

# Atmospheric electrical conductivity measurements and modeling for application to air pollution studies

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Received 21 January 2009; received in revised form 24 May 2009; accepted 27 May 2009

## Abstract

The experimentally measured ground level atmospheric electrical conductivity is validated from a simplified ion–aerosol model for which the inputs are ionization rate from surface radioactivity, aerosol density and meteorological parameters. Also estimated from the model is the reduction in conductivity for assumed aerosol levels. It is seen that for an increase of ambient aerosols by threefold the percent reduction in conductivity is 7% and it is 10% for an increase by sixfold. Thus, the variations in the measured ground level conductivity can be used to examine the atmospheric pollution, if any.

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*Keywords:* Ionization; Electrical conductivity; Aerosols; Meteorological parameters; Ion–aerosol model; Air pollution

## 1. Introduction

Atmospheric electrical conductivity, ion mobility and small ion number density, etc. are important parameters for understanding the electrical nature of the atmosphere. The electrical conductivity of the air in an aerosol free atmosphere is mainly due to small ions. However, in a polluted atmosphere these ions soon get attached to the aerosol particles and form the intermediate and large ions. Since the mobility of small ions is at least two orders of magnitude more than that of large ions, the small ions are still considered to be, if not the only, the main contributors to the local electrical conductivity (Dhanorkar and Kamra, 1997). Since the presence of aerosol particles depletes the small ions, the electrical conductivity and aerosol concentration are generally considered to have an inverse relationship in the atmosphere and the electrical conductivity has been often proposed to act as an index

of air pollution. The decrease in electrical conductivity with an increase in air pollution has been reported under different meteorological conditions such as in continental air (Misaki, 1964; Mani and Huddar, 1972), near coastlines (Misaki and Takeuti, 1970; Morita et al., 1972; Kamra and Deshpande, 1995), in marine air (Cobb and Wells, 1970), at the level of inversion (Rosen and Hofmann, 1981) and during volcanic eruption (Srinivas et al., 2001).

The small ions consisting of aggregates of few molecules determine the electrical conductivity over the region (Israel, 1970). The number density of these ions are controlled by ionizing mechanisms for the production of ions and electrons, and the loss processes for these charged species. The radioactive gas radon and its short-lived decay products polonium, lead and bismuth are valuable natural tracers for the study of these processes in the troposphere, in particular in the boundary layer near ground level. Radon is formed in the ground and released into the atmosphere through exhalation. After the radioactive decay the radon progenies are rapidly fixed on the aerosol particles of the air. Ion-production is chiefly due to radioactive substances present in the earth's crust, cosmic rays coming from the

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extra-terrestrial origin, and the resulting electrons and positive ions rapidly undergo hydration reactions which lead to the formation of negative and positive molecular ion clusters referred to as 'small ions'. Only singly charged ions are important since the cross-section for the production of multiply charged ions by particle impact are smaller than those for the production of singly charged ions by an order of magnitude or more (Hoppel and Frick, 1986). Further, the multiply charged ions that are formed will rapidly undergo charge transfer reaction within neutral molecules to result in singly charged ions (Meyerott et al., 1980). The small ions have mobilities large enough to move appreciably under the influence of electric field and thus determine the electrical conductivity of the atmosphere.

Measurements of atmospheric electrical conductivity are in general difficult to interpret because of large variety of influencing factors. Therefore, a thorough theoretical and experimental analysis is necessary in order to conduct research in atmospheric electricity. In the atmospheric surface layer, particularly the lowest few meters above the ground, large number of factors will dominate, for example, radioactive emanation from the ground; porosity, dampness and temperature of the soil; aerosol concentration; atmospheric electric field and mobility of small ions. Close to the ground surface, in continental regions, the radioactive radiation from ground and galactic cosmic rays are major sources of ionization. The higher mobility small ions, which are formed due to ionization, attach themselves to the larger aerosol particles and form smaller mobility larger ions. The ion-production rate due to ground radioactivity and aerosol concentration close to the earth's surface largely depends on the prevailing meteorological conditions (Hoppel et al., 1986). The electrical conductivity is very sensitive to the presence of aerosols. Thus, the aerosol loading has a bearing on the conductivity of the atmosphere. The aerosols reduce the conductivity of the atmosphere by (i) converting the highly mobile small ions into less mobile aerosol ions through ion-aerosol attachment and (ii) neutralizing the small ions through the aerosol ion-small ion recombination. Another process that makes the ion-aerosol attachment rate faster is the charged aerosol-aerosol recombination. In the present communication ion-aerosol interactions are taken into account to develop a model for the electrical conductivity of the atmosphere. It is validated by comparing the computed values of conductivity with the experimental values.

Several model studies on the electrical conductivity of the atmosphere of higher altitude are available (Datta et al., 1987; Prasad et al., 1991; Srinivas and Prasad, 1993, 1996). Most of the model studies have considered the loss of small ions as solely due to (i) ion-ion recombination (ii) ion-attachment to aerosols. The other two types of loss of small ions arise from (i) the recombination of molecular ions with oppositely charged aerosol and (ii) charged aerosol-aerosol recombination, and hence further deplete the small ions. Obviously, addition of these two terms result in more realistic values (Srinivas et al., 2001). The equilibrium density of small ions is governed by the

equations of continuity for the production and loss of these ions, where the gain and loss due to transport are negligible. The effective recombination of small ions is altered in the presence of aerosols, since these aerosols interact with the ions through various attachment and recombination processes. The attachment of small ions to neutral aerosols produce charged aerosols referred to as 'large ions', which are less mobile than the smaller molecular ions. The subsequent recombination of charged aerosols with ions as well as oppositely charged aerosols would result in the depletion of small ion concentration more rapidly than in the absence of aerosols. Therefore, the formation of less mobile aerosol ions and the reduction of more mobile molecular ions alter the electrical conductivity of the atmosphere. Thus, the pollution due to aerosols/dust in the atmosphere can considerably reduce the atmospheric conductivity. Hence, the atmospheric pollution level can be monitored through electrical conductivity measurements and conductivity is used as index of air pollution.

