CHAPTER I

1. INTRODUCTION

1.1 THE ATMOSPHERIC ELECTRICAL CIRCUIT

The existence of electricity in the earth's atmosphere was first discovered by the French scientist T.F. d'Alibart on 10th May 1752 at Marly near Versailles, and reported three days later to the Académie des Sciences in Paris, although it is generally attributed to the renowned scientist-statesman Benjamin Franklin of the United States. Franklin, without knowing about the Frenchman's discovery, independently conducted the experiment in June of the same year and obtained similar results. Both these experimenters, and several others who repeated the experiment, had confined themselves to the observation of the electrical nature of lightning strokes. The discovery that the atmosphere exhibits certain electrical characteristics even on a day of very fine weather was made by another French scientist, L.G. Lemonnier. He soon concluded that electrical phenomena are a permanent property of the atmosphere. Another important discovery of the early phase was that of C.A. Coulomb, who found that a well-insulated conductor, exposed to air, soon lost its charge. He concluded that air must be slightly conducting. Although this discovery was made in 1785, it was not properly appreciated at that time and lay ignored until the experiment was repeated a hundred years later.

The first attempt to explain the observed atmospheric electrical phenomena was made by Alessandro Volta. He hypothesized that as
water evaporates from the surface, it carries away some positive charge, leaving the earth negatively charged. Although this theory was eventually found to be incorrect, it is interesting to note that his theory has, in common with the modern understanding of the generation process of the atmospheric electric field, the phase transition of water contributing to the generation of the electric field. Later, A. Peltier proposed a slightly modified version of the theory. He proposed that the earth had an acquired negative charge which is carried upward by water evaporating from the surface. However, since the resultant charge concentration is less in the atmosphere than on the earth, the lower negative charge was being observed as a positive charge. In spite of its limitations, his theory is considered to be remarkably clear and consistent, and it enabled the problem to be tackled mathematically. This apparently helped later investigators like W. Thomson (Lord Kelvin) to virtually revolutionize the investigation of atmospheric electricity.

The modern theory of the atmospheric electrical circuit was originally formulated by C.T.R. Wilson (1920, 1929) and A. Wigand (1927 a,b), who were the first to suggest that the driving force behind the atmospheric electric circuit was to be found in the so-called "disturbed" regions of the atmosphere – namely, the large number of active thunderstorms always present around the globe. The existence of ions in the atmosphere (Elster & Geitel, 1899), and that of the highly conducting layer in the upper atmosphere, the Kennelly-Heaviside layer, had already been established by then. Still the world was not very willing to accept the new theory, mainly because it conflicted with the existing knowledge about the thunderstorm at that time. Their theory has, however, come to stay, and the accepted model of the atmospheric
electric circuit largely follows the lines suggested by Wilson and Wigand. Generally known as the "spherical capacitor theory", an outline of the model is given below.

1.1.1 The spherical capacitor theory

Electrical processes in the earth's atmosphere have their origin in the production of ions in the air. Ionization of air below about 60 km is mainly due to galactic cosmic rays. As the cosmic rays penetrate deeper into the atmosphere, they produce greater ionization, down to about 15 km altitude. Below this altitude ionization is seen to decrease progressively down to about 2 to 3 km. Over land, from the surface up to 2 to 3 km, the dominant ionizing agent is radioactivity. Very close to the surface, the nuclear radiations from the radioactive minerals in the soil dominate. Their influence, however, is limited to a very short distance. At higher altitudes, radioactive gases released from the soil and their decay products which are radioactive, only are important. The concentration of these gases, and consequently the ionization produced by them, decreases with altitude.

The ionization of air results in air having a finite conductivity. The conductivity of air depends on the concentration and mobility of ions. Mobility is the drift velocity acquired by an ion in a unit electric field. It depends on the mass, being higher for lower masses. To be precise, the conductivity due to one type of ions is the product of the concentration $n$ and mobility $\mu$ of the ions and the charge on the ions. If more than one type of ions are present, then the contribution from
each type will have to be accounted for. Thus the positive or negative polar conductivity can be written as:

$$\lambda^\pm = \sum n^\pm e \mu^\pm$$ (1.1)

where \(n^+, \mu^+,\) and \(e\) are the number density, the mobility, and the charge on the ions, respectively, and the summation is taken over the different types of ions present. Since both positive and negative ions are present in the atmosphere, the total conductivity of air is the sum of the polar conductivities, that is, \(\lambda_{\text{tot}} = \lambda^+ + \lambda^-\). Virtually all the ions found in the atmosphere are singly charged, so that the \(e\) in the equation becomes equal to the electronic charge. Ion number density does not vary very widely in the region of the atmosphere below about 70 km. On the other hand, ion mobility, being a function of mean free path, increases exponentially with altitude. Conductivity also consequently increases rapidly with altitude, except in the region from the surface up to 2 to 3 km. (This is the region where ionization is mainly due to radioactivity, and conductivity decreases with altitude). A typical conductivity profile from the surface up to 35 km, measured from Hyderabad, India (Murali Das, et al., 1991) is shown in Figure 1.1.

