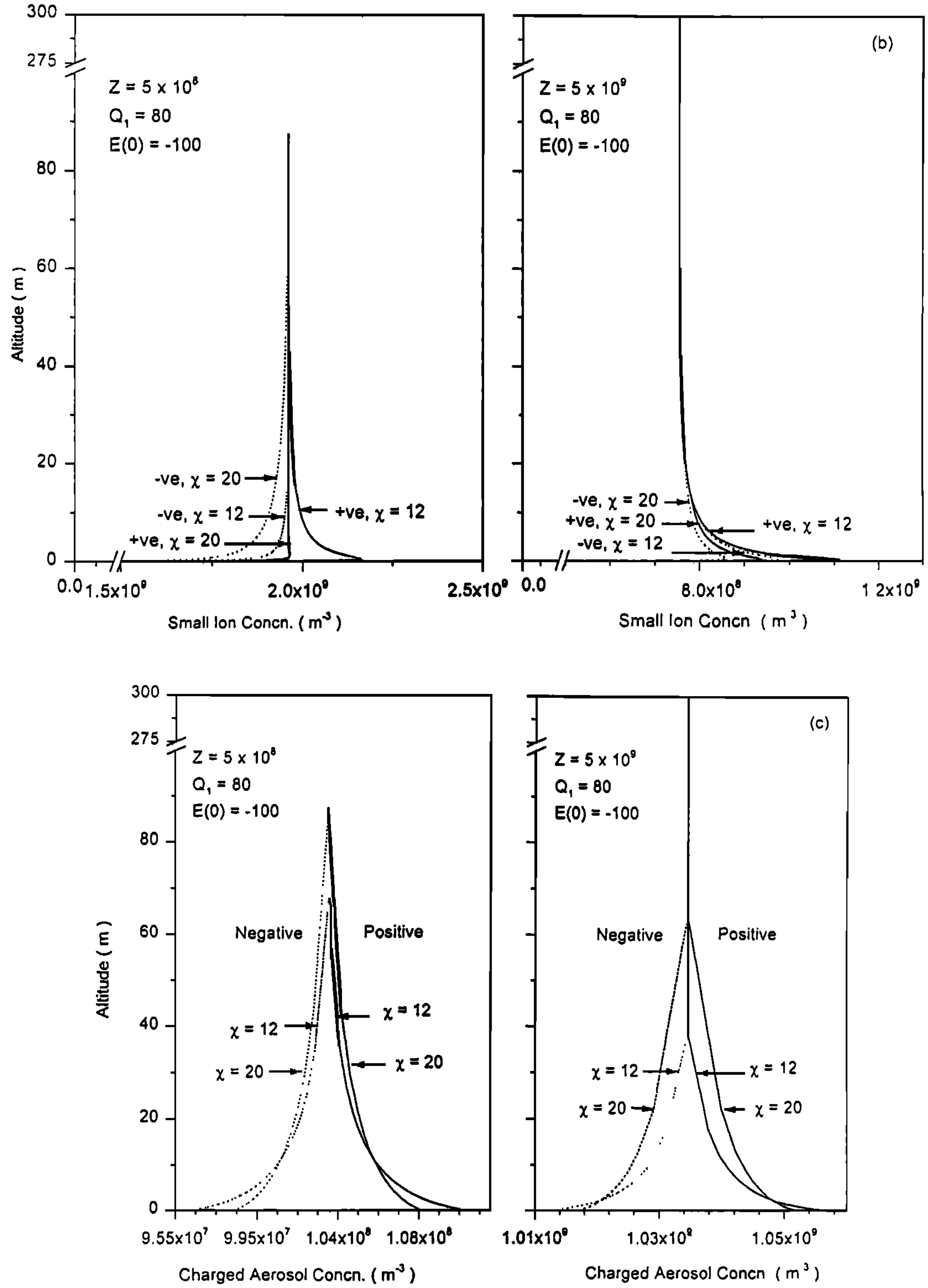


Figure 2. (continued

are higher and aerosol concentrations are lower at all levels when $Z = 5 \times 10^8$ m^{-3} than when $Z = 5 \times 10^9$ m^{-3}.