In an experimental programme at Pune (18°32'N, 73°51'E, 559 m above mean sea level), India measurements of radon and its progeny, aerosol number density and atmospheric conductivity are measured. Using the ionization rate from radioactivity, ambient aerosol density and meteorological parameters such as temperature, pressure and relative humidity, the small ion concentration and hence the conductivity of the atmosphere is estimated from an ion-aerosol model. Model computed conductivity of the atmosphere is used to validate the measured conductivity from a Gerdien condenser setup. Nagaraja et al. (2006) have described the experimental method for the measurement of ground level atmospheric electrical conductivity near the earth's surface and its validation using a simple ion-aerosol model. The present model work is an extension of the earlier work for the estimation of percent reduction in conductivity for assumed higher ambient aerosol levels, which may be the result of increased pollution due to vehicular exhaust, industrial effluents, anthropogenic activity, etc. Thus, monitoring of ground level atmospheric conductivity can be useful in air pollution studies.

## 2. Experiment and methodology

### 2.1. Radon concentration in air

Concentration of radon in air at a height of 1 m above the surface is measured using the Low Level Radon Detection System. The procedure briefly consists of sampling the air in a collection chamber and exposing a circular metallic disc to the radon inside the collection chamber. A delay of at least 10 min is normally allowed for any thoron, which may be present in the chamber to decay completely. The positively charged polonium atoms created in the chamber get collected on the metallic plate maintained at an optimum negative potential that should be sufficient to force all the polonium atoms onto the plate. The collection is carried out for an optimized period and thereafter the

charged plate is removed from the chamber and alpha-counted. Then the concentration of radon ( $\text{Bq m}^{-3}$ ) is estimated (Nagaraja et al., 2003a) with the expression:

$$R_n = \frac{1000C}{EFVZ} \quad (1)$$

where  $C$  is the total number of counts,  $E$  is the efficiency of alpha counting system,  $F$  is the efficiency of collection of polonium atoms on the metallic disc and is empirically related to the relative humidity, ( $H$ ) by:

$$F = 0.9[1 - \exp(0.039H - 4.118)]$$

$V$  is the volume of the chamber used,  $Z$  is the correction factor for build up and decay of radon daughter atoms on the metallic disc during the exposure and counting period.

### 2.2. Radon progeny concentration in air

An air flow meter kept at a height of 1 m above the surface is used to measure the radon progeny concentration. Air is drawn through a glass fiber filter paper by means of a suction pump at a known flow rate. The radon progeny in air sample are retained on the filter paper. The filter paper is then alpha-counted at any specific delay time. Total activity on the filter paper is measured at three different counting intervals of 2–5, 6–20 and 21–30 min. Activities of polonium (RaA), lead (RaB) and bismuth (RaC) ( $\text{Bq m}^{-3}$ ) are calculated using the modified equations given by Raghavayya (1998):

$$\text{RaA} = \frac{+4.249019C_1 - 2.062417C_2 + 1.949949C_3}{VE} \quad (2)$$

$$\text{RaB} = \frac{-0.355129C_1 + 0.006232C_2 + 0.240618C_3}{VE} \quad (3)$$

$$\text{RaC} = \frac{-0.215175C_1 + 0.371319C_2 - 0.502945C_3}{VE} \quad (4)$$

$$R_d = \frac{+0.048445C_1 - 0.019335C_2 + 0.037053C_3}{VE} \quad (5)$$

where  $C_1, C_2$  and  $C_3$  are the gross counts during the three counting intervals,  $E$  is the efficiency of alpha counting system,  $V$  is the sampling rate in liters per minute,  $R_d$  is the concentration of radon progeny in Working Level.

### 2.3. Ion-pair production rate

The ion-pair production rate due to radon and its progeny is calculated using the expression:

$$Q = \frac{\varepsilon}{32} \quad (6)$$

$$\varepsilon = 5.49R_n + 6.00R_{\text{aA}} + 0.85R_{\text{aB}} + 7.69R_{\text{aC}}$$

where  $R_n$  is the activity concentration ( $\text{Bq m}^{-3}$ ) of radon,  $R_{\text{aA}}, R_{\text{aB}}$  and  $R_{\text{aC}}$  are the concentration ( $\text{Bq m}^{-3}$ ) of radon progenies *i.e.*, polonium, lead and bismuth,  $\varepsilon$  is the total energy ( $\text{MeV}$ ) released by the decay of radon and its progeny,  $Q$  is the ion-pair production rate (ion-pairs  $\text{m}^{-3}\text{s}^{-1}$ ).

### 2.4. Aerosol concentration near the earth's surface

The concentration of aerosols were measured with an Electrical Aerosol Analyzer in the size range from 3 to 1000 nm diameter. The instrument works on the principle of diffusion charging-mobility analysis of particles. The ambient air is sampled at a rate of 50 L/min. The samples is first exposed to a Kr-85 radioactive neutralizer and then passed through a mobility analyzer that contains concentric cylindrical electrodes and a central collector rod. A pre-determined voltage is applied between the electrodes to produce an electric field in the condenser. The charged particles are deflected towards the collector rod by the electric field and the concentration of aerosols is measured in terms of mobility spectrum (Liu and Pui, 1975). A computer is interfaced with analyzer to measure the size distribution.

### 2.5. Electrical conductivity of the atmosphere

Both positive and negative polarities of the electrical conductivity of the atmosphere is simultaneously measured with two Gerdien condensers housed separately in a single unit. The apparatus consists of two identical cylindrical tubes of 100 mm diameter and 410 mm length joined by a U-shaped tube. The atmospheric air is sucked through them with a single fan fixed at the end of U-shaped tube. The flow rate in each tube is about 19 L/s. The inner coaxial aluminum electrode in both the tubes are of 10 mm diameter and 200 mm length, and are fixed well inside the outer electrodes with Teflon insulation. The outer electrodes are shielded from any external electric field by two coaxial cylinders of 110 mm diameter and 350 mm length separated from the outer electrodes with Bakelite rings. Opposite but equal potentials of  $\pm 35$  V are applied to the outer electrodes of the two condensers. The critical mobility of the instrument is greater than  $2.93 \times 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$  (Dhanorkar and Kamra, 1993) and is capable of resolving the values of conductivity as small as  $3 \times 10^{-16} \Omega^{-1} \text{ m}^{-1}$  (Dhanorkar and Kamra, 1992). Each sensor is scanned every 1 min, and hourly average values of atmospheric conductivity of both polarities are recorded on a computer. Both positive and negative signals from the conductivity apparatus are separately amplified with an amplifier. Amplified signals are then carried through separate coaxial cable and are recorded on a data logger card that has a voltage range of  $\pm 15$  V with 10 mV resolution. The card has the capability of storing data at the maximum of 100 samples per second. In our case we made 60 samples per second and then it was averaged for a minute or for any desired length of time with the help of an external program.