At an altitude of about 60 to 65 km, the conductivity is sufficiently high for any electrical disturbance at one point to be distributed all over the globe within a time period that is small compared to the time scales of the electrical processes in the atmosphere. This equalization layer is usually called the electrosphere. Often, the ionosphere is taken as the equalization layer.

The electrosphere and the earth's surface together form a spherical capacitor that acts as the main element in the atmospheric electrical circuit. This capacitor is charged continuously by the
Figure 1.1 Variation of positive polar conductivity between the earth's surface and 35 km altitude measured from Hyderabad, India (after Murali Das, et al., 1991).
roughly 1500 active thunderstorms present around the globe at any given moment. The electrospheric potential has been found to be about 250 to 300 kV (for instance, Markson, 1985). This is maintained by the charging current from the thunderstorms and a corresponding discharge current that flows through the fair weather region of the atmosphere. The charging current from the thunderstorms to the electrosphere is mainly a conduction current. Charge transfer from thunderstorms to the earth takes place in different forms. Lightning is the most obvious process. The rain from these clouds also carry some charge (Chalmers, 1951 a). Point discharge currents from pointed objects beneath the thunderstorm is also important (Chalmers, 1951 b; Kamra & Varshneya, 1967). Significant currents may be provided even by point discharge beneath dust storms (Kamra, 1969,b), which are known to be electrified. The discharge current is a conduction current that flows from the electrosphere to the earth, the magnitude of which at a given place depends upon the columnar resistance of the atmosphere at that place. Since it may be assumed, as a first approximation, that there are no current sinks in the atmosphere, the electrosphere-earth current can be considered to be constant with altitude. This, in combination with the varying conductivity, creates an electric field that varies with altitude in a manner that is opposite to that of conductivity. This electric field is almost entirely oriented in a vertical direction since horizontal gradients of electric charge are of a very small magnitude throughout the atmosphere. The electric field \( E \), the conduction current density \( J \), and the conductivity \( \Lambda \) at any point in the atmosphere are related by the equation \( J = \Lambda E \). From the discussion above, it can be seen that the independent parameter here is the conductivity \( \Lambda \), the other two being dependent on it (and the electrospheric potential).
Figure 1.2 Schematic diagram of the atmospheric electric circuit.

The spherical capacitor consisting of the earth and the electrosphere, the power source formed by the large number of active thunderstorms around the globe that charges this capacitor, and the fair weather region of the atmosphere that acts as a leaky dielectric and provides the discharge path together forms the atmospheric electric circuit. Figure 1.2 shows a schematic diagram of the atmospheric electric circuit. Analytical and numerical models of the whole circuit and parts of it have been constructed and studied by several workers, for instance, Hoppel (1967), Chand & Varshneya, (1973), Hays & Roble

The description given above is for an ideal situation where there are no external factors that influence the circuit. Since the earth and the electrosphere are considered to be almost perfect conductors of electricity, it used to be presumed that electrical influences from outside this region would not penetrate below the electrosphere. However, there is growing evidence to the contrary. For instance, coupling between ionospheric and lower atmospheric processes have been reported (Park & Dejnakantrina, 1973; Park, 1976; Dutra et al, 1992). Solar flare has been found to modify electric fields in the stratosphere (Holzworth & Mozer, 1979) and at the surface (Cobb, 1967; Sao, 1967; Reiter, 1969; Reiter, 1971). Markson (1978), Muir (1979) and Markson & Muir (1980) have suggested the possibility of sunspots and other sun-related phenomena affecting the electrical processes on the earth and thereby even the weather.

1.2 ION PRODUCTION IN THE ATMOSPHERE

As mentioned in the previous section, the main reason for the existence of electrical phenomena in the earth's atmosphere is that air is a conductor of electricity, although a weak one. This is due to the presence of ions in the air. Both positive and negative ions are present in equal numbers so that on the whole the air is neutral. These ions are produced in air by the removal of one or more electrons from some of the air molecules. This is possible if sufficient energy for the removal of the electrons is supplied by some external source. After
ionization, the ions formed undergo changes very quickly, through electrostatic interactions with other molecules and aerosols present in the air, until a relatively stable structure is formed. This survives in a more or less unchanged form until two ions of opposite polarity meet and combine to form neutral species. A brief outline of the processes involved is given in this section.

1.2.1 Sources of ionization

In the earth's atmosphere, ionization is produced by different agencies in different regions. Above about 60-65 km altitude, the main source of ionization is electromagnetic radiations from the sun, ranging from X-rays to the ultraviolet. In the region below, galactic cosmic rays form the main source, except in a thin layer, of about 2 to 3 km, over land. In this region, the dominant sources of ionization are the nuclear radiations from radioactive minerals in the soil, and the radioactive gases released into the atmosphere from the soil and their daughter products. In the region where ionization is due to solar radiation, the rate of ionization shows large variations with time because of the variations in the incident radiation. Since galactic cosmic ray intensities remain more or less uniform over long periods, the ion production rate in the region of the atmosphere from about 2 to 3 km to about 60-65 km altitude remains constant with time; but it shows a variation with latitude. The occurrence of radioactive minerals varies widely from place to place, and the presence of radioactive elements in the air is also influenced by meteorological factors. Ionization due to radioactivity is therefore strongly dependent on the place and time. Since the present work is confined to a region close to the surface,
natural radioactivity and its atmospheric electrical effects will be discussed later in somewhat greater detail.

