MEASUREMENT OF SPACE CHARGE DENSITY OVER FLAT GROUND IN
NEARLY NEUTRAL STRATIFIED ATMOSPHERIC SURFACE LAYER

R. Lelwala* S. Israelsson and K.P.S.C. Jayaratne*

Department of Meteorology, Uppsala University, Box 516, S 751
20, Uppsala, Sweden

*Department of Physics, University of Colombo, Colombo 03,
Sri Lanka

Abstract. Space charge density and α -activity profiles were measured simultaneously at a 0-1.6 m layer above the ground. Measurements were obtained with one instrument to measure α -activity profile and with two Obolensky filters to measure space charge density where one Obolensky filter was used as a reference instrument. Theoretical space charge profiles were calculated with the electrode effect model given by Tuomi (1982) and they were compared with experimental profiles measured. From the analysis of the recordings, the electrode effect was observed. The agreement between theoretical and experimental results has been discussed. Best agreement between the theoretical and experimental results was obtained for the height variation between 0.2-0.8 m when the ionization rate is constant.

1. Introduction

The basic electrical phenomena in the atmospheric boundary layer are elaborated, and vary within a large range of space and time scales. All these phenomena are closely correlated to the meteorological conditions at the ground level and properties of ground surface which acts as an electrode. Most investigators use the concept of electrode effect to explain the structure of basic electrical constituents over the earth surface. Israel (1971) observed the electrode effect as a source of space charge at ground level. A critique on the electrical phenomena in the lower atmosphere is given by Hoppel et al. (1986). The electrode effect is used to explain the overall inhomogeneity occurred to all the electric constituents in response to all the atmospheric processes at the ground level. Many scientists have treated electrode effect under restricted atmospheric and surface conditions.

In stable and aerosol-free atmosphere of uniform ionization rate with height, the atmospheric vertical electric field repels negative ions away from the earth surface. This results in a thin layer of positive space charge. Under realistic meteorological conditions this phenomenon is sophisticated due to the presence of aerosol particles, non-uniform ionization, turbulence and roughness of the surface. The theoretical analysis of the electrode effect under convection and turbulent mixing with and without aerosol particles has been given by a number of authors. Willett (1978, 1979, 1983) presented many

papers in this field under more realistic boundary and atmospheric conditions. From the theoretical calculations, it has been concluded that the electrode effect does exist (see Hoppel, 1967; Willett, 1978, 1979, 1983; Tuomi, 1982). However, the results of many such experiments are inconclusive and contradictory.

This disagreement can be explained partially, by the different measuring methods and the varying local meteorological conditions during the measurements. Varying surface radioactivity level, trapping of radio active emanations and aerosol concentration give different results. Another complication is the large signal fluctuations observed during the measurements (Israel, 1973). The purpose of this investigation was to study the turbulent electrode effect by measuring space charge density and α -activity profiles above a flat surface under nearly neutral stratified atmosphere.

In the nonturbulent atmosphere, space charge density in the atmospheric surface layer is mainly due to trapping of radioactive emanations and surface radioactivity. Hoppel (1967) has shown that the resulting rapid increase in ionization rate with decreasing height can actually reverse the electrode effect. There is still a thin layer of positive space charge at the surface, as in the classical electrode effect, but this can be overlain by a thicker layer containing a larger net negative charge, due to the upward drift of negative ions from the region of high ionization.

The electrical conductivity of the air is due to ions produced primarily by ionizing radiation. The primary source of ions in the atmospheric surface layer is natural radioactivity originating from the ground. This ionization source can be divided into two: radiation directly from the ground and radiation from radioactive gases and their radioactive daughter products exhaled from the ground. Ionization due to radioactive gases in the air is variable and depends not only on the amount exhaled from ground but also on atmospheric dispersion. According to Hoppel et al. (1986) it is difficult to measure surface ionization caused by the radiation directly. The height distribution of radon, thoron and their daughter products in the atmosphere as a function of turbulent diffusion has been observed by a number of investigators and used to determine the turbulent diffusion coefficient. Ionization at 1 to 2 m due to radioactive gases and their short-lived daughter products is typically in the range of 10^6 to 2×10^7 ionpairs $\text{m}^{-3}\text{sec}^{-1}$ and is predominantly caused by α particles.

The occurrence of natural α -activity of the air near the ground is studied by Israelsson et al. (1972). Those profile studies show that the gradients were fairly steep near the ground and decreased rapidly with height. This was most pronounced in stable temperature stratification.