The profiles of charged aerosol concentrations for $E(0) = -50$, -100, and -200 V m^{-1} in Figure 3 show an interesting feature for a practical use of this work. Here, the large-ion space charge at the ground has a direct linear relationship with the surface electric field. This is so even when $\chi = 40$ m^2 s^{-1}, where the effect of trapped radon activity is almost absent. Moreover, the asymptotic values are reached at lower altitudes for the smaller surface electric fields.

Figure 4 shows the profiles for $Q_l = 4.8$ when χ varies from 12 to 40 m^2 s^{-1}. The asymptotic values are reached at higher levels than in Figure 1, where $Q_l = 80$. Moreover, the large-ion space charge systematically increases with the decrease in χ but the relative variation of the charged aerosols with height is very small. There is not much difference in the curves for

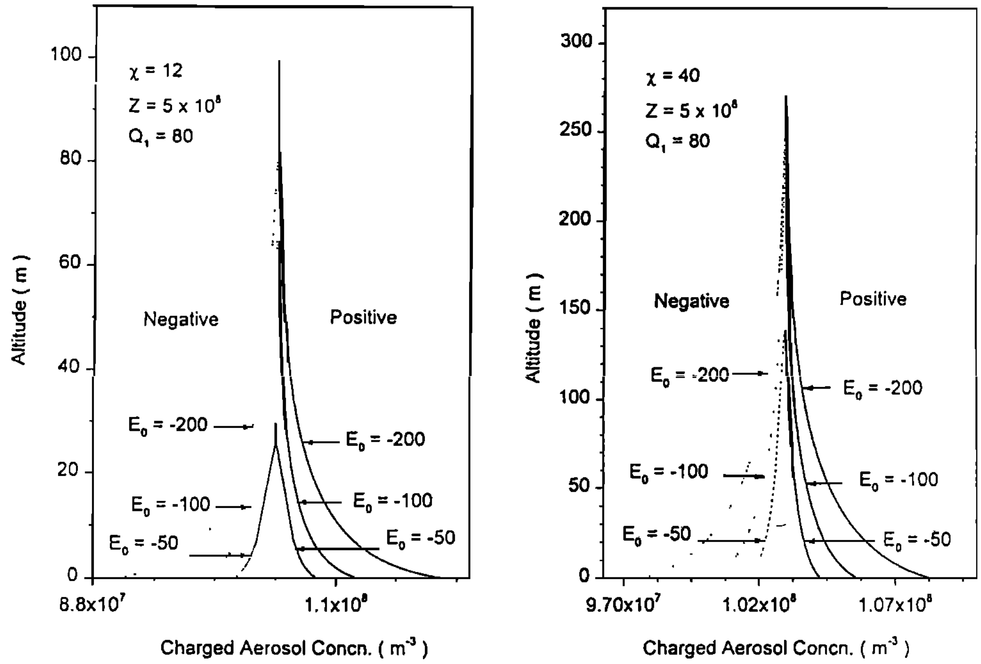


Figure 3. Vertical profiles of charged aerosol concentration when χ = 12 and 40 $m^2\ s^{-1}$, Q_1 = 80, $Z = 5 \times 10^8\ m^{-3}$, and $E(0)$ = -50, -100 and –200 V m^{-1}.