There are other sources in the atmosphere whose contribution to the total ionization is rather small, but may be important at specific places during specific time periods. The lightning discharge is one of them. Lightning is produced mainly as a part of thunderstorm activity, although similar discharges have been observed during volcanic eruptions, and even during a strong dust storm (Kamra, 1969,b). Snow storms and dust storms are known to be highly electrified (Kamra, 1972, a). Kamra (1972, b) observed sparks extending a few metres upward into the air over gypsum dunes in New Mexico when strong winds were blowing large quantities of sand into the air. Apart from these phenomena involving intense activity, it has been found that ions are generated in several common processes. For instance, it has been found that the water splashing at the bottom of a waterfall releases ions into the atmosphere (Lenard, 1892; Pierce & Whitson, 1965). Water drops falling from a height, for instance during rainfall, on different types of surfaces release ions at different rates (Chate and Kamra, 1992). This mechanism does not produce ions of both polarities in equal quantities, so that a net space charge results. Sea surf is another mechanism that generates ions of one polarity, namely positive, preferentially (Muir, 1977). Human activities like industrial plants, automobile exhausts, etc. and structures like high voltage power lines and even tall buildings, communication towers, chimneys, etc. (Kamra, 1991) can also release ions into the atmosphere.
1.2.2 Ionization due to radioactivity

The earth's atmosphere contains radioactive elements that contribute to the ionization of air. Of these, the largest fraction is contributed by the radioactive elements present in the rocks and soils in the form of minerals. Rocks and soils contain radioactive elements like uranium and thorium. Nuclear radiations from them ionize air in a thin layer close to the ground. In addition, their decay products are radioactive gases which are released into the air and are transported vertically and horizontally, and contribute to ionization over a much larger region of the atmosphere. Another group of naturally produced radioactive nuclei are those generated in the atmosphere by the collision of cosmic rays with air molecules. These are insignificant in quantity and can be ignored for the purposes of atmospheric electricity. The third group is of recent origin and consists of radioactive elements released into the atmosphere due to human activity. Nuclear tests carried out in the atmosphere were a major source for this before such tests were banned in 1964. The effect of these explosions on atmospheric electric parameters have been studied, and are discussed in a later section. At present only the inadvertent leaks of radioactive gases into the atmosphere fall in this category, and can be ignored. However, large scale leaks, like the one from the ill-fated reactor at Chernobyl, do produce significant changes in the atmospheric electrical parameters, as discussed later. In this section, a brief account is given of the naturally occurring radioactive elements and their influence on atmospheric electricity.
The rocks and soil in the solid earth contain radioactive elements like uranium and thorium in the form of minerals like monazite and uraninite, their concentration varying from region to region. Decay of these elements releases α, β and γ radiations, along with daughter products, which themselves may or may not be radioactive. Some of the daughter elements are gases like radon and thoron. These gases either are released into the atmosphere or get trapped within the rock/soil, depending on the permeability of the surrounding material. The radioactive gases released from the soil get mixed with air and contribute to ionization during their decay. The concentration of these gases vary from place to place, and with altitude at any given place. The distribution of these gases with altitude depends on atmospheric stability. The decay products of these gases are mostly radioactive elements, and they also contribute to the ionization of air.

Apart from the radioactive gases released from the soil and their daughters, the nuclear radiations from the radioactive minerals in the soil also produce ionization in the air. However, only γ rays, and to a lesser extent β rays, are important in this respect. The α rays and much of the β and γ rays produced beneath the top most surface of the soil get absorbed in the soil itself. The α rays penetrate only a few centimetres into the atmosphere, losing their energy very fast through ionising interactions with air molecules. While β rays penetrate to a somewhat greater distance, γ rays have a much smaller interaction with air and thus penetrate several metres into the atmosphere. Several metres above the ground, the intensity of ionization due to the different ionizing radiations is as follows (Bricard, 1965):
Cosmic Rays 20 %

From air:
\[\begin{align*}
\alpha \text{ rays} & \quad 44 \% \\
\beta \text{ rays} & \quad 0.3\% \\
\gamma \text{ rays} & \quad 1.5\%
\end{align*}\]

From soil:
\[\begin{align*}
\beta \text{ rays} & \quad 3 \% \\
\gamma \text{ rays} & \quad 32 \%
\end{align*}\]