### 2.6. Meteorological parameters

The meteorological parameters such as temperature, pressure, wind speed and wind direction near the surface of the earth are obtained by automatic weather station

installed near the observatory. Relative humidity is estimated from the wet and dry bulb thermometers.

### 3. Simple ion–aerosol model

There have been no reports on modeling study of the electrical conductivity in the lower part of the troposphere, in particular near the surface. Modeling for this region requires, ionic aerosols, in addition to the molecular ions. Based on this, a simple ion–aerosol model (SIAM) is proposed. The schematic diagram of SIAM is shown in Fig. 1. The SIAM involves primary ion-pair production rate due to surface radioactivity and cosmic rays, the small ion densities ( $N_{\pm}$ ) and the aerosol number density. For the model prediction of equilibrium ion density and conductivity, it is necessary to use all the four loss processes of ions involved. The various recombination coefficients that enter into the model are:

- (a)  $\alpha_i$  due to the loss of oppositely charged small ions,
- (b)  $\alpha_a$  due to oppositely charged aerosol ions,
- (c)  $\alpha_s$  between small ions and aerosol ions,
- (d)  $\beta$  due to attachment of small ions of similar polarities with aerosols.

The temperature, pressure, relative humidity, ionization rate and aerosol number density along with the different attachment/recombination coefficients are the input parameters for the model. With these inputs the electrical conductivity is estimated. However, the model gives the total conductivity and does not makes any distinction between positive and negative ion conductivities.

#### 3.1. Theoretical description of the Model

The polar conductivity of air is defined as

$$\sigma = neb \tag{7}$$

where  $n$  is the concentration of ions of mobility  $b$  and having an elementary charge  $e$ . In the absence of aerosol particles, polar conductivity is mainly due to the high-mobility small ions. However, in the presence of aerosol particles, small ions get attached to the aerosol particles. For the estimation of the conductivity an simple ion–aerosol model

used. In the present model, the detailed reaction paths for the formation of individual cluster ions are not considered. The total number density of positive and negative ions are assumed to be equal from the charge neutrality criterion. The equilibrium ion densities are computed from the equations of continuity where the effect of transport is neglected. These equations include the afore mentioned four types of loss processes. The two values of  $\beta$  (for attachment of positive and negative ions with neutral aerosols) and  $\alpha_s$  (for recombination of positive and negative ions with oppositely charged aerosols) are assumed to be equal.

The equations of continuity (i) for small ions in the absence of aerosols and in the presence of aerosols and (ii) the charged aerosols are given by:

$$\frac{dN_o}{dt} = q - \alpha_i N_o^2 \tag{8}$$

$$\frac{dN_{\pm}}{dt} = q - \alpha_i N_{\pm}^2 - \beta Z N_{\pm} - \alpha_s A_{\mp} N_{\pm} \tag{9}$$

$$\frac{dA_{\pm}}{dt} = \beta Z N_{\pm} - \alpha_s A_{\pm} N_{\mp} - \alpha_a A_{\pm}^2 \tag{10}$$

where  $q$  is the ion-production rate due to radioactivity and cosmic rays,  $N_o$  is the positive/negative ion density in the absence of aerosols,  $N_{\pm}$ ,  $N_{\mp}$  is the positive/negative ion density in the presence of aerosols,  $A_{\pm}$  is the positively/negatively charged aerosol density,  $Z$  is the neutral aerosol number density,  $\beta$  is the aerosol–ion attachment coefficient,  $\alpha_i$  is the ion–ion recombination coefficient,  $\alpha_s$  is the charged aerosol–ion recombination coefficient,  $\alpha_a$  is the charged aerosol–aerosol recombination coefficient.

Under steady state conditions Eqs. (8)–(10) reduce to

$$q - \alpha_i N_o^2 = 0 \Rightarrow N_o = \left[ \frac{q}{\alpha_i} \right]^{\frac{1}{2}} \tag{11}$$

$$q - \alpha_i N_{\pm}^2 - \beta Z N_{\pm} - \alpha_s A_{\mp} N_{\pm} = 0 \tag{12}$$

$$\beta Z N_{\pm} - \alpha_s A_{\mp} N_{\pm} - \alpha_a A_{\pm}^2 = 0 \tag{13}$$

The ion–ion recombination coefficient  $\alpha_i$  has been computed using the parametric formula of Smith and Adams (1982):

$$\alpha_i = 6 \times 10^{-8} \left[ \frac{300}{T} \right]^{\frac{1}{2}} + 1.25 \times 10^{-25} \left[ \frac{300}{T} \right]^4 [M] \tag{14}$$

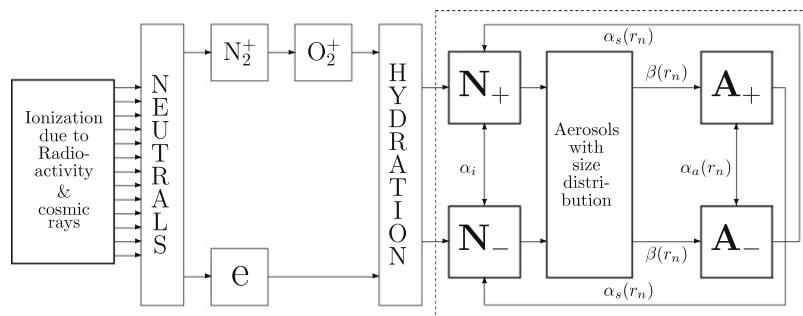


Fig. 1. Simple ion–aerosol model for atmospheric conductivity.

where  $[M] = 2.45 \times 10^{19}$  is the neutral density (Cole and Kantor, 1978),  $T$  is the ambient air temperature.