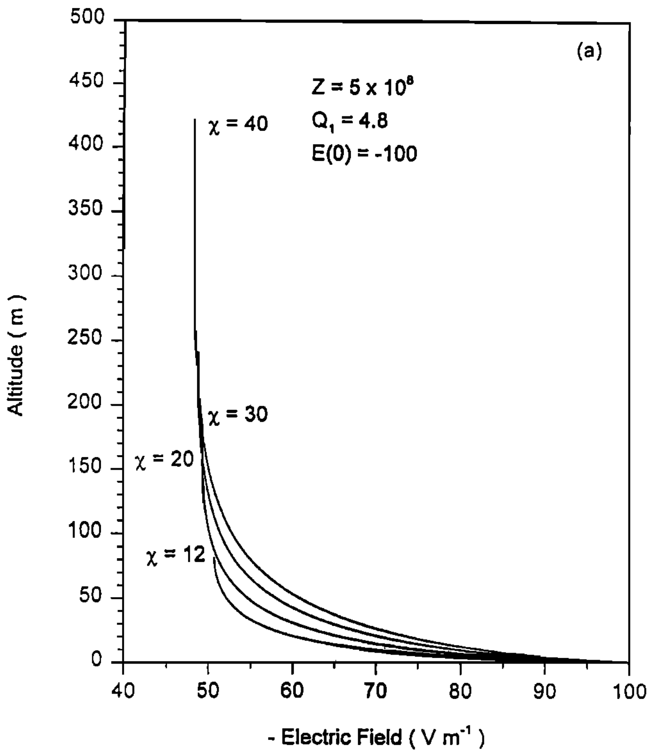


Figure 4. Vertical profiles of (a) electric field (b) small-ion concentration, and (c) charged aerosol concentration when χ = 12, 20, 30, and 40 $m^2\ s^{-1}$, $Q^1 = 4.8$, $Z = 5 \times 10^8\ m^{-3}$ and $E(0)$ = -100 V m^{-1}.

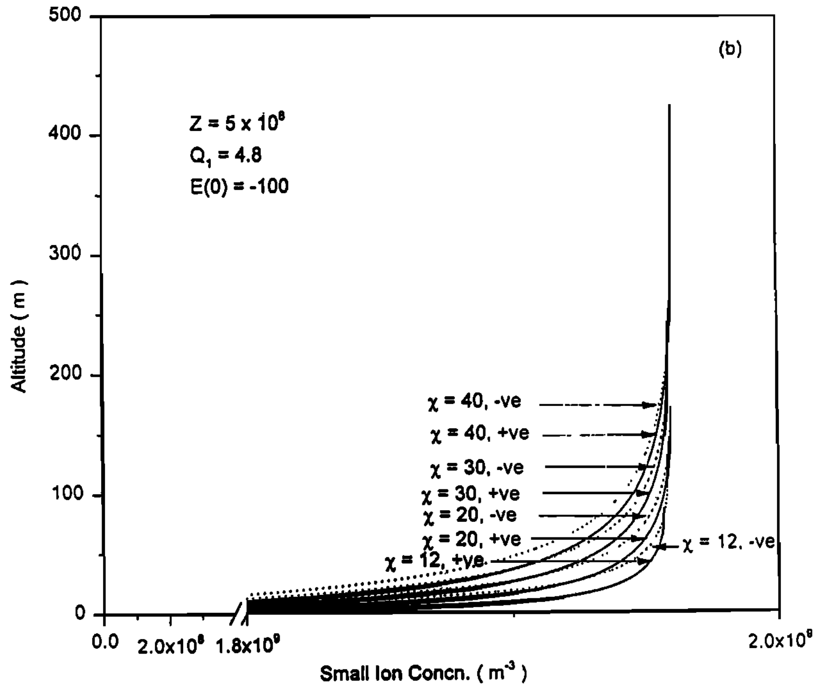
Q_1 = 80 and 4.8 for χ = 40 $m^2\ s^{-1}$ (Figures 1 and 4). Thus, in the limit of strong turbulent mixing, the effect of radon is just like the effect due to β radiation.