Thus the land surface provides another source for atmospheric ionization. Ionization due to radioactivity decreases with altitude and becomes comparable to that due to cosmic rays at altitudes around 2.5 to 3 km. The vertical profile of conductivity is thus modified by the presence of surface radioactivity. It may also be mentioned here that surface radioactivity has no effect on the air above water bodies because the nuclear radiations cannot penetrate the water layer. Above the oceans, the total natural radioactivity is reduced to a few hundredths of its value above the ground (Bricard, 1965). Since atmospheric electrical conductivity is lowest in the bottommost portion of the atmosphere, the contribution to conductivity by radioactivity assumes significance as far as atmospheric electrical processes are concerned. And since this source of ionization is at the surface, it cannot be ignored during investigations at the surface. A brief description of the exhalation of the isotopes of radon from the soil and their distribution in the atmosphere is given in a separate section below.
1.2.3 Formation and recombination of ions

When ionizing radiation interacts with atmospheric air, the ions created are mostly nitrogen and oxygen molecular ions since these gases constitute about 99% of air. These ions cannot exist as such. Due to electrostatic interaction, they are soon surrounded by neutral molecules. The ions become stable only when each ion is surrounded by about 20 to 30 neutral molecules. This is known as a small ion, and has a mobility of the order of $10^{-4}$ m$^2$V$^{-1}$s$^{-1}$. The charge can also get transferred to other molecules or atoms present in the atmosphere by ion chemical reactions that have not been fully understood. The electron released during the ionization immediately attaches itself to a neutral molecule, forming a negative ion. This also undergoes growth and transformation like the positive ion, although the chemical species to which the negative ions get attached are different from that of positive ions. The negative ion has been observed to have a somewhat higher mobility, or in other words, a lower mass, than the positive one.

Ions in the air tend to adhere to aerosol particles, thus becoming considerably heavier and less mobile. The aerosol particle sizes involved are mainly between about 0.01 μm and 1 μm. The mobility of these so-called large ions become as low as about $10^{-8}$ m$^2$V$^{-1}$s$^{-1}$ and their contribution to conductivity can be ignored for most purposes. Hence, from this point of view, it may be said that the small ions that get attached to large aerosol particles are effectively "lost", so that attachment is often treated as one of the loss processes of atmospheric ions. 

Jonassen & Wilkening (1965), for instance, show that both positive
and negative polar conductivities are well correlated with the corresponding small ion densities.

The ultimate loss of both polarities of ions is by mutual recombination. This occurs during chance collisions between positive and negative ions during their Brownian motion. If recombination is the only mode of ion loss, then we can write an approximate equation for the ion balance in air. Let $q$ be the ion pair production rate, $n$ the number of positive or negative ions, and $a$ the recombination coefficient. $a$ is the number of ion pairs undergoing recombination per second per ion pair present, or the probability of an ion being lost through recombination. Then we can write:

$$\frac{dn}{dt} = q - an^2.$$  \hspace{1cm} (1.2)

Since the left hand side of the equation will tend to zero under equilibrium conditions, we can solve for $n$ to get:

$$n = \sqrt{\frac{q}{a}}.$$  \hspace{1cm} (1.3)

### 1.2.4 Effect of aerosols

Aerosols are small solid and liquid particles suspended in the air. They are of interest to the student of atmospheric electricity because atmospheric small ions tend to adhere to these particles and get converted to large ions having very low mobility. The simple picture presented in the previous section therefore is only that of an ideal situation, and the effect of aerosols has to be taken into account before a realistic picture can be formed.
The sizes of aerosol particles range from about $10^{-9}$ m to less than $10^{-4}$ m. They are generally classified into three, namely, (i) Aitken particles whose diameters are less than 0.1 μm, (ii) large particles whose diameters range from 0.1 to 1 μm, and (iii) giant particles which are larger. Their concentration can vary widely, depending on the type of environment. In marine air, especially in remote regions like the Antarctica, counts as low as $10^8$ m$^{-3}$ are seen. In continental areas, the concentration is around $10^9$ to $10^{10}$ m$^{-3}$ in relatively clean rural air. In urban areas, and close to industrial establishments, the count could go as high as $10^{11}$ to $10^{12}$ m$^{-3}$ (Twomey, 1977, p18). Aerosol particles are generated mainly from two different mechanisms, namely dispersal of materials from the earth's surface, and chemical reaction and condensation from atmospheric gases and vapours (Mészáros, 1981, p98). Particles injected into the atmosphere from the bursting of gas bubbles at the surface of sea water, and mineral particles blown into the air by wind are examples of the former. These are usually larger than 0.1 μm and hence fall into the category of large particles. The smaller Aitken particles are usually generated by the second mechanism. Apart from these, there are other sources that may be insignificant on a global level, but could be important at specific locations or times. Volcanic eruptions, meteors, forest fires, industrial and automobile exhausts, etc. are some examples. Apart from these, particles of biological origin like pollen grains and bacteria also form important components in certain specific environments. Aerosol particles are usually composed of several materials, and the composition can vary with place and time. This is because the particles are continuously interacting with the surroundings and going through coagulation, condensation and gas adsorption processes. The composition is also different for the different size ranges.
Ammonium sulphate, sodium chloride, sulphuric acid, organic compounds, nitrates, etc. are some of the commonly encountered substances. The concentration of aerosols reduces rapidly with altitude.