Solving Eqs. (11)–(13) for  $N_{\pm}$  with  $A_{\pm} = N_o - N_{\pm}$ , we get:

$$N_{\pm} = \frac{(\alpha_a N_o + \beta Z) \pm \sqrt{(\alpha_a N_o + \beta Z)^2 - (\alpha_a - \alpha_i)(q + \alpha_a N_o^2)}}{(\alpha_a - \alpha_i)} \quad (15)$$

Solving Eqs. (12) and (13) simultaneously, we get:

$$\beta Z = \frac{[q - \alpha_i N_{\pm}^2 + \alpha_a A_{\pm}^2]}{2N_{\pm}} \quad (16)$$

$$\alpha_s = \frac{[q - \alpha_i N_{\pm}^2 - \alpha_a A_{\pm}^2]}{2A_{\pm} N_{\mp}} \quad (17)$$

The ion depletion  $\Delta N$ , i.e., loss of molecular ions in the presence of aerosols and is given by  $\Delta N = N_o - N_{\pm}$ . Further, the ion depletion is equal to the charged aerosol concentration,  $A_{\pm}$ . Hence, the fractional depletion,  $\eta$  of small ions is also used in the present computation as:

$$\eta = \frac{\Delta N}{N_o} = \frac{A_{\pm}}{N_o} \quad (18)$$

Using Eqs. (18) and (11), we can write Eqs. (16) and (17), respectively, as

$$\beta Z = \frac{N_o \eta [\alpha_i (2 - \eta) + \alpha_a \eta]}{2(1 - \eta)} \quad (19)$$

$$\alpha_s = \frac{[\alpha_i (2 - \eta) - \alpha_a \eta]}{2(1 - \eta)} \quad (20)$$

The conductivity of the atmosphere in the absence and presence of aerosols, respectively, are given by:

$$\sigma_o = N_o e b_{\pm} \quad (21)$$

$$\sigma_{\pm} = N_{\pm} e b_{\pm} \quad (22)$$

where  $e$  is the charge of an electron,  $b_{\pm}$  is the ionic mobility,  $\sigma_o$  is the conductivity of the atmosphere in the absence of aerosols,  $\sigma_{\pm}$  is the conductivity of the atmosphere in the presence of aerosols.

The reduction in conductivity ( $\Delta\sigma$ ) due to depletion of small ions is given by:

$$\Delta\sigma = \sigma_o - \sigma_{\pm} \quad (23)$$

The ionic mobility  $b_{(\pm)}$  is expressed in terms of the reduced mobility ( $b_o$ ) at Normal Temperature and Pressure, and the ambient temperature ( $T$ ) as well as pressure ( $P$ ) (Meyerott et al., 1980) as follows:

$$b_{\pm} = \frac{b_o P_o T}{T_o P} \quad (24)$$

The value of  $\Delta\sigma$  is computed in terms of the model parameters  $\alpha_i$ ,  $\alpha_s$ ,  $\beta Z$  from Eqs. (11)–(24). By following the method of Gringel et al. (1978), we get:

$$\Delta\sigma = \frac{[(2\alpha_i - \alpha_s)\sigma_o + \beta Z e b_{\pm}] \mp \sqrt{[(2\alpha_i - \alpha_s)\sigma_o + \beta Z e b_{\pm}]^2 + 4(\alpha_s - \alpha_i)\sigma_o \beta Z e b_{\pm}}}{2(\alpha_i - \alpha_s)} \quad (25)$$

The reduction in conductivity (Eq. 25) reduces to zero as  $\beta Z$  tends to zero for aerosol free environment and hence the positive sign for the quantity under square root is appropriate. In the presence of aerosols and depending on the magnitude of  $\alpha_i$ ,  $\alpha_s$  and  $\beta Z$ , the model gives range of values for  $\Delta\sigma$ . For a realistic situation, it is considered only the values of  $\Delta\sigma$  that lies between zero and  $\sigma_o$ , and satisfies the conditions  $0 < N_{\pm} < N_o$  and  $0 < \sigma_{\pm} < \sigma_o$ . The present model by making use of the inputs on  $q$ ,  $\alpha_i$ ,  $\alpha_a$ ,  $\alpha_s$  and  $\beta Z$ , gives the values of  $\sigma_o$ ,  $\sigma_{\pm}$  and  $\Delta\sigma$ .

### 3.2. Model computations of conductivity

Modeling the conductivity of the atmosphere requires a knowledge of recombination coefficients  $\alpha_i$ ,  $\alpha_a$  and  $\alpha_s$ . The value of  $\alpha_i$  is estimated from the parametric formula (Smith and Adams, 1982; Datta et al., 1987). From the theoretical considerations, Hoppel (1985) has shown that, for singly charged aerosols, the relative magnitudes of  $\alpha_a$  and  $\alpha_s$  are such that  $\alpha_a \leq \alpha_s \leq \alpha_i$ . Initially, with a suitable assumed value of  $\alpha_a$ , the value of  $\eta$  is computed from Eq. (18), then the value of  $\alpha_s$  is computed using Eq. (20). It is noted that, in this step,  $\alpha_s$  becomes negative if the assumed value of  $\alpha_a$  is unrealistically large. In the present computations  $\alpha_a = 10^{-13} \text{ m}^3 \text{ s}^{-1}$  is found to be suitable. By knowing the experimental values of  $q$ ,  $Z$ ,  $T$ ,  $P$  and different attachment and recombination coefficients computed from the SIA model, it is possible to estimate the values of  $\sigma_o$ ,  $\sigma_{\pm}$  and  $\Delta\sigma_{\pm}$ .

## 4. Results and discussion

In the present paper, the observations of the diurnal variation of radon, its progeny, aerosols and conductivity for a typical day in the month of April are described. There are several days of observations of similar type. All these observations, although different quantitatively, show similar trends of variations over a day. Variability in the data of any of these parameters can be associated with different meteorological conditions. Moreover, simultaneous measurements of the diurnal variations of radon, its progeny, aerosols, conductivity, dry and wet bulb temperature, and wind speed and direction at the same observatory confirm that the day chosen is in no way electrically or meteorologically abnormal from other fair weather days. Thus, the observations described below can be reasonably generalized for other fair weather days as well.

The results of collocated measurements of the parameters such as concentrations of radon and its progeny, ionization rate, aerosols, electrical conductivity and meteorological parameters such as temperature, relative humidity are examined for a typical day and are taken as representative.

Fig. 2(a) shows the diurnal variations of activity of radon and its progeny near the earth's surface. The radon concentration varies from 2.1 to 23.0 Bq m<sup>-3</sup> with a median of 6.8 Bq m<sup>-3</sup> showing a significant diurnal variation,