3.2. Comparison With Other Studies

Willett [1978] and *Tuomi* [1982] have calculated the values of conductivity and space charge and plotted their results in terms of the dimensionless quantities: electrode layer scale $L = (2\varepsilon_0 \chi / \lambda_\infty)^{1/2}$, dimensionless height $z_i = z/L$, dimensionless space charge density $\rho_l = (L\, n_\infty\, e / \varepsilon_0\, E_\infty).[(n_1 / n_\infty) - (n_2 / n_\infty)]$ and dmensionless conductivity $\lambda_i = (1/2)[(n_1 / n_\infty) + (n_2 / n_\infty)]$. Our results for K = 0.118 and 0.396 $m^2\ s^{-1}$ at 1 m are compared with their results in Figure 5. Because of the inclusion of surface radioactivity our curves are somewhat steeper and tend toward the curves of constant ionization at higher values of the mixing parameter. The major difference between the results of *Willett* [1978] and *Tuomi* [1982] and our results is that the asymptotic values are reached at greater heights in their curves than in ours since the surface electric field in their case is twice that of ours.

Our profiles of space charge density in Figure 6 are in good agreement with the measured profiles of *Knudsen et al.* [1989] when friction velocity $u^* = 0.1\ m\ s^{-1}$, $q = 0.8 \times 10^6\ m^{-3}\ s^{-1}$, $k = 1.25 \times 10^{-4}\ m^2\ V^{-1}\ s^{-1}$, $E(0)$ = -106 V m^{-1} and λ = 27.8 f S m^{-1}. The major difference between our results and Knudsen et al.'s measurements is only in the value of $q(z)$. As expected, the effect of surface radioactivity decreases with the increase in eddy diffusivity.

In Figure 7 we compare our conductivity profiles with those measured by *Israelsson et al.* [1993] for λ_∞ = 30 f S



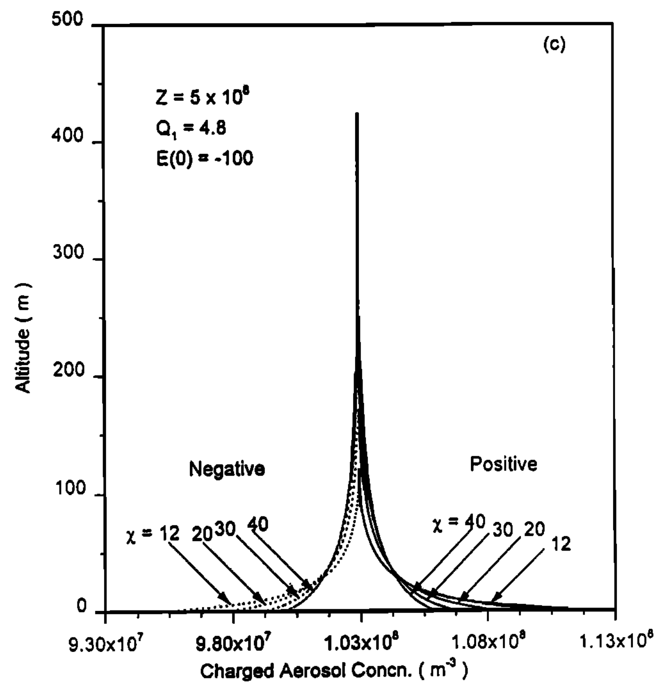


Figure 4. (continued)

m^{-1}, $u_* = 0.19$ m s^{-1}, roughness height $z_0 = 0.001$ m, and $L = 45$ m. The measurements are made under low radioactive emanations and the average conductivity measured between 0.05 m and 1.55 m is about 73% of λ_∞. The wind speed is <6.2 m s^{-1} at 10 m and $K = 0.08$ m^2 s^{-1}. For our calculated results for $K = 0.118$ m^2 s^{-1} at 1 m ($\chi = 12$ m^2 s^{-1}), the average conductivity between 0.05 m and 1.55 m is 74% of λ_∞. The wind speed derived from *Tuomi's* [1982] formula is 5.9 m s^{-1} when $K = 0.118$ m^2 s^{-1} and will be higher when $K = 0.396$ m^2 s^{-1}. Above 5 cm the conductivity decreases with increasing wind speed (i.e., for higher value of χ), which is also in accordance with their measurements.