The particles of interest in atmospheric electricity are the Aitken particles. They are the ones which contribute most to the conversion of small ions into large ions. The attachment coefficient of small ions to aerosol particles is different for different particle sizes. A theoretical analysis that takes into consideration the aerosol spectrum and the variation of attachment coefficient with particle size is very involved and many of the parameters required are still unknown. However an approximate calculation using total aerosol concentration and a suitable average attachment coefficient can be made. From such an analysis, the concentration of small ions in the presence of aerosols is given by the equation (Twomey, 1977):

\[
n = \frac{-\eta_1 N_1 - \eta_0 N_0 \pm \sqrt{\left(\eta_1 N_1 + \eta_0 N_0\right)^2 + 4\alpha q}}{2\alpha}
\]

where \(\eta_0\) and \(\eta_1\) are the recombination coefficients for an ion with a neutral particle and ion of opposite polarity respectively, and \(N_0\) and \(N_1\) are the concentrations of neutral and charged aerosol particles. The effect of aerosols on small ion concentration is illustrated in Figure 1.3. The values used are: \(q = 20 \text{ cm}^{-3}\text{s}^{-1}\), \(\alpha = 1.6 \times 10^{-6} \text{ cm}^{3}\text{s}^{-1}\), and attachment coefficients are the highest and the lowest values given by Israel (1971), p 162.

Aerosols thus influence the concentration of small ions. Highly polluted regions therefore tend to have much lower electrical conductivity than regions having clear air. Ion lifetimes are reduced from about
Figure 1.3 Variation of small ion concentration with aerosol concentration.

300 s in clear air to about 20 s in highly polluted air (Cobb, 1973). In polluted regions, therefore, atmospheric electrical measurements may have to be supplemented with aerosol measurements if any comparison is to be made with data from other regions.

1.3 DIURNAL AND SEASONAL VARIATIONS

The atmospheric electrical circuit described above does not remain in a constant steady state at all times. Various environmental factors influence the circuit so that the circuit parameters are constantly changing. Near the earth's surface, two different kinds of variations can be discerned. One is global in nature, felt uniformly all over the earth, and is mainly due to the variation in global thunderstorm activity
and the consequent variation in the electrospheric potential. The second is of local origin, and is due to local changes in weather, human activity, etc. Pollution is another parameter that varies not only with place, but also with time, and influences the electrical parameters. Traditionally, the study of atmospheric electrical phenomena has been divided into two different areas, namely, the fair-weather and the disturbed weather portions. In the former, only data pertaining to fair-weather periods, defined as periods without rainfall, with low cloud cover and wind speed, etc., are selected. Disturbed weather studies normally concentrate on periods of thunderstorm activity, including effects of lightning. Therefore the normal diurnal and seasonal variation patterns of the atmospheric electrical parameters usually refer to that during the fair-weather periods. A brief description of these variations is given below.

Global thunderstorm activity shows a clear diurnal pattern. This follows the movement of the sun across the major continental land masses where it initiates thunderstorm activity. A higher thunderstorm activity results in a larger flow of charging current, and thus to a higher electrosphere voltage. This is reflected in a well-defined diurnal variation pattern in the vertical electric field observed over the oceans and in remote areas like Antarctica. Since this global variation is usually masked by local effects, it cannot be easily observed from a land station, especially one that has a significant population. One of the earliest observations of the global diurnal variation of the vertical electric field was carried out during a cruise of the research vessel Carnegie. Since the observations were carried out entirely over the oceans, local perturbations that are present over land regions were
Figure 1.4 Diurnal variation of the vertical electric field over the oceans observed in the cruise of the research vessel Carnegie.

virtually avoided. The observed pattern, shown in Figure 1.4, has come to be known as the Carnegie curve, and is universally accepted as the standard diurnal variation of the electrospheric potential.

1.3.1 Temporal variation of conductivity

Near the earth's surface, electrical conductivity is not constant with time. Long period observations at various sites have shown that atmospheric electrical conductivity shows well defined diurnal and seasonal variations during fair weather periods. The exact nature of variation is different for different stations, and the mean values and amplitudes are also different. For a given station, the pattern of variation of conductivity at the surface normally remains more or less
constant during a year. The mean behaviour at each station may therefore be said to constitute a characteristic of the "atmospheric electric climate" for that station. But some similarities are seen in the diurnal behaviour of conductivity at most stations. For instance, conductivity is usually high during night time. This is possibly a reflection of the general rhythm of the atmosphere, since nights are usually calmer, with low winds and hardly any convective motion, and therefore conducive for the accumulation of radon and other radioactive species near the surface. A sharp fall associated with sunrise is seen at many stations. This is believed to be due to an increase in the aerosol concentration due to onset of circulation and human activity, and has often been called the "sunrise effect", although a slightly different and unexplained phenomenon is known as the sunrise effect, as explained later. The behaviour during the rest of the day differs from station to station. Some stations show a single oscillation type of pattern, with one maximum and one minimum, while some others show a double oscillation behaviour. Figure 1.5 shows typical examples of the diurnal variation of conductivity. The curve showing the single oscillation is for Gulmarg (Raina & Raina, 1988), and the other is for Athens, Greece (Retalis & Zervos, 1976).