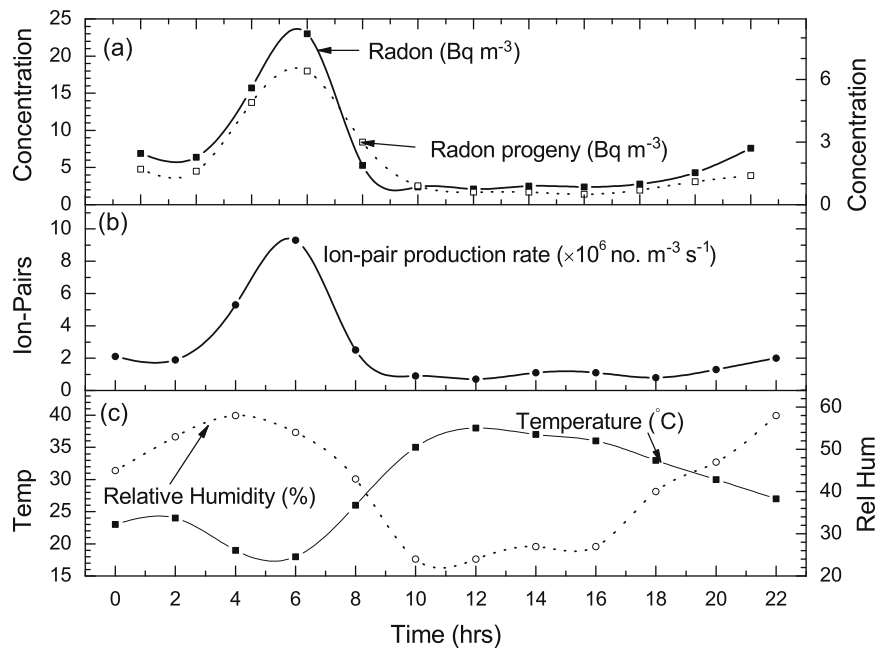


Fig. 2. Diurnal variation of (a) radon and its progeny (b) ionization rate and (c) temperature and relative humidity.

whereas values of radon progeny vary between  $0.5$  and  $6.4 \text{ Bq m}^{-3}$  with a median of  $2.0 \text{ Bq m}^{-3}$ . It is seen from the figure that the concentrations are maxima during the early morning hours, generally between 0500 and 0700 h of Indian Standard Time (IST). The concentration decreases after sunrise, attaining minima during the afternoon, 1000–1800 h of IST. The variation of meteorological parameters such as temperature and relative humidity are shown in Fig. 2(c). It is observed that the concentration of radon and its progeny follow the trend of the relative humidity, in general. This is due to the fact that as temperature increases, the saturation vapour pressure increases so that the given air can take more water vapour. Consequently the relative humidity will decrease (Wilkening, 1990). The raise of temperature causes increased vertical mixing and raising of aerosols to the higher altitudes resulting in lower concentration of radon at the ground level (Hoppel et al., 1986). When the temperature decreases and relative humidity increases, the vertical mixing and raising of aerosols to the higher altitude reduces. As a consequence, the aerosol to which radon is attached, will be present at higher concentrations during night and in the early morning hours at ground level. This results in the increase of radon concentrations near the surface of the earth (Wilkening, 1990; Porstendörfer, 1994; Lebedyte et al., 2002).

Over continents, radon exhaled from the soil is of prime interest for small ion-production. During the daytime unstable conditions, the radioactive gases get dispersed to higher altitudes and thus cause small ionization rates close to the earth's surface. During the low wind and temperature inversion conditions at nighttime, the radioactive gases accumulate close to the earth's surface and thus cause higher ionization rates (Chalmers, 1967; Dhanorkar and

Kamra, 1993, 1994). Experimental observations of Porstendörfer et al. (1991) confirms such accumulation of radon and its short-lived decay products close to the earth's surface during calm and stable conditions at nighttime. The observations of Nagaraja et al. (2003b) *i.e.*, maximum concentrations of radioactivity in the early morning hours also support such accumulation of radioactive gases near to the earth's surface. Shenber (1992) reported the temporal variation of radon and its short-lived decay products on the surface air at Tripoli. He reported the average monthly morning activity to be varying from  $2.42$  to  $5.0 \text{ Bq m}^{-3}$ . The annual mean activity concentrations (in  $\text{Bq m}^{-3}$ ) of short-lived decay products have been reported to be  $2$  for  $^{218}\text{Po}$ ,  $1.8$  for  $^{214}\text{Pb}$  and  $1.72$  for  $^{214}\text{Bi}$ . Wasiolek and Schery (1993) measured the concentration of radon at a height of  $1 \text{ m}$  in New Mexico during winter months and reported a mean value of  $12.5 \text{ Bq m}^{-3}$ . Debaje et al. (1996) and Nagaraja et al. (2003a) carried out the similar type of measurements at Pune, and the results obtained are of the same order. In principle, the similar diurnal behaviour is observed worldwide.

The ionization due to radioactivity also exhibits the diurnal variation as that of concentration of radon and its progeny and is shown in Fig. 2(b). At a height of  $1\text{--}2 \text{ m}$  above the surface ionization due to radioactive gases and their short-lived daughter products is predominantly caused by alpha particles. The radon exhaled from the surface causes ionization of the atmosphere (Israël, 1970). It also shows a maximum in the early morning hours and a minimum in the afternoon. The ion-pair production rate varies between  $0.7$  and  $9.3 \times 10^6 \text{ ion-pairs m}^{-3} \text{ s}^{-1}$  with a mean of  $2.4 \times 10^6 \text{ ion-pairs m}^{-3} \text{ s}^{-1}$ . At night, ionization rates close to the ground are enhanced because of the accumulation of radioactive emanations from ground under

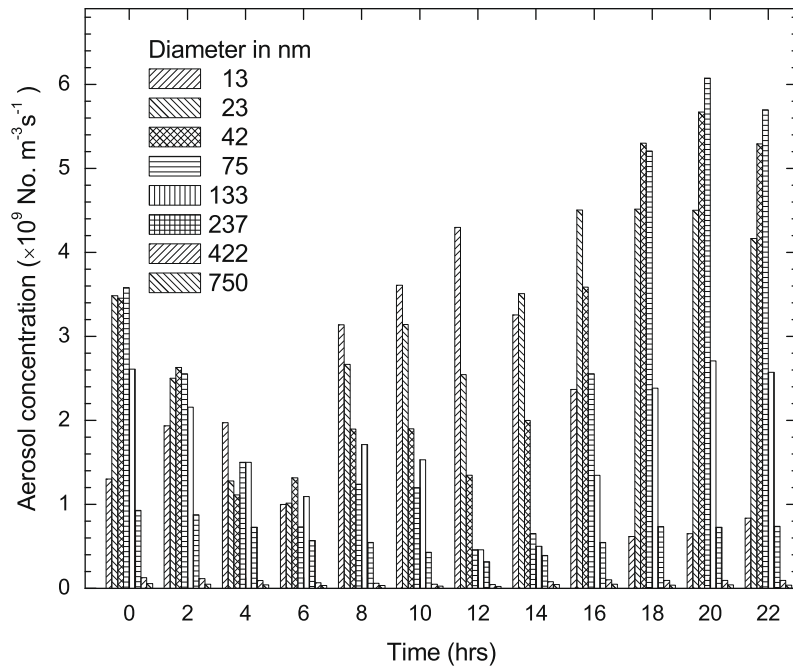


Fig. 3. Diurnal variation of aerosol concentration.