4. Determination of Eddy Diffusivity

In steady state turbulent conditions the small-ion space charge density gradient at ground is the main factor which alters the distribution of atmospheric electricity variables. *Hoppel and Gathman* [1971] suggested that the value of χ over the ocean surface can be calculated with the help of the

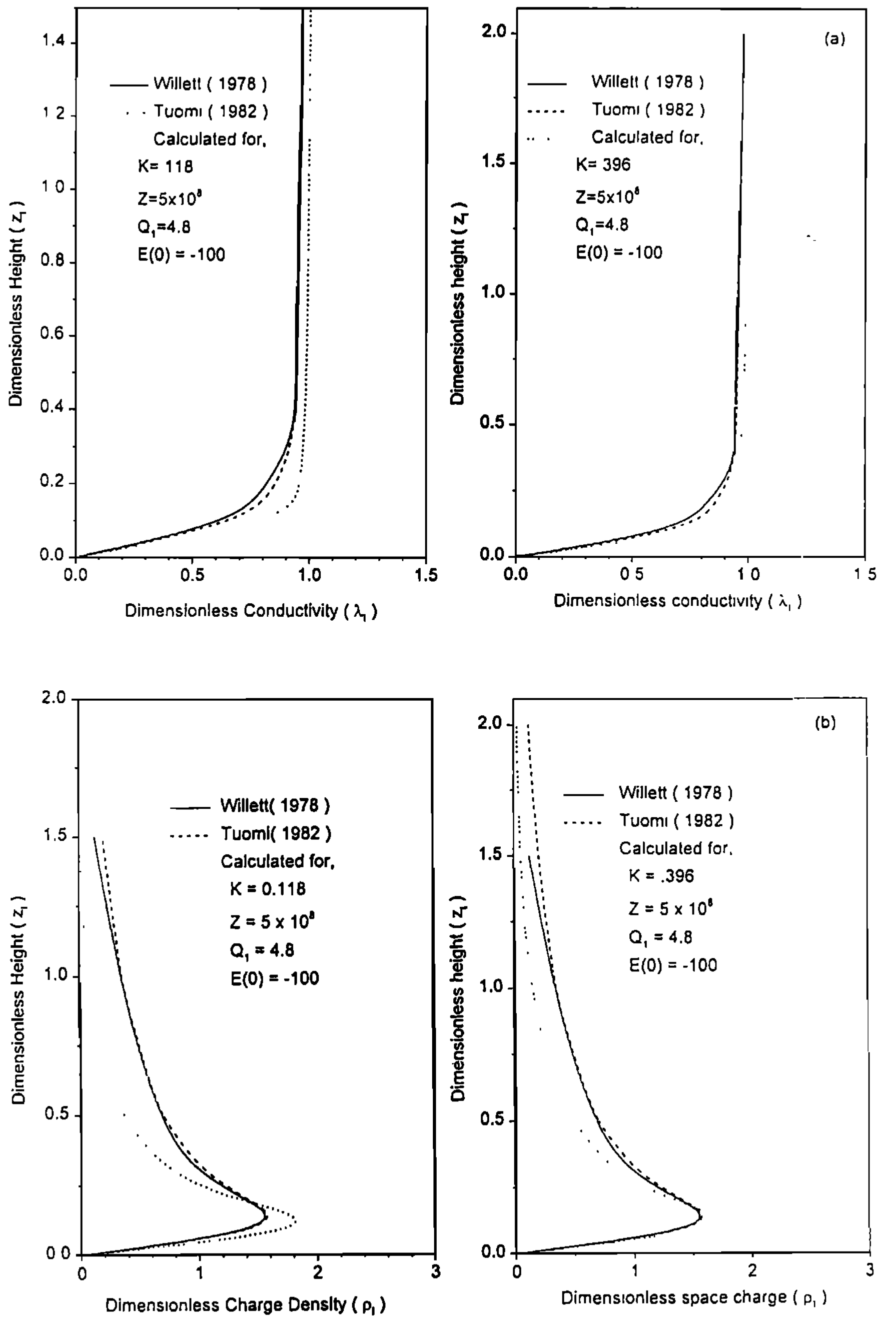


Figure 5. Comparison of calculated results of variation of (a) dimensionless conductivity and (b) dimensionless space charge density with dimensionless height when $\chi = 12$ and 40 $m^2\ s^{-1}$ ($K(z) = 0.118$, 0.396 $m^2\ s^{-1}$), $Q_1 = 4.8$, $E(0) = -100$ V m^{-1}, and $Z = 5 \times 10^8$ m^{-3} with previous theoretical results by *Willett* [1978] and *Tuomi* [1982].