The situation is different over the oceans, with hardly any change between locations. In marine air, the mean conductivity is slightly higher than that over land but the diurnal amplitude is very low. And unlike over land, conductivity is minimum in the late afternoon and early evening hours and remains low during night. It rises to a peak in the forenoon and is followed by a gradual decline. This is almost a mirror image of the pattern seen over continental stations. Further,
Figure 1.5 Examples of (a) single and (b) double oscillation types of diurnal variation of positive polar conductivity.
while the positive polar conductivity displays a clear variation in the manner described, the variation in the negative polar conductivity has a very low amplitude and is just discernible. The ratio of polar conductivities thus exhibits a clear diurnal pattern over oceans (Israel, 1971, p 97).

1.3.2 Temporal variation of the vertical electric field

Apart from the global variation observed in marine environment, described in the previous section, the vertical electric field measured at any continental station (other than Antarctica) shows a diurnal pattern that is due to local perturbations. If $R$ is the columnar resistance of the atmosphere (the resistance of a vertical column of unit cross section) and $V$ is the potential of the electrosphere, then the electrosphere-earth current density $J$ will be $V/R$. Now if $\rho$ is the resistance of an air column of unit height and unit cross section at the measurement site, then the potential drop across this height, equal to the vertical electric field at that point will be $E = J \cdot \rho = (\rho/R) V$. The columnar resistance of air is almost constant in all fair-weather regions of the atmosphere, having a value of about $10^{17}$ ohms per square metre. The vertical electric field is thus seen to have a dependence on the specific resistance of air at the location, or in other words to the conductivity of air. As explained below, the conductivity of air at any land station shows a certain diurnal pattern that can vary from place to place, and is also affected by environmental factors like the weather, pollution, etc. This is consequently reflected in the vertical electric field also.
Electric field measurements have shown that the strength of the vertical electric field is more or less similar over land and sea. Marine measurements have indicated a certain latitude dependence, the field being higher at higher latitudes. Diurnal and seasonal variations have been observed over land stations. Israel (1971) classifies these into three types, namely,

i) the **single oscillation continental type**, where the field strength passes through a single oscillation with the minimum around 0400 hr local time and a maximum in the late afternoon;

ii) the **double oscillation continental type**, where it shows a double oscillation with the minima around 0400 and 1400 hr and maxima around 0900 and 2100 hr local time; and

iii) the **universal time type**, where a single oscillation is seen with minima around 0400 hr UT and maxima around 1600 - 1800 hr UT.

The first two types are observed only over continental stations. The type of variation depends on the season, weather and locality. In winter, the single oscillation type and in summer the double oscillation type usually occurs. However, some stations have the same type of variation throughout the year. Type (iii) is seen only in the polar regions and also over the oceans (Israel, 1971). Some examples of the three types of variations are shown in Figure 1.6. Factors that alter the normal pattern of variation are solar eclipse (Anderson & Dolezalek, 1972), sea breeze (Trevitt, 1984), etc.

An interesting feature in the behaviour of the vertical electric field is a sharp increase seen after sunrise. Since a decrease in
Figure 1.5 Examples of the three types of diurnal variation of the vertical electric field (after Israel, 1971).

Conductivity is seen around this time, the increase in electric field is natural. What makes it interesting is the fact that the change in electric field is not commensurate with that of conductivity. In other words, it is accompanied by an increase in the air-earth current density. The increase in the electric field is in agreement with the decrease in conductivity and the increase in air-earth current density. The effect is more pronounced at low altitude stations in the plains and less evident at mountain tops. It shows a clear increase from winter to summer (Israel, 1971, p 405-8). A pseudo-sunrise effect has been observed at the end of a solar eclipse also (Anderson, 1972).

Although first observed by E.H. Nichols in 1916, and rediscovered by R.E. Holzer in 1955 (Chalmers, 1967), this phenomenon is yet to be explained fully. Kasemir suggested that the positive space charge that accumulates near the earth's surface at night is transported upward with the onset of circulation, thus constituting a current in the opposite direction from the one that normally flows, and that this may be the reason for the observed increase in electric field and air-earth current. Chalmers, however, showed that this cannot give a complete account of the phenomenon. Kamra (1969,a) argued that the effect was related to
the increase in air temperature in the morning rather than to sunrise, and that the cause is related to the increase in aerosols due to the onset of circulation. Muir (1975) suggested that the sunrise effect may be due to an increase in the electrospheric potential, and suggested a mechanism that could produce the desired effect.