2. Measurement Site and Instrumentation

The measurements were made at the Marsta Observatory ($59^\circ 55' \text{N}$, $17^\circ 35' \text{E}$). The observatory is located in very flat farming country area 10 km north of Uppsala in southern Sweden.

The nearest forest is more than 1 km away from the observatory. No industrial establishments by which condensation nuclei might be produced were in the surroundings of the observation place and no burning took place during the observations. A map of the Marsta Observatory is presented by Israelsson et al. (1973).

In the present study the average α -activity and space charge density profiles were recorded in the 0-1.6 m layer above the ground surface; the former by filtration method that has been used by Israelsson et al. (1972) and the latter by aspiration method that has been presented by Knudsen et al. (1989).

To measure the fine structure of the vertical space charge profile, an instrument which measures the space charge density in a thin layer is required. For this purpose the filter method was found to be suitable and an instrument constructed according to the modified version of the Anderson apparatus (see Anderson, 1966) was used. The instrument is shown schematically in a previous paper (Knudsen et al. 1989). Natural α -activity of the air is measured by a method used in a previous study, Israelsson et al. (1972). It is in principle according to the method described by Israel and Israel (1966).

The electric potential gradient was measured with a radioactive collector method at 1 m height level. The conductivity was measured at 0.5 m height using double Gerdien-aspirator having critical mobility of $2 \cdot 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$. Data of the wind velocity and temperature profiles were taken from the continuous recordings at Marsta observatory.

3. Method of Measuring

To measure fine structure of vertical space charge profile or α -activity profile, their volume densities have to be measured at several levels at the same time. Therefore several instruments of same type are required for each profile. Because of practical problems of having several instruments from same type at the same time, two Obolensky filters for measuring space charge density profile and one ionization chamber for measuring α -activity profile were used, where one Obolensky filter was kept at 0.6 m level as fix reference level while the other was being moved to the different levels 0.1, 0.2, 0.4, 0.8 and 1.6 m. Before starting the experiment, sensitivities of instruments were closely checked.

Initial setting for the Obolensky filters was done for each profile at the beginning of each recording by keeping both Obolensky filters at the reference level one aside to the other and adjusting the gain constant of the movable instrument as both instruments gave same reading. Simultaneous recordings of 5 min. interval, at each height, were recorded by a computer.

4. Results

Eight different space charge profiles measured under near neutral stratified atmosphere ($R_i \approx 0$) are treated in the present study. The survey of the results is given in Figure 1. In the study we will basically treat the simultaneous measurement of space charge density and α -activity in the surface layer of the atmosphere.

During the period of measurement of each profile, the atmospheric stratification was almost near neutral. The meteorological and electrical data here the frictional velocity, u_* (Fric. Vel.), and electric field (Ele. Fld.) are given in the Figure 1 and other parameters are the average value for the measurement period usually 2-3 h. The average values of space charge density and α -activity were used to plot the graphs. The time required to measure a profile is about 2-3 h. (u_* is defined by the identity $u_*^2 = (\tau_s/\rho)$, where the subscript s indicates the value at the surface, τ_s is surface stress and ρ is air density) Therefore it must be kept in mind that all the points in a graph are not taken at the same time. The meteorological conditions that prevail during a period of measurement of one point may considerably vary from those prevail during a measurement at another point of the same profile. In order to calculate the roughness length z_0 and the friction velocity u_* the following equation was used;

$$\hat{u} = (u_*/k) \ln(z/z_0)$$

where k is a universal constant called von Karmans constant which has an experimentally determined value of $k=0.4$, $\hat{u}$ is average wind velocity at the height z over the earth surface. From the gradient and interception of the graph of u versus $\ln(z/z_0)$, u_* and z_0 were calculated.

Fig. 1. Experimental space charge density profiles

Every space charge profile shows well pronounced decrease in the space charge density with increasing height. This indicates that the profiles show a good qualitative agreement with the electrode effect and correlation between them is fairly high. Recordings show that, during 5 min. period of the measurement, space charge density would change by a considerably large factor but changing between reference and measuring levels during the same period of measurement is only by a very limited factor.

5. Comparisons with Theoretical Profiles

To calculate the theoretical space charge density profile, the electrode effect model given by Tuomi (1982) was used. The model includes turbulent ion transport and makes a linearization of the steady state equations that governs the atmospheric electricity near the ground, see Willett (1978). Tuomi linearized and decoupled these system of equations by substituting asymptotic values of n_1 and n_2 at proper places. The solution of the linearized equation included modified Bessel function of second kind, which was approximated using their asymptotic form for large values and exhibits accurate behavior near the ground. Tuomi found the results of the approximation to agree very well with the results of Willett (1978).