surface level space charge density gradient for the known values of surface electric field and aerosol concentration. However, because of the inclusion of surface radioactivity in our case the asymptotic field becomes a combined function of χ and the space charge density gradient at ground. Since ions are annihilated at the surface, ion densities increase from the ground to some distance upward which varies with the strength of turbulence [*Hoppel and Gathman*, 1971]. When the radon radioactivity is included in our case, the positive ion density first increases but then decreases with height. The height up to which the positive ion density increases is dependent on χ (Figure 1). Suppose the maximum in positive ion density occurs at a height L_1 for $\chi = \chi_1$ and at L_2 for $\chi = \chi_2$. Then with the scale analysis procedure described by *Willett* [1978] when the scales of L_1 and L_2 are much less than the corresponding electrode layer scales, we can write

$$\frac{\lambda_1^+}{\lambda_2^+}\frac{L_1}{L_2} = \frac{\chi_1}{\chi_2}. \tag{26}$$

Therefore the product of the maximum value of positive conductivity and the height at which this maximum occurs can become a function of χ when the surface radioactivity is included. Since the surface radioactivity first causes an increase and then a decrease in λ^+ with increasing height, the

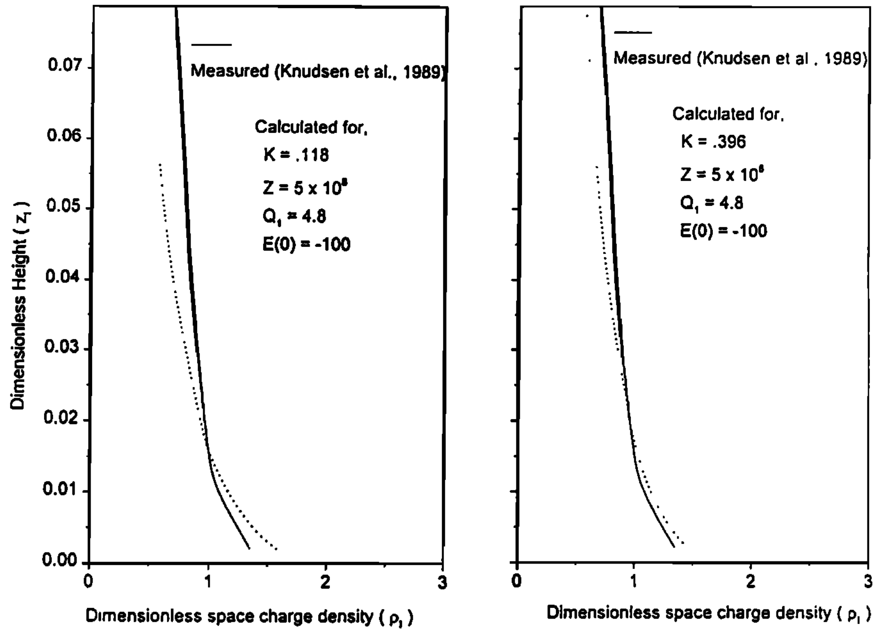


Figure 6. Comparison of calculated results when χ = 12, 40 $m^2\ s^{-1}$($K(z)$ = 0.118, 0.396 $m^2\ s^{-1}$), Q_1 = 4.8, $E(0)$ = -100 V m^{-1}, and Z = 5 x 10^8 m^{-3} with experimental results by *Knudsen et al.* [1989] for the variation of dimensionless space charge density with dimensionless height.

height at which the maximum in λ^+ occurs becomes a function of the turbulence, provided that other conditions are the same.