temperature inversions and due to their lesser dispersion because of low winds (Hoppel et al., 1986). It also shows that the concentration of radon and its daughter products is low at noon when air is unstable and is highest during the night and early morning hours, when mixing is low. The radioactive emanations from the ground are trapped below inversions, and their accumulation causes an increase in ionization in the lower stable atmosphere during the nighttime. Large rates of ionization, produced due to these radioactive emanations in the presence of large aerosol concentration at night, produce large concentrations of ions of all categories. The accumulation of radioactive emanations will increase through the night until morning, when there are rapid changes in the stability of the atmosphere. In the morning, the vertical mixing caused due to increased eddy diffusivity will dilute the concentration of aerosols and radioactive emanations close to the ground. This may explain the occurrence of large concentrations at nighttime as compared to daytime (Dhanorkar and Kamra, 1993).

Fig. 3 represents two hourly values of the aerosol concentration obtained for each of the eight size categories in the range of 13–750 nm. It shows a diurnal variation with the concentration showing a minimum during the early morning around 0600 h IST and an increasing trend towards noon-hours. Early in the morning, due to anthropogenic activity and also due to the onset of convection resulting from the increase in atmospheric temperature, aerosols are pushed into the atmosphere resulting in an increased aerosol concentration (Israelsson et al., 1994; Sasikumar et al., 1995).

The size distribution of aerosols is plotted in Fig. 4. Size distributions are generally bimodal with their maxima at 75

and 23 nm during night (1800–0400 h). After 0400 h with slight shift in maxima in the accumulation mode towards the higher size. During daytime, particularly in the afternoon, the shift in maxima in the accumulation mode to a higher diameter of 133 nm is distinct and the maxima in the nucleation mode seems to shift to smaller diameter. As a result of increase in the concentration of small particles, the size distribution curves during daytime are mostly open ended at the small particle side (Murugavel and Kamra, 1999). The magnitude of the peaks varies with time.

Diurnal variation of experimental positive and negative ion conductivities are shown in Fig. 5(a). The positive and negative conductivities are approximately equal and their diurnal variations are generally mirror images to each other. It is observed that the conductivity of both polarities show maxima in the early morning hours between 0400 and 0700 h of IST, it decreases after sunrise, and attains minimum in the afternoon. This is due to the fact that the raise in temperature causes increased vertical mixing and rising of aerosols to the higher altitudes, which results in the lower value of ionization rate, and hence conductivity at the ground level (Dhanorkar et al., 1989; Nagaraja et al., 2006). The positive conductivity varies between  $0.3$  and  $1.8 \times 10^{-14} \Omega^{-1} \text{ m}^{-1}$  with a median of  $0.8 \times 10^{-14} \Omega^{-1} \text{ m}^{-1}$  and the negative conductivity varies between  $0.2$  and  $2.0 \times 10^{-14} \Omega^{-1} \text{ m}^{-1}$  with a median of  $0.7 \times 10^{-14} \Omega^{-1} \text{ m}^{-1}$ .

During nighttime the atmosphere is relatively calm with low winds and little convective motion. The radon exhaled from the soil therefore accumulates near the ground and leads to increased ionization and higher conductivity. After sunrise, due to human activity and also due to the onset of convection resulting from the increase in atmospheric

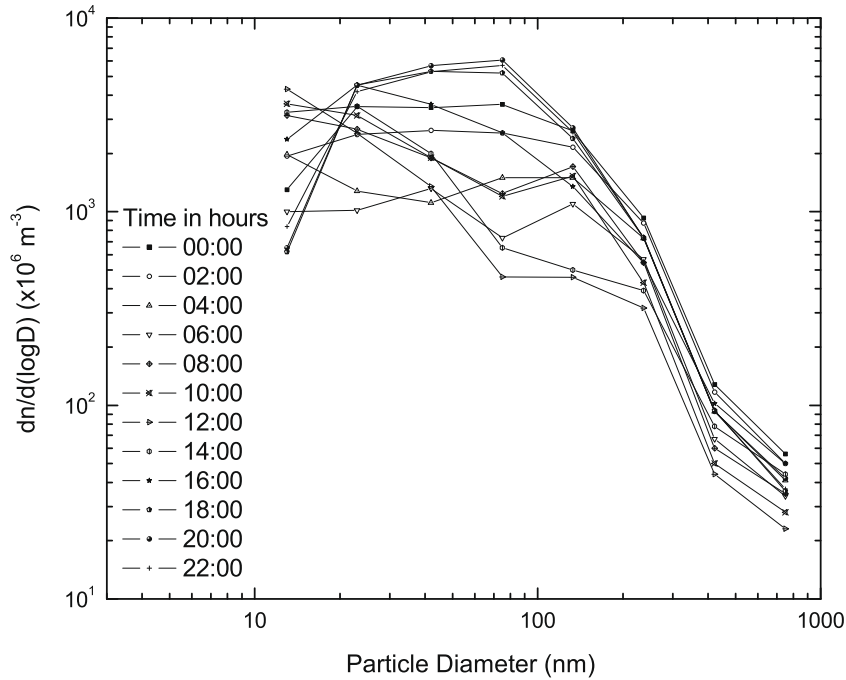


Fig. 4. Size distribution of aerosols.

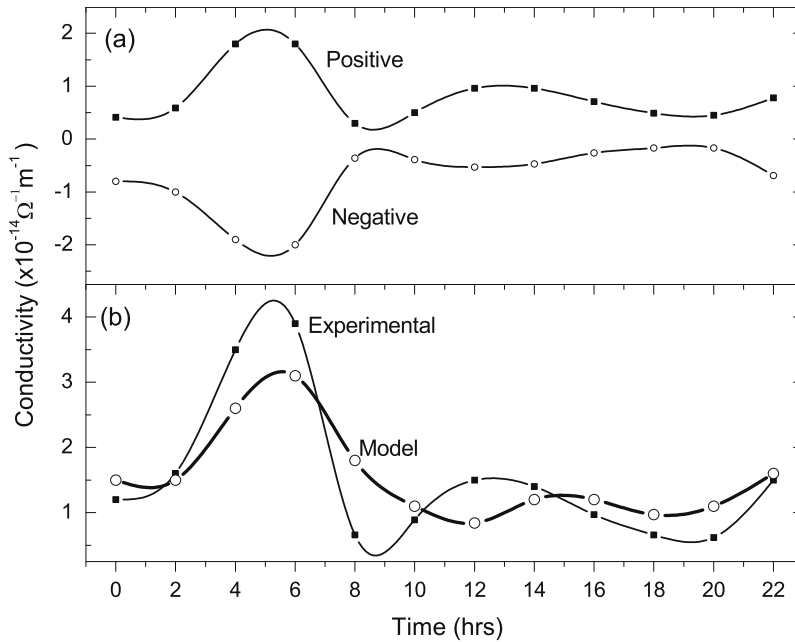


Fig. 5. Diurnal variation of (a) positive and negative conductivity (b) experimental and model conductivity.