The system of equations that describes the electrode effect over plane smooth bare ground are;

$$\begin{aligned}\frac{\partial n_1}{\partial t} + \frac{d}{dz} (-kn_1X - Kn_1') &= q - \alpha n_1 n_2 - \beta_{10} n_1 N_0 - \beta_{12} n_1 N_2 \\ \frac{\partial n_2}{\partial t} + \frac{d}{dz} (kn_2X - Kn_2') &= q - \alpha n_1 n_2 - \beta_{20} n_2 N_0 - \beta_{21} n_2 N_1 \\ -X' &= \left(\frac{e}{\epsilon}\right) (n_1 - n_2 + N_1 - N_2) \\ N &= N_0 + N_1 + N_2 \\ \frac{d}{dz} (-KN_1') &= \beta_{10} n_1 N_0 - \beta_{21} n_2 N_1 \\ \frac{d}{dz} (-KN_2') &= \beta_{20} n_2 N_0 - \beta_{12} n_1 N_2 \\ \beta_0 &= \beta_{10} = \beta_{20} \\ \beta &= \beta_{12} = \beta_{21}\end{aligned}$$

where

n_1 and n_2 are positive and negative small ion densities.

N_0 , N_1 , N_2 and N are neutral, positive, negative and total aerosol densities.

K is eddy diffusivity coefficient.

k is the small ion mobility.

q is ion production rate per unit volume.

X is potential gradient

e is charge of an electron

ϵ is the permittivity of air
 α is the recombination coefficient of small ions
 β_{ij} is the attachment coefficient for large ion with a small ion and the first index denotes polarity of small ion and the second index denotes that of the large ion.
 β_0 is the attachment coefficient of small ion with a neutral large particle.
 β is the attachment coefficient of small ion with oppositely charge particle.
 t is time

z is height over the surface
 and prime denotes derivatives with respect to height.

Tuomi's complete solution is;

$$n_{1,2} = n_{\infty} \left[1 - \left(\frac{x_0}{x} \right)^{\pm v} \frac{K_v(x)}{K_v(x_0)} \right]$$

where

$$K_v(x) = \left[\left(\frac{\pi}{2x} \right) e^{-x} \right]^{\frac{1}{2}} \left[\frac{x}{\left(x + \frac{2}{\pi} \right)} \right]^{\frac{(1+v)(1-2v)}{4}}$$

$$x = \left[\left(\alpha + \frac{ke}{\epsilon} \right) \frac{n_{\infty}}{c} (z + z_0) \right]^{\frac{1}{2}}$$

$$v = \frac{k X_0}{K}$$

X_0 is electric field at the ground level

z_0 is roughness height

$x \geq 0.01$ and $0 \leq v \leq 1$

Following values of the parameters have been used by Tuomi (1982) and Willett (1978); $q = 10^7 \text{ m}^{-3} \text{ s}^{-1}$; $\alpha = 1.6 \cdot 10^{-12} \text{ m}^3 \text{ s}^{-1}$; $k = 1.5 \cdot 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$; $u_* = 0.1 \text{ m s}^{-1}$ and $z_0 = 0.018 \text{ m}$. The values used in the present study are $\alpha = 1.6 \cdot 10^{-12} \text{ m}^3 \text{ s}^{-1}$; $k = 1.25 \cdot 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ (Israelsson et al., 1970); $u_* = 0.01 \text{ m s}^{-1}$; $z_0 = 0.01 \text{ m}$.

The α -activity was converted into ionization rate by multiplying a factor of 10^7 (i.e. $1 \text{ pCi l}^{-1} \Rightarrow 10^7 \text{ m}^3 \text{ s}^{-1}$). The theoretical space charge density profiles were calculated from the model given by Tuomi (1982) by substituting above mentioned values. Figure 2 shows the direct comparisons between

calculated and experimental profiles of space charge density under different conditions. All the data except average mobility of an ion are measured within short period of time. Only average mobility of ions is a value measured earlier (Israelsson et al., 1972). Meteorological and electrical data used here are compatible with those used by Tuomi (1982) in his study. From the diagrams it can be concluded that experimental profiles differ somewhat from theoretical profiles calculated.

Fig.2. Comparison of space charge density profiles.

Figure 3 shows direct comparison of theoretical and experimental space charge density profiles at each level and Figure 4 shows the average comparison ratio of theoretical value to the experimental value.

Theoretical profiles in Figure 2 show attachment effect

near the ground since theoretical profiles were calculated using electrode effect model. But experimental profiles do not show the attachment effect since the fine structure near the ground could not be obtained due to limitation of the vertical height resolution of the instrument.