Large-ion space charge depends on four variables, namely, the aerosol concentration, the mixing parameter χ, the surface electric field, and the ionization rate. Our results do not show any appreciable change in the surface value of the large-ion space charge with the ionization rate. Further, the large-ion space charge at ground varies almost linearly with the surface electric field for a fixed value of χ. Therefore it is suggested that the eddy diffusivity can be determined from the surface measurements of electric field and large-ion space charge for the fixed values of the total aerosol concentration.

5. Conclusions

(1) The stability of the lower atmosphere is dominant in determining the behavior of all atmospheric electric variables close to the Earth's surface. For low values of χ the surface radioactivity plays an important role. (2) The mixing parameter and the surface radioactivity are important for the

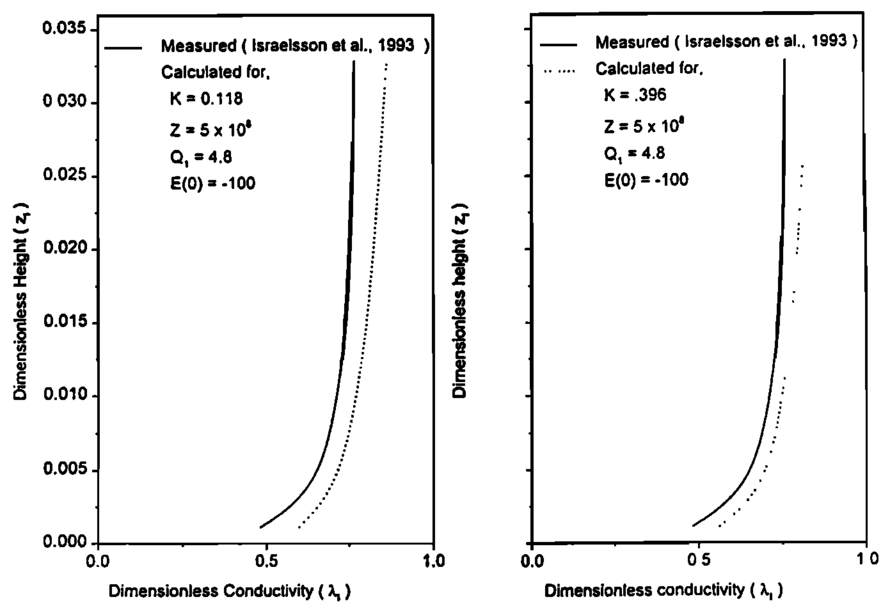


Figure 7. Comparison of calculated results when χ = 12, 40 $m^2\ s^{-1}$ ($K(z)$ = 0.118, 0.396 $m^2\ s^{-1}$), Q_1 = 4.8, $E(0)$ = -100 V m^{-1}, and Z = 5 x 10^8 m^{-3} with the experimental results by *Israelsson et al.* [1993] for the variation of dimensionless conductivity with dimensionless height.

occurrence of negative space charge at lower levels under the reverse electrode effect, while the presence of aerosols is less significant. (3) The concentrations of charged aerosols at ground level are dependent on the mixing parameter χ. When diffusivity is high, the large-ion space charge spreads to higher levels in the mixing layer than the small-ion space charge. Diffusivity also controls the magnitude of the space charge for large as well as small ions. Also, the space charge due to charged aerosols is relatively constant with height. (4) The nature of the profile for positive ions is more sensitive to the surface radioactivity and less sensitive to χ and that for negative ions is more sensitive to χ and less sensitive to the surface radioactivity. (5) The rate of change of the small-ion space charge density with height depends upon the surface radioactivity, and the region in which this variation occurs depends upon the value of χ. (6) Although the asymptotic value of the electric field is the same for different values of χ for the case of constant ionization, its value changes if the rate of ionization decreases with height at lower levels. (7) Our numerical results are in good agreement with the previous theoretical and experimental results where the aerosol concentration is low. So this model can be used over polar regions, over plateaus, or in rural conditions to determine the eddy diffusivity.

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