temperature, aerosols are pushed into the atmosphere. This causes a conversion of small ions, that are responsible for conductivity, into large ions through attachment, and an increase in the destruction of small ions through recombination with large ions of opposite polarity. The onset of circulation also removes radon from near the ground to higher altitude regions. These factors contribute to the observed reduction in conductivity in the afternoon (Subbaramu and Vohra, 1969; Petrov et al., 1999). In the evening, with

decreasing ground temperatures and also the anthropogenic activity, the aerosols that had been pushed to higher altitudes begin to settle down, and a greater fraction of small ions is lost through attachment. Conductivity therefore again starts raising after sunset. Finally, at nightfall, the aerosols settle down, and the conductivity recovers its normal night time high values (Dhanorkar and Kamra, 1999). Since the major contribution to ionization at the surface comes from surface radioactivity and radon/thoron emanating from the soil, one



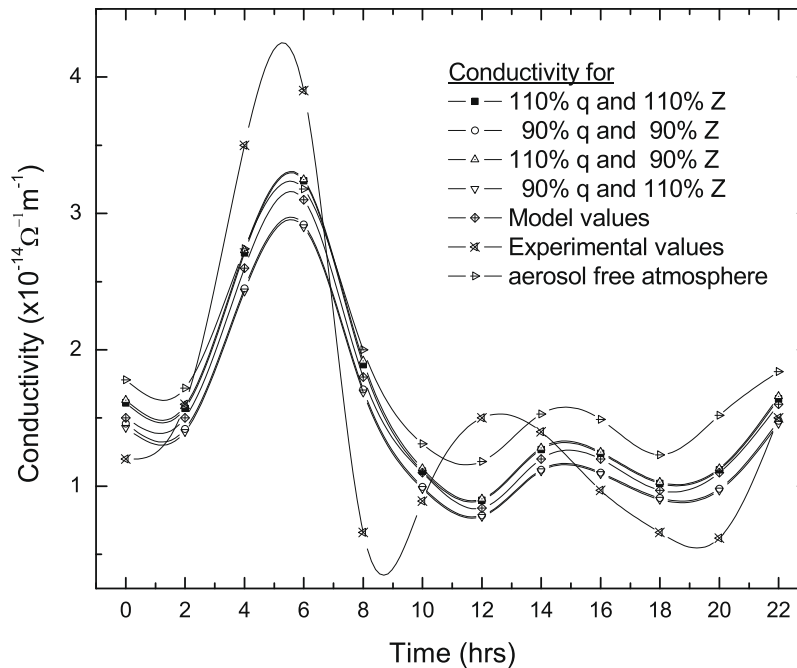


Fig. 6. Variation in the model computed conductivity with respect to 10% variation of  $q$  and/or  $Z$ .

would expect the diurnal variation pattern of conductivity to reflect that of the radon concentration near the surface. Radon and its short-lived daughters are understood to show a diurnal variation in concentration with a maximum early in the morning and a minimum in the afternoon (Nagaraja et al., 2003a). This is ascribed to the variations in the vertical mixing of air near the surface, which is controlled by atmospheric stability. As convection builds up with solar heating of the ground, radioactive gases are also transported upward, where they add to the ambient ionization. This leads to a reduction in the concentration of these gases, and consequently of ionization, near the surface (Nagaraja et al., 2003b). Therefore one should expect higher conductivities during the period of atmospheric stability, with the values decreasing with the onset of turbulence (Sasikumar et al., 1995; Prasad et al., 2005). Wilkening and Romero (1981) reported the values of ionization rate, positive conductivity and negative conductivity, respectively, as  $15 \times 10^6 \text{ m}^{-3} \text{ s}^{-1}$ ,  $1.4 \times 10^{-14} \Omega^{-1} \text{ m}^{-1}$  and  $1.4 \times 10^{-14} \Omega^{-1} \text{ m}^{-1}$ , for free atmosphere. These are of the same order as our measurements reported in this paper. The total conductivity is the algebraic sum of the experimentally measured values of polar conductivities *i.e.*, positive and negative conductivity. The variation of total conductivity is shown in Fig. 5(b). It varies between 0.6 and  $3.9 \times 10^{-14} \Omega^{-1} \text{ m}^{-1}$  with a median of  $1.5 \times 10^{-14} \Omega^{-1} \text{ m}^{-1}$ . Higazi and Chalmers (1966) observed and reported that the mean values of total conductivity at ground level comes to be  $1.09 \times 10^{-14} \Omega^{-1} \text{ m}^{-1}$ . Adarsha Kumar et al. (1998) have estimated the conductivity for different orographic features in India and reported values are of the order of  $10^{-14} \Omega^{-1} \text{ m}^{-1}$ . Our measurements agrees with these reported conductivity values.

The experimental conductivity fluctuations in Fig. 5 is due to the similar variations in  $q$  which in turn is affected by the variations in meteorological parameters such as temperature, humidity, wind speed, etc. The model of this study has reproduced well this trend of the diurnal variation in conductivity. It is seen that there is no exact one to one match between the experimental and model conductivities at certain points. However, there is a correlation coefficient of more than 90% between experimental and model derived conductivity values, which is an indication of correctness of the model results.

In this study, the standard deviation in the measured ionization rates and aerosol concentration are both less than 10%. The effect of these variations in  $q$  and  $Z$  on the model predicted conductivity is shown in Fig. 6. Also shown are the experimental conductivity and model computed conductivity profiles for aerosol free environment for comparison. It is observed that the variations in the model conductivity values for the 10% variations in  $q$  and/or  $Z$  show variations of about 7% or less. It is evident that the simple ion–aerosol model of this study has adequately reproduced the experimental conductivity. It is to be noted that this simple ion–aerosol model is the first of its kind for the ground level conductivity.