1.4 RADIOACTIVITY IN THE ATMOSPHERE

As mentioned in Section 1.1, surface radioactivity plays an important role in atmospheric electrical processes near the earth's surface. While there have been some investigations into the behaviour of atmospheric electrical parameters under the influence of radioactivity, detailed studies have been very rare. This section gives a brief outline of atmospheric radioactivity and the studies carried out in relation to atmospheric electricity.

1.4.1 Radioactivity at the surface and in the atmosphere

Radioactive atoms in the earth's atmosphere can be divided into three groups based on how they are produced. The first, and by far the biggest, group consists of the radioactive gases released from the soil and their daughters. These are mainly the three isotopes of radon, namely, radon (Rn$^{222}$), thoron (Rn$^{220}$) and actinon (Rn$^{219}$), and their decay products, which are not all gases. The second group consists of the radioactive isotopes produced in air by the action of cosmic rays. The third group is of a relatively recent origin - that of isotopes released into the air by atmospheric nuclear explosions and other anthropogenic
causes. In the context of atmospheric electricity only the first group is important.

The earth's crust contains small quantities of uranium\(^{238}\), uranium\(^{235}\), and thorium\(^{232}\) in the form of minerals. They are present everywhere in varying concentrations. All of them decay into isotopes of the same noble gas, namely radon. These gases accumulate inside the soil and slowly diffuse up into the atmosphere. The rate of diffusion depends on the porosity of the soil and other environmental conditions. Once the gases escape into the atmosphere, they are transported horizontally and vertically by atmospheric turbulence. The rate of transport then depends on the strength of the turbulence.

A simple model proposed by Israel (1958) and discussed by Junge (1963) for the exhalation and atmospheric mixing of the radioactive gases is useful to demonstrate the essential features of the processes. Let \(c_s\) be the concentration of the gas in the soil air, \(d\) its diffusion constant, and \(a\) its rate of production within the soil (in number of atoms per unit volume per second). If the soil is sufficiently porous, then the equilibrium condition within the soil can be expressed by the following equation:

\[
\frac{\partial c_s}{\partial t} = 0 = d \frac{\partial^2 c_s}{\partial z^2} + a - \Lambda c_s
\]

(1.5)

where \(z\) is the depth, \(t\) the time, and \(\Lambda\) the decay rate of the gas. The solution of this equation is:

\[
c_s = \left(\frac{a}{\Lambda}\right) \left[1 - \exp\left(-\sqrt{\Lambda/d} \cdot z\right)\right]
\]

(1.6)

where \(c_0 = \frac{a}{\Lambda}\) is the concentration of the gas in undisturbed soil air in deeper layers of the soil. The exhalation rate is then given by:
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\[ E_r = (d \frac{\partial c_a}{\partial z})_{z=0} = a \sqrt{d/\Lambda}. \tag{1.7} \]

The constants \( a \) and \( \Lambda \) being fixed for a particular kind of emanation, the exhalation rate naturally depends only on the diffusion constant in the soil, or, in other words, the porosity of the soil. The corresponding equation for the vertical transport of the gas in the atmosphere can be obtained from equation 1.5 by setting \( a = 0 \) and replacing \( d \) by the eddy diffusion coefficient \( D \). Although \( D \) is highly variable over space and time, and also with altitude, we can assume it to be constant with altitude, as a first order approximation. The concentration of the gas in the air at any altitude \( h \) is then given by:

\[ c_a = c_{a0} \cdot \exp(-\sqrt{\Lambda/D}h). \tag{1.8} \]

A typical profile of the concentration of radon in the air above the surface and in the soil is given in Figure 1.7.

The exhalation rate of radon depends on the soil conditions. Apart from the variations due to the porosity of soil, soil temperature and moisture, and meteorological factors like rainfall are known to influence the exhalation rate. Decreases of up to 70% due to rainfall have been observed. Seasonal variations generally show a minimum during summer and a maximum during winter. There are, however, several exceptions to this rule. In the eastern Alps, for instance, it shows a maximum in late spring. This is probably because the soil is frozen during winter, and radon is not able to escape (Junge, 1963, p217). Similar could be the case in the regions of our sub-continent where heavy rains during the monsoon could suppress radon exhalation.

There are several studies on the exhalation of radon from the soil and its distribution in the atmosphere. Schery et al. (1984) measured radon exhalation rate from a gravelly sandy loam in a semi-arid climate.
Figure 1.7 Theoretical profile of the concentration of radon above and below the soil surface (after Junge, 1963).
They found that the meteorological factors that affected the exhalation rate most were pressure and rainfall. Effects of other factors like temperature and wind were minor. The exhalation rate of Rn$^{220}$ was seen to be less influenced by pressure variations than that of Rn$^{222}$.