Fig. 3. Direct comparison of theoretical space charge density and experimental space charge density at each level. Here q - E constant represent the theoretical profiles assuming a constant ionization rate and electric field with height. q - E variable represent the theoretical profiles assuming a variable ionization rate and electric field with height. q -constant, E -variable represent the theoretical profiles assuming a constant ionization rate and variable electric field with height. q -variable, E -constant represent the theoretical profiles assuming a variable ionization rate and constant electric field with height.

Inlet of the Obolensky which is 10 cm diameter cannot give a good vertical height resolution enough to measure the fine structure. Attachment effect is significant at the few centimeters above the ground. Influence of the attachment effect at higher levels is assumed to be insignificant.

Fig.4. Comparison of ratio of theoretical value to experimental value. Here q-E constant represent the theoretical profiles assuming a constant ionization rate and electric field with height. q-E variable represent the theoretical profiles assuming a variable ionization rate and electric field with height. q-constant, E-variable represent the theoretical profiles assuming a constant ionization rate and variable electric field with height. q-variable, E-constant represent the theoretical profiles assuming a variable ionization rate and constant electric field with height. Vertical axis represent height over the surface in meter while horizontal axis represent the ratio of theoretical value to the the experimental value.

6. Conclusion

Using same principles of measuring and same equipment several other experiments have been carried out successfully and have been obtained well acceptable results in the same observatory. Therefore no doubt about the accuracy of the instruments. Finally it can be concluded that the best agreement between the theoretical and experimental space charge density profiles can be observed for the height variation 0.2-0.8 m under constant ionization rate. Our experimental results does not agree with the Tuomis (1982) solution to the electrode effect model in the lowest 1.6 m of the atmospheric surface layer under near neutral stabilized stratification. Further modification to the solutions of the electrode effect model given by Tuomi (1982) is required in order to apply it to all layers of the atmospheric surface layer under near neutral stabilized stratification. This disagreement could be due to approximations that has been made to decouple positive and negative ion balance equations. In the approximation Tuomi has substituted asymptotic values of positive and negative space charge densities to the corresponding parameters in selected terms of the ions balance equations but it has not been justified.

Acknowledgements. Authors wish to thank the International Science Program of the Uppsala University, Sweden for supporting the collaborative research link program between the universities of Colombo, Sri Lanka and Uppsala, Sweden, and the Natural Resources, Energy & Science Authority of Sri Lanka for supporting this project by a grant (RG/92/P/04).

References

- Anderson, R.V., Absolute measurements of atmospheric charge density, *J. Geophys. Res.* 71, 5809, 1966.
- Hoppel, W., Theory of electrode effect, *J. Atm. Ter. Phys.* 29, 709, 1967
- Hoppel, W., R. V. Anderson and J.C. Willett, Atmospheric electricity in the planetary boundary layer, in the earth's Electrical environment, *Studies in Geophysics*, National Academy Press, USA, 149-165, 1986.
- Israel, H., Atmospheric Electricity I, US. Dept. of commerce Springfield, VA22151, Vol 1, 1971.
- Israel, H., Atmospheric Electricity II, US. Dept. of commerce Springfield, 1973.
- Israel, H. and G.W. Israel, A new method of continuous measurements of radon (Rn^{222}) and thoron (Rn^{220}) in the atmosphere, *Tellus* 18, 557-561, 1966
- Israelsson, S., E. Knudsen, and E. Ungethum, On the natural β -activity of the air in the atmospheric surface layer, *Atm. Environ.*, Pergamon Press, Vol 7, 1127-1137, 1973.
- Knudsen, E., S. Israelsson, and B. Hallberg, Measurements of the electrode effect over flat snow-covered ground, *J. Atm. Terr. Phys.*, 51 No 6, 521-527, 1989.
- Tuomi, T.J., The atmospheric electrode effect over snow, *J. Atm. Terr. Phys.* 44, 737, 1982.
- Willett, J.C., An analysis of the electrode effect in the limit of strong turbulent mixing, *J. Geophys. Res.*, 83, 402, 1978.
- Willett, J.C., Fair weather electricity charge transfer by convection in an unstable planetary boundary layer. *J. Geophys. Res.*, 84, 703, 1979.
- Willett, J.C., The turbulent electrode effect as influenced by interfacial ion transfer, *J. Geophys. Res.*, 88, 8453-8469, 1983.

(Received April 14, 1997; revised July 10, 1997;
accepted July 14, 1997.)