The conductivity of air is entirely due to small ions and depends upon the number of small ions present in the atmosphere. The conductivity decreases if the small ion concentration reduces. The small ion concentration is altered by the presence of aerosols due to attachment with aerosols, apart from the usual loss due to mutual recombination between the ions of opposite polarity. Hence, the conductivity alters due to the presence of aerosols in the

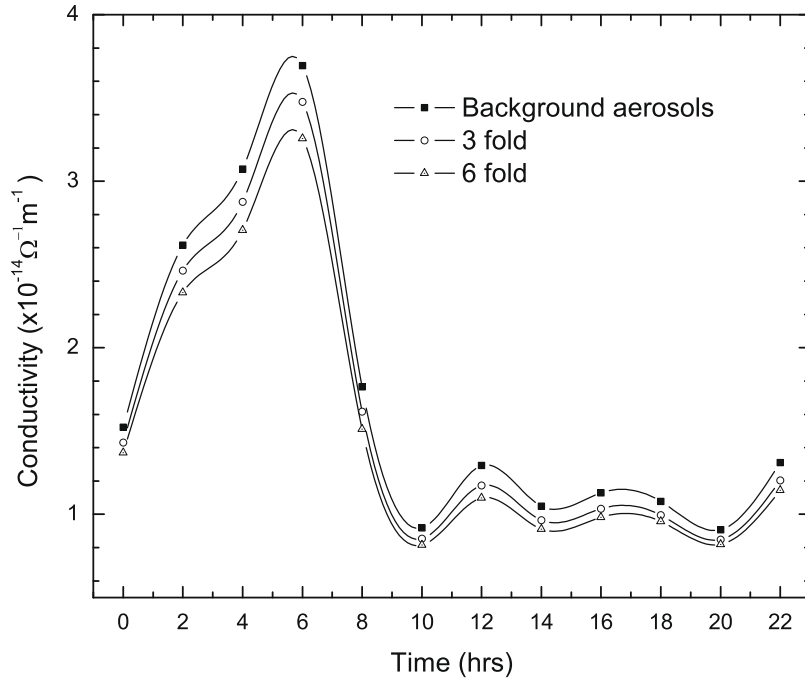


Fig. 7. Model predicted diurnal variation of conductivity under enhanced aerosol conditions.

atmosphere. Variation of conductivity due to enhanced (from the background) aerosols is plotted in Fig. 7. Three curves indicates that the conductivity decreases as the aerosol concentration increases.

Fig. 8 shows the percent reduction in conductivity due to the presence of aerosols derived from the model for normal condition. In the early morning hours the concentration of aerosols is less and the conductivity is more (Houghton, 1985). Convective currents in the morning

carry aerosol particles up from ground surface and the aerosols change the high-mobility small ions into low mobility large ions. Thus the conductivity decreases after sunrise (Dhanorkar et al., 1989; Petrov et al., 1999). As the day advances the aerosol concentration increases due to anthropogenic activities and conductivity decreases. The percent decrease in conductivity shows a diurnal variation with a minimum in the early morning hours when the aerosol concentration is minimum and reaches a maximum

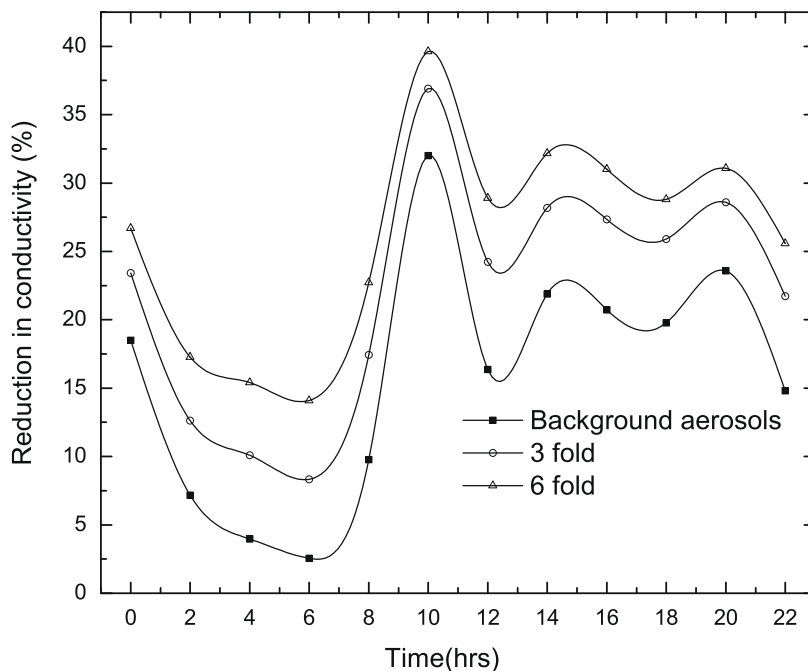


Fig. 8. Diurnal variation of percent reduction in conductivity under enhanced aerosol conditions.

(30–32%) in the afternoon when aerosol concentration also shows maximum. Due to pollution the concentration of aerosols increases and leads to decrease in conductivity of the atmosphere near the surface (Retalis et al., 1991; Dhanorkar and Kamra, 1993). Thus the measurement of atmospheric conductivity can be used as an index of pollution in the atmosphere.

Also estimated from the ion–aerosol model is the reduction in small ion concentration and hence the conductivity of the atmosphere for varying levels of aerosols and as seen in Fig. 8. The results reveals that, for an increase of background aerosols by threefold the percent reduction in conductivity is 7%, and for an increase of aerosols by sixfold the reduction in conductivity is 10% from the measured ambient aerosol level.

## 5. Summary

The electrical conductivity of the atmosphere is mainly due to the radioactive substances in the earth's crust and their emanation near the surface. The radiation emitted by the radioactive substances ionize the atmospheric air and leads to conductivity. The conductivity gets altered because of the existence of aerosols in the atmosphere. A simple ion–aerosol model has been developed to deduce the conductivity theoretically by using ionization rate, aerosol concentration, and different attachment and recombination coefficients for the loss of small ions as input to the model. The model agrees well with the experimentally measured conductivity. In addition to this, it is seen from the model that the percent reduction in conductivity is 7% and 10% for an increase of ambient background aerosols by threefold and sixfold, respectively.

## Acknowledgements

The authors (Nagaraja and Prasad) are thankful to Dr. A.K. Kamra and Dr. S.D. Pawar, Indian Institute of Tropical Meteorology, Pune, India for the fabrication of the Gerdien condenser and helping in taking measurements in their Institute.

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