The radon content of surface air depends on the exhalation rate and atmospheric turbulence, the latter being the dominant factor. During a quiet day, it shows a maximum around sunrise when turbulent mixing is minimum, and a minimum in the afternoon when mixing is at its maximum. Wilkening (1959), apart from observing this kind of a diurnal pattern, also reports a good correlation with the gustiness of air. A minimum in the radon concentration that he observes during spring is attributed to the higher average wind speed. Moses et al. (1960) studied the effect of meteorological variables on the vertical and temporal distribution of radon at the Argonne Meteorological Laboratory, and found a strong relationship between the stability of the atmosphere and the concentration of radon. Liu et al. (1984) analyzed the data from several reported measurements and showed that in summer, about 55% of the Rn$^{222}$ is transported above the planetary boundary layer, which is considerably more than in the other seasons. They also found that in summer about 20% rises to over 5.5 km.

The decay products of these gases are heavy metals. They adhere to aerosols and are brought down by meteorological processes like rainfall.
1.4.2 Studies on relationship between radioactivity and atmospheric electricity

There have been several studies on the effects of radioactivity on the electrical structure of the atmosphere. Both natural and artificial sources of radioactivity have been objects of study. The former have mostly concentrated on ionization and the latter on the effect on the vertical electric field.

Pierce (1958) measured the variation in ion production rate with height from 1 cm to 1 m. He found that ion pair production rate decreased from about 60 cm⁻³ s⁻¹ at 1 cm to about 8 at 1 m. His results give a qualitative idea about the manner of variation with altitude of ionization by surface radioactivity.

Pierce (1957) studied the effect of nuclear explosions on the vertical electric field, and Pierce (1972) studied the secular effects of nuclear fallout. He found that for the period before 1952, the vertical electric field data shows no consistent change from year to year. After 1952, the field was found to decrease progressively to reach a minimum in 1959. A partial recovery was seen in 1960 and 1961 to be succeeded by a further decline in 1962-63. The vertical electric field started recovering to its earlier values from 1964 onwards. This behaviour corresponds to that of atmospheric testing of nuclear explosives carried out globally. Israelsson & Knudsen (1986) used polar conductivity, electric field and space charge data from Uppsala, Sweden, to identify the effect of the accident at the nuclear power plant at Chernobyl, USSR. They found that the conductivity increased about 11 times, the
electric field decreased about 10 times and the space charge density decreased about 10 times. These sudden changes were seen shortly after a rainfall on 29.4.1986, before which only a small and gradual change in the parameters was seen. They also found that after fairly heavy rainfall during May 11 to 13, the values recovered to normal. A similar study by Retalis (1987) showed that the small ion concentration started increasing on May 3rd and reached its highest daily mean value on May 5th. These maximum values were four times the normal for positive ions and 5 times for negative ions. Retalis & Pitta (1989) reported the effect of the Chernobyl accident on the vertical electric field, conductivity and small ion concentration at Athens. They also compared the results with radionuclide concentration and exposure rate in the air near the ground.

Wilkening & Romero (1981) measured the positive and negative ion densities, mobilities and polar conductivities in the Carlsbad caverns. Being unventilated, the air inside contained very high levels of Rn, although the surrounding rock strata contained only normal levels of uranium. They found the conductivities and ion densities to be two to three orders of magnitude higher than in the free atmosphere, indicating ion pair production rates higher by a factor of about 200. The small ion mobilities were found to be about half of that seen outside, possibly due to the high humidity inside.

Pierce & Whitson (1964) measured the vertical electric field in an area adjacent to the nuclear test site in Nevada, USA. The measurement was carried out both at the surface and up to 2 km using a balloon. They found the surface value to be about one third the normal.
vertical profile also was seen to be very much different from that over uncontaminated ground. The electric field was found to increase from the surface value of about 30 Vm\(^{-1}\) to about 100 Vm\(^{-1}\) at about 1.1 km, and then decrease gradually with altitude. As per their calculations, the normal field should be around 100 Vm\(^{-1}\) at about 500 m altitude. The difference seen over the contaminated ground was explained as being caused by the enhanced ion concentration over that region.

Thus the study of the effects of radioactivity on atmospheric electricity has been limited to a few isolated observations in regions that had a relatively higher concentration of radioactive substances. In all these cases, except the measurements in the Carlsbad caverns, the radioactivity has been from man-made sources. There appears to have been no concerted study of the behaviour of atmospheric electrical parameters in regions of high natural radioactivity.

**1.5 PRESENT STUDY**

As mentioned earlier, the study of atmospheric electrical phenomena has been traditionally divided into the fair-weather and the disturbed weather portions. While studying fair-weather phenomena, all efforts were made to eliminate the effects of meteorological and other influences by monitoring these parameters also and selecting data for periods when the values of these parameters were within specified limits. The study of disturbed weather phenomena was almost exclusively confined to thunderstorms and lightning.
In the present study, polar conductivity data have been obtained from four environmentally different sites in all kinds of weather conditions. The data are then analyzed together with meteorological data obtained from stations of the India Meteorological Department to bring out the influence of these parameters on conductivity. Of the four sites, two are coastal, very close to the sea, with one having a large deposit of the radioactive mineral monazite. The second coastal site and one of the inland sites have very little radioactivity. The fourth site is inland, though not very far from the sea, and has a moderate level of background radioactivity. The data from three aircraft surveys of polar conductivities covering the region of study are also presented and discussed.